PBL Netherlands Environmental Assessment Agency

ON THE SCIENCE OF CARBON DEBT

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Contents

Key recommendations

Six key recommendations are drawn from the discussion and analysis presented in this report:

1. When developing or reviewing policies directed towards supply and use of biomass, for bioenergy or non-energy purposes including for wood products the following points should be taken into account:
   - Openly acknowledging and addressing the risks that supplying biomass can incur a carbon debt.
   - Recognising the possibility for biomass to be carbon neutral.
   - Actively considering the potential opportunities for synergies between producing biomass and conserving or enhancing carbon stocks in terrestrial vegetation and soils.

2. Significant caution is advisable when considering whether published scientific studies of the greenhouse gas emissions associated with biomass use, particularly those concerned with 'biogenic carbon' emissions (see definition later in this summary), are relevant for informing policies on biomass sustainability. A set of key critical tests could be developed for referring to when reviewing studies, covering points such as whether a clear research question is stated, whether this question is relevant for informing policies, and whether the technical methods are appropriate for addressing the question.

3. Simplistic statements and claims about the climate impact of biomass-based products including bioenergy, such as illustrated by examples in this report, should be avoided in communications about biomass policies and biomass sustainability.

4. Existing technical methods supporting policies, such as biomass sustainability criteria, should be compared with the refined and elaborated methods proposed tentatively in this report, to identify where they are consistent and where there may be gaps.

5. Consideration should be given to further development and testing of the technical methods described in this report, where needed to ensure the use of biomass contributes positively to climate change mitigation objectives.

6. It must be recalled that biogenic carbon emissions represent one issue amongst several that need to be addressed by sustainability frameworks addressing biomass use. It is important to clarify the relationship between policies addressing the greenhouse gas emissions of biomass and wider sustainability frameworks, to ensure their effective and efficient integration.

Extended summary

As pointed out in the Dutch National Climate Agreement, biomass will likely play an important role in a climate-neutral, circular economy. Since the public and political debate on biomass is ongoing, the Dutch Cabinet intends to set up an extended sustainability framework for biomass as laid out in as laid out in letters to the parliament in October 2020 and April 2022. It builds upon the existing framework which covers both transport fuels and electricity and heat from biomass and is consistent with European biomass-related legislation as laid out in the Renewable Energy Directive (REDIII) and the EU-Deforestation, FuelEU Maritime, and the ReFuelEU Aviation Regulations. The extended framework is mainly aimed at mandatory criteria for bio-based plastics and building products.

What is 'carbon debt?'

'Carbon debt' is a frequently encountered term in discussions about whether using biomass, for bio-based products and especially for bioenergy, makes a positive or negative contribution towards climate change mitigation. The term refers to CO_2 emissions that may result from supplying and using biomass from agricultural land and forests. These emissions are principally related to negative impacts on carbon stocks in terrestrial vegetation and soil caused by biomass harvesting. The CO_2 emissions are considered a 'debt' insomuch as they can be 'paid back' through use of bioenergy and other bio-based products to displace other products causing higher emissions including fossil fuels. It must be stressed that, although 'carbon debt' can be described quite simply as a concept, it requires careful definition in technical discussions. The situation is complicated because there is no universally accepted definition, and scientific studies and policy reports on biomass and bioenergy can use the term with different meanings and interpretations. The precise definition of carbon debt used in this report is given later in this summary (Box S2), along with definitions for the related terms 'biogenic carbon', 'carbon neutrality', 'carbon gain', and 'carbon payback time'.

Carbon debt in legislation

Attempts to include the issue of carbon debt in legislation has been going on for more than a decade, but has not (yet) succeeded, mainly due to the complexity of the issue. Therefore, the letter in 2020 also announced that PBL will report on the scientific state of affairs concerning the subject of 'carbon debt' in relation to biomass use. This report is intended to do so by providing an overview of scientific understanding of the phenomena of carbon debt and carbon payback times and it also suggests science-based policy principles and recommendations to minimise the risk of high carbon debts and long payback times.

Purpose and scope of this report

This report aims to:

- Clarify the circumstances under which biomass produced from forests can result in a carbon debt or carbon gain, or might be carbon-neutral, with the main focus on biomass used for energy;
- Analyse the reasons why studies on forest biomass show differing results for carbon losses or gains;
- Identify where variability in the carbon balance of forests supplying biomass is systematic, with underlying causes that might conceivably be understood, and so enabling the management of both risks and opportunities when deploying forest biomass resources;

- Explore the options for practice and policy to support the effective use of forest biomass as a renewable energy source that contributes to climate change mitigation.

Biomass from agriculture

The report focuses on forest bioenergy, because the question of whether forest bioenergy could help reduce greenhouse gas emissions has been hotly debated in recent years. Supplying biomass including for bioenergy, from agricultural sources involves similar opportunities and risks to those explored in detail in this report for forest biomass. Similar methods can be applied to quantify the effects on the carbon balance of agricultural biomass production and extraction. In principle, the kinds of framework proposed for managing the carbon impacts of forest biomass sources (see later in this summary) could be designed to also cover agricultural sources. Generally, understanding and managing carbon dynamics in forests involves more complexities than for agricultural systems because of the long rotations involved in growing and managing trees (often over many decades). In contrast, agricultural crops are usually grown and harvested annually or on rotations of a few years at most. As a result, carbon dynamics in agricultural crops are generally much simpler than for forests and therefore easier to understand, as are the implications of management decisions (for example for levels of biomass production). Often the main concern in agricultural systems is how to manage any effects on soil carbon resulting from changes in agricultural practices.

General observations about biomass

To begin with, it is appropriate to reflect on 'what defines biomass', the reasons why biomass is important, and why there is so much discussion about its future role.

Biomass: a nature-based renewable resource

Biomass is a naturally occurring renewable resource – we can literally grow and re-grow what we use, for a diversity of possible applications, including wood-based products such as structural timber and paper, and burning biomass as an energy source ('bioenergy'). Examples of biomass resources include crops grown for their fibrous or woody stems and branches, residues from agricultural crops (e.g. straw and seed husks), wood harvested from forests, 'waste' biomass (e.g. offcuts of wood and sawdust produced in the forestry sector), post-consumer waste products derived from biomass, and animal manure and sewage.

Biomass has a multitude of uses

Biomass is unique as a natural resource in that it has a wide variety of applications, including for food, structural materials (such as sawn wood products and wood-based panels), paper, chemicals, plastics, pharmaceuticals, and various types of fuel. Many of these products would otherwise need to be made from non-renewable resources. Sustainable biomass offers unique opportunities to rapidly reduce emissions as it can be used to produce a wide range of alternatives to non-renewable and carbon-intensive products and fossil fuels. In the longer term, biomass has potential to reduce emissions in hard-to-abate sectors, such as construction and transport, including aviation and shipping. Biomass is also a natural store of energy, making it valuable as a complement to other intermittent renewable energy sources.

Biomass is key to developing a 'circular economy'

Biomass can be re-used, repurposed, recycled, and, ultimately, burnt with energy recovery. As such, it has a vital contribution to make to a 'circular economy', an economy that prioritises the use of renewable resources and aims to reduce overall resource consumption. A circular economy is essential in facilitating the transition away from fossil fuels and to achieve net-zero emission goals. Capturing carbon emissions from bioenergy could enable them to be stored in geological formations (a process known as bioenergy with carbon capture and storage, or 'BECCS'), contributing net negative emissions when using bioenergy. The captured carbon can also be used in, for example, the food, beverage, and manufacturing industries, or to produce fuels. However, discussion of applications relying on carbon capture is outside the scope of this report.

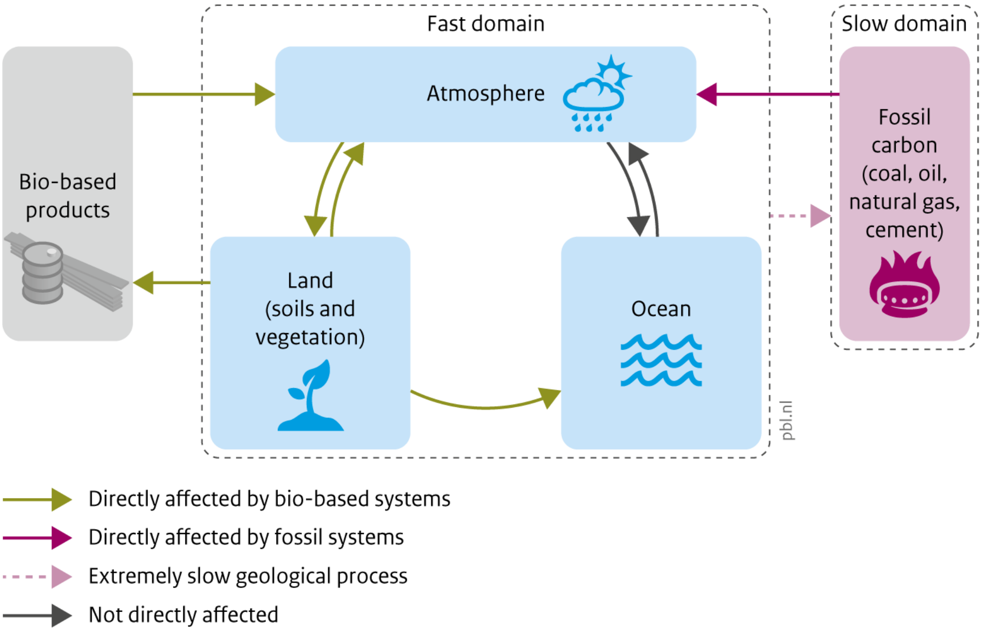
Biomass production can be a friend to sustainable development, but can also be a foe
Expanding biomass production can support progress towards sustainable development goals in a number of ways. Creating new areas of biomass crops and trees can help to restore degraded land, and the economic value of managing land to produce biomass can also sometimes encourage improvements in the management of farmland and forests. Some biomass production systems can diversify land use and offer a range of benefits, such as agroforestry systems with a more complex vegetation composition, which reduce the overall pressure on soil and provide a mixture of food and biomass products. Diversifying crops and trees can also increase their resilience to the negative effects of climate change. Biomass supply chains can support rural economies, creating and diversifying job opportunities.

But it must always be remembered that the capacity of terrestrial ecosystems to supply sustainable biomass and other products is not unlimited, and that some practices involved in biomass production can be detrimental. For example, there are significant negative impacts if biodiverse forest ecosystems are converted to biomass plantations, and increasing the rate of sustainable biomass harvesting from agricultural land and managed forests can diminish carbon stocks in vegetation and soil, in some circumstances. Fast growing biomass crops and forest plantations can relieve the pressure on forests with high conservation value but may put pressure on soils and water resources. Also, expanding biomass crops and forests can displace food production and local communities. In general, the production of biomass implicitly makes demands on land use and requires decisions about priorities when managing the finite land resource.

Fossil energy and bioenergy share similarities but also show important differences
The principal focus of this report is on the potential impact on CO_2 emissions resulting from the use of forest biomass as a source of energy. When carbon is released into the atmosphere as CO_2 by burning either fossil fuels or forest bioenergy, the effect on climate warming is essentially the same. In this sense, emissions from bioenergy are no different from those from fossil fuels and from production and use of other fossil-based products such as cement. However, in other respects, there are very important differences in the 'carbon cycles' of forest bioenergy and fossil fuels. These differences exist because of the very different rates at which carbon is accumulated in biological and geological systems (see Figure S1).

Carbon extracted from fossil sources is often called 'fossil' or 'geological' carbon, while carbon harvested from terrestrial vegetation systems is often called 'biogenic' carbon. Carbon accumulates in fossil reservoirs (i.e. coal, oil, natural gas, and limestone) at such a slow rate that losses from these reservoirs, when fossil fuels are combusted or cement is produced, can be regarded as effectively a one-way flow. Essentially, carbon is transferred irreversibly from geological reservoirs to the atmosphere. This is in contrast to the relatively fast circulation of carbon between biological systems (terrestrial and aquatic), the oceans, and the atmosphere.

Figure S1
The global carbon cycle



Source: Chalmers University of Technology, Sweden

Biomass use involves managing the balance between carbon sequestration and emissions

There is a continuous circulation of carbon between the biogenic carbon pools (i.e. agricultural crops, forests, wood products) and the atmosphere. Growing biomass takes carbon out of the atmosphere through the process of photosynthesis, using energy from the sun, and returns carbon to the atmosphere as the biomass decomposes or is burnt. Biomass use, including for bioenergy, can therefore influence carbon sequestration in terrestrial ecosystems and bio-based products as well as releasing CO_2 emissions. Such a possibility does not exist for fossil carbon derived from natural processes over relevant timescales.

Because the use of either fossil fuels or bioenergy involves very different interactions with atmospheric CO_2, their respective impact on the global temperature also differs. Cumulative net CO_2 emissions to the atmosphere have an approximately linear relationship with global mean temperature change. When fossil fuels are burnt for energy, the CO_2 emissions accumulate effectively irreversibly in the atmosphere, because of the essentially one-way flow from geological carbon stores to the atmosphere. As a result, the global mean temperature responds in a simple linear way to cumulative smokestack/exhaust emissions from fossil fuels. In contrast, when biomass is used for bio-based products including bioenergy, the related temperature impacts depend on how carbon stocks in the agricultural and forest ecosystems supplying the biomass are affected by growing and harvesting it. The retention of carbon in bio-based products such as wood products manufactured from forest biomass is also a factor. When producing biomass leads to a sustained decline in agricultural and/or forest carbon stocks, this results in the transfer of CO_2 to the atmosphere where it has an equivalent global warming effect to using fossil fuels.

Conversely, when carbon stocks are increased through agricultural or forest management as part of biomass production, this removes CO_2 from the atmosphere and will result in a global temperature decrease. Because the impacts of biomass use on atmospheric CO_2 vary depending on the specific circumstances, the temperature impacts of using bioenergy cannot be inferred by simply considering cumulative smokestack/exhaust CO_2 emissions. Instead, the overall impact on the carbon balance of the agricultural and forest ecosystems supplying the biomass needs to be considered in addition to the CO_2 emissions to the atmosphere that result from burning biomass for energy. Any related impacts on carbon retained in (or lost from) wood products also need to be allowed for.

Carbon sequestration in forests – happening anyway?

Sometimes it is asserted that only the negative impacts on forest carbon stocks directly resulting from biomass harvesting should be counted when estimating emissions from using forest biomass for wood products and/or as bioenergy (including smokestack emissions). This would mean ignoring any carbon sequestration happening in growing stands that also form part of the managed forest areas where the biomass is being produced, based on an argument that it 'would be happening anyway'. It is selective and imbalanced to insist on including the negative impacts of forest harvesting on the one hand, whilst denying the possibility that forest management could also be actively contributing to carbon sequestration in the relevant forest areas on the other hand. Such an approach is bound to give incorrect results for emissions from bioenergy use. In real-life situations, the overall impact on cumulative CO_2 emissions of managing forests to produce biomass (for wood products and/or for bioenergy) can be positive, neutral, or negative in different circumstances, as discussed below and in further detail elsewhere in this report. This does stress the critical importance of clearly identifying and quantifying the carbon flows in forest ecosystems that are attributable to their management to contribute to biomass supply chains. This can be complicated to assess, and can involve pitfalls, as also explored thoroughly in this report.

Potential for wood products and bioenergy to substitute for geological resources

There can also be indirect interactions between the use of biomass and geological resources, not shown in Figure S1, which can have impacts on fossil and biogenic carbon flows. Importantly, increasing the supply and use of wood products and bioenergy from forests could potentially displace greenhouse gas-intensive non-renewable materials and fossil fuels through competition from the increased availability of bio-based products. If the wood products and bioenergy can be produced while maintaining or enhancing carbon stocks and sinks in forests (as defined in this report), the CO_2 emissions from their manufacture and use will be low and even negative (net carbon sequestration). This can indirectly lead to a reduction of greenhouse gas emissions by avoiding the emissions from the production and use of the displaced non-renewable resources. This potential role of wood products and bioenergy is usually referred to as 'wood product substitution (or displacement)' and 'bioenergy substitution (or displacement)', respectively. The resultant reductions in net greenhouse gas emissions may be referred to as 'greenhouse gas emissions displacement' or 'wood product and bioenergy substitution effects'. When emissions are avoided by replacing one technology with another that involves lower emissions, the consequent reductions in emissions are sometimes described as 'avoided emissions' or 'greenhouse gas (emissions) savings'.

The substitution role of bioenergy and other bio-based products can contribute towards less reliance on fossil and geological resources and towards a decarbonised global economy. However, this potential is only realised if the harvesting and utilisation of biomass does not also lead to a significant increase in flows of biogenic carbon to the atmosphere. A key question is therefore how to identify the best practices for producing and utilising biomass from forests (for certain end-use products including bioenergy) to *reduce* net greenhouse gas emissions and avoid increasing the concentration of atmospheric CO_2 (and other greenhouse gases). It is equally important to identify practices that are likely to present risks of *increased* CO_2 emissions, and where it may be preferable to retain carbon in the forest ecosystems, rather than harvesting and extracting biomass from forests. The differing characteristics of the fossil carbon and biogenic carbon pools have a strong bearing on these questions.

Finding the right balance between carbon sequestration and mobilising biomass resources

In practice, the impacts of extracting biomass on forest carbon balances can vary significantly. The assessment of the fossil and biogenic carbon cycles and the wider analysis in this report do not serve as a justification for managing all forests so as to maximise wood products and bioenergy production. Equally, they do not support the case for protecting all forests for the purpose of maximising the accumulation of forest carbon stocks. Rather, a balanced approach allowing for context is suggested, which would involve:

- Retaining fossil carbon in geological formations as much as possible.
- Retaining carbon in existing relatively intact or unmanaged forests with high carbon stocks, particularly where there are low risks of natural disturbances, tree growth rates are slow in terms of potential biomass production, and/or there is high biodiversity, or there are other non-carbon benefits in conserving the forests.
- Reducing the risks of losses of carbon stocks and sequestration potential in forests that are highly vulnerable to environmental change, through management supporting forest adaptation.
- Allowing for the consequences of significant reductions in the supply of biomass for wood products and bioenergy from existing managed forests when considering options to protect forests to accumulate carbon stocks. Otherwise, this would restrict opportunities for sequestering carbon in wood products and would be likely to increase the use of greenhouse gas-intensive materials and energy sources to replace the supplies of wood products and bioenergy. Alternatively, other forest areas might come under pressure to supply more biomass to compensate for the reductions in supply when actions are taken to protect forests previously managed for some wood production.
- Adjusting management practices in managed forests to enhance wood products and bioenergy production as well as enhancing forest carbon stocks at the landscape scale.

Sustainable forest management: not just about carbon

Taking a broader perspective ultimately suggests considering impacts of forest management on other ecosystem services in addition to carbon sequestration. Conserving biodiversity is recognised as a key objective alongside climate change mitigation; there have been attempts to assess biomass sources with respect to both carbon and biodiversity impacts. Technical methods addressing wider sustainability concerns with multiple criteria have also been proposed in the scientific literature, which are similar to 'site-by-site' or 'regional-scale' assessment considered in this report. However, it is suggested here that multi-criteria assessment of biomass sources is a work in progress. The methods outlined in this report are appropriate for managing carbon impacts but would be challenging to extend to apply to biodiversity as well. As stated, we assume forest biomass is required to originate from forests managed according to the wider principles of Sustainable Forest Management (SFM). Formal standards for SFM did not cover forest carbon stocks and sequestration when originally developed. More recently developed concepts, such as Climate-Smart Forestry and Natural Climate Solutions, explicitly consider both mitigation and adaptation to climate change as well as biodiversity and ecosystem services, and may form viable approaches when combined with existing SFM standards. It is important to recognise that SFM is intended, *inter alia*, to support the conservation of biodiversity in managed forests. Addressing the need to conserve or enhance biodiversity can involve synergies but also trade-offs with other environmental and socioeconomic targets, which need to be considered when developing or implementing climate policies, including providing incentives for greater use of biomass for bioenergy and/or wood products.

Action to promote sustainable use of biomass is frustrated by ongoing disagreements

The ongoing dispute in the media and scientific literature about biomass sustainability and its relevance to meeting net zero greenhouse gas emissions is preventing the development of a generally accepted framework to support biomass use. Biomass is not unique in having potential positive and negative impacts. This is equally true when expanding the deployment of any new technology or practice, including other renewables. However, biomass has received particularly strong attention in discussions about how to achieve sustainable development and net-zero emissions goals. Policymakers are unsettled by the lack of consensus in the interpretation of the available scientific evidence and the opposing claims made by lobbying groups, which erode confidence in all scientific studies and all evidence. This itself presents risks: either policymakers will hesitate to support the use of biomass to its full potential, when it is a much-needed resource to support the development of circular, low-carbon economies, or there is a risk that biomass use will be expanded without adequate safeguards in place, undermining sustainable development. In contrast, if policymakers are provided with sufficient, objective, and balanced interpretations to make sense of the otherwise confusing scientific evidence, then they are more likely to have the confidence to utilise the information to develop policies that support or constrain biomass use as appropriate. Such an objective and balanced understanding of the benefits and risks of expanding biomass use is possible if there is a willingness amongst stakeholders to support its development.

Carbon debt, gain, and neutrality are all real

As set out in detail in this report, and outlined below, producing biomass from forests for use in wood products and for bioenergy can result in carbon neutrality, carbon debt, or carbon gain. That is, all three outcomes are possible and can occur in practice. However, assessing real-life situations to see whether a carbon debt, neutrality, or gain is actually occurring in a biomass supply chain, usually requires modelling and can involve many assumptions. Hence, all such assessments are theoretical to some degree. Nevertheless, these phenomena do not occur randomly or arbitrarily. Instead, they are linked explicitly to identifiable factors, including the quantity of biomass harvested in relation to the growth rates of the forests, the forest management practices involved in producing the biomass, and how the biomass is utilised (e.g. just burnt as bioenergy as the sole product or used for a range of bio-based products with bioenergy as a by-product).

Forest biomass and carbon neutrality

In some situations, the management of forests to produce biomass can have negligible impacts on the development of carbon stocks in forests. In these situations, utilising the extracted biomass, including for bioenergy, does not result in net CO_2 emissions to the atmosphere, other than when non-renewable resources (e.g. fossil fuels) are consumed in biomass supply, processing, and conversion chains. Biomass produced in these circumstances is commonly described as being 'carbon neutral' (see Box S1).

Box S1 Defining forest biomass carbon neutrality

For the purposes of this report, the term 'carbon neutral' is used to refer to situations in which the act of producing biomass from forests for wood products and bioenergy results in zero or negligible net emissions of CO_2 to the atmosphere, when the complete life cycle of forest growth (and re-growth) and harvesting and consumption of biomass is considered. This can occur if CO_2 emissions from harvesting and using forest biomass, including burning some for bioenergy, are exactly balanced by carbon sequestration in the forests that produced the biomass (including carbon retained in wood products, in situations where this is relevant). Theoretical examples presented in this report illustrate the kind of circumstances in which such a scenario can occur. Note that 'process chain greenhouse gas emissions', such as emissions from fossil fuels consumed in machines and trucks used in harvesting, transporting, and processing the biomass, are excluded in this definition. Biomass process chain greenhouse gas emissions are left out of the definition of carbon debt because the concern is with biogenic carbon emissions. Fossil-based emissions from biomass process chains are generally relatively small, but we include them in our characterisation of carbon payback times, that is, when determining if and when negative impacts of biomass deployment on emissions are compensated for (see Box S2).

The illustration in Figure S2 shows how continued harvesting of biomass from a managed forest can involve no net losses of carbon stocks from the forests[1], and therefore not result in net emissions of CO_2. This is not a subjective observation open to interpretation or argument – it is an undeniable physical fact. Carbon neutrality occurs when the net uptake of CO_2 during forest growth (A minus B) perfectly balances out the losses to the atmosphere (L, C, P, E). In practice, there may be periods of net uptake and net losses over time; carbon neutrality occurs as long as positive and negative fluctuations are short term and there are no net gains or losses when these are time-averaged.

Arguments against the possibility of carbon neutrality

The possibility that biomass supplied from forests can be 'carbon neutral' is challenged by some commentators and researchers who are sceptical about the possibility of biomass use, particularly for bioenergy, being a relevant measure for contributing towards mitigation of greenhouse gas emissions. Statements that challenge the carbon neutrality of biomass are frequently expressed simplistically and unequivocally. For example, it may be pointed out that it takes minutes to cut down a tree but decades for a replacement tree to grow back, implying that there is an initial carbon loss when harvesting in forests that takes decades or longer to be replaced by regrowth. The observation that trees can be cut down quickly but take a long time to grow is undeniably correct. However, this ignores the fact that the relatively slow gains and fast losses of carbon stocks that can occur in an individual tree or a managed stand can cancel each other out when considering

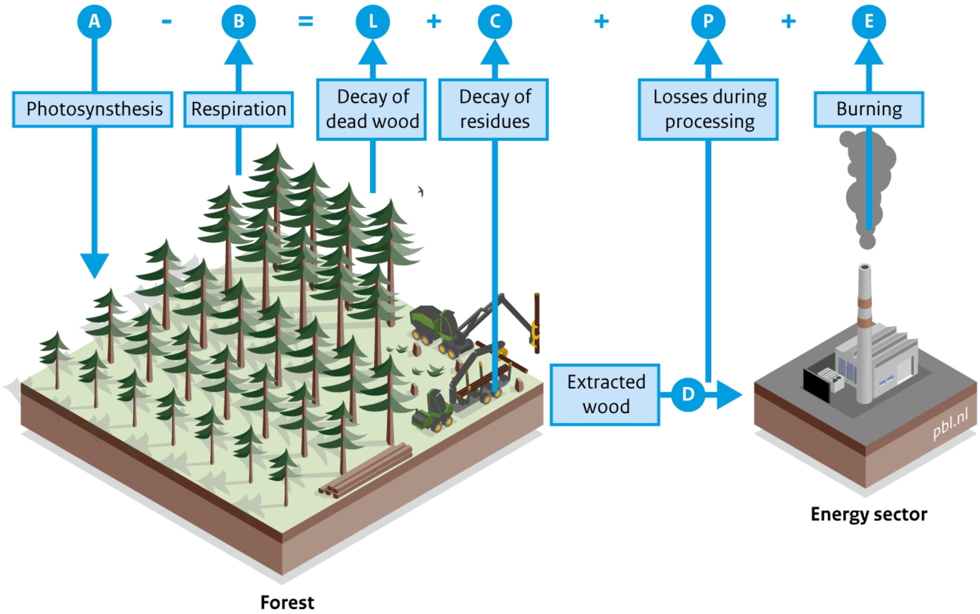
[1] The examples presented in this report are simplified and idealised as an aid to clear interpretation. For example, in Figure S2, carbon from decaying wood (L and C) is assumed to be lost immediately, while in reality some would remain in deadwood, forest litter and residues for some time. Carbon lost to the atmosphere from decaying wood (in the forest or in wood products) is assumed to consist of CO_2 emissions, whereas generally some will be emitted as methane, a stronger greenhouse gas than CO_2. Several examples are given in this report in which all wood harvested from a forest is assumed to be used for bioenergy, but this is not usual in practice.

larger scale and large tree populations, as illustrated and discussed thoroughly in this report. See also the earlier discussion under '*Carbon sequestration in forests – happening anyway?*') We acknowledge that care is needed when deciding on the spatial scale to consider and the 'system boundary' to apply in assessments of emissions from forest biomass supply chains, to ensure that all relevant processes are included (and irrelevant ones are excluded).

Figure S2

Carbon balance of a forest-bioenergy system where the forest has been under long-term management for bioenergy production

Forest under long-term management (carbon neutrality)



Source: Forest Research UK

Some researchers propose that a scenario in which forests are managed to produce biomass should always be compared against the option of leaving forests unharvested, assuming that the trees would grow on and reach maximum carbon stocks for that site. However, as discussed further below and in the main report, the assumption of 'no harvesting' is often not the correct choice of an alternative scenario, for example when assessing forest areas that are already under established management for wood supply. Comparisons of managed forests with an alternative 'no harvesting' scenario do not alter the fact that, intrinsically, forests managed according to the conditions listed below can produce biomass, including for bioenergy, with zero or negligible emissions to the atmosphere.

Conditions for carbon neutrality of biomass

Carbon neutrality is most clearly associated with situations where *all* of the following conditions are met:

- The quantities of biomass being extracted from forests are stable over time assuming harvesting is not constrained by factors such as uneven distribution of tree/stand ages.
- The quantities of biomass being extracted do not exceed the regrowth of biomass.
- The forest management practices involved in biomass supply are constant over time (such as, levels of thinning and rotation ages in stands being kept the same).
- The existing uses of biomass are maintained (such as, biomass is not diverted from other existing uses such as the manufacture of material products to use for bioenergy).

It must be acknowledged that, in real situations, perfect carbon neutrality is likely to occur only in exceptional circumstances, because the rates of biomass supply and the forest management approaches to produce the biomass are rarely unchanging over time.

Forest biomass, carbon debt, and carbon payback time

When taking actions to increase the supply and use of forest biomass above pre-existing rates of supply, the adjustments to forest management and/or to the way biomass is utilised to achieve this, can result in a diminution of carbon stocks overall in forests and wood products. The finite net reduction in carbon stocks occurring in these situations is commonly termed a 'carbon debt' and the time needed to compensate for this reduction is termed 'carbon payback time' (see Box S2).

Box S2 Defining forest biomass carbon debt and carbon payback time

For the purposes of this report, we define 'carbon debt' as the *cumulative net emissions of biogenic* CO_2 to the atmosphere that occur in certain circumstances when forest management is changed in certain ways to increase the supply of forest biomass (see Figure S3). This includes allowing for the overall '*biogenic*' carbon emissions from the biomass supply chain and from combustion of biomass to produce energy (see earlier discussion of Figure S1). There is a 'carbon debt' if a decision to increase the production of biomass results in net emissions of CO_2 to the atmosphere, even after allowing for carbon sequestration in the forests producing the 'extra' biomass (i.e. increasing the quantity supplied).

The CO_2 emissions from biomass supply and use are calculated by:

- Working out how carbon stocks in the relevant forest areas develop over time, allowing for the management practices including harvesting involved in producing the biomass.
- Working out how carbon stocks in the relevant forest areas develop over time for a *counterfactual scenario* in which biomass supply is not increased and forest management practices are not changed for this purpose. Rather, management practices are assumed to develop as they would have done otherwise (which may still involve the supply of some biomass, but not in the increased amounts).
- Calculating the cumulative CO_2 emissions from the difference in carbon stocks at any specified time for the scenario in which biomass supply is increased, compared with the counterfactual scenario.

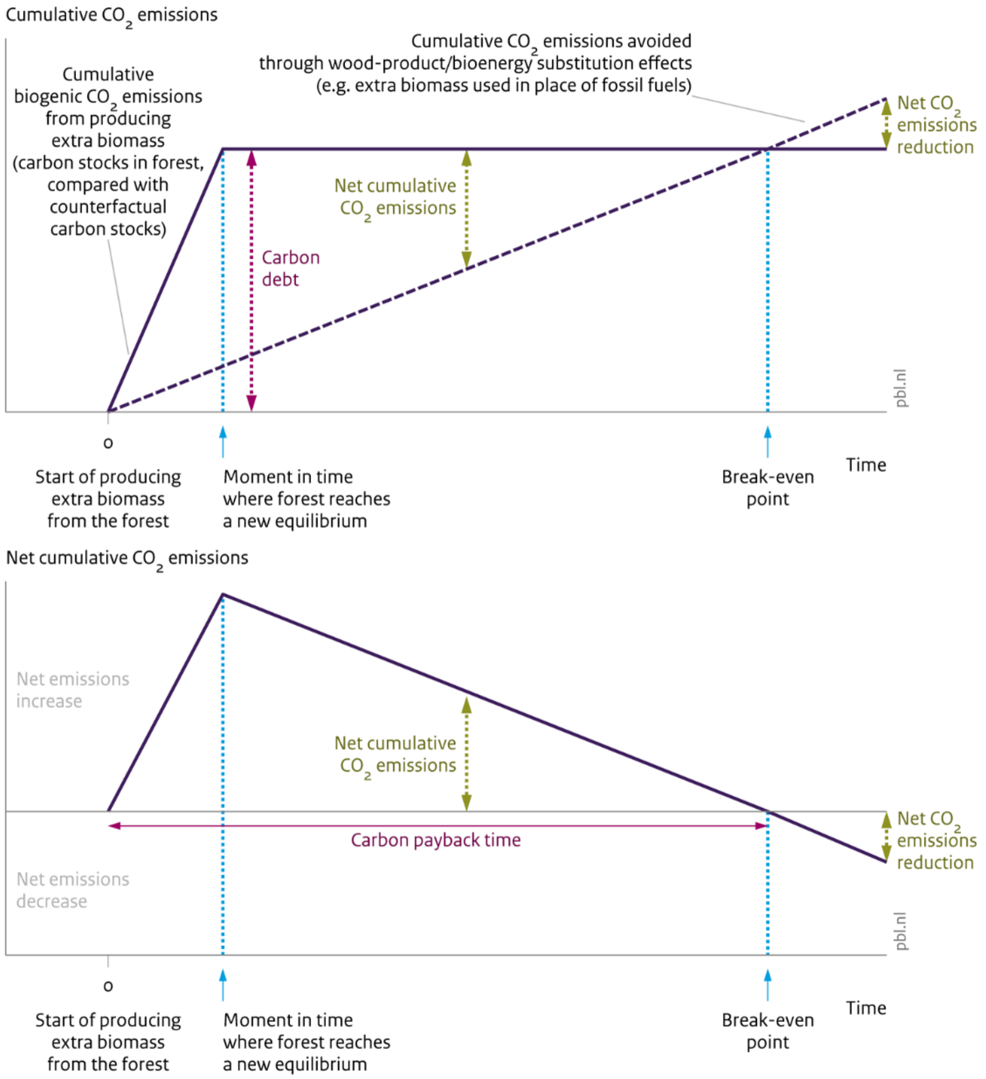
A hypothetical example of the development of cumulative emissions over time is illustrated by the solid lines in Figure S3. The upper graph in the figure shows, separately:

- The cumulative biogenic CO_2 emissions from producing extra biomass (solid line), calculated by comparing the development of forest carbon stocks with how carbon stocks would develop in the counterfactual scenario (no extra biomass produced).
- The cumulative CO_2 emissions avoided (or 'saved') through wood product and bioenergy substitution effects (for example by using extra bioenergy in place of fossil fuels; dashed line).

Our definition of carbon debt excludes the greenhouse gas emissions savings provided by using the extra biomass for wood products and bioenergy, through wood product substitution effects, which are considered as a separate component of the carbon balance in this report, but allowed for when calculating relevant parameters such as carbon payback times (see definition of carbon payback time below).

Figure S3

Carbon debt and payback time



Source: Forest Research UK

The definition also excludes the 'process chain greenhouse gas emissions', such as emissions from fossil fuels when machines are used in tree establishment or harvesting, and during biomass transport, as well as during processing such as wood sawing or chipping. These emissions are allowed for in the calculation of net greenhouse gas emissions savings from wood product substitution effects. If the emissions avoided by using bioenergy in place of non-renewable resources, such as fossil fuels, are more than the carbon debt (as defined here), then bioenergy can still provide net emissions reductions in these circumstances. However, the presence of a carbon debt always implies diminished climate benefits, regardless of whether net emissions after allowing for wood product substitution effects are positive or negative.

In the illustration in Figure S3, the net biogenic CO_2 emissions (solid line) resulting from producing the extra biomass accumulate up to a maximum quantity over a finite time period. Examples presented in this report illustrate why this can occur, and how the magnitude of the net CO_2 emissions and the time over which they accumulate vary considerably, depending on the details of the types of forest, changes made to forest management, and how harvested and extracted biomass is utilised. The magnitude and duration of the period of increased net CO_2 emissions are critical factors in determining whether the biomass contributes towards reducing greenhouse gas emissions in a short enough timescale or detracts from such a goal.

Carbon payback time

The term 'carbon debt' implies that the biogenic CO_2 emissions resulting from producing extra biomass (including for bioenergy) can eventually be 'paid back'. This follows from assumptions about the other resources (materials and/or fuels) that would need to be consumed instead of the biomass, in the event that the extra biomass is not produced and used (the 'counterfactual'). The manufacture and use of these alternative materials and fuels would also involve emissions. In the case of materials such as steel or brick and fossil energy sources, the emissions from consuming these resources will accumulate indefinitely, as shown by the dashed lines in the upper graph of Figure S3. These emissions can be avoided by producing and using the biomass (these are the wood product substitution effects). Eventually, the cumulative emissions avoided (or 'saved') exceed the cumulative emissions from using the biomass, as shown in Figure S3 by the point where the dashed line crosses the solid line in the upper graph. The lower graph in Figure S3 shows the cumulative net CO_2 emissions, calculated by subtracting the cumulative greenhouse gas emissions savings from the cumulative emissions increases. Cumulative emissions avoided exceed the cumulative emissions from using the biomass at the point where the line returns to zero in the lower graph. The time taken to reach this point is defined here as the 'carbon payback time'.

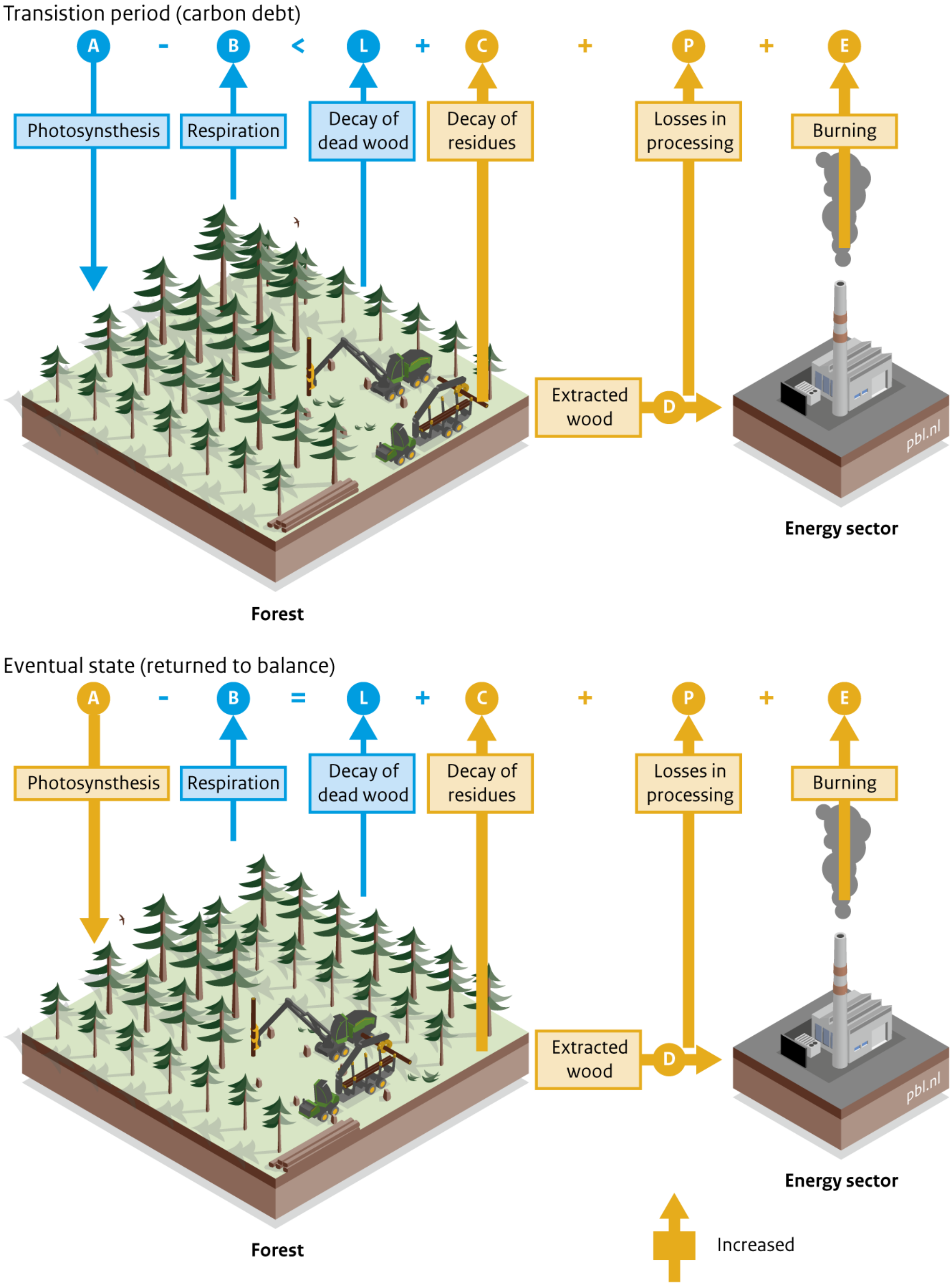
Figure S4 illustrates how managing forests to produce biomass can result in a 'carbon debt'. The illustration considers a managed forest where rotations are shortened to produce more wood for bioenergy, and how this impacts the carbon balance. The *initial state* of the forest, before changing rotations, has been described in the earlier discussion of carbon neutrality and is shown in Figure S2 presented earlier.

The upper diagram in Figure S4 illustrates the impacts on carbon flows in the *period of transition*, during which rotations are shortened to increase biomass production. The lower diagram shows the *eventual state* of the forest, following this period of transition. During the transition period, losses to the atmosphere (L, C, P, E) increase and exceed the uptake of CO_2 during forest growth (A minus B). However, eventually, when the forest is entirely managed on the shorter rotations, the overall rates of forest growth and CO_2 uptake are increased and again match the losses. The total carbon stocks in the forest are smaller as a result of shortening the rotations, and the difference from the higher carbon stocks that were present previously represents the 'carbon debt'.

As is the case for the discussion of carbon neutrality, this description of how a carbon debt can occur is not a subjective observation open to interpretation or argument – it is an undeniable physical fact. There are real possibilities of this kind of situation occurring, especially when forest management practices are being adjusted or are evolving with the aim of mobilising extra biomass supply from existing forests, above levels possible based on pre-existing practices. For example, there is higher likelihood of a carbon debt occurring when management practices change with the objective to increase wood output quickly, especially in forests where the tree growth rates are slow. However, such an outcome is neither inevitable nor unavoidable. The key is to be alert to risks of where carbon debts could occur and to mitigate them as much as possible, as discussed later in this summary.

Figure S4

Impact on the carbon balance of a forest-bioenergy system when rotations are shortened in a managed forest to produce more wood for bioenergy



Source: Forest Research UK

Duration of carbon payback times

The time taken for deployment of a mitigation measure to start providing net emissions reductions is a critical parameter in determining its effectiveness for contributing towards a target of limiting atmospheric warming to no more than 2 °C and preferably to 1.5 °C or less. Generally, mitigation measures with shorter carbon payback times are to be preferred but defining an 'acceptable' carbon payback time for biomass sources is ultimately subjective, depending on the urgency with which reducing emissions is viewed. In this context, it may be observed that the overarching goal of the Paris Agreement is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels". To achieve this, the Paris Agreement calls for the rate of greenhouse gas emissions to peak "as soon as possible", with "rapid reductions thereafter … to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century".

As discussed earlier, cumulative net CO_2 emissions to the atmosphere have an approximately linear relationship with global mean temperature change. The implication of this is that when measuring the progress towards staying within an emissions budget for a given temperature target, every tonne of CO_2 emitted will cause around the same amount of warming, no matter when it was emitted, as long as this is within the carbon budget period. This has important relevance in determining if an increase in bioenergy will have a beneficial impact on limiting global warming. If the carbon payback time for a biomass source is within the carbon budget period, then using the biomass can contribute to achieving the specified temperature target. If the payback time stretches significantly beyond the carbon budget timeframe, then the contribution of bioenergy to limiting global warming is diminished. Modelled socioeconomic pathways to achieve the long-term target temperature range set by the Paris Agreement typically indicate the need to stabilise cumulative emissions within a timeframe to 2050; pathways admitting a slight overshoot of cumulative emissions followed by reductions through net CO_2 removals exhibit a peak in cumulative emissions no later than 2070. The above observations suggest that:

- Ideally, measures consistent with IPCC climate change mitigation pathways contribute net emissions reductions by 2050, and no later than 2070.
- Measures consistent with the text of the Paris Agreement contribute net zero emissions and preferably net emissions reductions by no later than the end of the century (2100).
- Human activities that lead to significant emissions well after the end of the century are very problematic.

This leads to a possible classification for carbon payback times into categories of 'Short', 'Medium', 'Long', and 'Very long', as shown in Table S1.

Table S1
Classification of biomass (as a source for all types of products) in terms of categories of carbon payback time.

Category	Payback time (years)	Interpretation
Short	0-15	Net emissions reductions by 2040 if activities start now, and by 2050 if started in the next 10 years. Compatible with pathways limiting warming to 2 °C or less.
Medium	15-30	Net emissions reductions by 2050 if activities start now, and by 2050 if started in the next 10 years. Compatible with pathways limiting warming to 2 °C or less, in which cumulative emissions overshoot and are then compensated for after about 2070.
Long	30-100	Net emissions reductions by the end of the century or a few decades thereafter. Only compatible with pathways limiting warming to 2 °C or less, if rapid and deep reductions in emissions are provided once the carbon debt is paid back.
Very long	> 100	Net emissions continue well beyond the end of the century. Very unlikely to be compatible with pathways limiting warming to 2 °C or less.

Forest biomass and carbon gain

An outcome that might be called a 'carbon gain' can occur when the supply of biomass from forests is sustained or increased and this goes hand in hand with enhanced carbon stocks overall in forests and wood products (see definition in Box S3).

Box S3 Defining forest biomass carbon gain

The term 'carbon gain' is used here to refer to situations in which producing biomass from forests results in net carbon sequestration from the atmosphere, when the overall carbon balance of the complete forest and biomass supply chain system is allowed for.

In other words, a decision to produce and use biomass (for wood/bio-based products and bioenergy) results in a net removal of CO_2 from the atmosphere, after allowing for carbon sequestration in the forest (and in wood products where relevant) in response to producing the biomass. This is likely to involve a finite total quantity of net carbon sequestration over a finite period of time. The net removal of CO_2 from the atmosphere resulting from managing forests to produce biomass is calculated in the same way as described for the 'carbon debt' case defined above. Theoretical examples presented in this report illustrate how such a scenario can occur[2].

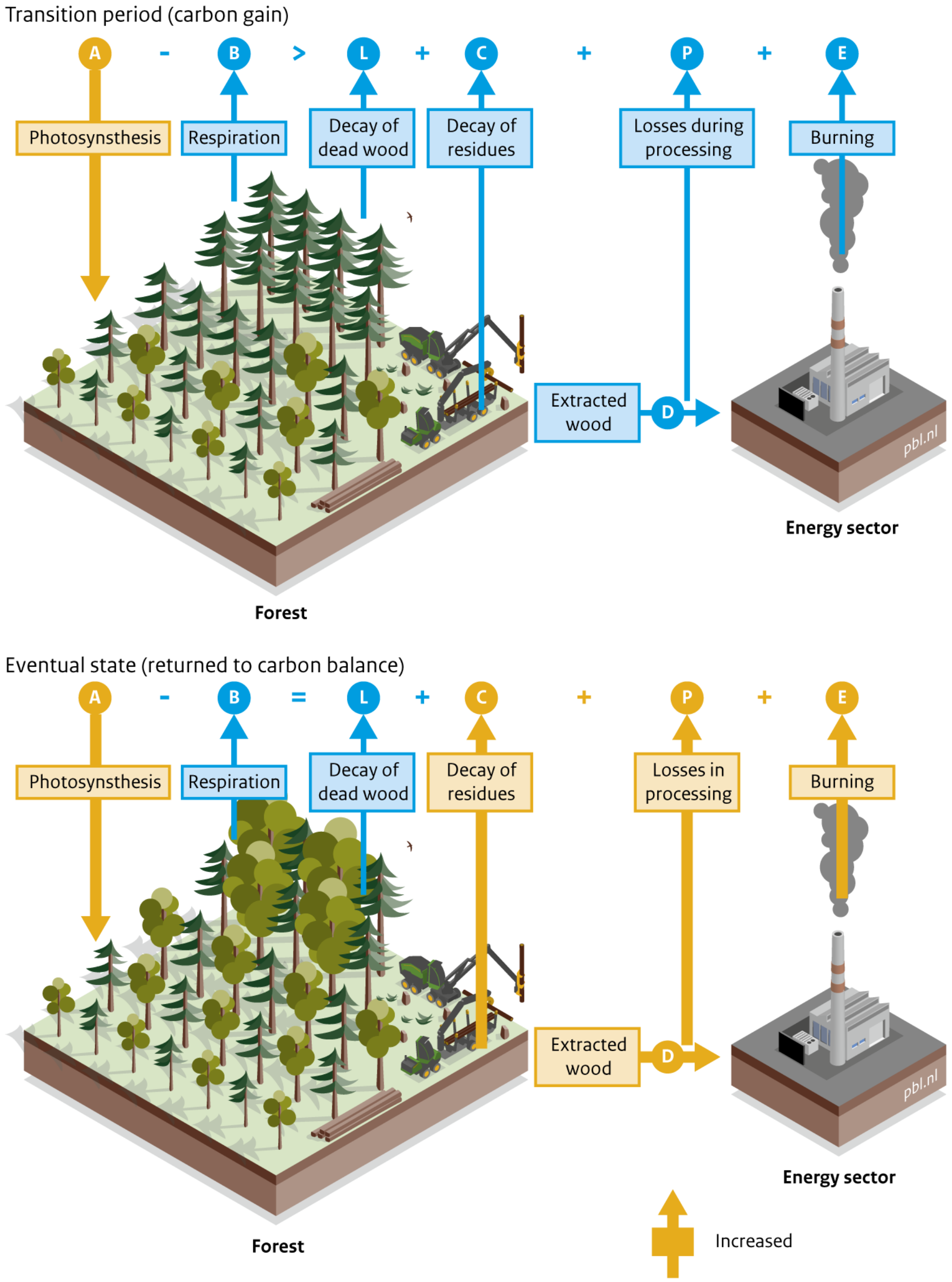
Figure S5 illustrates how increased harvesting of biomass and associated changes to the management of forest can involve a carbon gain, enhancing carbon stocks in the forests, and therefore resulting in net carbon sequestration. The example is a simplified illustration, similar to those presented in Figures S2 and S4, this time showing the impact of improving tree growth rates on tree carbon stocks. In this case, as the forest stands are felled, the newly planted replacement stands consist of a mixture of tree species, some of which have faster growth rates than the pre-existing tree species. The *initial state* of the forest, before changing the composition of the forests,

[2] Note that the use of the term 'gain' in this context should not be confused with the 'Gain-Loss Method' defined in IPCC Guidance for estimating national greenhouse gas inventories.

has been described in the earlier discussion of carbon neutrality and is shown in Figure S2 presented earlier. The upper diagram in Figure S5 illustrates the impacts on carbon flows in the *period of transition*, during which the existing trees are gradually replaced (when they are harvested) by the faster-growing mixture of tree species. The lower diagram shows the *eventual state* of the forest, following this period of transition.

Figure S5

Carbon balance of a forest-bioenergy system where the tree species in a managed forest are diversified to produce more wood for bioenergy



Source: Forest Research UK

Achieving these kinds of synergistic outcomes to enable a carbon gain may often involve conscious planning beyond what would be done routinely as part of 'Sustainable Forest Management'. Opportunities to manage biomass supply from forests whilst also enhancing carbon stocks are likely to be quite site-specific, for example where forest growth rates can be enhanced by diversifying tree species composition, where management can help restore damaged or degraded forests, or where forests can be managed to mitigate the effects of major natural disturbances. Such activities are also likely to face significant constraints, for example the introduction of fast-growing exotic tree species may be considered undesirable, whilst opportunities to create new productive forest areas are limited by land availability and suitability. The key is to be conscious of the principle of changing forest management practices to sustain or enhance biomass supply and carbon stocks at the same time, and to always actively consider possibilities for achieving this when developing new biomass supply chains and plans for future forest management.

There are examples from around the world where biomass supply from forests have been steadily increasing over periods of decades, whilst forest carbon stocks have also increased. However, as discussed in more detail later in this summary, increasing carbon stocks are not a sufficient indicator that biomass produced from forests can be regarded as carbon neutral or associated with a carbon gain.

The likelihood that bioenergy from forests actually involves positive activities resulting in carbon gains or low emission levels is doubted and challenged by bioenergy sceptics, while proponents from the forestry and biomass sectors will point to the positive aspects of their forest management activities and utilisation of biomass feedstocks. However, the question of whether or not bioenergy supply will result in low or high greenhouse gas emissions is perhaps not the main point. The salient insight is that producing forest bioenergy may involve either negative, low, or high emissions, depending on local circumstances and the type of forest management and biomass feedstock involved. The key questions, therefore, are whether the positive and negative practices can be distinguished and whether it is possible to support the positive practices and minimise or mitigate the negative ones. These questions apply equally to agricultural biomass sources. These issues are explored further below and in the main report.

Carbon impacts

For this report, we define 'carbon impacts' as the overall change in emissions to the atmosphere that can occur when forest management is modified in certain ways to increase or decrease the supply of forest biomass, or there is a change in the way biomass is utilised, for energy or for other bio-based products. This includes allowing for any carbon debt or carbon gain as defined above that occurs as a result of changes to forest management or wood utilisation, and any related changes in emissions resulting from wood product and bioenergy processing and substitution effects.

Rising forest carbon stocks do not always mean a carbon gain, falling stocks do not always mean a carbon debt

As noted earlier, it may be observed that, frequently, carbon stocks in forests that have been under long-term management for production of wood products and bioenergy are stable or steadily increasing, when assessed at large spatial scales. For example, according to national greenhouse gas inventories reported by some countries under the United Nations Framework Convention on Climate Change, forest areas available for wood supply have remained carbon sinks over many years (implying continuously increasing carbon stocks), whilst being managed for wood production, maintaining a steady flow of wood to the forest industries. Some of this is the result of actions to restore and improve the management of forest lands. Research studies have shown how improvements to forest management practices in the Nordic region of Europe and forest restoration activities in the southeastern USA are linked to increasing forest carbon stocks in the past 100 years. However, monitoring carbon stocks to show they are increasing cannot be used to conclude that the management of forests to produce biomass is resulting in a carbon gain or avoiding a carbon debt as defined in this report. Carbon stocks can also be rising in a forest at times for reasons that have nothing to do with how they are being managed.

Examples presented in this report illustrate how sometimes it might be easy to see the impacts of forest management decisions (or the lack of them) on carbon stocks by simply tracking the development of carbon stocks over time. However, these situations only occur in quite exceptional and unusual circumstances, such as when the distribution of tree ages forming the forest areas is perfectly even. In almost all real situations, managed forest areas have 'bumpy' or uneven distributions of tree ages. For example, there may be relatively more areas of young trees, or conversely of old trees, or of middle-aged trees. Further examples in this report show how, in these situations, carbon stocks in forests can increase steadily over many decades, whilst at other times they may steadily decline, even though the management of forest stands is unchanging. Hence, when carbon stocks in the example forests are increasing, this is not necessarily the result of 'good' or 'improving' forest management. Equally, when the carbon stocks are declining, this is not necessarily the result of 'bad' or 'worsening' forest management. Rather, the increases and decreases are principally a reflection of the non-uniform age distribution of the stands of trees in the forest. This point is very important, because it is sometimes suggested that producing biomass from forests whilst avoiding a carbon debt can be assured simply by monitoring the development of carbon stocks in forests, to confirm that they are stable over time, or increasing. It should be apparent from the illustrations given in this report that the impacts of forest management on forest carbon balances usually cannot be determined in this way. Indeed, attempting to do so is often likely to lead to false conclusions and misunderstandings.

Assessing the impacts of specific forest management scenarios on carbon stocks generally requires more sophisticated analysis, sometimes involving assumptions and modelling approaches that can be challenging to explain. However, practical, transparent, and verifiable (and preferably simple) methods are needed for assessing and managing the carbon impacts of forest management to supply woody biomass, to enable the forest sector and wood industries to provide renewable biomass whilst also meeting the goal of net-zero emissions. A solution is suggested by relating the varying carbon impacts (neutral, negative, or positive) to decisions to maintain or change forest management practices in forest areas in some way. This point is explored further in this report and is outlined later in this summary.

Understanding variability in carbon impacts and diverging research findings

Arguably, the science of the carbon cycles of vegetation systems is relatively straightforward, little more than 'carbon bookkeeping'. However, it is proving challenging to reach consensus on its implications for increasing the use of biomass as an energy source or for other bio-based products. There is a good scientific understanding of the interactions between carbon stocks and sinks in terrestrial vegetation and soil and the management of these systems to produce biomass. This is based on a considerable body of research and many published scientific papers. However, conclusions drawn about the carbon impacts of increased biomass production vary considerably. A bewildering array of results is reported in the scientific literature on the carbon impacts of biomass and bioenergy systems. At one extreme, studies find that using biomass, for bioenergy and/or for other purposes, can immediately deliver net reductions in greenhouse gas emissions. At the other extreme, studies conclude that biomass use involves indefinite net increases in emissions, particularly when used as bioenergy. Between these extremes, almost every conceivable outcome is reported in scientific studies, in terms of net impacts on emissions over time. As a result of the wide range of conclusions drawn in studies, there can be a perception that the available scientific evidence is confusing and self-contradictory. This can create a perception that the CO_2 emissions from using biomass sources, especially for bioenergy, are extremely wide-ranging and the causes are complex and uncertain. However, based on the analysis in this report and similar findings in earlier published reviews, it is concluded that there are clear and understandable reasons for the diversity displayed in the findings of different studies.

Divergence in study results reflects diversity in forest systems and biomass supply chains

There are certain characteristics of forests that can affect the carbon balance of biomass supplied from them. These characteristics can be described as a set of factors such as:

- The 'condition' of forests, defined in broad terms, e.g. intact primary, managed (regenerated forests or plantations), damaged/disturbed, and degraded.
- Natural disturbances, varying in terms of frequency, intensity and type, e.g. fire, storms, pest and disease infestations.
- Tree and stand growth rates, which can be defined in terms of the annual rate of stem volume growth.
- The distribution of tree/stand ages, characterised in terms of the relative areas of young, middle-aged, and old trees and stands.
- Forest management practices, considered in terms of existing practices already established in forest areas, particularly those involving harvesting, and any changes to practices that may be involved in increasing the supply of biomass from forests.

Different research studies can arrive at contrasting results and conclusions because they study forest systems that vary significantly in terms of one or more of these factors. Sources of biomass (feedstocks), individual biomass supply chains, and the conversion technologies involved can also be very diverse. Furthermore, sometimes even just one type of biomass, such as forest biomass, can be produced and utilised in very different ways, which can result in drastically differing impacts on the carbon cycle. These points are considered in detail in this report.

The findings of individual scientific studies can be analysed to determine how impacts on carbon storage in forests and wood products and consequent net emissions are systematically related to specific forestry practices and to how extracted biomass is utilised variously for energy or for other products. Forest biomass sources can thus be classified in terms of detrimental, neutral, or beneficial effects on carbon stocks, with respect to a set of factors representing local circumstances, differing approaches to forest management, and the differing purposes for which tree biomass feedstocks are utilised. The key challenges are, therefore, to clearly define the positive and negative practices and develop approaches to support the positive practices and minimise or mitigate the negative ones. These are also central subjects of this report.

Divergence in study results also reflects diversity in assessment methodologies

The detailed methodologies and assumptions adopted in scientific studies can have a strong influence on assessments of the carbon impacts of biomass systems, and therefore on the conclusions reached by individual studies. Important methodological aspects include:

- The *general methodological framework* applied (if any).
- The *spatial and temporal scales* over which assessments are made, such as a single stand of trees, or alternatively a population of tree stands within a landscape, and the time over which scenarios for forest management are assumed to develop.
- *Static or dynamic representation of forest areas and land use*, that is, whether or not methods allow for dynamic policy- and market-mediated responses in land use and land management.
- The *representation of forest management practices and uses of wood feedstocks* involved in biomass supply, including how scenarios for forest management and wood use are developed (based on assumptions, data, and/or economic modelling).
- The specifics of the *'counterfactual' land management scenario*, that is, how land use and land management are represented, assuming the biomass supply scenario being assessed is *not enacted* (i.e. the so-called 'counterfactual' or 'reference' scenario).
- The specifics of the *scenario for how biomass is used, and counterfactual resource use*, including how changes in non-biomass resources are represented. For bioenergy, determining the displaced energy source may depend on the context of the energy system, and therefore the greenhouse gas emissions displacement factor may take a range of values and involve significant uncertainty.
- The *'system boundary'* adopted, that is, the comprehensiveness with which activities and processes involved in biomass supply chains (directly and indirectly), and their associated emissions, are included in assessments.
- *Choice of metrics*, that is, the metrics selected for presenting results for emissions and/or climate warming impacts of biomass supply chains.

Discussion of the above factors in this report arrives at the following *key observations*:

- Studies reaching consistently negative conclusions about the possible role of forest management, wood products, and bioenergy in contributing towards climate change goals typically have narrow scopes, and/or assume simplistic or unrealistic scenarios for forest management or wood utilisation, and/or they employ some elements of incorrect methodology for addressing such subjects.
- Studies reaching consistently positive conclusions may not adequately represent impacts of biomass harvesting on forest carbon stock changes and/or they employ some elements of incorrect methodology for addressing such subjects (this is more likely in older studies). More recent studies reaching positive conclusions typically assume dynamic responses in forest management practices occur in response to increased demand for biomass, such as increased afforestation, reduced deforestation, or improvements to growth rates in existing forest areas.

Although representing often quite complex dynamic responses, the representation of individual forest management practices may still be simplistic in some cases.

- In contrast, studies that consider a broader range of scenarios for forest management and biomass use, that include a relatively detailed representation of forest management practices and resultant carbon stock changes, and that apply appropriate methodologies, tend to conclude that there is no single universally best option for forest management and biomass use, including the option of forest conservation. Rather, outcomes are variable, depending on local conditions and circumstances, the detailed choices made about forest management practices, and wood use to meet objectives, such as to supply certain levels of biomass, and decisions about how wood feedstocks are utilised (such as for bioenergy or non-energy purposes).

These observations can help to understand the variability of results and conclusions displayed in published scientific literature about the CO_2 emissions of forest management and biomass use. Studies addressing relevant questions, employing robust methods, suggest that the impacts on CO_2 emissions of expanding the use of biomass, for energy or non-energy purposes, can be very variable. This would present significant challenges to developing simple policies and measures regarding forest management and biomass use if the variability reflected randomness or uncertainty. However, based on the discussion in this chapter, it is suggested that the variability is likely to be systematic, and attributable to identifiable factors related to forest types, forest management practices, and how biomass is utilised for different purposes. A systematic analysis of these factors could help inform policies on forest biomass production and use.

The counterfactual scenario is crucial

The specifics of the counterfactual scenario for land management, especially forest management, can have a big influence on the estimated carbon impacts. Some studies do not allow for a counterfactual land use. The resultant estimates of carbon impacts are usually positive or neutral, leading to the conclusion that producing more biomass from forests will contribute towards reducing net greenhouse gas emissions.

Quite a number of studies on the carbon impacts of forest biomass and particularly bioenergy systems compare these systems with an alternative (‘counterfactual’) scenario of leaving forest areas untouched, assuming that the trees would grow on and accumulate very high carbon stocks, sometimes omitting consideration of disturbances from diseases, fires, or storms. Researchers who adopt this approach sometimes refer to this as the ’carbon sequestration forgone’ or ’opportunity cost’ attributable to managing forest areas for wood supply, even if the current management regime has long been established. Results of these particular kinds of studies can underestimate the near-term mitigation benefits of forest biomass use and/or overestimate any carbon debt. Hence, these types of studies frequently arrive at much more pessimistic conclusions about the potential of biomass and especially bioenergy use, compared with those studies that refer to a counterfactual scenario of continuation of pre-existing policies and practices. However, assessing carbon impacts of forest biomass chains by comparing against a ‘leave untouched’ scenario is often highly hypothetical. The inappropriate use of a ‘no harvest’ counterfactual in assessments of forest bioenergy systems can give very misleading results when the biomass comes from forests already under long-established management for wood production. The lack of a common understanding of the appropriate land use counterfactual scenario has contributed to misunderstanding and disagreements about the climate effects of bioenergy.

Divergence in study results also reflects diversity in the questions addressed by studies

A major cause of variation in results reported in scientific studies of the CO_2 emissions of bioenergy is related to individual studies addressing different questions. This situation is further complicated by many published studies not clearly stating the intended question, or sometimes applying methods that are not correct for addressing the question. Assessments aimed at addressing different types of questions generally give very different results for CO_2 balances. This does not mean that results are uncertain or incorrect, but it does stress the critical importance of:

- Being clear about the research question and intended application when making an assessment.
- Clearly stating the purpose of the assessment and the research question.
- Using the correct methods for the stated purpose and question, especially when developing scenarios used in the assessment.

Beware of confirmation bias and simplistic interpretations

The possibility has been raised of 'confirmation bias' having an influence in some, possibly many, scientific studies of biomass systems. This is the notion that researchers might (consciously or unconsciously) select scenarios for biomass supply chains for study (and their counterfactuals), or choose methods, assumptions, and parameters, that produce results for carbon impacts that reflect personal or corporate viewpoints. If this practice is occurring, this is performing a great disservice to the cause of sustainable development.

Sometimes, the selection of bioenergy and counterfactual systems by researchers may reflect their genuine experiences of bioenergy systems, but which may nevertheless represent a rather restricted set of cases or possibilities. This is not necessarily a problem, as long as the purpose of such studies is clearly stated (see above), and it is clear that results and conclusions refer to specific cases and should not be considered generally applicable to biomass or bioenergy.

There is an ongoing debate between proponents and sceptics regarding the potential of biomass as a renewable resource that can contribute towards reducing greenhouse gas emissions, with particular concerns over forest bioenergy sources. Contributors to this debate frequently cite differing studies and evidence sources to support their position, and sometimes use bold but simplistic statements to get their points across. Examples of such statements have been discussed and analysed in this report and two very pertinent examples supporting opposite points of view have been highlighted earlier in this summary:

- The statement that, '*it takes seconds to cut down a tree but decades or centuries to grow another to replace the carbon in the felled tree*'.
- The claim that forest biomass is 'carbon neutral' or better, if it is supplied from forest areas where overall carbon stocks in a forest landscape are stable or increasing over time.

Unfortunately, simple statements and interpretations rarely offer an objective, impartial, accurate, or balanced view of the benefits and risks involved in mobilising forest biomass resources for use as an energy source (or for other products). Examples given in this report illustrate how simplistic interpretations such as these present a distorted picture and lead to false conclusions about bioenergy and biomass more generally, either too negative or too positive.

Practical solutions for biomass supply and use

Possible solutions to the challenge of managing the effects on the carbon balance of harvesting and using forest biomass consist of two elements:

1. The policy framework supporting actions to use forest biomass while ensuring positive effects on the carbon balance, or at least minimising negative effects.
2. The technical methods used to assess and manage the supply and use of forest biomass while ensuring beneficial effects on the carbon balance or limiting negative effects.

Overview of policy frameworks

There are several kinds of policy framework potentially relevant in this context, which are considered briefly in this report:

- Regulations directly proscribing certain actions (such as deforestation).
- Regulations setting out mandatory sustainability standards (such as biomass sustainability standards).
- Voluntary sustainability standards (such as forestry and biomass certification schemes).
- Voluntary schemes encouraging certain environmental actions (such as forest carbon sequestration crediting schemes).
- 'Cap and trade' systems encouraging collective actions towards a defined outcome (such as emissions trading systems).
- Financial incentives directly supporting certain actions (such as grants for afforestation or improving forest management).

Technical methods underpinning policies

Policy frameworks generally refer to a set of supporting technical methods to enable policies to be put into practice and to verify compliance. This report suggests some options for technical methods addressing biogenic CO_2 emissions, also indicating the kinds of actors who might use the methods, and the policies they may be most relevant for. It must be stressed that all the options presented in this report are proposed as tentative solutions. More work would be needed to develop fully workable solutions applied in conjunction with specific policies.

The technical methods outlined in this report can be divided into three classes:

1. 'Forest-based' methods aim to support the management and/or monitoring of forest carbon stocks, to provide assurance that forest management, including biomass harvesting, is having a positive or neutral effect on biogenic CO_2 emissions. Three types are discussed in this report: 'site-by-site assessment', 'regional-scale assessment', and 'national/regional-scale reporting'.
2. 'Feedstock-based' methods are more concerned with the extraction and use of forest biomass for bioenergy. They aim to classify tree biomass feedstocks according to the likelihood of low or high associated biogenic CO_2 emissions, and screen them to prioritise the use of 'low-emissions' feedstocks for bioenergy. Two types are discussed in this report: 'biomass feedstock decision trees' and 'biomass feedstock criteria'.
3. 'Full LCA methods' aim to enable the comprehensive assessment of greenhouse gas emissions resulting from a new policy or business initiative to invest in the supply and use of biomass, for bioenergy and/or other bio-based products.

As a general point we assume that forest biomass is required to originate from forest areas managed according to wider principles of Sustainable Forest Management[3].

Assessment of technical methods

This report provides a preliminary assessment of the methods in terms of their:

- Effectiveness for informing understanding and decisions about the use of forest biomass sources and the effects on biogenic CO_2 emissions.
- Efficiency in terms of the administrative burden placed on biomass suppliers and consumers to demonstrate correct application of the methods and compliance with good practice.
- Readiness for putting into practice, for example, how fully developed methods are and whether data and expertise are generally available, or more technical investment is required.

The main conclusions that may be drawn from the assessment are:

- The methods are at varying stages of development and readiness for supporting policies aimed at encouraging biomass use with low associated biogenic CO_2 emissions. All require at least some further development.
- There are trade-offs between the effectiveness of methods in supporting the above aims and the administrative burdens and costs likely to be placed on biomass suppliers and consumers.
- There may be some challenges to achieving general acceptance of any particular method if it were to be proposed for general use. These can be partially addressed by transparent reporting of data, calculations, and results.

Indirect impacts on land use

It is important to recognise any limitations of the practical approaches described above. The main concern involves risks of leakage if technical methods for supporting biomass supply with low/negative emissions are not implemented comprehensively (that is, across all forest areas and by all actors). Specifically, the methods are designed to support forest management and woody biomass supply from forests in a clearly defined region of land. Forests outside of the defined region are thus not supported, unless similar approaches are being implemented outside the region as well. This could be important because it is possible that efforts to implement forest management measures within one region could indirectly affect how forests outside the region are managed. These indirect effects, generally taken to be market-mediated, are often referred to as 'leakage' and/or 'indirect land-use change' (iLUC).

An example of leakage is a situation in which efforts to protect carbon stocks by restricting tree harvesting from a defined region of forest result in more pressure on wood supply in a different, unprotected region (i.e. not covered by the methods considered here). The resulting additional harvesting from these forests could involve some losses of carbon stocks which detract from efforts to conserve carbon in the protected forests.

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[3] Forest Europe defines Sustainable Forest Management as 'the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems', see https://foresteurope.org/.

An example of iLUC is a situation in which creating new forests on cropland within a defined region through afforestation creates a demand for cropland elsewhere, to make up for the lost supply of food or feed. The cropland area could then expand outside the region, possibly on former forest land, with related negative impacts on carbon stocks.

The possibility of leakage and iLUC effects cannot be ignored. However, risk of these effects occurring is a weak argument against the technical methods considered in this report. It is important to recognise the limits of what can reasonably be done and controlled for by individual actors or groups of actors. In this respect, it seems difficult to justify holding actors who make positive forest management efforts responsible for other actors elsewhere, even if the management choices of those actors could be regarded as indirectly related. Rather, there could be an aspiration to encourage as many actors as possible to implement the kinds of methods considered here across as much land area as possible. The specific issue of deforestation for the expansion of agriculture could also be addressed explicitly by adopting strong governance measures to tackle this. Furthermore, if some actors are successful in demonstrating the effectiveness and benefits of the methods described above, these activities may act as an example and encourage more actors to adopt similar approaches. It may also be observed that the methods suggested in this report support synergies between woody biomass supply and the conservation or enhancement of forest carbon stocks and minimise and/or mitigate for trade-offs between these two goals, making leakage effects less likely.

No system can be completely flawless or foolproof, and certain limitations can be identified with the suggested methods as already discussed above. The methods outlined in this report obviously involve significant simplifications. For example, as discussed above, they only assess total changes in carbon stocks resulting from forest management, without any consideration of the time taken for these changes to occur, which will be variable. In principle, the methods proposed could be extended to allow for timing, but the aim has been to design a pragmatic system, and to only add complexity if it is needed to ensure that the system should work.

Integration into policies

The technical methods outlined above are tentatively suggested as possible ways of managing sources of forest biomass and providing information about the likely carbon impacts associated with their supply and use. Existing policies addressing biomass, bioenergy, and climate change could be enhanced by integrating these methods in different ways, and the specific policy choices may depend on context. For example, regulation may work in regions where forest land is publicly owned, under the control of a few management companies, or in situations where communities have an existing culture of land and forest stewardship. Financial incentives, mediated through the monetising of carbon sequestration and possibly involving a trading system, might be more workable in regions where there are numerous individual owners of relatively small land holdings.

Actions to mobilise biomass whilst sustaining or enhancing carbon stocks could be integrated explicitly into efforts towards so-called Climate-Smart Forestry. While we have not attempted to do so here, the approach to managing the carbon impacts of biomass use described in this report could be adapted to apply to agricultural biomass.

FULL RESULTS

1 Introduction

1.1 Why this report?

As pointed out in the Dutch National Climate Agreement, biomass[4] will likely play an important role in a climate-neutral, circular economy (Dutch Government, 2019). At the same time, there is ongoing public and political debate on biomass. Therefore, the Dutch Cabinet is setting up an extended sustainability framework for biomass (EZK, 2022; EZK and I&W, 2020). It builds upon the existing framework which covers both transport fuels and electricity and heat from biomass and is consistent with European biomass-related legislation as laid out in the Renewable Energy Directive (REDIII) and the EU-Deforestation (EC, 2022), FuelEU Maritime, and the ReFuelEU Aviation Regulations. The extended framework is mainly aimed at mandatory criteria for bio-based plastics and building products. Attempts to include the issue of carbon debt in legislation has been going on for more than a decade, but has not (yet) succeeded, mainly due to the complexity of the issue. To this end, the Ministry of Infrastructure and Water Management asked the advice of the Social and Economic Council of the Netherlands (SER, 2020). In this context, PBL was requested to provide an estimation of the availability and optimal use of sustainable biomass for the Netherlands, to serve as input for the SER advice (PBL, 2020). The SER-advice has been embraced by the Dutch Cabinet as laid out in a letter to Parliament in October 2020 (EZK and I&W, 2020). It contains an 'execution agenda for bioresources' which should result in the aforementioned sustainability framework. Also, the letter announces PBL will report on the scientific state of affairs concerning the issue of 'carbon debt' in relation to biomass use. In this context, this report, written by a team of five international experts on the topic, provides an overview of scientific understanding of the subject of 'carbon debt' in relation to biomass sources and also suggests science-based policy principles and recommendations to minimise the risk of high carbon debts.

What is 'carbon debt?'

'Carbon debt' is a frequently encountered term in discussions about whether using biomass, for bio-based products and especially for bioenergy, makes a positive or negative contribution towards climate change mitigation. This subject is currently under considerable debate. Very broadly speaking the term refers to CO_2 emissions (or more specifically increases in emissions) that may occur when supplying and using biomass from agricultural land and forests. These emissions are principally related to negative impacts on carbon stocks in terrestrial vegetation and soil caused by biomass harvesting. The CO_2 emissions are considered a 'debt' insomuch as they can be 'paid back' through the use of bioenergy and other bio-based products to displace fossil fuels and fossil-based

[4] In this report, 'biomass' refers to any biomass harvested and extracted from forests and agricultural systems for a range of possible uses. For forests this includes structural sawn timber, other biomass-based material products (e.g. wood-based panels and paper), biomass burned to generate bioenergy and converted into chemicals including plastics. The term 'wood products' refers to the range of possible products that can be manufactured from forest biomass including from stemwood (i.e. tree trunks). 'Bioenergy' refers primarily to solid biomass (e.g. chips and pellets) burned to generate energy, and biomass converted into liquid and gaseous fuels. Carbon harvested and extracted from terrestrial vegetation systems is referred to as 'biogenic' carbon, in contrast to carbon in fossil fuels, which is referred to as 'fossil' or 'geological' carbon (see Section 2.1).

products. It must be stressed that, although 'carbon debt' can be described quite simply as a concept, it requires careful definition in technical discussions. The situation is complicated because there is no universally accepted definition, and scientific studies and policy reports on biomass and bioenergy can use the term with different meanings and interpretations. The formal definition of carbon debt for the purposes of this report is given Section 2.4 of this report. The preceding sections of Chapter 4 provide the essential scientific context.

Purpose and scope of this report

The following two research topics are covered in this report:

1. An overview of the scientific understanding of the phenomena of carbon debt and carbon payback times related to the production and use of – mainly woody – biomass from forests.
2. The extent to which science suggests policy principles and recommendations to minimise the risk of high carbon debts and long payback times.

With respect to topic 1, scientific literature on forest carbon balances and the role played by harvesting and utilizing wood products, including biomass used for energy, presents a confusing and apparently conflicting picture. Some studies, and particularly, those conducted earlier, on the climate effects of bioenergy *assume* that biomass is carbon neutral. Put simply, 'carbon neutrality' implies that carbon dioxide (CO_2) emissions from using biomass for energy are zero, when considering the net impact of burning the biomass, biomass losses along the supply chain and any effects on the carbon balance of forest ecosystems related to the harvesting and extraction of the biomass. Other studies find that harvesting and utilizing woody biomass from forests involves a 'carbon debt'[5]. As discussed above, in simple terms, this implies that there can be significant net CO_2 emissions resulting from such activities.

Then there are studies that suggest that forest management to produce biomass and bioenergy can result in net carbon sequestration in forests, so that actions to utilise forest biomass, including for energy, can contribute to net negative emissions[6]. This last possibility could be referred to as a 'carbon gain' associated with the production and use of biomass and bioenergy from forests, in contrast to a 'carbon debt'. Carbon stocks in forests that have been under long-term management to supply wood products and bioenergy are frequently stable or steadily increasing, when assessed at large spatial scales. For example, according to national greenhouse gas inventories reported by some countries under the United Nations Framework Convention on Climate Change (UNFCCC, 1992), forest areas utilised for wood supply have remained carbon sinks over many years (implying continually increasing carbon stocks), while being managed for wood production, maintaining a steady flow of timber to forest industries. However, as explored thoroughly in this report, it cannot

[5] For example, Bernier and Paré, 2013; Birdsey et al., 2018; Booth, 2018; Böttcher et al., 2012; Brack, 2017; Buchholz et al., 2016; Cherubini et al., 2013, 2011; Colnes et al., 2012; FDA, 2022; Giuntoli and Searle, 2019; Holtsmark, 2013; Hudiburg et al., 2011; A M I Kallio et al., 2013; Laganière et al., 2017; Lamers et al., 2014; Marland and Schlamadinger, 1997; McKechnie et al., 2011; Mitchell et al., 2009, 2012; Nepal et al., 2012; Pa et al., 2011; Pingoud et al., 2016; Schlamadinger et al., 1995; Smyth et al., 2017; Stephenson and MacKay, 2014; Sterman et al., 2018; Ter-Mikaelian et al., 2011

[6] See for example Alam, 2011; Baul et al., 2017; Daigneault et al., 2012; Dwivedi et al., 2011, 2014; Favero et al., 2017, 2020; Fiorese and Guariso, 2013; Gustavsson et al., 2021; Jonker et al., 2014; Kim et al., 2018; Kraxner et al., 2003; Kurz et al., 2018; Lundmark et al., 2014; Nabuurs et al., 2017; Pyörälä et al., 2012

be concluded that forests managed to produce biomass result in a carbon gain or avoid a carbon debt, simply because forest carbon stocks are stable or increasing.

These divergent accounts in the literature and often complex analysis methods can bring confusion to the public and decision-makers and inevitably lead to the question: is the bioenergy produced from forests carbon neutral, or does its use involve either a carbon debt or a carbon gain? The answer to this question is that all three outcomes are possible[7], depending on the details of the management method and how the harvested biomass is utilised for the various end products (such as a mix of structural timber, wood-based panels, paper and/or bioenergy). As discussed further below, conclusions about carbon debt, gain or neutrality also depend on the methodology used for quantifying carbon balances, which means that the correct application of methodologies is critical.

This report aims to:

- Clarify the circumstances under which biomass produced from forests can result in a carbon debt or carbon gain, or might be carbon-neutral, with the main focus on biomass used for energy;
- Analyse the reasons why studies on forest biomass show differing results for carbon losses or gains;
- Identify where variability in the carbon balance of forests supplying biomass is systematic, with underlying causes that might conceivably be understood, and so enabling the management of both risks and opportunities when deploying forest biomass resources;
- Explore the options for practice and policy to support the effective use of forest biomass as a renewable energy source that contributes to climate change mitigation.

The first three bullets address topic 1 for this report and the fourth bullet addresses topic 2.
The report covers biomass supplied from forests anywhere in the world where forest management is consistent with the principles of Sustainable Forest Management[8].

This report does not focus on biomass production that involves either direct or indirect permanent loss of forest areas (i.e. deforestation), since this violates the EU sustainability criteria as laid down in the EU Renewable Energy Directive (EC, 2021). This report focuses on forest bioenergy, because the question of whether forest bioenergy could help reduce greenhouse gas emissions has been hotly debated in recent years. Generally, understanding and managing carbon dynamics in forests involves more complexities than for agricultural systems because of the long rotations involved in growing and managing trees (often over many decades). In contrast, agricultural crops are usually grown and harvested annually or on rotations of a few years at most. As a result, carbon dynamics in agricultural crops are generally much simpler than for forests and therefore easier to understand, as are the implications of management decisions (for example for levels of biomass production).

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[7] Exact carbon neutrality, whilst possible, is arguably a theoretical construct and only likely to happen in reality only in very specific and exceptional situations. See also discussion in Box 3.3.

[8] Sustainable Forest Management (SFM) is defined here as the management of forests according to the principles of sustainable development agreed at the United Nations' Conference on the Environment and Development in 1992 and subsequently through the Ministerial Conference on the Protection of Forests in Europe (MCPFE) in 1993.

Often the main concern in agricultural systems is how to manage any effects on soil carbon resulting from changes in agricultural practices. In general, the principles and issues identified for forest biomass also apply to agricultural biomass (see Section 5.8).

1.2 Structure of this report

Chapter 2 introduces and explains some essential concepts and terms. This includes a discussion of the similarities and differences between carbon derived from biological systems and from geological formations. Key terms, such as 'carbon debt' and 'carbon payback time', and concepts, such as how CO_2 emissions and carbon impacts of biomass supply chains can be assessed, are also explained in Chapter 2.

Chapter 3 presents the basic science of forest carbon balances, and how a carbon debt, carbon gain or carbon neutrality may occur when producing bioenergy from forests.

Chapter 4 then considers why scientific studies on forest biomass report varying results and conclusions on carbon debt or gain.

Chapter 5 presents the authors' understanding of where systematic variation occurs in the greenhouse gas impacts associated with various ways of producing biomass from forests, and considers what practices and policy principles may support the use of forest biomass while minimizing the risks of high carbon debts and long payback times.

Finally, Chapter 6 provides a brief summary of the main findings and conclusions.

2 Essential concepts and terms

An assessment of the emissions from harvesting biomass, to manufacture non-energy products or for use as bioenergy, requires an understanding of some essential concepts and terms, as discussed in this chapter. Most importantly, definitions are given at the end of this chapter for key terms including 'carbon neutrality', 'carbon debt' and 'payback time' as applied in this report. The preceding discussion in this chapter provides the scientific and technical context underlying these terms. Firstly, an outline is presented of the contribution of biomass to the global carbon cycle, and this is compared to the contribution of fossil fuels. This is followed by a discussion of the important subject of how to assess CO_2 emissions for terrestrial vegetation and biomass sources, and the relevance of scenarios when making such assessments. Finally, the relationship between CO_2 emissions and atmospheric warming is described.

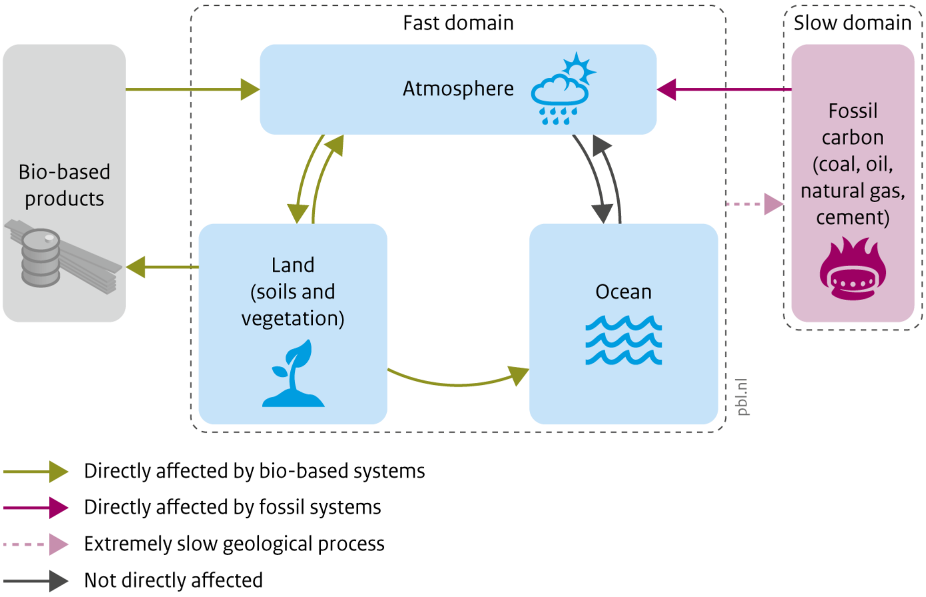
2.1 Biogenic and fossil carbon in the global carbon cycle

When considering the global carbon cycle, it is important to distinguish between two domains: the 'fast' domain and the 'slow' domain. Figure 2.1 shows a schematic overview of the global carbon cycle. The fast domain consists of carbon in the atmosphere, the ocean and surface ocean sediments, and on land in animals, plants, organic matter in soils, and fresh waterbodies. This domain involves large exchanges (or fluxes) of carbon and relatively 'rapid' turnover[9] of carbon in these reservoirs. For example, carbon stored in vegetation and soil organic matter has typical turnover times of 1 to 100 years, and 10 to well over 100 years, respectively. The slow domain consists of the carbon contained in rocks and sediments, including fossil fuels, which undergoes a relatively small natural exchange with the fast domain through volcanic emissions of CO_2, chemical weathering, erosion, and sediment formation on the sea floor. In these cases, turnover times are 10,000 years or longer.

Fossil fuel use and cement production transfer carbon from the slow domain to the fast domain of the carbon cycle, where fossil carbon is partitioned between atmosphere, ocean, and land. For terrestrial vegetation systems, the bi-directional carbon flows between land and atmosphere (driven by photosynthesis, respiration, decay and combustion) vary over time. They are also highly context-specific and influenced by climate change and therefore difficult to project and quantify. These bi-directional flows are one order of magnitude larger than the fossil carbon flow to the atmosphere, but combined, the net flow is relatively small. Bio-based products including bioenergy are within the fast domain and influence the bi-directional flows, and therefore also impact the net flow of carbon between land and the atmosphere.

[9] 'Carbon turnover' is used here to refer to the average time carbon is retained in a reservoir of carbon, such as the reservoir of carbon in terrestrial vegetation and soil. This is also sometimes referred to as 'mean residence time'.

Figure 2.1
The global carbon cycle



Source: Chalmers University of Technology, Sweden

Carbon extracted from fossil sources is often called 'fossil' or 'geological' carbon, while carbon stored in and harvested from terrestrial vegetation systems or retained in biobased products[10] is often called 'biogenic' carbon. Considered from the standpoint of basic chemistry and physics, when carbon is released into the atmosphere as CO_2, by burning either fossil fuels or bioenergy, the effect on climate warming is essentially the same. In this sense, emissions from bioenergy are no different from those from fossil fuels and from production and use of other fossil-based products such as cement. However, in other respects, there are very important differences in the 'carbon cycles' of forest bioenergy and fossil fuels. These differences exist because of the very different rates at which carbon is accumulated in biological and geological systems.

Carbon accumulates in fossil reservoirs (i.e. coal, oil, natural gas and limestone) at such a slow rate that losses from these reservoirs, when fossil fuels are combusted or cement is produced, can be regarded as effectively a one-way flow. Essentially, carbon is transferred irreversibly from geological reservoirs to the atmosphere. This is in contrast to the relatively fast circulation of carbon between biological systems (terrestrial and aquatic), the oceans, and the atmosphere (Cherubini et al., 2014; Cherubini, Strømman, et al., 2011). Carbon is also transferred between various biogenic carbon reservoirs, or 'carbon pools' (i.e. agricultural crops, forests, wood products). For example, carbon in vegetation is transferred to soils through root decomposition and plant litter. When a tree is harvested and used to produce sawnwood for the construction industry, some carbon is transferred from the forest into buildings (wood products pool).

[10] As a simplification for the discussion here, biobased products are considered included in the fast domain of the carbon cycle. However, some biobased products (biochar, and carbon from biomass stored geologically or through mineral carbonation) have much greater durability than carbon stored in vegetation and soil organic matter, and could be considered part of the slow domain of the carbon cycle.

There is a continuous circulation of carbon between the biogenic carbon pools and the atmosphere. Growing biomass takes carbon out of the atmosphere through the process of photosynthesis, using energy from the sun, and returns carbon to the atmosphere as the biomass decomposes or is burnt. Biomass use, including for bioenergy, can therefore influence carbon sequestration in terrestrial ecosystems and bio-based products as well as releasing CO_2 emissions. Such a possibility does not exist for fossil carbon derived from natural processes over relevant timescales.

There can also be indirect interactions between the use of biomass and geological resources, not shown in Figure 2.1, which can have impacts on fossil and biogenic carbon flows. Importantly, increasing the supply and use of wood products and bioenergy from forests could potentially displace greenhouse gas-intensive non-renewable materials and fossil fuels, through competition from the increased availability of bio-based products. If the wood products and bioenergy can be produced while maintaining or enhancing carbon stocks and sinks in forests (as defined in this report), the CO_2 emissions from their manufacture and use will be low and even negative (net carbon sequestration). This can indirectly lead to a reduction of greenhouse gas emissions by avoiding the emissions from the production and use of the displaced non-renewable resources. This potential role of wood products and bioenergy is usually referred to as 'wood product substitution (or displacement)' and 'bioenergy substitution (or displacement)', respectively. The resultant reductions in net greenhouse gas emissions may be referred to as 'wood product and bioenergy substitution effects'. When emissions are avoided by replacing one technology with another that involves lower emissions, the consequent reductions in emissions are sometimes described as 'avoided emissions' or 'greenhouse gas (emissions) savings'. More detailed discussion on this subject can be found in Appendix 1.

The substitution role of bioenergy and other bio-based products can contribute towards less reliance on fossil and geological resources, and towards a decarbonised global economy. However, this potential is only realised if the harvesting and utilisation of biomass does not also lead to a significant increase in flows of biogenic carbon to the atmosphere. A key question is therefore how to identify the best practices for producing and utilising biomass from forests (for certain end-use products including bioenergy) to *reduce* net greenhouse gas emissions and avoid increasing the concentration of atmospheric CO_2 (and other greenhouse gases). It is equally important to identify practices that are likely to present risks of *increased* CO_2 emissions, and where it may be preferable to retain carbon in forest ecosystems, rather than harvesting and extracting biomass from forests. The differing characteristics of the fossil carbon and biogenic carbon pools have a strong bearing on these questions, as explored in Box 2.1.

Box 2.1 Carbon in geological and terrestrial vegetation (i.e. forest) systems: the same or different?

Forest carbon and bioenergy researchers sometimes state that there is a 'fundamental difference' between carbon derived from geological formations, and carbon from terrestrial vegetation systems. This is clearly not true from the viewpoint of basic physics and chemistry, in terms of impacts on atmospheric warming. When carbon is released into the atmosphere as CO_2, the atmosphere reacts in the same way, regardless of where the carbon has come from. However, while the carbon is physically the 'same', the two carbon 'pools' or 'reservoirs' have different characteristics, which are important when deciding what to do with forests to mitigate greenhouse gas emissions, including whether or not to manage forests to produce biomass for wood products and bioenergy. These differing characteristics are assessed in Table 2.1, for the three systems of geological carbon, carbon in 'untouched' forests and carbon in managed forests. For this assessment, the term 'untouched forests' refers to:

- Forests where there has been no or hardly any disturbance caused by humans.
- Forests that were previously disturbed by humans, including managed forests, where changes are made to avoid all human interventions in forest development, other than to ensure the development and protection of high carbon stocks.

The term 'managed forests', here, refers to forests managed for wood products and bioenergy supply.

Table 2.1
Assessment of carbon in the three systems of geological formations, 'untouched' forests and managed forests. The characteristics in the table cover aspects of the carbon balance of forests or potential for mitigation of greenhouse gas emissions. The colours in the table indicate the importance of each property for the three systems. Dark green: High, moderate to high or moderate importance. Mid green: Low to moderate or low to high importance. Pale green: Low or no importance.

Characteristic	Geological carbon	Carbon in 'untouched' forests	Carbon in managed forests
Density of carbon stocks	High: Fossil carbon stocks in geological formations are high for the space occupied.	Moderate to high: Carbon stocks can be substantial (see Appendix 5), with varying degrees of stability (see below).	Moderate: Carbon stocks can be high but are usually lower than in 'untouched' forests (see Appendices 2 and 5).
Stability of carbon stocks	High: Generally, the carbon remains permanently underground in geological formations unless actively extracted for use as fossil fuels or industrial feedstocks.	Low to high: Carbon stocks depend strongly on frequency and intensity of natural disturbances. Forests with large carbon stocks can be more susceptible to disturbance (such as storms, fires and pests). Forests are likely to require some management, even if just for protection or to remediate damage.	Moderate: Managed forests have the same stability issues as undisturbed forests, but actively managed forests have economic value, so disturbances or loss of forest vigour are more likely to be remediated rapidly and thoroughly.
Capacity for sequestering extra carbon	None: Fossil carbon takes geological timescales to accumulate and so is not relevant as a meaningful option for sequestering more carbon.	Moderate to high: Possible to accumulate significant carbon stocks but potential is finite and dependent on context and stability (see above).	Moderate: Possible to accumulate some carbon (see Chapter 5) but options are very context-specific.

Characteristic	Geological carbon	Carbon in 'untouched' forests	Carbon in managed forests
Capacity for product substitution and greenhouse gas displacement	Low: Options consist of moving to more efficiently used and lower emissions fossil fuels (such as natural gas instead of coal).	Low: Biomass availability likely to be restricted, such as to salvage logging. Ceasing harvesting for wood production in managed forests would significantly limit availability of biomass.	Moderate to high: Wood products and biomass can be a substitute for greenhouse gas intensive materials and fuels. Policies would be needed to support 'best uses of biomass'. Significant carbon stock losses arising from changed forest management to produce biomass need to be avoided or minimised.
Opportunity for net carbon dioxide removal from the atmosphere via carbon capture and storage (CCS)	None: At best, combining with CCS could remediate part of the emissions from fossil fuel use.	Low: 'Untouched' forests would produce small quantities of biomass for subsequent application of BECCS (such as if and when salvage logging happens, see above).	Moderate to high: Potentially significant quantities of biomass could be produced for subsequent application of BECCS or biochar production and other options involving geological storage of biomass carbon, but these practices are not yet widespread.
Flexibility for changing actions in the future	None: Fossil fuels are non-renewable; they can only be used once, irreversibly. However, not using these fuels now allows the flexibility to use them later.	None to low: Accumulating carbon stocks by minimizing forest harvesting either constrains options for future management, or emissions resulting from future decisions to change forest management have to be compensated for elsewhere.	Low to moderate: A landscape with managed forest areas provides flexibility for adapting management over time, but measures to enhance carbon stocks face the same issues and constraints as for 'untouched' forests. The option is always available to cease harvesting in the future to accumulate higher carbon stocks (but see assessments of untouched forests).

Box 2.1 Continued

In essence, Table 2.1 shows that fossil carbon in geological formations can be retained in place effectively indefinitely unless it is actively extracted for use as an energy or chemical feedstock. Unless the fossil carbon is captured and injected back into an equally stable geological store, it irreversibly adds to the total amount of carbon in other pools, including most importantly the atmosphere and oceans.

'Untouched' forests can retain significant carbon stocks, and withdrawing management to leave forests 'untouched' can allow forests to accumulate significant carbon stocks, but outcomes may vary, depending on context, and any forest ecosystem can only sequester a finite quantity of carbon. Deciding now to leave forests untouched as an accumulated carbon store also commits future generations to protect the accumulated carbon stocks against losses. Alternatively, future generations would need to compensate for losses that occur (either as a result of deciding to manage the forests for a different objective or as a result of natural disturbances), for example, by undertaking carbon dioxide removal activities elsewhere.

Forests managed to supply wood products and bioenergy can also retain substantial carbon stocks, although often, but not always, in smaller quantities compared with 'untouched' forests. There are also opportunities to enhance carbon stocks in managed forests (see Sections 3.5, 5.2, 5.4 and Appendices 3 and 5), but the potential depends on context. As with 'untouched' forests, maintaining enhanced carbon stocks involves an indefinite commitment. Managed forests supply wood products and bioenergy that can retain carbon and substitute for greenhouse gas-intensive non-renewable materials and fossil fuels (see Appendix 1). Bioenergy produced in this way can also contribute to net carbon dioxide removal from the atmosphere, if combined with carbon capture and storage (BECCS). However, as explored thoroughly in this report, measures to increase wood supply from forests can have widely varying impacts on forest carbon stocks, and changes to forest management involving significant negative impacts on carbon stocks can negate any substitution or carbon dioxide removal benefits.

It should be apparent that the assessment in Table 2.1, and the wider analysis presented in this report, do not serve as a justification for managing all forests to maximise wood products and bioenergy production. Equally, they do not support the case for protecting all forests to maximise the accumulation of forest carbon stocks. The overall assessment of properties in Table 2.1 suggests a balanced approach allowing for context, involving:

- Retaining fossil carbon in geological formations as much as possible.
- Retaining carbon in existing 'untouched' forests, particularly where there are low risks of natural disturbances, tree growth rates are slow in terms of potential biomass production and/or there is high biodiversity or there are other non-carbon benefits in conserving the untouched forests.
- Reducing the risks of losses of carbon stocks and sequestration potential in forests that are highly vulnerable to environmental change, through management supporting forest adaptation.
- Allowing for the consequences of significant reductions in the supply of biomass for wood products and bioenergy from existing managed forests when considering options to protect forests to accumulate carbon stocks. Otherwise, this would restrict opportunities for sequestering carbon in wood products and would be likely to increase the use of greenhouse gas-intensive materials and energy sources to replace the supplies of wood products and bioenergy. Alternatively, other forest areas might come under pressure to supply more biomass to compensate for the reductions in supply when actions are taken to protect forests previously managed for some wood production.
- Adjusting management practices in managed forests to enhance wood products and bioenergy production as well as enhancing forest carbon stocks at the landscape scale (such as considered in detail in the example in Section 5.2).

The above analysis shows how biogenic carbon has different characteristics compared to fossil carbon, presenting opportunities to sequester carbon in forests whilst using harvested biomass in place of emissions-intensive alternative materials and fossil fuels. Nevertheless, it is important to assess the impacts of harvesting forest biomass for wood products and bioenergy on biogenic carbon balances (including carbon in forest systems and in the wood products pool). It is also necessary to assess indirect effects on emissions of fossil carbon and other greenhouse gases (through wood product and bioenergy substitution effects), to fully capture the impacts of biomass supply chains on atmospheric greenhouse gas concentrations over time.

2.2 Assessing CO_2 balances

On first impression, the steps involved in assessing the carbon or CO_2 balance of vegetation systems supplying biomass may seem straightforward. The steps involved could consist of:

- Identifying the vegetation systems involved, for example an area of forest, and the biomass products being supplied and used.
- Drawing an imaginary boundary around this system, referred to as the system boundary.
- Defining the time over which the balance is to be assessed.
- Working out all the flows of carbon or CO_2 across the system boundary, into and out of the system, during the period of interest.
- Adding up all the flows to give the total net carbon or CO_2 balance.

However, it is important not to take excessively simplistic approaches when estimating forest carbon sequestration and emissions from bio-based products, as is sometimes done in discussions about the role of biomass in actions to mitigate greenhouse gas emissions, especially in the case of bioenergy derived from forests:

- Sometimes, bioenergy is described as an energy source that involves high emission levels because, at the point of combustion, compared to fossil fuels, bioenergy typically generates less energy per unit of mass and emits more carbon per unit of power generated (Brack, 2017; Norton et al., 2019; Searchinger et al., 2018; Sterman et al., 2018; Walker et al., 2013).
- Conversely, sometimes it is assumed that emissions from bioenergy use can be counted as zero, based on the observation that the carbon is 'captured' by the growth of trees and then released when the bioenergy is burnt, suggesting that growing and harvesting bioenergy maintains a continuous cycle of carbon between forests and the atmosphere, with no net emissions to the atmosphere (Stupak et al., 2007; World Bioenergy Association, 2012).

Scientifically, neither of these perspectives is of use in studying the topic of carbon debt, because they do not accurately describe the carbon dynamics in forests and forestry that might cause a carbon debt, lead to carbon neutrality or to a carbon gain. In practice, vegetation systems and biomass supply chains such as forests and wood industry supply chains can be very complex and involve numerous flows of carbon, some of which can be difficult to identify and measure (see for example Morison et al., 2012). However, methods have been developed to address technical challenges to assessing carbon and CO_2 balances (see Section 3.4).

In addition to ensuring accurate quantification of carbon flows, it is even more important to ensure that calculation methods are appropriate for the purpose of any assessment being made, as illustrated by the two examples below.

As a first example, one purpose could be to measure the actual CO_2 balance as directly observed for a selected area of terrestrial vegetation. This is addressing the research question: 'What is the net CO_2 balance occurring in a defined area of land?' In this case, the results should provide an accurate representation of the net flow of CO_2 from the atmosphere into the system (carbon sequestration), or out of the system to the atmosphere (CO_2 emissions). However, a CO_2 balance derived in this way is made up of contributions from a combination of naturally occurring processes, such as tree growth and mortality, and the effects on these processes related to human activity, including tree harvesting. It can be difficult to separate the carbon flows and CO_2 fluxes attributable to human activity from those occurring as part of natural ecosystem processes, independently of human actions. Hence, this kind of result is not useful if the purpose of the assessment is to quantify the CO_2 emissions specifically resulting from forest harvesting and biomass use. The calculation methods need to be designed to be appropriate for addressing the question of interest.

As a second example, a different calculation approach is needed when assessing the impacts on CO_2 emissions of human actions in forests, including forest management and harvesting activities, and the use of harvested biomass. This approach requires the construction of scenarios. As for the previous example, the area of land (forest) is identified, and an imaginary system boundary is constructed around it. Assessments are then made of the CO_2 balance for this system, for two scenarios (see also Box 2.2):

1. A 'scenario of interest', representing the activities carried out in the forest and other relevant areas of the land within the system boundary (for example, harvesting, restocking, deforestation, afforestation).
2. A 'baseline', 'reference', or 'counterfactual' scenario, in which the activities specified in the scenario of interest are *not* carried out.

This kind of assessment essentially addresses questions of the type: 'What is the impact on CO_2 emissions of carrying out a specified activity, compared to not carrying out the activity?' A more specific example in the context of this report might be: 'What is the impact on CO_2 emissions of managing an area of land for agricultural production, compared to continuing the existing management (or non-management) of the land?' This concept may appear to be straightforward, but these example questions are very general. In practice, there are subtle variations in the precise question of this type addressed by individual published scientific studies. A major cause of variation in results reported in scientific studies of the CO_2 emissions of bioenergy systems is related to individual studies addressing different questions. This situation is further complicated by many published studies not clearly stating the intended question, or sometimes applying methods that are not correct for addressing the question. This point is discussed further in Section 4.5.

Box 2.2 Use of scenarios in assessing CO_2 balances

Certain important types of assessment of CO_2 balances of vegetation and biomass production systems involve the use of scenarios. The purpose of scenarios is to describe all the activities and processes involved in a chosen course of action, so that all the resultant carbon flows can be thoroughly identified and the CO_2 balance calculated accurately.

Typically, the CO_2 balance is first calculated assuming a scenario in which the activities of interest are carried out in the forest and other relevant areas of the land within the system boundary (for example, harvesting, restocking, deforestation, afforestation). This scenario may be referred to as the 'scenario of interest'. The CO_2 balance is then calculated again, but assuming a second scenario in which these activities are *not* carried out. This scenario is often referred to as a 'baseline', 'reference', or 'counterfactual' scenario.

The results for the two scenarios can then be compared, and the difference represents the quantified impact on the CO_2 balance of the human actions of interest.

For the 'scenario of interest' (in this context typically describing some kind of action to produce and use biomass from an area of forest), an inventory is made detailing all the forest management practices involved in supplying biomass, such as any forest harvesting and regeneration, and including any land-use changes where relevant (for example, afforestation and deforestation). The inventory of activities also specifies how any harvested biomass is processed, utilised for various wood products and/or bioenergy, and ultimately disposed of. The complete inventory of activities forms the basis for the calculation of all the carbon flows occurring under this scenario.

For the 'counterfactual scenario', another inventory is made of all the activities that happen 'directly' or 'indirectly' if the course of action being considered in the scenario of interest *is not* taken:

- Direct activities include how forests and other land areas are managed if, for example, action to harvest and utilise biomass is not taken. If some biomass is still supplied from the forests, but in increased or decreased quantities compared with the scenario of interest, these adjusted levels of supply are also represented in a counterfactual scenario.
- Indirect activities include anything else that is different under the counterfactual scenario as a result of the action to produce and supply biomass in the scenario of interest not being taken. For example, if less bioenergy is supplied, the counterfactual scenario represents the alternative activities that occur to supply the energy, such as the use of fossil fuel sources. Otherwise, the counterfactual scenario represents the actions taken to consume less energy, such as measures to improve energy efficiency.

In some situations, it may be possible to directly observe the activities involved in a scenario, if this consists of actions already taken or being taken. However, generally, developing scenarios involves many assumptions such as when assessing possible future actions, the details and consequences of which cannot be fully known. Assessments of CO_2 balances based on scenarios therefore involve uncertainties. These issues can be addressed in assessments by clearly stating all the assumptions involved and by carrying out an uncertainty analysis, to establish the likely range of estimates for CO_2 balances.

Table 2.2 gives examples of key questions that have been addressed in scientific studies of the CO_2 balance of land management to supply resources. The questions are given short labels for convenience: 'Here and Now', is the type of question implied by the first example purpose for making an assessment, as already described above. 'Human Footprint', 'Natural Alternative', and 'Pathways to Change' are variations of the second example question type above. These questions are quite closely related, but they clearly serve distinctly different applications. Furthermore, different calculation methodologies are needed to answer each of these three question types, notably regarding the construction of the scenario of interest, and the counterfactual scenario, as shown in Table 2.3.

Table 2.2
Types of question addressed by assessments of CO_2 balances.

Question label	Statement of question	Example application
Here and Now	What is the net emission or uptake of CO_2 occurring now in a defined area of land?	Inventories of greenhouse gas emissions for a country or organisation.
Human Footprint	What *is* the consequence for net CO_2 emissions or uptake of past and current management by people of a defined area of land, e.g. for agriculture, fibre supply (including woody biomass) or for other purposes such as urban development or recreation, instead of having left the land unused/untouched by humans?	Quantifying humankind's historical impact on CO_2 emissions and carbon sequestration in a specified area of land or terrestrial ecosystem.
Natural Alternative	What *would be* the consequence for net CO_2 emissions or uptake of continuing to manage a defined area of land as described above, instead of stopping management and leaving the land unused and un-interfered with by humans?	Quantifying the impact on CO_2 emissions and carbon sequestration of continuing to manage a specified area of land or terrestrial ecosystem to supply resources, compared to an alternative of ceasing management.
Pathways to Change	What *would be* the consequence for net CO_2 emissions or uptake of changing the way a defined area of land has been used or managed up until now, to meet a new purpose, e.g. to grow a new kind of crop, to manage land for increased or decreased supply of fibre (including woody biomass) or for some other new purpose, such as increased carbon sequestration or to create new wildlife habitats?	Quantifying the impact on CO_2 emissions and carbon sequestration of changing the management and/or use of a specified area of land or terrestrial ecosystem and/or the supply or use of resources, compared to continuing existing management of the land and/or use of harvested resources.

Table 2.3
Methodologies for constructing scenarios consistent with research questions in Table 2.2

Question label	Scenario of interest	Counterfactual scenario	
		Direct activities	Indirect activities
Here and Now	Measure (or calculate using models) the CO_2 losses from and gains into the land area that are actually occurring (i.e. are or would be directly observed) at the time of interest, and work out the net balance of CO_2 losses and gains.	A counterfactual scenario is not relevant/valid for this kind of question.	
Human Footprint	Calculate the total CO_2 losses from and gains into the land area that have actually occurred, for the period starting from when human management began, up to the present. Work out the net balance of total CO_2 losses and gains. Also calculate the total resources supplied by using/managing the land over the period (food, fibre, etc.)	Calculate the total CO_2 losses from and gains into the land area that would have occurred over the same period as for the scenario of interest, if the land had been left unused/untouched by humans. Work out the net balance of total CO_2 losses and gains.	Normally, the counterfactual scenario should also represent how people would have provided themselves with the food, fibre or other resources, if the land has not been used or managed. For example, for land managed for bioenergy supply, this might involve supplying the equivalent energy from fossil fuels. The CO_2 emissions or uptake are also estimated for these counterfactual resources. If this element is not included, the methodology is implicitly assuming that the alternative to people managing the land for resources is for people to not exist.

Question label	Scenario of interest	Counterfactual scenario	
		Direct activities	Indirect activities
Natural Alternative	Make a projection of the total CO_2 losses from and gains into the land area that will occur, starting from now, assuming that the existing land management practices are continued, up to some specified future time of interest. Work out the net balance of total CO_2 losses and gains. Also calculate the total resources supplied by continuing the existing use/management the land over the period (food, fibre, etc.) Essentially this would be a 'Business As Usual' scenario.	Make a projection of the total CO_2 losses from and gains into the land area that would occur over the same period as for the scenario of interest, if human interference in the land area were to be stopped and the land left unused/untouched by humans. Work out the net balance of total CO_2 losses and gains. Essentially this would be a 'natural regeneration' scenario.	Normally, the counterfactual scenario should also represent how people would provide themselves with the food, fibre or other resources, if the land is not used or managed for this purpose. For example, for land managed for bioenergy supply, this might involve supplying the equivalent energy from fossil fuels. The CO_2 emissions or uptake are also estimated for these counterfactual resources. If this element is not included, the methodology is implicitly assuming that the alternative to people managing the land for resources is for people to stop consuming the resources from any possible source, or for there to be fewer people needing resources.

Question label	Scenario of interest	Counterfactual scenario	
		Direct activities	Indirect activities
Pathways to Change	Make a projection of the total CO_2 losses from and gains into the land area that will occur, starting from the time when management of the land is changed, up to some specified future time of interest. Work out the net balance of total CO_2 losses and gains. The scenario should also include a projection of the supply of resources made possible by land use/management. This should allow for any increase or decrease in the supply of resources resulting from the changes in land use/management.	Make a projection of the total CO_2 losses from and gains into the land area that will occur, assuming that the existing land use/management practices are continued, over the same period as for the scenario of interest. Work out the net balance of total CO_2 losses and gains. Essentially this would be a 'Business As Usual' scenario.	Normally, the counterfactual scenario should also represent the continuation of current consumption of resources and the management required to supply these. For example, if land has been managed until now for bioenergy supply, this might involve assuming bioenergy supply continues at recently observed rates. Additionally, the counterfactual scenario should represent the consumption of other resources, if the use or management of the land is not changed. For example, if bioenergy supply is increased in the scenario of interest, the counterfactual scenario might assume that fossil fuel is consumed instead of the extra bioenergy. The CO_2 emissions or uptake are also estimated for these counterfactual resources. Essentially this would be a 'Business As Usual' scenario.

Assessments aimed at addressing these different types of questions generally give very different results for CO_2 balances. This does not mean that results are uncertain or incorrect, but it does stress the critical importance of:

- Being clear about the research question and intended application when making an assessment
- Clearly stating the purpose of the assessment and the research question
- Using the correct methods for the stated purpose and question, especially when developing scenarios used in the assessment.

All the question types described above are relevant for assessing the CO_2 balances of forestry and biomass supply chains, depending on the context and the purpose of an individual study. However, we assert here that the "Pathways to Change" question type is pre-eminent when investigating whether managing forests to supply wood products and bioenergy could contribute towards, or detract from, a goal of reducing CO_2 emissions in a specified timeframe.

Some researchers have advocated, explicitly or implicitly, that the correct counterfactual scenario for forest management should always be the option of leaving forests unharvested, and assuming that the trees would grow on and reach maximum carbon stocks for that site, sometimes omitting consideration of disturbances from diseases, fires or storms (Freer-Smith et al., 2021; Helin et al., 2013; Hudiburg et al., 2019; Koellner et al., 2013; Milà i Canals et al., 2007; Peng et al., 2023). The difference in carbon stocks and sequestration rates for the managed forest, compared to what would occur in the unharvested forest, is sometimes referred to as the 'carbon sequestration forgone' or 'opportunity cost' attributable to managing forest areas for wood supply, even if the current management regime has been long established. Although such a comparison is valid in certain situations, often comparison with 'no harvesting' or 'no management' is entirely hypothetical. Curiously, the approach appears only to be advocated when assessing forest biomass as a potential renewable resource. For example, it would be unusual to assert that assessments of the carbon impacts of creating solar farms or windfarms on former cropland or pasture land should always involve assuming a counterfactual scenario of abandoning the pre-existing agricultural land use and management practices, and allowing the land to revert naturally to a wilderness (with assumed eventual high carbon stocks).

When making assessments to inform actions to reduce net greenhouse gas emissions, or meet a goal of net zero greenhouse gas emissions, relevant research questions take the general form: 'What would be the impacts on greenhouse gas emissions of changing what we are doing now, by doing something different instead?' For forests, if the starting position is a forest where no harvesting is taking place, then 'no harvesting' is the relevant counterfactual scenario ('what we are doing now'), to which other scenarios should be compared. However, if the starting position is a forest already under management with harvesting for wood supply (at some particular harvesting rate), then this is the counterfactual scenario, which is therefore the one to apply when assessing areas of existing managed forests. In other words, when considering options for reducing overall greenhouse gas emissions, we are setting a question of the 'Pathways to Change' type, not of the 'Natural Alternative' type, which would involve a counterfactual scenario of leaving land unharvested in all cases.

A scenario of 'no harvesting' or 'no management' is of course one possible and perfectly legitimate scenario that can be assessed alongside other possible scenarios that could be 'pathways to change', but it is not the baseline against which to assess all other possible scenarios.

2.3 CO_2 emissions and atmospheric warming

The overarching goal of the Paris Agreement[11] is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels." To achieve this, the Paris agreement calls for the rate of greenhouse gas emissions to peak "as soon as possible", with "rapid reductions thereafter … to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century …". It is therefore essential to understand the relationship between CO_2 emissions and the global temperature change, and the implications for forest management and biomass use. The purpose of the discussion below is to present the key aspects

[11] https://unfccc.int/process-and-meetings/the-paris-agreement

of current scientific understanding of this relationship. Climate effects of non-CO_2 greenhouse gases (such as, methane, nitrous oxide, volatile organic compounds) and non-greenhouse gas phenomena such as albedo are outside the scope of this report. The inclusion of these effects would not fundamentally change the discussion and conclusions of in this report[12].

Cumulative net CO_2 emissions to the atmosphere have an approximately linear relationship with global mean atmospheric temperature change (MacDougall, 2016). This is referred to as the 'transient climate response to cumulative emissions' of carbon dioxide. This relationship can be used to derive a 'remaining global carbon budget', which is the maximum amount of cumulative CO_2 emissions that would result in global warming being limited to a given temperature level with a given probability, taking into account the effect of other greenhouse gases and other climate forcers (IPCC, 2018). As it is the cumulative CO_2 emissions that drive global temperature change, every ton of CO_2 emitted or sequestered during a specified period can be taken to have the same importance or 'weight' in determining the global average temperature at the end of the period, regardless of when it is emitted[13]. This has important relevance in determining how forest management and biomass use contribute to holding the increase in global average temperature below a specified level, such as 2°C or 1.5°C above pre-industrial levels.

As explained in Section 2.1, when fossil fuels are burnt for energy, the CO_2 emissions accumulate effectively irreversibly in the atmosphere, because of the essentially one-way flow from geological carbon stores to the atmosphere. As a result, the global mean temperature responds in a simple linear way to cumulative smokestack/exhaust emissions from fossil fuels.

In contrast, when biomass is used for bio-based products including bioenergy, the related temperature impacts depend on how carbon stocks in the agricultural and forest ecosystems supplying the biomass are affected by growing and harvesting it. The retention of carbon in bio-based products such as wood products manufactured from forest biomass is also a factor. When producing biomass leads to a sustained decline in agricultural and/or forest carbon stocks, this results in the transfer of CO_2 to the atmosphere where it has an equivalent global warming effect to using fossil fuels. Conversely, when carbon stocks are increased through agricultural or forest management as part of biomass production, this removes CO_2 from the atmosphere and will result in a global temperature decrease. Because the impacts of biomass use on atmospheric CO_2 vary depending on the specific circumstances, the temperature impacts of using bioenergy cannot be inferred by simply considering cumulative smokestack/exhaust CO_2 emissions. Instead, the overall impact on the carbon balance of the agricultural and forest ecosystems supplying the biomass needs to be considered in addition to the CO_2 emissions to the atmosphere that result from burning biomass for

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[12] Albedo effects can influence linkages between forest carbon balances and global temperature change, especially in boreal biomes (Strengers et al., 2010). These interactions may be allowed for when developing optimal strategies for forest management and biomass use to meet climate goals. See for example Graf et al. (2023).

[13] More strictly, there are two broad cases. In the first case, CO_2 is emitted earlier and then CO_2 is removed from the atmosphere later, to arrive at a certain amount of cumulative emissions by the end of the defined period. In the second case, CO_2 is removed from the atmosphere first and then emitted later to arrive at the same amount of cumulative emissions. The former case results in a lower temperature at the end of the period, compared with the latter case, because of carbon cycle feedbacks and the influence of atmospheric CO_2 concentration on CO_2 uptake by the ocean and vegetation systems. The former case is most relevant in discussions of carbon debt.

energy. Any related impacts on carbon retained in (or lost from) wood products also need to be allowed for.

Sometimes it is asserted that only the negative impacts on forest carbon stocks directly resulting from biomass harvesting should be counted when estimating emissions from using forest biomass for wood products and/or as bioenergy (including smokestack emissions). This would mean ignoring any carbon sequestration happening in growing stands that also form part of the managed forest areas where the biomass is being produced, based on an argument that it 'would be happening anyway'. It is selective and imbalanced to insist on including the negative impacts of forest harvesting on the one hand, whilst denying the possibility that forest management could also be actively contributing to carbon sequestration in the relevant forest areas on the other hand. Such an approach is bound to give incorrect results for emissions from bioenergy use. In real-life situations, the overall impact on cumulative CO_2 emissions of managing forests to produce biomass (for wood products and/or for bioenergy) can be positive, neutral or negative, in different circumstances, as discussed below and in further detail in Chapter 3. This does stress the critical importance of clearly identifying and quantifying the carbon flows in forest ecosystems that are attributable to their management to contribute to biomass supply chains. This can be complicated to assess and can involve pitfalls.

When determining how the use of bioenergy in place of fossil fuels contributes to keeping the increase in global average temperature below a specified level, it is necessary to assess the changes in biogenic carbon stocks and avoidance of fossil CO_2 emissions that result from using the bioenergy in the period up to the year in which the global average temperature reaches the specified maximum or 'peak' level of warming. Although in practice it is not possible to know in advance with absolute certainty when peak warming will occur, or what the peak temperature will be, it is still possible to define an assessment period for an emissions budget on the basis of meeting specified climate targets. For example, a target may be set to achieve a 50% reduction in greenhouse gas emissions by 2030, or to reach net zero greenhouse gas emissions by 2050.

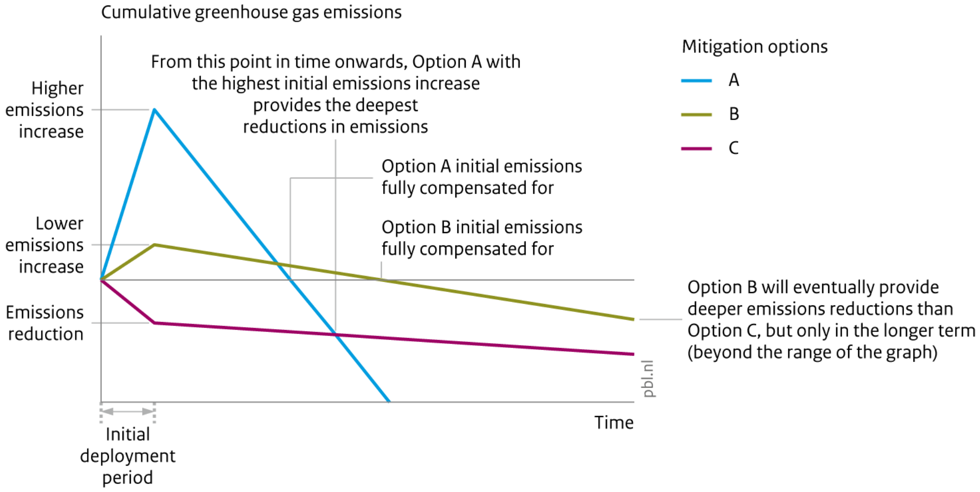
If the CO_2 emissions and sequestration that occur because of bioenergy use balance each other out over a given emissions budget period, such as up to 2050, then the global average temperature at the end of that period will not be *directly* affected by the use of bioenergy, because the cumulative emissions from the bioenergy use over the period will be zero. The extent to which bioenergy use has contributed to limiting global warming at the end of the period is then determined by the avoided CO_2 emissions resulting from the displacement of fossil fuels by the bioenergy. If the CO_2 emissions from using the bioenergy exceed the carbon sequestered in the vegetation systems supplying the bioenergy at the end of the period, then bioenergy use has resulted in cumulative net emissions of biogenic CO_2 to the atmosphere, reducing any mitigation benefit from displacing fossil fuels with the bioenergy. Conversely, if the CO_2 emissions from bioenergy use are exceeded by any related carbon sequestration in the vegetation system at the end of the period, this supplements the mitigation benefits from any fossil fuel displacement.

Some example scenarios are illustrated in Figure 2.2, which shows how cumulative emissions could develop for three contrasting hypothetical options for mitigation actions. The figure illustrates how different options for mitigation measures can have variable emissions and savings over time, leading to different trajectories of cumulative net emissions. Note that the lines in this simplified diagram do not correspond to any real cases.

The three options illustrate cases with:

A. High initial emissions during the deployment of the mitigation measure followed by rapid emissions reductions.
B. Modest initial emissions increase, followed by modest reductions.
C. Initial reduction in emissions (for example through carbon sequestration) followed by gradual emissions reductions.

Figure 2.2
Cumulative greenhouse gas emissions related to three mitigation options



Source: Chalmers University of Technology, Sweden

As can be seen, for two of the options (Options A and B in Figure 2.2), there is an initial period in which cumulative emissions increase. This could happen for mitigation measures involving promoting and deploying bioenergy-based technologies, if there is an initial deployment phase during which the emissions from harvesting and using the bioenergy are higher than the emissions saved by avoiding the use of fossil fuels. Following the deployment phase, cumulative emissions decrease again and eventually reach zero and then become negative. For a bioenergy source, this could occur if the emissions saved by using the bioenergy instead of fossil fuels eventually completely compensate for and then exceed the initial increases in emissions during the deployment phase (see Section 2.4). This pattern may also be observed if changes to forest management (including creating new forest areas) and harvesting over time result in net emissions initially, mainly related to harvesting, but this is followed by net carbon sequestration related to forest management changes, which, together with avoided CO_2 emissions from displacing fossil fuels, outweighs the CO_2 emissions from biomass harvesting and use.

The third mitigation option in Figure 2.2 (Option C), results in immediate reductions in net emissions during the deployment phase, after which emissions continue to decrease but at a slower rate. For mitigation measures involving bioenergy, this could happen for example when land is planted with trees to meet anticipated future wood demand, causing an increase in land carbon stocks, so providing mitigation benefits through carbon sequestration, in addition to those associated with the use of the harvested biomass for wood products and bioenergy.

Comparing these hypothetical examples, the mitigation option with the highest initial cumulative net emissions (Option A) eventually provides the largest annual net emissions savings (the line for Option A in Figure 2.2 has the steepest downward slope after the initial deployment period). After the point in time when the initial net emissions are fully compensated for by subsequent emissions savings, this mitigation option provides the most rapid and deepest cuts in emissions, compared with the other options in Figure 2.2. In contrast, the option that provides immediate emissions reductions (Option C) eventually has the slowest annual rate of emissions reductions (the line in Figure 2.2 has the most gradual downward slope after the initial deployment period). Option B will ultimately provide deeper reductions in cumulative net emissions than Option C, but only in the long term (beyond the end of the period shown in Figure 2.2).

It follows that the magnitude and duration of any net emissions during the period of deployment for a mitigation technology is important, but these initial emissions need to be considered in conjunction with the net emissions reductions that an option can ultimately deliver, as well as the speed with which the point when overall savings in cumulative net emissions is reached. In particular, if deployment of an activity initially leads to significant emissions increases, this does not rule out its relevance as a potentially useful mitigation measure, if this is balanced or exceeded by net emissions reductions within the timescale specified for an emissions budget. These critical properties of potential mitigation options can be characterised by parameters such a 'carbon debt', 'carbon gain' and 'carbon payback time', as defined in Section 2.4.

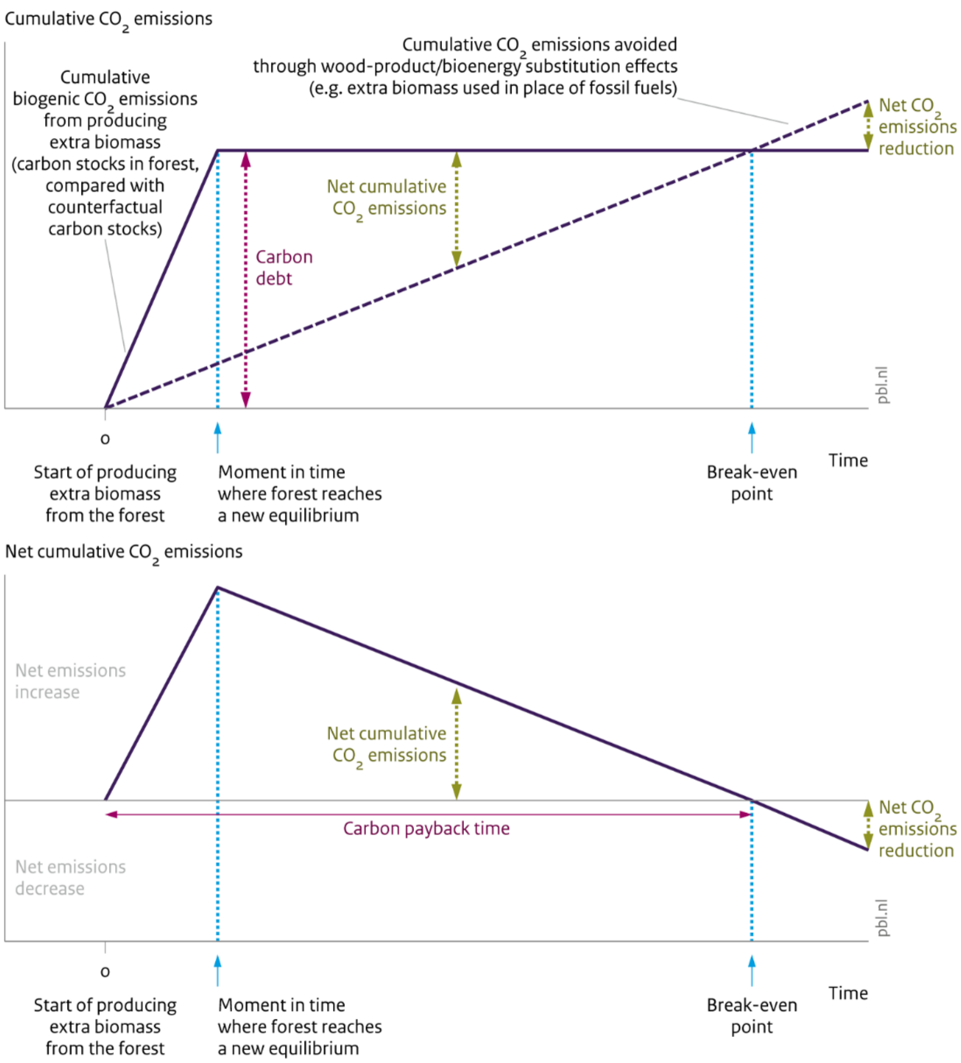
Forest management and biomass use could have an important mitigation role beyond the end of an emissions budget period and after peak warming is reached. For example, mitigation measures for removing CO_2 from the atmosphere involving agricultural and forest management and bioenergy use may be needed to balance hard-to-abate emissions, including non-CO_2 greenhouse gases, to achieve net zero greenhouse gas emissions. Achieving net-zero greenhouse gas emissions is also not an end point, as societies may plan for a net-negative greenhouse gas trajectory after achieving this.

2.4 Defining 'carbon debt', 'payback time', and other terms

One of the reasons why confusion and disagreement can occur over the impact of using wood products and bioenergy on greenhouse gas emissions is that different parties tend to use different definitions for key terms such as 'carbon debt' and 'carbon neutrality', often implicitly. It is therefore very important to be clear about the definition for such terms referred to in this report. These definitions are given below, using the concepts and terms discussed earlier in this chapter as a basis. In particular, it should be emphasised that the definitions are intended to be consistent with research questions of the type 'Pathways to Change' (see Section 2.2). To assist the discussion, Figure 2.3 illustrates the concepts of carbon debt and carbon payback time, as defined in this report, in the context of forestry.

Figure 2.3

Carbon debt and payback time



Source: Forest Research UK

Carbon debt

For the purposes of this report, we define 'carbon debt' as the *cumulative net emissions of biogenic CO_2* to the atmosphere that occur in certain circumstances when forest management is changed in certain ways to increase the supply of forest biomass. This includes allowing for the overall '*biogenic*' carbon emissions from the biomass supply chain and from combustion of biomass to produce energy. There is a 'carbon debt' if a decision to increase the production of biomass results in net emissions of CO_2 to the atmosphere, even after allowing for carbon sequestration in the forests producing the 'extra' biomass (i.e. increasing the quantity supplied). The CO_2 emissions from biomass supply and use are calculated by:

- Working out how carbon stocks in the relevant forest areas develop over time, allowing for the management practices including harvesting involved in producing the biomass.
- Working out how carbon stocks in the relevant forest areas develop over time for a *counterfactual scenario* in which biomass supply is not increased and forest management practices are not changed for this purpose. Rather, management practices are assumed to develop as they

would have done otherwise (which may still involve the supply of some biomass, but not in the increased amounts).
- Calculating the cumulative CO_2 emissions from the difference in carbon stocks at any specified time for the scenario in which biomass supply is increased, compared with the counterfactual scenario.

The above calculation method is consistent with addressing a question of the 'Pathways to Change' type as defined in Section 2.2. A hypothetical example of the development of cumulative emissions over time is illustrated by the solid lines in Figure 2.3.

The upper graph in the figure shows, separately:
- The cumulative biogenic CO_2 emissions from producing extra biomass (solid line), calculated by comparing the development of forest carbon stocks with how carbon stocks would develop in the counterfactual scenario (no extra biomass produced).
- The cumulative CO_2 emissions avoided (or 'saved') through wood-product and bioenergy substitution effects (for example by using extra bioenergy in place of fossil fuels; dashed line).

Our definition of carbon debt covers the first component but excludes the second, the emissions savings provided by using the extra biomass for wood products and bioenergy, through wood product substitution effects (see Section 2.1 and Appendix 1). This component is considered as a separate part of the carbon balance in this report but is allowed for when calculating relevant parameters such as carbon payback times (see next definition). The definition also excludes the 'process chain greenhouse gas emissions', such as emissions from fossil fuels when machines are used in tree establishment or harvesting, and during biomass transport, and during processing such as wood sawing or chipping[14]. If the emissions avoided by using bioenergy in place of non-renewable resources, such as fossil fuels, are more than the carbon debt (as defined here), then bioenergy can still provide net emission reductions in these circumstances. However, the presence of a carbon debt always implies diminished climate benefits, regardless of whether net emissions after allowing for wood product substitution effects are positive or negative.

The lower graph in Figure 2.3 shows the cumulative net CO_2 emissions, calculated by subtracting the cumulative emissions savings from the cumulative emissions increases related to the carbon debt. The net biogenic CO_2 emissions from forest carbon stock dynamics, resulting from producing the extra biomass (i.e. the carbon debt) accumulate up to a maximum quantity over a finite time period. Examples presented in Chapter 3 and Appendix 2 illustrate why this can occur, and how the magnitude of the net CO_2 emissions and the time over which they accumulate vary considerably, depending on the details of the types of forest, changes made to forest management, and how harvested and extracted biomass is utilised. The magnitude and duration of the period of increased net CO_2 emissions are critical factors in determining whether the biomass contributes towards reducing greenhouse gas emissions in a short enough timescale or detracts from such a goal.

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[14] Note that these emissions are always included when making full life cycle assessments of the greenhouse gas emissions resulting from biomass supply chains, and when calculating wood product emissions displacement factors, applied when estimating emissions savings from wood product substitution effects (see Appendix 1).

Carbon payback time

The term 'carbon debt' implies that the biogenic CO_2 emissions resulting from producing extra biomass (including for bioenergy) can eventually be 'paid back'. This follows from assumptions about the other resources (materials and/or fuels) that would need to be consumed instead of the biomass, in the event that the extra biomass is not produced and used (the 'counterfactual'). The manufacture and use of these alternative materials and fuels would also involve emissions. In the case of materials such as steel or brick and fossil energy sources, the emissions from consuming these resources will accumulate indefinitely, as shown by the dashed line in the upper graph of Figure 2.3[15]. These emissions can be avoided by producing and using the biomass (these are the wood product substitution effects). Eventually, the cumulative emissions avoided (or 'saved') exceed the cumulative emissions from using the biomass, as shown in Figure 2.3 by the point where the dashed line crosses the solid line in the upper graph or where the line returns to zero in the lower graph. The time taken to reach this point is defined here as the 'carbon payback time'.

As discussed in Section 2.3, the time taken for deployment of a mitigation measure to start providing net emissions reductions is a critical parameter in determining its effectiveness for contributing towards a target of limiting atmospheric warming to no more than 2 °C and preferably to 1.5 °C or less. Generally, mitigation measures with shorter carbon payback times are to be preferred but defining an 'acceptable' carbon payback time for biomass sources is ultimately subjective, depending on the urgency with which reducing emissions is viewed.

Duration of carbon payback times

As also discussed in Section 2.3, cumulative net CO_2 emissions to the atmosphere have an approximately linear relationship with global mean temperature change. The implication of this is that when measuring the progress towards staying within an emissions budget for a given temperature target, every ton of CO_2 emitted will cause around the same amount of warming, no matter when it was emitted, as long as this is within the carbon budget period. This has important relevance in determining if an increase in bioenergy will have a beneficial impact on limiting global warming. If the carbon payback time for a biomass source is within the carbon budget period, then using the biomass can contribute to achieving the specified temperature target. If the payback time stretches significantly beyond the carbon budget timeframe, then the contribution of bioenergy to limiting global warming is diminished. Modelled socio-economic pathways to achieve the long-term target temperature range set by the Paris Agreement typically indicate the need to stabilise cumulative emissions within a timeframe to 2050 (Riahi et al., 2022); pathways admitting a slight overshoot of cumulative emissions followed by reductions through net CO_2 removals exhibit a peak in cumulative emissions no later than 2070.

The above observations suggest that:

- Ideally, measures consistent with IPCC climate change mitigation pathways contribute to net emissions reductions by 2050, and no later than 2070.

[15] Sometimes it is argued that this kind of result involves the assumption that the industries producing these resources do not become decarbonised in some way, or that it makes no allowance for the possibility that some of these resources could be exhausted in the future, such as fossil fuels. See discussion in Appendix 1.

- Measures consistent with the text of the Paris Agreement contribute to net zero emissions and preferably net emissions reductions by no later than the end of the century (2100).
- Human activities that lead to significant emissions well after the end of the century are very problematic.

This leads to a possible classification for carbon payback times into categories of 'Short', 'Medium', 'Long' and 'Very long', as shown in Table 2.4. Different possible measures involving forest management options or the use of different biomass feedstocks for bioenergy can, therefore, be assessed according to this classification, as considered in detail in Chapter 5.

Table 2.4
Classification of biomass (as a source for all types of products) in terms of categories of carbon payback time.

Category	Payback time (years)	Interpretation
Short	0-15	Net emissions reductions by 2040 at the latest if activities start now, and by 2050 if started in the next 10 years. Compatible with pathways limiting warming to 2 °C or less.
Medium	15-30	Net emissions reductions by 2040-2055 if activities start now, and by 2050-2065 if started in the next 10 years. Compatible with pathways limiting warming to 2 °C or less, in which cumulative emissions overshoot and are then compensated for after about 2070.
Long	30-100	Net emissions reductions in the second half the century or up to a few decades after 2100. Only compatible with pathways limiting warming to 2 °C or less, if rapid and deep reductions in emissions are provided once the carbon debt is paid back.
Very long	> 100	Net emissions continue well beyond the end of the century. Very unlikely to be compatible with pathways limiting warming to 2 °C or less.

Carbon neutrality[16]
For the purposes of this report, the term 'carbon neutral' is used to refer to situations in which the act of producing biomass from forests for wood products and bioenergy results in zero or negligible net emissions of biogenic CO_2 to the atmosphere, when the complete life cycle of forest growth (and regrowth) and harvesting and consumption of biomass is considered. The biogenic CO_2 emissions from biomass supply and use are calculated in the same way as for the 'carbon debt' case described above, consistent with addressing a question of the 'Pathways to Change' type defined in Section 2.2. 'Carbon neutrality' is also used to describe situations where biomass is being produced from a forest that is literally in perfect carbon balance with the atmosphere, as assessed in terms actual flows of carbon, consistent with addressing a question of the 'Here and Now' type defined in in Section 2.2. This can occur if biogenic CO_2 emissions from harvesting and using forest biomass, including burning some for bioenergy, are exactly balanced by carbon sequestration in the forests that produced the biomass (including carbon retained in wood products, in situations where this is

[16] Other definitions of 'carbon neutrality' are sometimes used, such as the somewhat more complicated one used in DESNZ (2023), which is intended to be compatible with IPCC scenarios that limit atmospheric warming of 2 °C or 1.5 °C. Working with the DESNZ definition would not fundamentally change any conclusions about the role of forest biomass in contributing to reducing CO_2 emissions but further discussion of this point is beyond the scope of this report.

relevant). Theoretical examples presented in Chapter 3 and Appendix 2 illustrate the kind of circumstances in which such a scenario can occur. Note that 'process chain greenhouse gas emissions', such as emissions from fossil fuels consumed in machines and trucks used in harvesting, transporting and processing the biomass, are excluded in this definition.

Carbon gain

The term 'carbon gain' is used here to refer to situations in which producing biomass from forests results in net carbon sequestration from the atmosphere, when the overall carbon balance of the complete forest and biomass supply chain system is allowed for. In other words, a decision to produce and use biomass (for wood/biobased products and bioenergy) results in a net removal of CO_2 from the atmosphere, after allowing for carbon sequestration in the forest (and in wood products where relevant) in response to producing the biomass. This is likely to involve a finite total quantity of net carbon sequestration over a finite period of time. The net removal of CO_2 from the atmosphere resulting from managing forests to produce biomass is calculated in the same way as described for the 'carbon debt' case defined above, consistent with addressing a question of the 'Pathways to Change' type defined in Section 2.2. Theoretical examples presented in Chapter 3 and Appendix 3 illustrate how such a scenario may occur. Note that the use of the term 'gain' in this context should not be confused with the 'Gain-Loss Method' defined in IPCC Guidance for estimating national greenhouse gas inventories (IPCC, 2006).

Carbon impacts

Colloquially, the term 'carbon impacts' in the context of biomass use could refer, for example, to the net emissions or uptake of CO_2 occurring in a defined area of land and an associated biomass supply chain, consistent with a research question of the types 'Here and Now' or 'Human Footprint' (see Section 2.2). However, this is not how the term is used in this report. Instead, we define 'carbon impacts' as the overall change in emissions to the atmosphere that occur when forest management is modified in certain ways to increase or decrease the supply of forest biomass, or there is a change in the way biomass is utilised, for energy or for other bio-based products. This includes allowing for:

- Any carbon debt or carbon gain as defined above that occurs as a result of changes to forest management or wood utilisation.
- Supply chain emissions from fossil fuels and materials consumed in growing, harvesting, extracting and processing the biomass.
- Related changes in emissions resulting from wood product and bioenergy substitution effects.

Can carbon neutrality, debt and gain actually occur in practice?

Before getting further into detailed discussion of the carbon balances of forests and their management to supply biomass, it should be clearly stated up front that producing biomass from forests for use in wood products and for bioenergy can result in carbon neutrality, carbon debt, or carbon gain. All three are real phenomena and not artificial constructs, and all three outcomes are possible and can occur in practice. However, assessing real-life situations to see whether a carbon debt, neutrality or gain is actually occurring in a biomass supply chain usually requires modelling and can involve many assumptions. Hence, all such assessments are theoretical to some degree. Nevertheless, these phenomena do not occur randomly, instead they are linked explicitly to identifiable factors, including the quantity of biomass harvested in relation to the growth rates of the forests, the forest management practices involved in producing the biomass, and how the biomass is utilised (e.g. just burnt as bioenergy as the sole product or used for a range of bio-based products with bioenergy as a by-product).

It should also be noted that scenarios in which producing biomass from forests results in a carbon debt or a carbon gain are more likely than the often rather theoretical scenario of carbon neutrality in which the carbon flows between forests, wood products and the atmosphere are in perfect balance.

Other mitigation actions can incur a carbon debt

It Is also important to recognise that many climate-change mitigation measures outside the forestry and other land use sector can be associated with a 'carbon debt' in the sense that their deployment can cause some net greenhouse gas emissions that, for a period of time, can sometimes be larger than the emissions avoided due to the deployment itself. Meeting the goal of the Paris Agreement will require mitigation measures outside the forestry and other land use sectors that may cause significant up-front greenhouse gas emissions, such as expansion of railway networks (Olugbenga et al., 2019; Saxe et al., 2017; Westin and Kågeson, 2012), vehicle electrification and use of light-weight materials (Costa et al., 2021; Dunuwila et al., 2021; Hill et al., 2019; Morfeldt et al., 2021; Xiong et al., 2021), ramping up reservoir hydropower (Ocko and Hamburg, 2019) and solar PV capacities (García-Valverde et al., 2009; Grant et al., 2020; Grant and Hicks, 2020; Liu and van den Bergh, 2020). Mitigation benefits from the deployment can thus involve a delay that depends on the magnitude of the initial net emissions and of the emissions savings ultimately achieved. The possibility that mitigation options are associated with such up-front emissions is not in itself a sufficient reason to exclude them from the list of potentially relevant mitigation strategies. However, neither should up-front emissions occurring when deploying mitigation measures, including those involving the use of biomass simply be ignored. Up-front emissions need to be assessed and the drawback of such emissions needs to be weighed against the longer-term benefits of deploying mitigation measures.

As illustrated for hypothetical scenarios in Section 2.3, mitigation options may initially increase net greenhouse gas emissions but later provide products and services with low, neutral or even net negative emissions (Hausfather, 2019; UIC, 2016). For example, electrification of road transport may make slow progress because of low vehicle turnover rate and may for some time contribute to increasing atmospheric CO_2 levels if electricity for battery manufacture and especially charging is produced in ways that cause high emissions. However, promotion of electric vehicles can be justified if they are able to provide efficient transport services that cause low emissions once countries have overcome the challenge of phasing out fossil fuel use for electricity generation.

3 Forest bioenergy, carbon neutrality, debt, and gain

This chapter presents simple examples and illustrations to explore and clarify the circumstances under which each of the three outcomes of carbon neutrality (Section 3.1), carbon debt (Sections 3.2, 3.3 and 3.4 and Appendix 2), and carbon gain (Section 3.5 and appendix 3) can occur, with specific reference to bioenergy produced from forests. It does not cover scenarios of biomass production that involve the permanent loss of forest areas (i.e. deforestation), on the basis that such forest management should be avoided. All the scenarios considered in this section assume the application of the principle of sustainable-yield forest management (see Box 3.1). This is a fundamental criterion for sustainably managed forests and should be a specified requirement for any scenario in which forests are utilised to supply bioenergy or wood products, more generally.

Box 3.1 Relevance of sustainable yield forest management

Sustainable yield is one of the fundamental principles of sustainable forest management under which forests are managed in such a way that, in the long term, the rate of wood harvesting matches or is less than the rate of wood growth. This practice is well understood in the forest sector as the 'principle of sustainable yield management'. This principle is important to the discussion presented above and below. Sustainable yield management does not constitute a comprehensive approach to sustainable forest management or sustainable wood production that considers all possible criteria and impacts. A comprehensive approach would consider other impacts including the stability of forest sites (such as with respect to wind risk), the nutrient and water balance at those sites, the eutrophication of surrounding watercourses and lakes, forest biodiversity and that of the surrounding landscape, as well as economic and social factors. Rather, sustainable yield management has a narrower but crucial focus on ensuring that rates of wood supply from forests can be sustained, given the estimated potential for forest growth. In reality, a more comprehensive consideration of the sustainability of specified levels of forest bioenergy production is needed.

The illustrations in Sections 3.1 to 3.5 and Appendices 2 and 3 are based on simplified theoretical scenarios of forest management and bioenergy production and simplified calculations. This approach was chosen for clarity when explaining the fundamental science of carbon balances and the potential impact of tree harvesting and bioenergy production. The examples also highlight where important sensitivities and uncertainties may occur in estimates of net CO_2 balances for bioenergy production from forests. These sensitivities can be related to the scenarios assumed for forest management and biomass utilisation, and/or differences in the completeness of calculations and underlying assumptions.

The climate impacts of forests and forest management are also influenced by non-CO_2 greenhouse gases and non-greenhouse gas climate phenomena such as albedo[17]. These impacts, although important in some cases, are secondary to the scope of this report and are not considered in the examples presented below.

Source of numbers used in example calculations

The results for forest carbon stocks and stock changes referred to in the calculations in Sections 3.1 to 3.5 and Appendices 2 and 3 were derived from outputs of the CARBINE forest sector carbon accounting model. The CARBINE model was first developed in 1988 and has been under continuous development since then[18]. It is now one of several forest carbon accounting models that have been developed worldwide. The general purpose of the CARBINE model is to address questions about the carbon and greenhouse gas balances of forestry systems, and to inform the development of forest policy and practice, particularly with regard to climate change mitigation.

3.1 How can bioenergy from forests be carbon-neutral?

The first example presented here is a deliberately simplified illustration of how, theoretically, growing, harvesting, and burning forest biomass as an energy source can result in no net emissions. A simple forestry system is considered, consisting of uniform stands of trees grown on a fixed rotation. All the trees are harvested at a fixed age, with no harvesting during the rotation period (i.e. no thinning or pruning). The forest consists of stands that are planted at different times, with the same area of stands in each age class (with stand ages from 1-year up to those at rotation age). Each year, the forest stands that have reached the rotation age are harvested, whilst trees in other areas are left to continue to grow (see Section A2.4 for more details).

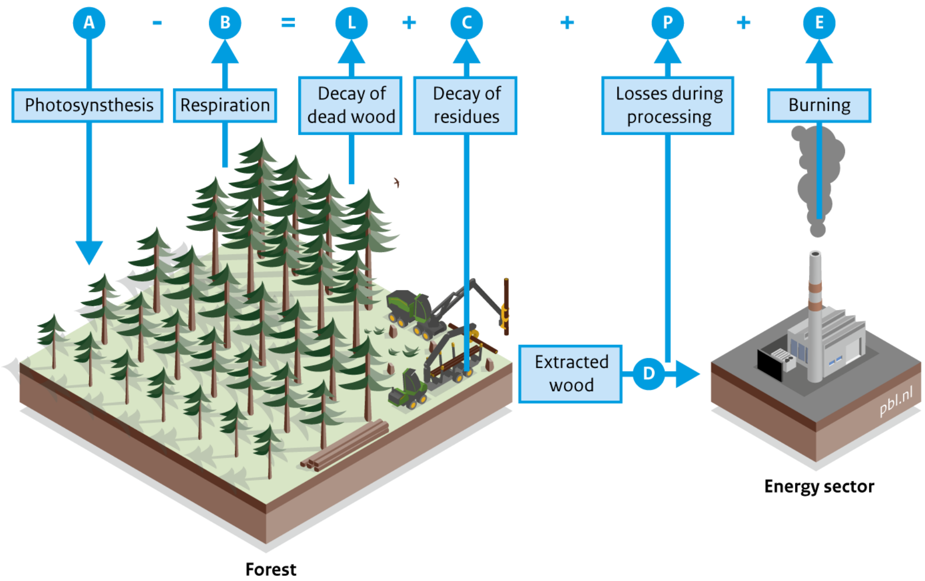
Figure 3.1 illustrates the essential exchanges of carbon involved in the CO_2 balance of forests in simplified form. The simplifications (see Box 3.1) are made to help explain the basics of forestry carbon balances. It must be stressed that these simplifications do not invalidate the example, but they do mean that it is theoretical and only presents part of the carbon balance of a typical forestry system. In particular, it is very atypical for the harvested stemwood to be used entirely for bioenergy. In reality, stemwood is usually used for a combination of products, with bioenergy as a by-product.

The forest in the example is already under management to produce woody biomass for use as a bioenergy source. The left-hand part of Figure 3.1 describes the forest. Flows of carbon into this part indicate CO_2 removed from the atmosphere, as shown by the ingoing flux, whilst outgoing fluxes show carbon lost from the forest.

[17] A brief description of current understanding of these effects can be found in Section 2.10 of Matthews (2020b).
[18] https://www.forestresearch.gov.uk/research/the-carbine-forest-sector-carbon-accounting-model/

Figure 3.1

Carbon balance of a forest-bioenergy system where the forest has been under long-term management for bioenergy production



Source: Forest Research UK

> **Box 3.2 Description of Figure 3.1 on carbon neutrality**
>
> The portrayal of forest carbon balances in Figure 3.1 is deliberately simplified to aid clarity. For example, carbon from decaying wood (L and C) is assumed to be lost immediately, while in reality, some would remain in deadwood, forest litter, and residues for some time. Carbon lost to the atmosphere from decaying wood (in the forest or in wood products) is assumed to consist of CO_2 emissions, whereas generally some will be emitted as methane, a stronger greenhouse gas than CO_2. Furthermore, several examples given in this chapter and in the appendices assume that all wood harvested from a forest is assumed to be used for bioenergy. The possibility of harvested wood being used to make products such as structural timber, furniture, and paper, as well as being used for bioenergy, is not considered. In addition, the example does not consider the greenhouse gas emissions related to forest management activities, such as from fossil fuels powering the machinery involved in forest management and tree harvesting. Carbon neutrality occurs when the net uptake of CO_2 during forest growth (A minus B) perfectly balances out the losses to the atmosphere (L, C, P, E). In practice, there may be periods of net uptake and net losses over time; carbon neutrality occurs as long as positive and negative fluctuations are short term and there are no net gains or losses when these are time-averaged.

The net exchange formed by the fluxes A and B represents the uptake of CO_2 from the atmosphere into the trees through photosynthesis and capture of carbon in tree biomass (as carbohydrate compounds, such as cellulose, lignin, and sugars), represented by A, minus the carbon losses represented by B that result from respiration by the trees. Losses of carbon from essentially *natural processes* such as tree mortality and natural disturbances (such as fires, storms, pests, and diseases) that lead to the decay of forest biomass are represented by flux L. Fluxes C and D represent the flows of carbon out of the forest that result from *human activity*, such as the felling of trees and harvesting biomass as part of forest management. Flux C represents carbon losses to the atmosphere from the parts of felled trees that are left to decay in the forest (i.e. '*forest residues*'). Flux D represents the carbon leaving the forest in the biomass that is harvested and extracted to be used for bioenergy. In this simplified example, only the stemwood of the felled trees is extracted and it is all used for bioenergy, with forest residues left to decay in the forest (which is assumed to occur immediately). Carbon losses from biomass can also occur in the supply chain delivering bioenergy to the energy sector; these losses are represented by flux P.

This net forest carbon balance of A, B, C, L, and D determines the amount of carbon sequestered in the trees, deadwood, plant litter, and soil organic matter of the forest. This reservoir of carbon in the forest may also be referred to as the 'forest carbon pool' and the amount of carbon in the pool may be referred to as the 'carbon stock' of the forest. If the net balance of A, B, L, C, and D is positive (net inflow to the forest), the carbon stock in the forest increases. If the balance is negative, this carbon stock will become smaller.

The right-hand part of Figure 3.1 represents the energy sector. Flows of carbon into and out of this part suggest inputs of carbon in the biomass harvested from forests and emissions of CO_2 from the burning of forest biomass to generate energy:

- Flux P represents losses that can occur as the wood extracted from forests is transported and processed into useful products (in this simplified case, this concerns bioenergy as the only product).
- The input of biomass into the energy sector consists of the net flow of biomass extracted from the forest represented by flux D, minus the losses from the supply and processing chain represented by flux P.
- Flux E represents the CO_2 emissions from the energy sector that result from the burning of biomass for bioenergy.

An important insight may be gained by considering the carbon flows between the atmosphere and the parts of the system indicated by fluxes A, B, L, C, P, and E in Figure 3.1: *If a forest has been under the same management for bioenergy production for a long time, such that the rate of wood harvesting matches the growth rate of the forest biomass, then*

$$A - B \text{ [Growth]} = L + C + P + E \text{ [Losses]}$$

or

$$A - B - L - C - P - E = 0.$$

That is, the system is in exact carbon balance. It follows that continuing to harvest biomass from the forest to produce bioenergy at rates consistent with pre-existing harvesting rates results in zero net CO_2 emissions.

This observation is the basis for the conclusion that bioenergy from forests is or at least can be carbon neutral. It is not a subjective observation open to interpretation or argument, but rather an undeniable physical fact. Carbon neutrality is most clearly associated with situations where *all* the following conditions are met:

- The quantities of biomass being extracted from forests are stable over time (assuming harvesting is not constrained by factors such as uneven distribution of tree/stand ages).
- The quantities of biomass being extracted do not exceed the regrowth of biomass.
- The forest management practices involved in biomass supply are constant over time (such as, levels of thinning and rotation ages in stands are kept the same).
- The existing uses of biomass are maintained (such as, biomass is not diverted from other existing uses such as the manufacture of material products to use for bioenergy).

It may seem counterintuitive to suggest that harvesting trees can involve zero net CO_2 emissions, particularly given the obvious emissions that occur at the moment that biomass is burnt. Indeed, this possibility is frequently challenged, particularly by critics of the use of bioenergy. The point is still being debated at present, and the current arguments and counterarguments are discussed and assessed in Box 3.3.

Box 3.3 Carbon neutrality of biomass: myth or real?

The possibility that biomass supplied from forests can be 'carbon neutral', as defined in this report, is challenged by some commentators and researchers who are sceptical about the possibility of biomass use, particularly for bioenergy, being a relevant measure for contributing towards mitigation of greenhouse gas emissions.

Statements that challenge the carbon neutrality of biomass are frequently expressed simplistically and unequivocally (see also Section 4.6.3). For example, it may be pointed out that it takes minutes to cut down a tree but decades for a replacement tree to grow back, implying that there is an initial carbon loss when harvesting in forests that takes decades or longer to be replaced by regrowth.

The statement that trees can be cut down quickly but take a long time to grow is undeniably correct. However, this ignores the fact that the relatively slow gains and fast losses of carbon stocks that can occur in an individual tree or a managed stand can cancel each other out when considering larger scale and large tree populations. This is a very important point that is thoroughly explained in Appendix 2 (Section A2.4). We acknowledge that care is needed when deciding on the spatial scale to consider and the 'system boundary' to apply in assessments of emissions from forest biomass supply chains, to ensure that all relevant processes are included (and irrelevant ones are excluded).

Some critics of forest harvesting (and forest bioenergy in particular) focus on carbon stock losses in the part of the forest that is being harvested at any one time. For example, Peng et al. (2023) have commented, "Many approaches give the impression of low, zero or even negative greenhouse gas emissions from wood harvests because, in different ways, they offset carbon losses from new harvests with carbon sequestration from growth of broad forest areas … These forms of accounting do not accurately capture the effects of new forest harvests for the basic reason that the forest growth and regrowth used to offset the effects of new harvests would happen anyway".

Statements such as these are valid in some situations. For example, if harvesting activities are started in an area of forest where previously there was little or no harvesting, the continuing carbon sequestration in the parts of the forest not (yet) harvested has no relevance to the impacts on forest carbon stocks of starting to harvest. However, the above logic does not apply in the situation described in this section and in detail in Sections A2.1 to A2.4 of Appendix 2, where an area of forest is purposefully managed at landscape scale to ensure that harvesting does not cause negative impacts on carbon stocks.

Comparisons of managed forests with an alternative 'no harvesting' scenario do not alter the fact that, intrinsically, forests managed according to the conditions listed earlier in this section can produce biomass, including for bioenergy, with zero or negligible emissions to the atmosphere.

3.2 How can bioenergy from forests result in a carbon debt?

In Figure 3.2 an example is given in which managing forests to produce biomass results in a 'carbon debt'. It describes how shortening rotations in a managed forest to produce more biomass used for bioenergy affects forest carbon stocks and the carbon balance. This example is an extension of the simplified illustration given in Section 3.1. The idea of shortening forest rotation periods is to increase the rate of biomass production by harvesting trees at a younger age, which is when tree growth is closer to its fastest. For many situations, this is not a realistic scenario for increasing forest biomass production, but such an example is sometimes used to illustrate how forest management could, at least theoretically, be modified in response to demand for biomass (for example, see Hektor et al., 2016).

As in the previous example, a simple forestry system is considered, consisting of uniform stands of trees grown on a fixed rotation. However, in this case, as the forest stands are felled, the newly planted replacement stands are managed on a shorter rotation (see also Section A2.5 in Appendix 2). All the trees are harvested at the end of the rotation period (original or shortened), with no harvesting during the life cycle of stands (i.e. no thinning). As in the previous example, only the stemwood is harvested and all of it is used for bioenergy. Only the carbon in trees is considered in this example, ignoring the carbon retained in and lost from dead wood, forest litter, and soil, as well as the possibility of harvested wood being used to make products.

The initial state for the forest in Figure 3.2 is described previously in Section 3.1 and illustrated in Figure 3.1. The upper diagram in Figure 3.2 illustrates the impacts on carbon flows in the period of transition, during which rotations are shortened to increase biomass production. The lower diagram shows the eventual state of the forest, following this period of transition.

Initial state

The initial state of the forest, and associated carbon flows, are described in Section 3.1 and illustrated in Figure 3.1. The changes in carbon flows resulting from shortening rotations are illustrated by the two diagrams in Figure 3.2, which should be compared with the initial state.

Period of transition

During the period of transition, rotations are gradually shortened to increase the supply of biomass. The upper diagram in Figure 3.2 illustrates this process. Compared to the situation in Figure 3.1:

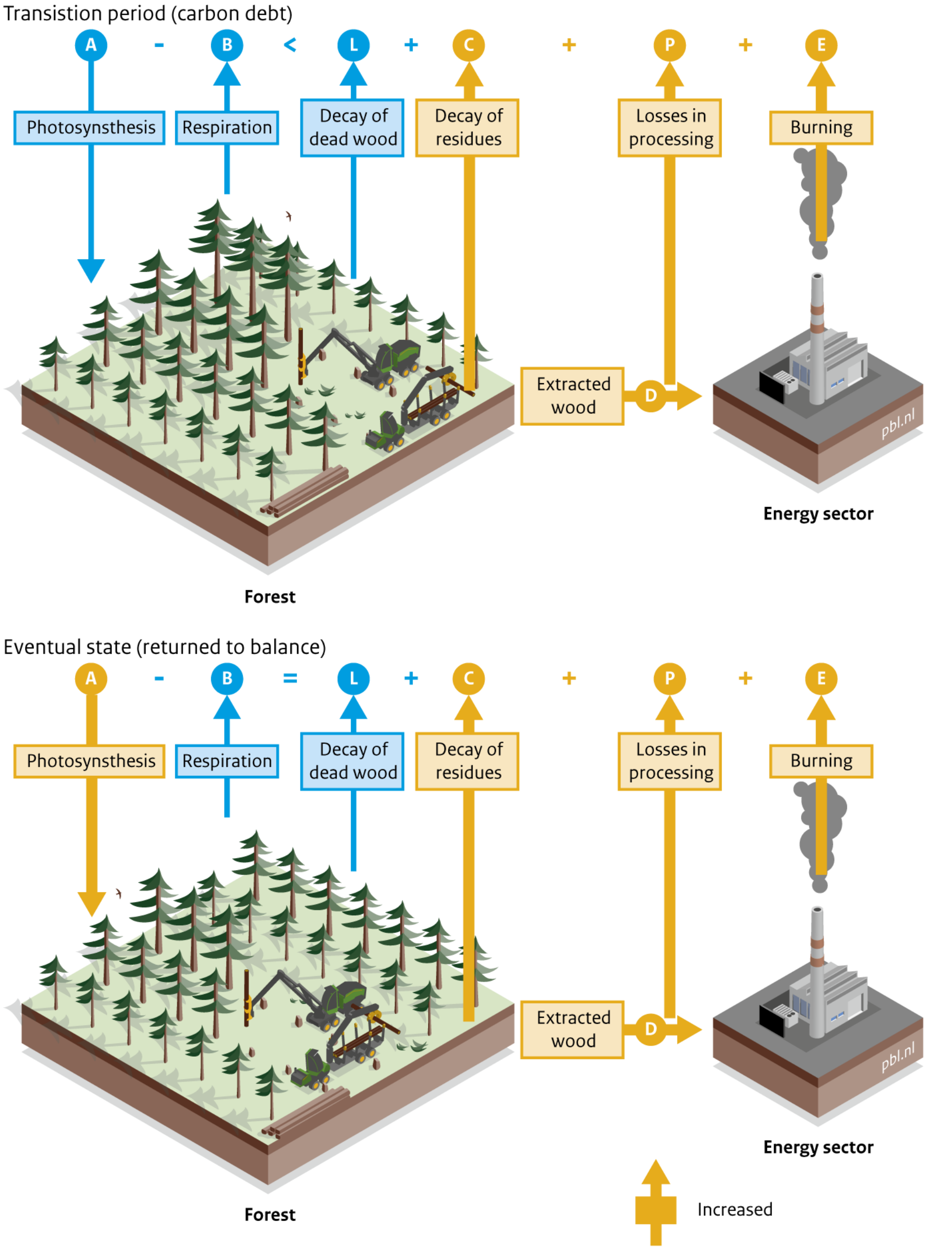
- The outflow of carbon from the forest has increased (thick orange arrows C and D), so that the outflow and the net inflow (A – B) are no longer in balance. Related to this, the forest carbon stock is diminished. It should be stressed that, *in this example*, this *must* be the case, because the approach to increasing wood production through forest management is predicated on reducing the average age of trees in the forest, to increase their growth rates (see Appendix 2, Sections A2.3 and A2.5 for more details). Younger trees are smaller than older ones and, therefore, have smaller carbon stocks.
- Here, it is assumed that changing rotation periods has a negligible impact on the carbon losses from natural disturbance processes (flux L).
- The carbon losses from the biomass supply and processing chain are also increased (thick arrow P), because more biomass is flowing through the processing chain.

- The inflow of carbon to the energy sector, in the form of biomass supplied for use as bioenergy D, has increased, but so has the outflow E at the point where the bioenergy is burnt.

Since the magnitudes of C, D, P, and E have increased, the impact on L is negligible — while A and B initially remain more or less unchanged, the forest bioenergy system is no longer in carbon/CO_2 balance and has instead become a net emitter of CO_2.

Figure 3.2

Impact on the carbon balance of a forest-bioenergy system when rotations are shortened in a managed forest to produce more wood for bioenergy



Source: Forest Research UK

Eventual state

The lower diagram in Figure 3.2 illustrates the eventual state of the forest, by which point all of the affected forest areas have undergone the transition to being managed on the shorter rotation, and the system has re-equilibrated:

- The outflow of carbon from the forest (thick arrows C and D) is continuing at an increased rate. Losses from the supply and processing chain and direct emissions from burning bioenergy also continue at higher rates (thick arrows P and E).
- However, the net inflow of carbon to the forest has now increased to match the outflow. This occurs because the younger trees that form the re-growing areas are, on average, growing faster over their rotations, compared with the older trees that were previously managed on longer rotations. This strengthens the rate of carbon inflow to the forest, represented by the thick orange arrow A in the lower part of Figure 3.2[19]. It must be stressed that, *for this example*, this *must* be the case, provided that the forest areas are managed according to the principle of sustainable yield, i.e., that the rate of wood harvesting does not exceed the rate at which the forest grows to produce more biomass (see Appendix 2, Sections A2.1 to A2.3, for more details). On the basis of this observation, it is sometimes stated that *active forest management strengthens or maintains the uptake of carbon in forests as well as the flow of forest products*. As is clear from the example presented here, this is the ultimate consequence of changing forest management (orange arrow A in Figure 3.2). However, also in the case of this example, this does not occur immediately (i.e. there is a delay between the increased outflow and the increased inflow).

Section A2.5 provides a more detailed explanation of how a period of increased CO_2 emissions can occur as a result of shortening forest rotations to produce more bioenergy. The outcome of the example given in Section A2.5 can be described as follows:

- The fluxes of biogenic CO_2 in and out of the forest (either directly or when extracted biomass is burnt) are in balance before any changes in management are implemented (Figure 3.1).
- In the example in Section A2.5, as a result of the changed management (shortened rotations), an extra 30 TJ/yr of biomass is supplied by the forests and used for bioenergy, from the start of the transition period, which continues at this increased rate after the transition has taken place. Note that 30 TJ/yr represents the increase in the rate of annual wood supply that can be sustained in the long term after the period of transition has taken place. The increased annual supply during the transition period may be higher than this and applying the rate of 30 TJ/yr during the transition period is a simplifying assumption (see Section 3.4.1).
- Initially, during the transition period, the shorter rotations cause an imbalance in the system, leading to *net biogenic CO_2 emissions* (Figure 3.2, upper diagram). In the example in Section A2.5, the net biogenic CO_2 emissions during the transition period amount to 16.3 $ktCO_2$/yr, which accumulate over the 56 years to a total of 915 $ktCO_2$. This amount of emissions is an example of what can be referred to as a *'carbon debt'*, which can occur in some circumstances when changing forest management to increase the supply of biomass.
- Eventually, when all stands are managed on shorter rotations, flows of CO_2 into and out of the system *come back into balance* as the system reaches a new equilibrium. Under this new equilibrium, biomass harvesting, supply, and its consumption as bioenergy continues at a higher rate than before shortening the rotations (Figure 3.2, lower diagram).
- Although the system eventually comes back into balance, the carbon stocks in the forest are *diminished* (because, in the initial state, the average age of the trees forming the forest was older, compared to after the transition period).

[19] Note that, strictly, not only the rate of photosynthesis A in Figure 3.2 but also the rate of respiration B and rate of losses from natural mortality and disturbance processes B and L will be affected by the changed management. For simplicity, the net effect of all three changes is indicated by the orange arrow A in the lower diagram.

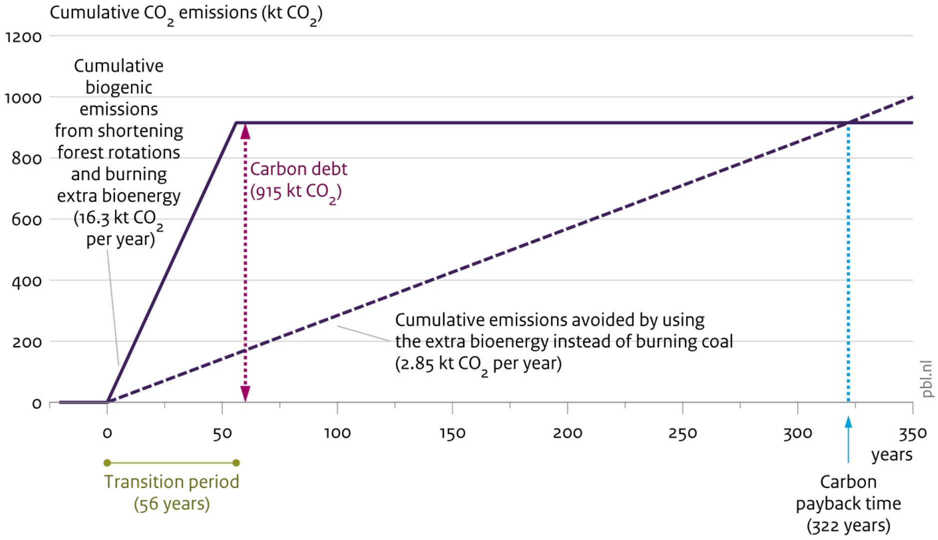
If forest management is not changed (i.e. rotations are not shortened), energy supply and emissions continue as in the initial state (Figure 3.1). Thus, the zero biogenic CO_2 emissions associated with the supply of bioenergy from the forest will continue to be zero. However, the extra 30 TJ/yr bioenergy will not become available (and will therefore not be supplied). Hence, whilst the bioenergy supplied at pre-existing levels may be carbon-neutral, there will be no additional mitigation benefit.

If it is assumed that the 30 TJ/yr energy is still needed, then it is necessary to supply this energy from another source. Suppose that this other source is coal, then, the annual CO_2 emissions from generating this 30 TJ/yr is 2.85 ktCO_2/yr. These emissions are significantly smaller than those associated with the extra bioenergy over the 56-year transition period under the 'bioenergy' scenario (16.3 ktCO_2/yr). However, after the transition period, the additional emissions from the bioenergy stop accumulating, while those from burning coal will continue, assuming coal will be used indefinitely as the alternative fuel. These *counterfactual* emissions from burning the coal are *avoided* by using the bioenergy.

Because the net emissions of biogenic CO_2 only occur for a finite period, while the emissions from burning the coal would continue indefinitely, there must come a point when the cumulative emissions from burning coal would exceed the total CO_2 emissions released by the forest-bioenergy system during the transition period. In fact, the time at which this occurs is 322 years, calculated from the results above and illustrated in Figure 3.3. After this time, the bioenergy supplied delivers net CO_2 emissions reductions.

Figure 3.3

Carbon debt and carbon payback time arising from producing extra bioenergy from a Sitka spruce forest by shortening rotations



Source: Forest Research UK

Hence, for this scenario and example, the 'carbon debt' is eventually repaid after more than three centuries. This is an extreme example and similar to a scenario of harvesting relatively undisturbed forest areas with high carbon stocks. Such actions are already legislated against in EU Regulations (REDIII), avoiding carbon debts of this magnitude. However, the example emphasises the importance of presenting assumptions, calculations, and parameters as transparently as possible, including clearly and thoroughly defining the scenario under which bioenergy is produced from forests, and its counterfactual scenario, wherever this is relevant. These points are explored further in Chapter 4.

It must be recognised that there are real possibilities of a carbon debt occurring, especially when forest management practices are being adjusted or are evolving with the aim of mobilising extra biomass supply from existing forests, above levels possible based on pre-existing practices. For example, there is higher likelihood of a carbon debt occurring when management practices change with the objective to increase wood output quickly, especially in forests where the tree growth rates are slow. However, such an outcome is neither inevitable nor unavoidable. The key is to be alert to risks of where carbon debts could occur and to mitigate them as much as possible.

It is important to consider more complete assessments and realistic scenarios for the carbon impacts of bioenergy production from forests (see Sections 3.4, 3.5, and 4.5). The specific results for carbon debt and payback time in Figure 3.3 are also sensitive to the simplifying assumptions made in the example and to the values assumed for key parameters used in calculations. This is discussed briefly in Section 3.4.1. Subject to these caveats, this example gives two insights.

Firstly, the possibility of a 'carbon debt' associated with bioenergy produced from forests is not an artefact of modelling — it is undeniable that this outcome can be a physical fact under certain circumstances, just as it is physically possible for forest bioenergy to involve net zero biogenic CO_2 emissions. Both scenarios are possible, depending on the amount of bioenergy produced from the forests and how the forests are managed to produce biomass.

Secondly, although the calculations in the example and in Appendix 2 are simplistic, it should be clear that the magnitude and duration of any carbon impacts associated with forest management and biomass production are inextricably linked to the quite numerous parameters and assumptions that underly the calculations. Changes in these parameters and assumptions mean that the direction, magnitude, and duration of any carbon impacts will also change, potentially to a considerable degree. This is one of the key reasons why estimates of CO_2 emissions related to forest bioenergy systems reported by different scientific studies can vary widely and why the respective conclusions of studies may be in disagreement. A sensitivity analysis of the calculations presented here and in Section A2.5 (not presented in this report) revealed that the magnitude and duration of the carbon debt were extremely sensitive to assumptions about the initial and final rotations applied to the Sitka spruce forest and to the quantities of biomass produced by the forest before and after changing forest management (see also discussion in Section 3.4.1.).

3.2.1 Rising forest carbon stocks do not always mean a carbon gain, falling stocks do not always mean a carbon debt

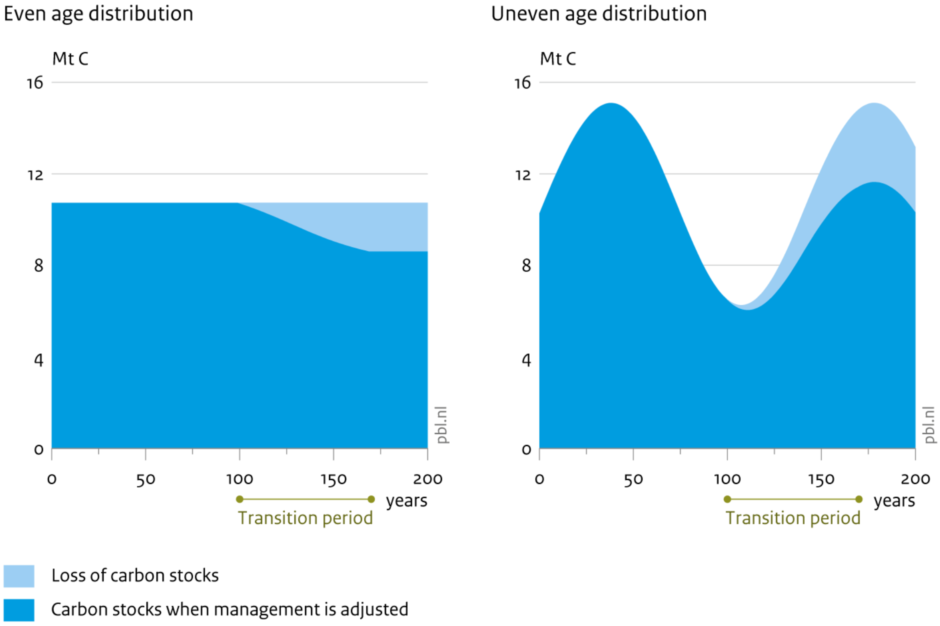
Frequently, carbon stocks in forests that have been under long-term management for production of wood products and bioenergy are stable or steadily increasing, when assessed at large spatial scales. For example, according to national greenhouse gas inventories reported by some countries under the United Nations Framework Convention on Climate Change, forest areas available for wood supply have remained carbon sinks over many years (implying continuously increasing carbon stocks), whilst being managed for wood production, maintaining a steady flow of wood to the forest industries. Some of this is the result of actions to restore and improve the management of forest lands. Research studies have shown how improvements to forest management practices in the Nordic region of Europe and forest restoration activities in the UK and southeastern USA are linked to increasing forest carbon stocks in the past 100 years (see Box 3.6 in Section 3.5).

Sometimes it is suggested that, as long as forests are continuing to accumulate carbon over time, this must mean that any biomass harvested from them (for bioenergy, wood products, or other purposes) will not result in a carbon debt. This idea has an intuitive appeal but unfortunately it is an oversimplification, because, even if carbon stocks are accumulating, the rate of accumulation may be reduced when rates of biomass harvesting are increased above pre-existing levels, depending on how forests are managed to achieve this. Carbon stocks can also be rising in a forest at times for reasons that have nothing to do with how they are being managed.

Figure 3.4 shows the development of carbon stocks over time in two examples of forests that have the same total area, formed of the same tree species with the same growth rate. The forests are also managed in a similar way, with harvesting by felling after a rotation period of 140 years, with no thinning during the rotation period. The area of each forest is 140,000 ha, formed of pine trees with a maximum potential stem volume growth rate of 4 m^3/ha/yr when managed on an optimal rotation period of around 70 to 80 years. The only difference between the two forests in Figure 3.4 (left-hand and right-hand graphs) is that the one on the left has a perfectly 'even' or 'rectangular' distribution of tree ages between 1 and 140 years, whilst the one on the right has an 'uneven' or 'bumpy' distribution of tree ages over the same age range (with more trees in the mid-range ages and fewer younger and older trees). The two scenarios shown in the figure are described in detail in Section A2.4.1. The development of carbon stocks in these two forests is shown in Figure 3.4 as the sum of the dark blue and light blue areas. For simplicity, the results are for carbon stocks in trees only, i.e., no account is taken of carbon stocks in deadwood, litter, and soil, or of the contributions from wood products.

Figure 3.4

Forest carbon stocks over time and the effect of adjusting management



Source: Forest Research UK

When the age distribution is perfectly 'even', a constant carbon stock of 10.7 million tons of carbon (MtC) is maintained, neither increasing nor decreasing, as shown in the left-hand graph in Figure 3.4. This means that harvesting biomass is having a neutral effect on carbon stocks, and the production and use of the biomass can be regarded as 'carbon neutral' (see discussion in Section 3.1 and Appendix 2, particularly Section A2.4).

The perfectly 'level' development of carbon stocks in the left-hand graph can be contrasted with the 'wavy' line in the right-hand graph, where the forest has a 'bumpy' age distribution. The two forests are being managed using exactly the same rotation periods (without any thinning involved). This means the undulating carbon stocks in the right-hand graph are solely the result of the 'uneven' or 'bumpy' distribution of tree ages in the forest. When carbon stocks are decreasing (such as between years 38 and 111 and between years 178 and 200), this is not the result of 'bad' or 'unsustainable' management. Equally, when carbon stocks are increasing (such as between years zero and 38, and between years 111 and 178), this is not the result of 'good' or 'improving' management. It may also be noted that the mean carbon stock in this forest measured over many decades is 10.7 MtC, the same as in the example forest with the perfectly 'even' age distribution (left-hand graph). Note that levels of harvesting in the forest with a 'bumpy' age distribution also go up and down, depending on the area of trees that has reached the rotation age.

Figure 3.4 also illustrates a further scenario, where management is changed in part of the area of the two forests to 'mobilise' (increase) the supply of biomass by shortening the rotation period, making it closer to the optimal age for maximum production (70 years, see details in Section A2.5.1 of Appendix 2). These changes are implemented during a transition period of 70 years, between year 101 and year 170 as indicated in Figure 3.4. The resultant development of carbon stocks is shown by the dark blue area in the left-hand and right-hand graphs in the figure, with the change from continuing pre-existing management indicated by the light blue area.

The effect of the changes to management on carbon stocks is obvious for the forest with a perfectly 'even' age distribution (left-hand graph in Figure 3.4). Evidently, carbon stocks go down during the transition period, and then flatten off again, at a value of 8.6 MtC. This can be seen, even without comparing with the results for the scenario in which management is unchanged. The finite change in carbon stocks represents the 'carbon debt' that occurs as a result of changing forest management (as considered in this specific example) to increase the sustainable-yield supply of biomass. The illustration is similar to the example already considered earlier in this section and in Section A2.5 of Appendix 2.

The situation is not so obvious in the forest with a 'bumpy' age distribution, as shown in the right-hand graph in Figure 3.4. The development of carbon stocks after changing the management in part of the forest is again shown by the dark blue area in the graph, with the change from pre-existing management show by the light blue area. The effects of changing management are clear when comparing the two results for carbon stocks over time (for changed and unchanged management). However, it is only possible to directly measure and monitor carbon stocks and stock changes over time that *actually occur* in forests. This means that the results for unchanged management in the figure would not normally be available for comparison, because they represent a hypothetical scenario. Instead, in most practical situations, it would only be possible to obtain the results for the dark blue areas by direct monitoring of carbon stocks.

For the forest with a perfectly 'even' age distribution, it is still possible to interpret the results for actual carbon stock changes, because the scenario is very simple. However, the effects of management cannot be clearly discerned in the forest with a 'bumpy' age distribution because of the tree age-related cycles in the development of carbon stocks. Without the results for unchanged management for comparison, it might be noted that the carbon stocks are increasing during the transition period when management is being changed (right-hand graph in Figure 3.4), leading to a simplistic and incorrect conclusion that the changes to management are having a positive effect on carbon stocks.

This illustrates how it is not possible to rely on the fact that forest areas are accumulating carbon stocks over time as an indicator for biomass harvested from the forests not resulting in net emissions of CO_2. It should be further noted that a very similar analysis was presented ten years ago in a report by Cowie et al. (2013, see their Figures 1b and 1c), so this point is far from a new insight.

The above analysis has implications for practical methods for managing and monitoring the impacts of forest management activities on carbon stocks. It is evident that simply measuring carbon stocks in forests, to ensure they are stable or increasing, does not guarantee that carbon neutrality or positive carbon impacts are achieved when managing forests to produce biomass. Monitoring of forest carbon stocks is useful as one indicator of sustainable management, but this is insufficient for determining whether woody biomass harvested and extracted from forests involves or avoids a carbon debt. Practical methods to support the avoidance or minimising of a carbon debt being associated with biomass supply, and ideally to enable a carbon gain, are explored in Chapter 5.

3.3 How can changing patterns of wood use result in a carbon debt?

There are other possible impacts on CO_2 emissions, related to the use of wood products, that can occur without changes to forest management and without impacts directly on the forest CO_2 balance, as illustrated by the example in Figure 3.5. The figure shows the carbon balance of a forest-wood products system and the impact of increasing the harvested biomass that is utilised for energy rather than for non-energy products. The upper diagram in the figure shows the initial situation in which harvested biomass is being used for wood products, such as long-lived timber in buildings, with lower quality wood used for lower value and shorter-lived products, such as pallets.

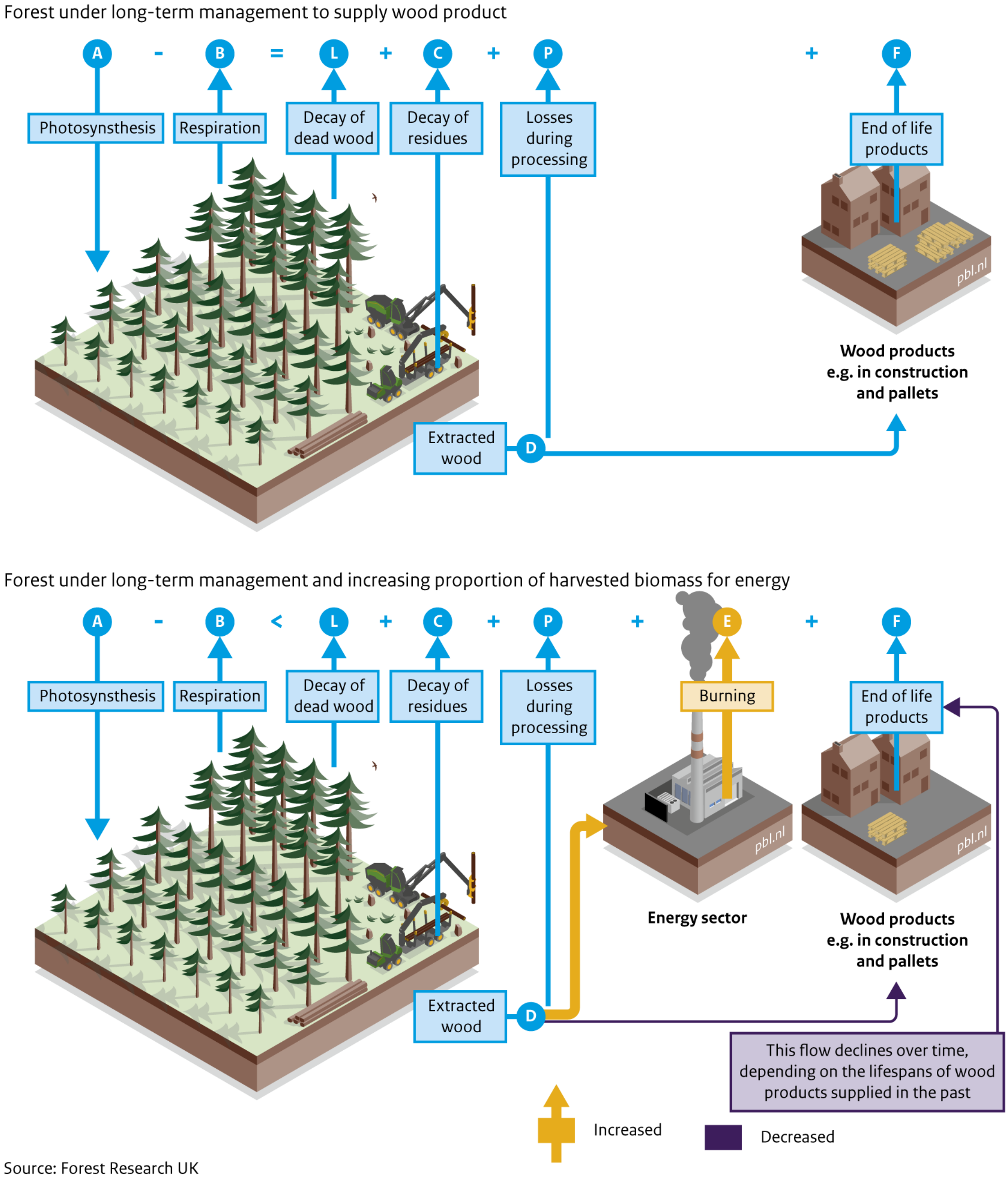
The lower diagram depicts the transition and eventual state after the use of some lower value wood has been diverted from use for non-energy products to bioenergy. Here, also, it must be stressed that this example involves a simplified illustration, intended to help explain the basics of forestry carbon balances. These simplifications do not invalidate the example but do mean that the example is theoretical and only presents part of the typical carbon balance of a forestry system.

Initial state

The upper diagram in Figure 3.5 is similar to the diagram in Figure 3.1, but here, harvested biomass is used for 'wood products' (such as construction timber, furniture, pallets), rather than being used for bioenergy in the 'energy sector'.

Figure 3.5

Carbon balance of a forest-wood products system and the impact of increasing the proportion of harvested biomass used for bioenergy rather than non-energy products



Source: Forest Research UK

The outflow of harvested biomass from the forest, represented by flux D in the upper diagram of Figure 3.5, goes into the 'wood products' (apart from losses from the supply and process chain, flux P) and is utilised to produce a range of non-energy wood products. The carbon in the wood of various non-energy products is not immediately released to the atmosphere but is retained in the wood during the use, reuse, or recycling of these products until they are disposed of, either by incineration or in landfill. The carbon is then released to the atmosphere possibly partly as methane in the case of disposal to a 'wet' landfill, which is not considered further here. The upper diagram of Figure 3.5 shows the outflow of carbon from these non-energy wood products at end of life, represented by flux F.

The 'net wood product balance' is defined here as the combined balance consisting of D – P – F. As part of this balance a reservoir of carbon is retained in the wood products, referred to as the 'wood products carbon pool'. The amount of carbon in this pool is the 'carbon stock' in wood products.

For a given constant flow of wood into the 'wood products' in the upper diagram of Figure 3.5, the size of the carbon stock in wood products is determined by their lifespan. The typical lifespan of an individual wood product can vary considerably, from very short for paper to multiple decades for construction timber. However, in all cases, the lifespan is finite (i.e. no wood product lasts forever). If the flow of carbon into the wood products, D – P, is constant, and the lifespan of wood products is unchanging, then only a finite carbon stock will accumulate in wood products. The size of this stock is determined by the combination of the rate of inflow and the product lifespan.

A further insight may be gained from the discussion above: *If the supply of wood for the manufacture of products remains at the same level for many years, and continues to do so, and if the pattern of wood utilisation for various products also stays the same, the outflow will eventually match the inflow, that is, D – P – F = 0, meaning that the wood products system is in exact carbon balance.*

Hence, considering the complete upper diagram in Figure 3.5: *If the forest has been under management for woody biomass production for a long time, such that the rate of wood harvesting matches the growth rate of the forest, and if the supply of biomass to make wood products remains at the same level for many years and continues to do so, and if the pattern of wood utilisation for different products also stays the same, then the system is in exact carbon balance. As in the example in Section 3.1 (Figure 3.1), it follows that continuing to harvest biomass from the forest at rates consistent with pre-existing harvesting rates results in zero net CO_2 emissions from the forest.*

Transition period and eventual state

Now consider what can happen if the above situation is changed, as in the lower diagram in Figure 3.5. Suppose that, as a result of incentives to encourage the use of bioenergy, a proportion of the supply of biomass is diverted for use as bioenergy, rather than to make lower value non-energy wood products, such as pallets. The immediate result is an increase in the outflow of biogenic carbon from the energy sector E, and a reduced flow of carbon into non-energy wood products. As carbon is retained for a finite period in wood products, the outflow of carbon from these products is not immediately affected (blue arrow F), because it takes years for many products to be discarded, and so initially the outflow from wood products is related to the disposal of products manufactured some years ago. Hence, the overall forest-wood products system is thrown out of carbon balance for a period, the duration of which depends on a number of factors.

Eventually, the increased outflow of CO_2 from the energy sector resulting from increased bioenergy use continues, but the outflow of carbon from non-energy products has diminished (see purple text box near arrow F in Figure 3.5), as has the carbon stock in lower value wood products. This is because the lower input of wood supply to make non-energy wood products has 'worked through the system', resulting in a smaller overall stock of wood products, and so fewer wood products are being disposed of. Hence, eventually, the system comes back into carbon balance.

It follows that actions to increase the supply of bioenergy from forests can result in increased CO_2 emissions, at least for a finite time, even if forest management is not changed, if the actions result in wood use being diverted from non-energy products to bioenergy.

It should be pointed out that diversion of higher value products is very unlikely to occur because of the price difference between these wood products such as structural timber and bioenergy products. It is more likely that the bioenergy supply might be diverted from making lower-value products such as paper, pallets, and wood-based panels. Another scenario might be a change in the rate of wood production combined with changes in the pattern of wood utilisation.

3.4 Towards a more complete assessment

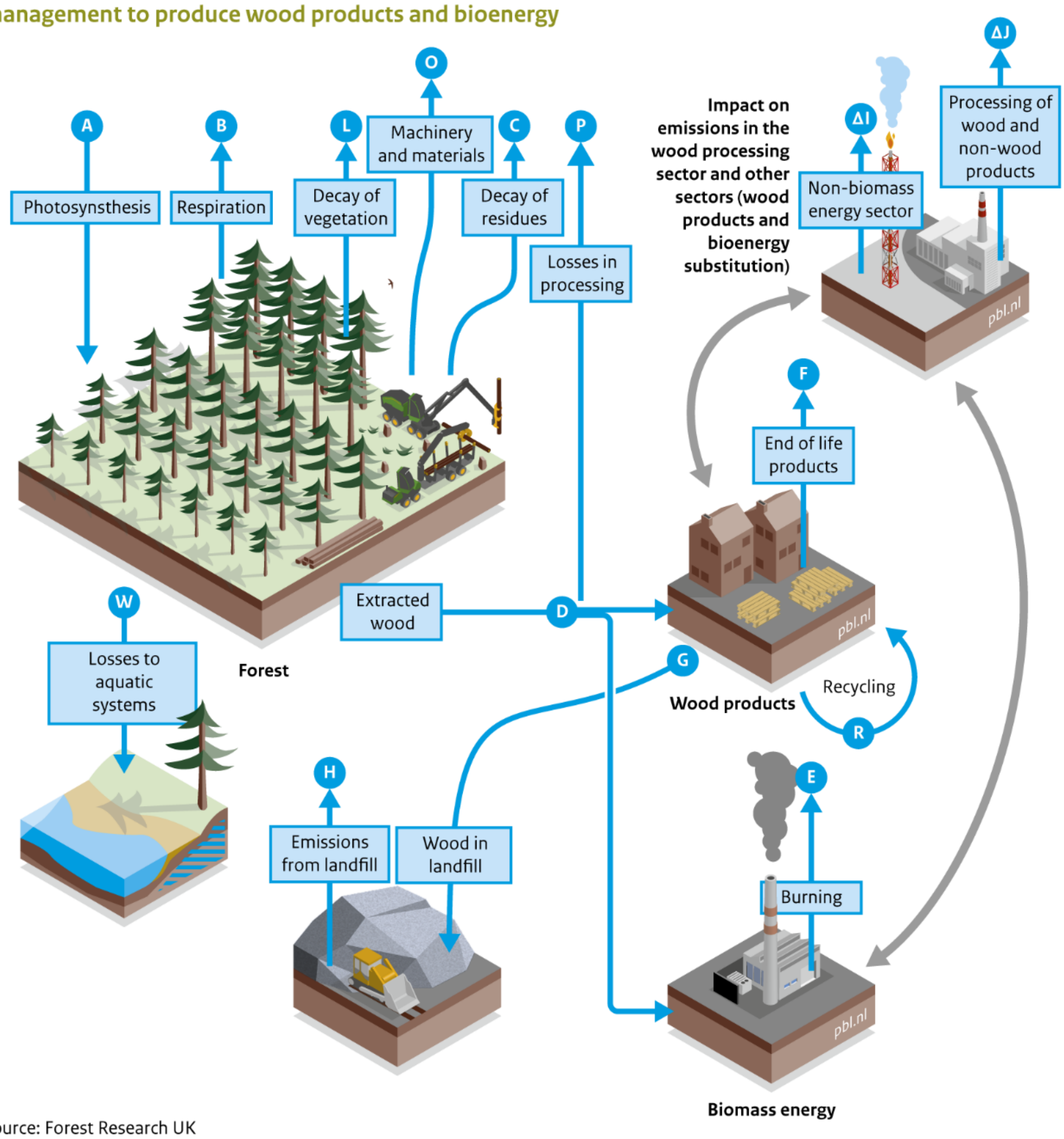
The discussions in Sections 3.1, 3.2 and 3.3 repeatedly stress that the examples presented are highly simplified. The key simplifications are:

- Only carbon in tree biomass is considered in terms of detailed carbon dynamics (other forest carbon pools, deadwood, forest litter and soil, are represented simplistically, essentially assuming they are and remain in carbon balance).
- In Sections 3.1 and 3.2, all of the harvested and extracted tree biomass is assumed to be used directly for bioenergy (the use for wood products is not represented, nor is the possible carbon sequestration in wood products).
- A simple approach to forest management is assumed (i.e. tree planting, no thinning, and clear-felling at fixed rotation ages).
- Very simple forest structures are considered (in most cases, it is assumed that there are perfectly equal areas of forest with ages over the rotations applied as part of management).
- A 'static' landscape is assumed (i.e. the forest area is assumed to be constant, without considering deforestation or afforestation).
- Detailed dynamics of the forest carbon balance are not represented; instead, the carbon stock changes over time move from an 'initial state', through a 'transition period' to an 'eventual state'.
- The examples do not consider any potential impacts of climate change on the terrestrial carbon balance, including tree growth and mortality.

The following discussion explores the implications of allowing for carbon dynamics in other carbon pools, and how this may influence estimates of the carbon impacts of biomass production systems. Sections 3.5 and 3.6 consider the more complex scenarios involving more sophisticated forest dynamics and management. Figure 3.6 shows the carbon pools and carbon/greenhouse gas exchanges associated with a forest managed to produce biomass for wood products and bioenergy. A key to the labelled flows of carbon/CO_2 and greenhouse gases shown in the figure is given in Box 3.4. Tracking all the carbon and greenhouse gas flows in Figure 3.6 may seem challenging. Methods have been developed by the IPCC (2006) for assessing the net balance of the carbon flows into and out of forests and wood products, as briefly described in Box 3.5.

Figure 3.6

The complete system of carbon pools and flows of CO_2 and greenhouse gases for a forest under management to produce wood products and bioenergy



Source: Forest Research UK

Box 3.4 Key to CO_2/greenhouse gas fluxes in Figure 3.6

A: Uptake and capture of CO_2 in a forest ecosystem through photosynthesis; B: CO_2 emitted via respiration; L: Decay of vegetation that has died from natural mortality or natural disturbances; W: Losses of forest litter and soil carbon to aquatic systems; C: Decay of forest residues from tree harvesting; D: Carbon leaving the forest in the form of extracted wood; P: Losses from wood supply and processing chains; E: CO_2 emissions from burning wood for bioenergy; F: Decay or destruction of wood products at end of life; G: Carbon from disposal of wood products at end of life to landfill; H: Emissions (as carbon dioxide and methane) from discarded wood products in landfill; R: Reuse, repurposing and recycling of wood products; O: Greenhouse gas emissions from use of fossil fuels, machinery and materials in forestry operations; ΔI: Changes in greenhouse gas emissions from the extraction and consumption of counterfactual non-bioenergy fuels (such as fossil fuels) in response to bioenergy production; ΔJ: Changes in greenhouse gas emissions from the manufacture of wood products and counterfactual non-wood products (such as those made from steel, concrete, plastic) in response to supply of wood products.

As in previous examples, the diagram includes two major parts, comprising the carbon stocks in forests and those in wood products, but in this example also includes further elements:

- The forest sector not only includes detailed representation of the carbon in the biomass of the living trees but also the associated carbon stocks and dynamics in deadwood, forest litter and soil (instead of representing these components simply, such as assuming that deadwood decays and releases carbon immediately).
- The wood products sector is expanded to also include a range of products, such as structural timber, furniture, pallets, panels and paper, with bioenergy produced as a by-product; therefore, a carbon stock is retained in non-energy products, as discussed in Section 3.3.

The flows into and out of these parts of the system are described in more detail, specifically also containing:

- Carbon losses from forests into aquatic systems, consisting of dissolved organic carbon (DOC) and particulate organic carbon (POC) (flux W).
- Carbon losses from wood products and their ultimate disposal as landfill (as opposed to incineration) are represented as flux G, as are the carbon cycles associated with reuse, repurposing and recycling of wood products, flux R.

In addition, greenhouse gas emissions from forest operations (flux O) are also included (such as from fuel, machinery and materials used during land cultivation, tree planting and harvesting), as well as those from processing wood into finished products (flux F). Usually, impact assessments of greenhouse gas emissions resulting from use of wood products assess the net change in emissions that results from producing fewer or more alternative materials. These estimates also allow for changes in emissions that occur from wood product substitution, i.e. when using more or fewer alternative materials (ΔI) and energy sources (ΔJ) rather than wood (such as metal, plastic, brick, bioenergy), depending on the availability of wood products and bioenergy.

Box 3.5 The 'Stock Difference' method of the IPCC

The range of carbon pools involved in forest carbon balances and the types of issues raised above may give the impression that forest carbon balances are difficult to understand and quantify; particularly in terms of the impacts of changes made to forest management. However, as has been pointed out by Maclaren (2000), for most purposes, forest carbon balances can be understood and modelled more simply by considering changes in carbon stocks. Maclaren uses the example of the carbon budget of a pig to illustrate this point.

Suppose a farmer wants to know if a pig is a carbon sink or carbon source. Answering this question could involve assessing the flows of carbon into and out of the pig, such as those associated with food intake, excretion of dung, and breathing, all of which would require monitoring and measurements (or modelling), involving complex machinery and the related chances of error. Alternatively, the pig's carbon balance could be estimated by monitoring carbon stock changes, by weighing the pig to track weight changes over time. As a concept, the principle behind this approach applies equally to forest carbon balances: losses and sequestration of carbon are directly associated with changes in vegetation and soil carbon stocks. The overall net carbon sinks or sources may thus be understood as net changes in a forest's vegetation and soil carbon stocks. This principle is applied extensively in the discussion in this chapter and the associated appendices. It is widely understood and is the basis of the 'Stock Difference' method specified in IPCC Good Practice Guidance on the compilation of National Greenhouse Gas Inventories(IPCC, 2006). It must be stressed that the main relevance of the pig analogy and of the consideration of carbon stock changes in this discussion is to illustrate and help to understand the net results of sometimes complex exchanges of carbon between the atmosphere and a number of carbon pools associated with forests and wood products.

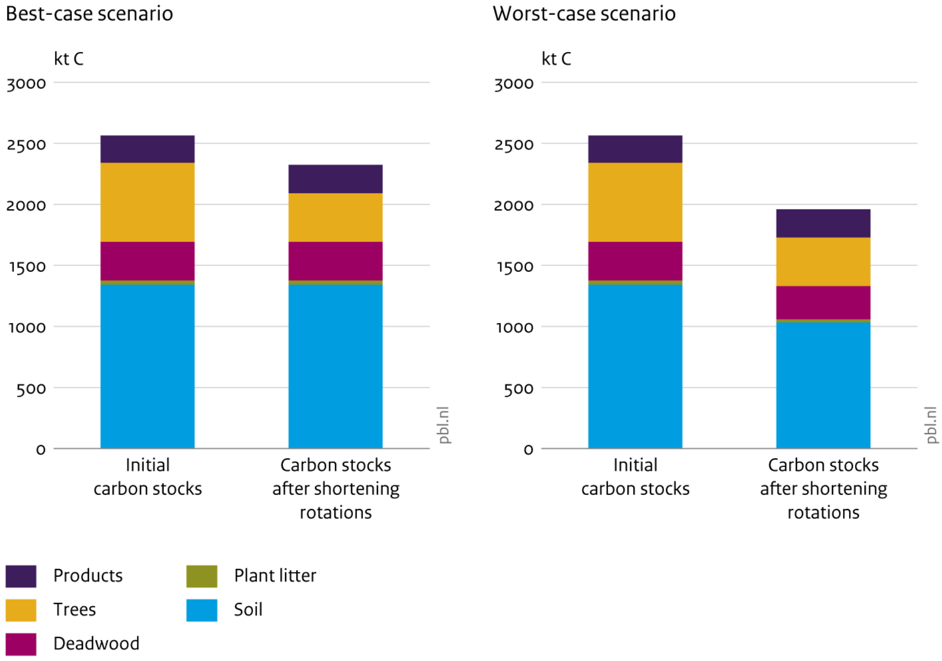
A simple conversion factor can be used to convert results for carbon stock changes to units of CO_2, and if other greenhouse gases are involved (generally small amounts in the case of forestry, but important for wetland and agricultural systems), quantities can be expressed in equivalent units of CO_2 equivalent (IPCC, 2021).

Application of Stock Difference to example of adjusting rotations in a managed forest

Section 3.2 gives a simple example of a theoretical Sitka spruce forest in the United Kingdom, in which rotation periods are adjusted to produce more biomass. Here, this example is elaborated to include more detailed carbon stocks and carbon and greenhouse gas exchanges between the atmosphere and the carbon pools of deadwood, forest litter, soil and wood products. Figure 3.7 shows the results from a more complete analysis for carbon stocks and stock changes. In most other respects, the example is still simplified, notably in the assumptions of a simple forest structure and approach to management, as discussed in Section 3.2 and Appendix 2. The figure describes the carbon stock changes in the carbon pools of forest and wood products that can occur when changing the rotation periods applied. However, an important difference here is that only 30% of the harvested tree stem biomass is assumed to be utilised for bioenergy, with the remaining 70% used for non-energy products. It is also assumed that imperfectly shaped stem sections, branches and roots of harvested trees are discarded and the decay of these tree components in the forest is represented as part of the calculations.

Figure 3.7

Impact of shortening rotations on carbon stocks in a Sitka spruce forest



Source: Forest Research UK

Figure 3.7 shows results for two cases, representing the extremes of variability in carbon stock changes in deadwood, forest litter and soil. The first bar in each pair shows carbon stocks in the Sitka spruce forest before the changes in forest management. The second bar in each pair shows the carbon stocks that ultimately result from the management changes described in Sections 3.2, A2.3 and A2.5. The left-hand pair of bars shows results in the case of changes in management having negligible impacts on deadwood, forest litter and soil carbon stocks. This represents the best-case scenario for the change in management considered in this example. The right-hand pair of bars show the worst-case scenario, in which the changes in management result in significant losses of carbon in deadwood, forest litter and soil.

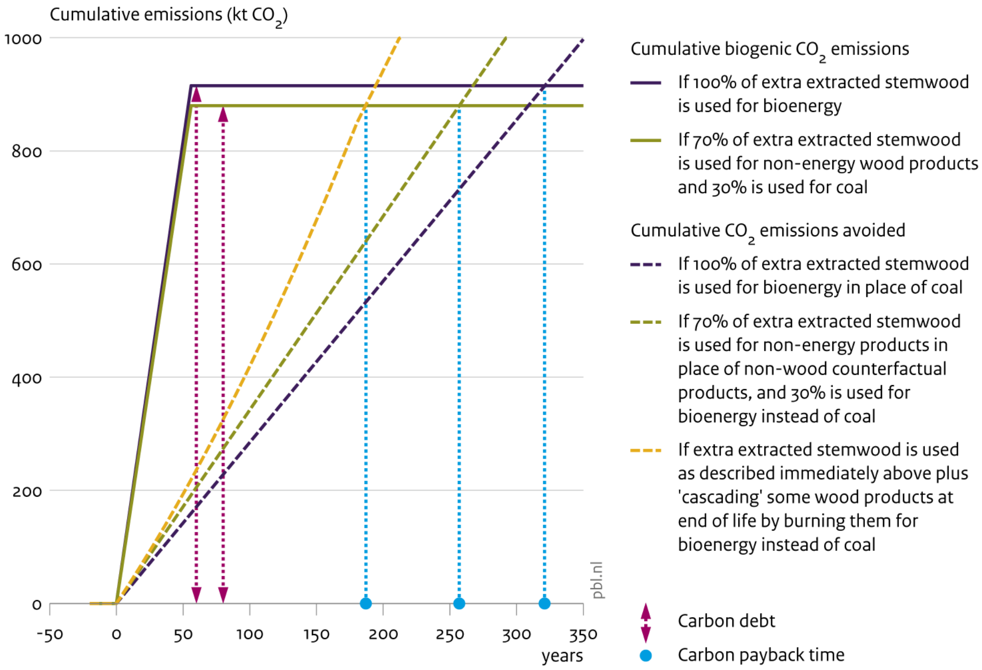
Considering the best-case scenario first, the change in the carbon stocks in the trees is already discussed for this example in Sections 3.2 and A2.5. The carbon stock in wood products is increased slightly (by almost 10 ktC). This reflects the increased wood production resulting from the changes in forest management. However, the increase is relatively small because there is only a relatively small increase in production and not all of the extra biomass is utilised for long-lived wood products. The overall impact of the management changes in the Sitka spruce forest consists of a diminished carbon stock in trees and a modest increase in carbon stocks in wood products, giving an overall reduction in all carbon pools combined (noting that carbon stocks in deadwood, forest litter and soil are unaffected), equates to a carbon stock loss (or 'carbon debt') of 240 ktC (9.3%, equivalent to 880 ktCO_2). This is a slightly smaller loss than calculated for just tree carbon stocks (250 ktC or 915 ktCO_2, see Section 3.2).

The worst-case scenario in Figure 3.7 also includes significant losses of carbon stocks in deadwood, forest litter and soil. The combined reduction in carbon stocks in these three carbon pools under this scenario is 360 ktC (21%). In reality, these carbon stock changes are likely to occur over decades, and possibly centuries in some of these carbon pools, but if the whole change is assumed to occur during the transition period of 56 years, this would represent an annual loss of 6.5 ktC/yr over this period. The reduction(or 'carbon debt') in all the carbon pools together (trees, products, deadwood, forest litter and soil) in the entire system is almost 24% (600 ktC or 2,200 ktCO_2) or almost 11 ktC/yr (40 ktCO_2/yr), if all of the carbon stock changes are assumed to take place during the transition period.

The ultimate results for the more complete calculation of the carbon debt associated with this simple example of changed forest management, allowing for different uses of the extra extracted biomass, are shown in Figure 3.8 (solid green line). Only the best-case scenario considered above is illustrated in the figure; the worst-case scenario is also discussed below.

Figure 3.8

Carbon debt and carbon payback time arising from different uses of the extra wood supplied from shortening rotations in a Sitka spruce forest



Source: Forest Research UK

Best-case scenario

The results for the best-case scenario can be compared with those based on the less complete calculation for changes in the carbon stock in trees only, which are also shown in the figure (solid purple line). An explanation of how to interpret results such as in Figure 3.8 has already been provided as part of the description of Figures 3.3 and A2.11. Figure 3.8 shows that the calculated carbon debt is only marginally smaller when also allowing for carbon stock changes in non-energy wood products. However, there is another effect of utilising the majority of harvested stemwood for non-energy products rather than for bioenergy, as these products can displace the use of other materials such as metals, cement, plastics and bricks. If this reduces the use of these non-wood materials, in general, the greenhouse gas emissions from the manufacture of these materials would be avoided. The amount of greenhouse gas emissions that would be avoided when non-energy wood products displace non-wood products is uncertain. However, recent reviews suggest a typical value ('displacement factor') of around 1.2 tCeq in emissions avoided by not consuming a non-wood product, for every tC of carbon in an equivalent wood product (FAO, 2021; JRC, 2021a; Leskinen et al., 2018;

see Appendix 1). This assumed displacement factor can be used to calculate the greenhouse gas emissions avoided by using the extra non-energy wood products in the scenario considered here. The annual greenhouse gas emissions avoided by using the extra harvested biomass for a combination of non-energy products as well as bioenergy is estimated at 3.42 $ktCO_2$/yr. This result is shown by the dashed green line in Figure 3.8. The estimated avoided emissions are 2.85 $ktCO_2$/yr if all of the biomass were to be used for bioenergy, see Section 3.2. This result is shown in Figures 3.3 and 3.8 for comparison (dashed purple line).

The overall effect of the slightly smaller carbon debt and increase in avoided emissions when most of the extra harvested biomass is used for non-energy products is the shortening of the payback time from 322 to 250 years). This is still unacceptably long as also explained for Figure 3.3, but it shows that utilising the majority of harvested stemwood for non-energy products when appropriate (such as when wood is suitable for making structural timber products), rather than for bioenergy can shorten the payback time substantially (by 22% in this example).

When wood products come to the end of their useful lives, instead of discarding them in landfill or incinerating them as waste, they can be reused, repurposed, recycled or burnt with energy recovery. These actions, which are sometimes described collectively as ‘wood product cascading’ or ‘biomass cascading’, can have further carbon impacts. Frequently, this aspect of the utilisation of harvested wood is not represented in carbon balance studies of forestry systems. The calculation of avoided emissions resulting from utilizing the extra harvested biomass can be further elaborated for the example considered here, by taking the impacts of biomass cascading into account. The possible contribution of cascading effects was calculated by assuming that 80% of the wood in products would be burnt at the end of their life with energy recovery, that is, utilised for bioenergy. This bioenergy was assumed to displace the consumption of fossil fuels with an emissions displacement factor representative of a mix of fossil fuels (natural gas, oil and coal). The potential impact of allowing for contributions to avoided emissions from biomass cascading is shown in Figure 3.8 by the dashed dark yellow line. The overall impact is to further shorten the payback time of the carbon debt, in this example to shorter than 200 years; a reduction of almost 40% compared to the original situation.

As already highlighted for Figure 3.3 (Section 3.2), the specific results for carbon debt and payback time in Figure 3.8 are sensitive to simplifying assumptions in these examples and to assumptions about key parameter values used in calculation. This is discussed briefly in Section 3.4.1. It must be emphasised that any carbon impacts are highly sensitive to the specific details of the scenario involved in producing biomass from forests, for a range of wood products including bioenergy. In particular, outcomes depend strongly on any changes in forest management involved, so that carbon payback times can vary from a few years to centuries. This is a central concern of this report and is explored further below and in Chapters 4 and 5.

Worst-case scenario
Under the worst-case scenario developed for this example, the greenhouse gas emissions avoided by using non-energy products and bioenergy in place of non-wood alternatives are assumed to be the same as for the best-case scenario, as discussed above. In fact, the assumptions could be altered to make them ‘worse’, for example by assuming that the bioenergy displaces natural gas, rather than coal, which would result in less avoided emissions. The key difference considered here is the magnitude of the carbon debt resulting from forest carbon stock changes. The magnitude of the carbon debt is significantly larger for this scenario (see above). When combined with the same

avoided emissions as estimated for the best-case scenario (and ignoring possible biomass cascading effects), this gives a payback time for the carbon debt of nearly 650 years (!). Note that this is a highly theoretical calculation, intended to illustrate an extreme situation in which payback times could become extremely long because of poorly informed decisions about biomass use and the forest management involved in its supply. As indicated before, this is already legislated against in EU Regulations (REDIII).

3.4.1 Sensitivity to assumptions and parameters

The best- and worst-case scenarios illustrated for the example system presented above have shown how outcomes for carbon debt and payback time are sensitive to many factors. The specific factors considered in the examples included:

- The size of the carbon stock changes in forest deadwood, litter and soil related to changes in forest management (greatly shortened rotations in this case)
- The substitution effects of non-energy wood products, when bioenergy is supplied from forests as a co-product with non-energy wood products (which is a very common scenario in practice)
- The increase in carbon sequestered in the non-energy co-products as a result of extra wood supply (quite small in this example, but this is not always the case)
- The contribution effects of biomass cascading, i.e. if wood products can be re-used in some way, including waste wood products being burnt as bioenergy at end of life.

The sensitivity of results to simplifying assumptions has also been mentioned. As an example, in the illustrations above and in Section 3.2 and A2.5, it was assumed that the forest age distribution was perfectly even, and that wood was supplied from the forest at a constant annual rate before, during and after the transition. The effects of allowing for an uneven age distribution and varying the rate of wood supply in relation to this have been explored in Section 3.2 (Figure 3.4). In the simple examples (Figures 3.3 and 3.8), it was also assumed that wood was supplied at a constant higher rate after the transition period, and that this rate also applied during the transition whilst rotations were being adjusted. It is more likely that wood supply will be further enhanced during the transition period, related to the pattern of harvesting stands at different ages as part of restructuring the age distribution of the forest. Further calculations allowing for this were made for the example forest system considered above. The enhanced wood supply resulted in bigger wood product substitution effects during the transition period, which shortened the resultant carbon payback times to under 150 years, a reduction by more than 50%,when biomass cascading was also included in calculations. Again, as indicated, this is still very long but it shows how payback times can be reduced significantly.

Results are also sensitive to the values assumed for key parameters in modelling scenarios such as considered above. For example, the differing results for carbon stock changes in deadwood, litter and soil in the best- and worst-case scenarios may be related to parameters and their values assumed in litter and soil models, such as turnover rates (see Sections 2.1 and 5.1.2). The values assumed for emissions displacement factors when estimating wood product substitution effects can have a big influence on results. For example, if a more optimistic value for non-energy products is assumed in the calculations made for Figure 3.8 (2 tCeq/tC instead of 1.2 tCeq/tC), results for carbon payback times are shortened significantly. A payback time shorter than 100 years is estimated if this higher value is assumed when also allowing for biomass cascading and for enhanced wood production during the transition period when rotations are being shortened.

The above points show how variation in results for carbon debt and payback time (and carbon impacts more generally) are often related to the completeness and detail with which a scenario is described, and on parameter values assumed in calculations. This is crucial to understanding the variability in published results for the carbon impacts of using forest bioenergy, as discussed more thoroughly in Chapter 4.

3.5 How is it possible for bioenergy from forests to result in a carbon gain?

The scenarios considered, so far, for increasing biomass supply from forests all involve a key simplifying assumption. Specifically, whilst assumptions are made about the management of forests, it is also assumed that the extent of the forest areas and the composition of their growing stock (for example in terms of tree species and growth rates) are static. That is, the forest area neither increases (through afforestation activities) nor decreases (as a result of deforestation activities), and the growing stock remains essentially the same, in terms of tree species composition and growth rate, without any improvement or degradation.
In practice, the forest sector may respond positively to incentives to produce more biomass, such as by creating new productive forest areas through afforestation. The increased economic worth of forests can also provide an incentive for retaining existing forest areas, instead of converting them to other land uses, thereby discouraging deforestation. It is also possible that forest management practices in existing forest areas could be modified to enhance the productive potential of the growing stock. Examples of relevant practices include:

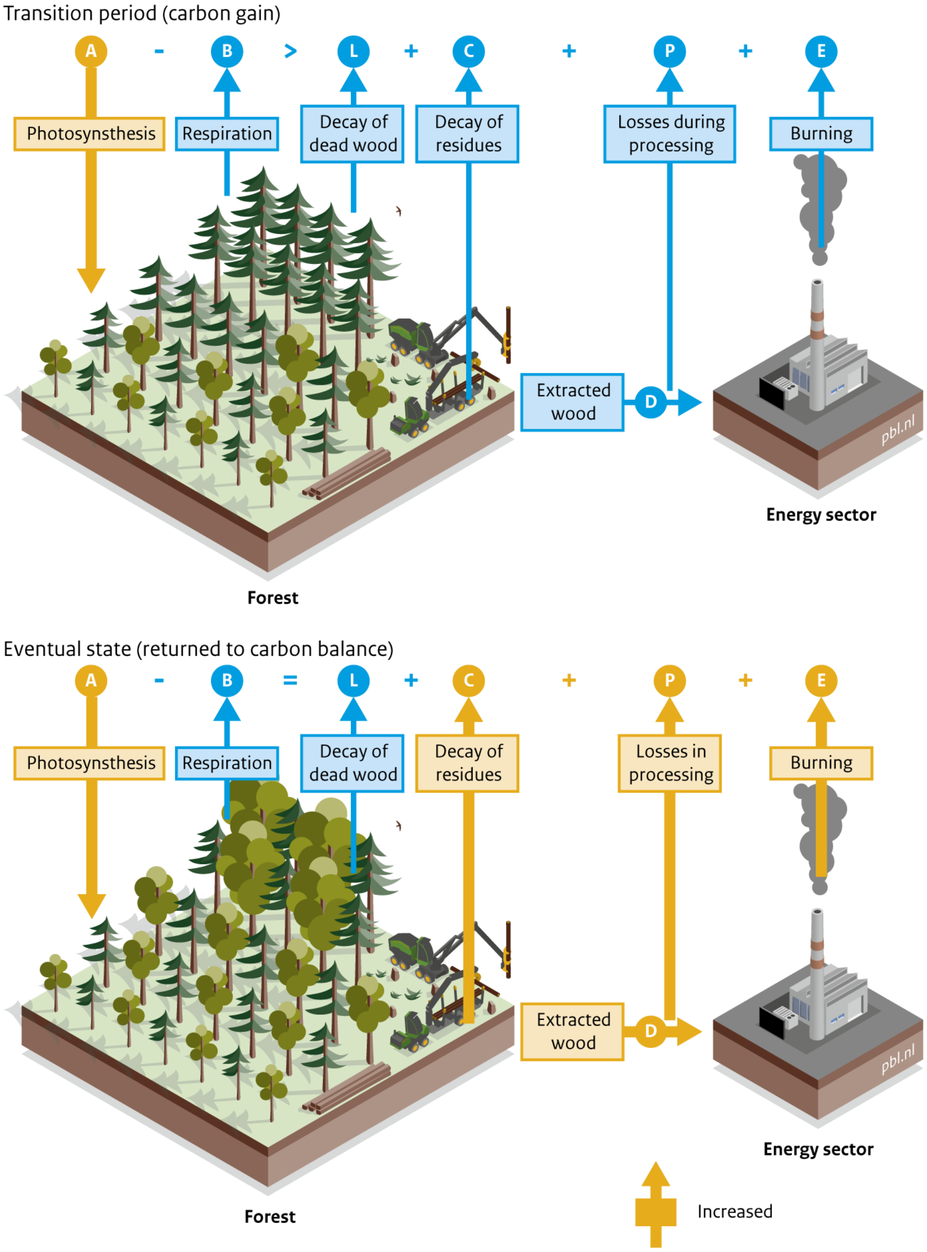
- Improvements to tree planting and ensuring fast natural tree regeneration when harvested areas are restocked.
- Protection of trees against pests, diseases, grazing animals, storms and fires.
- Fertilisation where this can improve the nutrient regime of forest sites.
- Improvements to tree growth rates by selecting more productive tree species (or species mixtures) when replanting forest areas, including tree species already in the forest but with individual specimens selected for superior growth potential.

The example in Figure 3.9 illustrates the potential impacts on the carbon balance when actions to increase biomass production from forests are accompanied by such changes in forestry practices. It shows how the improvement of growth rates of trees forming a forest to produce more wood for use as bioenergy affects the carbon balance. As in previous examples (Sections 3.1 and 3.2), a simple forestry system is considered, consisting of uniform stands of trees grown on a fixed rotation. However, in this case, as the forest stands are felled, the newly planted replacement stands consist of a mixture of tree species, some of which have faster growth rates than the pre-existing tree species. All the trees are harvested at the end of the rotation period, with no harvesting during the life cycle of stands (i.e. no thinning). As in the previous example, only the stemwood is harvested and all of it is used for bioenergy. Only the carbon in trees is considered in this example, ignoring the carbon retained in and lost from dead wood, forest litter and soil, as well as the possibility of harvested wood being used to make products (such as structural timber, furniture and paper).

For this example, the *initial state* is similar to that described previously in Section 3.1 and illustrated in Figure 3.1. The upper diagram in Figure 3.9 illustrates the impacts on carbon flows in the *period of transition*, during which the existing trees are gradually replaced (when they are harvested) by the faster-growing mixture of tree species. The lower diagram shows the *eventual state* of the forest, following this period of transition.

Figure 3.9

Carbon balance of a forest-bioenergy system where the tree species in a managed forest are diversified to produce more wood for bioenergy



Source: Forest Research UK

Period of transition

During the period of transition, the tree species composition of the forest is gradually modified as areas are felled and replanted to increase the growth rate and the supply of biomass. The upper diagram in Figure 3.9 illustrates this process. Compared to the situation in Figure 3.1:

- The net inflow of carbon to the forest (A – B) increases, as the composition of the forest gradually changes, with a new mix of tree species with higher overall growth rates replacing the pre-existing trees when they are felled. This strengthens the rate of carbon inflow to the forest, represented by the thick orange arrow A in Figure 3.9. Note that, strictly, not only the rate of photosynthesis A in Figure 3.9 but also the rate of respiration B and rate of losses from natural mortality and disturbance processes B and L will be affected by the changed management. For simplicity, the net effect of all three changes is indicated by the orange arrow A in the diagrams.

- The outflow of carbon from the forest does not change initially (blue arrows C and D). This is because, during the transition, the pre-existing trees with lower productivity are still being harvested, and these are only gradually being replaced by the more vigorously growing mixture of trees, which are not yet ready for harvesting. As a result, the net inflow (A – B) exceeds the outflow. Related to this, the forest carbon stock is increased. It should be stressed that, *in this example*, this *must* be the case, because the approach to increasing wood production through forest management is predicated on increasing the productivity of the forest whilst also enhancing carbon stocks, by introducing a more vigorously growing mixture of tree species (see Appendix 3 for a specific example).
- The carbon losses from the biomass supply and processing chain are also unchanged initially (flux P), because initially the rate of wood supply is not increased (see above).
- The inflow of carbon to the energy sector, in the form of biomass supplied for use as bioenergy D, is also initially unchanged, as is the outflow E at the point where the bioenergy is burnt.

Since the magnitude of the net carbon uptake A – B has increased, while C, D, P and E remain more or less unchanged, the forest bioenergy system is no longer in carbon/CO_2 balance and has instead become a net sink of CO_2.

Eventual state

The lower diagram in Figure 3.9 illustrates the eventual state of the forest, by which point all of the affected forest areas have undergone the transition to a more complex mixture of tree species, and the system has re-equilibrated:

- The net inflow of carbon to the forest (A – B) is continuing at an increased rate. For simplicity, it is assumed here that carbon losses from natural disturbance processes L are more or less unaffected.
- However, the outflow of carbon from the forest (thick orange arrows C and D) has now also increased. This is because, the more productive forest areas created during the transition period have now grown to the point where they are being harvested. As a result, the net outflow now balances the inflow (A – B), as long as harvesting rates are consistent with the principle of sustainable yield.
- The inflow of carbon to the energy sector, in the form of biomass supplied for use as bioenergy D, is also increased, as is the outflow E at the point where the bioenergy is burnt.

Overall, the outflow to the atmosphere C, D, P and E has increased to match the net inflow A – B, so that the system is returned to carbon/CO_2 balance but with a higher rate of wood production and supply.

Worked example

Appendix 3 provides a more detailed worked numerical example of how a period of increased carbon uptake can occur as a result of changing the composition of forests as part of management to produce more bioenergy. As in previous examples, a relatively simple forestry system is considered, in this case consisting of stands of Scots pine with a mean growth rate over an optimum rotation of 4 m^3/ha/yr. This type of forest was chosen for this example as being representative of pine stands growing in Scandinavia and the Baltic states of Europe, where some practices for improving the productivity of forests are also sometimes carried out. The Scots pine stands are assumed to be managed with regular thinning during the rotation period, followed by clear-felling at the optimum rotation age of 90 years for stemwood production. Thinning the stands can smooth out wood production over time, and poorer quality trees can be selected for thinning, to improve the overall quality of the trees left to continue growing to the end of the rotation period. This can help to ensure that good quality stemwood is produced later in the rotation, suitable for use for structural timber, for example.

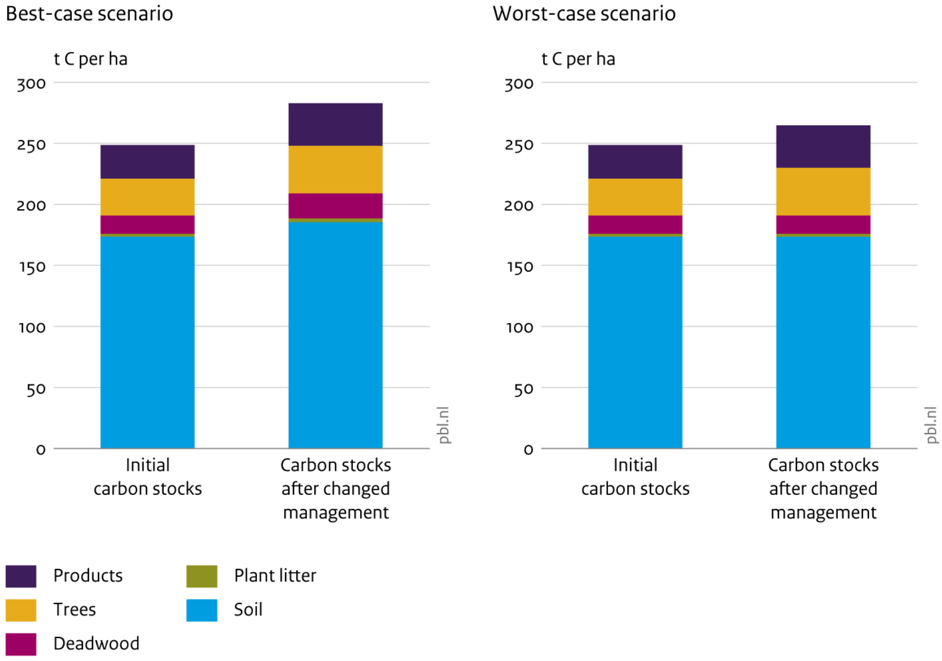
It is possible to calculate the mean carbon stock in trees over a rotation period for this kind of Scots pine stand, in the same way as for the Sitka spruce stands considered in earlier examples. Further details of the calculations for the Scots pine stands described above are given in Appendix 3, where it is shown that the mean carbon stock in trees over a rotation of 90 years is 30.2 tC/ha. Now suppose that the forest sector responds to an increased interest in biomass (for non-energy products and bioenergy) by taking the kinds of actions outlined above. These actions might happen as a result of increased economic incentives to supply biomass, or possibly in response to policy measures to support an increase in the supply of forest biomass. Suppose the additional forest management practices result in an increase in the stemwood growth rate of the Scots pine stands from 4 to 6 m^3/ha/yr over an optimum rotation period. Because the growth rate is increased, the optimum rotation age is also shortened, from 90 to 78 years.

The mean carbon stocks in the faster growing Scots pine stands can be calculated as 39.1 tC/ha (see Appendix 3). Hence, the changes in forest management practices result in an increase in mean carbon stocks of 8.9 tC/ha. This equates to a removal of CO_2 from the atmosphere of 32.5 tCO_2/ha. Suppose that the additional management practices are introduced over 90 years (the original rotation applied to the Scots pine stands). If the change in mean carbon stocks happens over this 'transition period', this gives a mean rate of carbon sequestration of 0.1 tC/yr (0.36 tCO_2/ha/yr). The increased biomass production results in changes in the carbon stocks in non-energy wood products. There can also be changes in carbon stocks in deadwood, forest litter and soil in forest stands resulting from the changed management. The overall change in carbon stocks in forest and wood product carbon pools in an individual stand is shown in Figure 3.10.

As discussed in Section 3.4, changes in carbon stocks in deadwood, forest litter and soil may vary and are context-specific. Figure 3.10 shows the results for two cases, representing the extremes for such changes, in two pairs of stacked bars. The first bar in each pair shows carbon stocks in the Scots pine forest without changes in forest management. The second bar shows the carbon stocks that ultimately result from management being changed as described above and in Appendix 3. The left-hand pair of bars shows results when such management changes involve significant increases in the carbon in deadwood, forest litter and soil, reflecting the faster growth rate and higher mean carbon stocks of the trees (i.e. the best-case scenario). The right-hand pair of bars shows the worst-case scenario, when changes in management have negligible positive impacts on deadwood, forest litter and soil carbon stocks.

Figure 3.10

Impact on carbon stocks of improving the productivity of a Scots pine forest stand



Source: Forest Research UK

Under the worst-case scenario, the change in carbon stocks in trees is the same as already discussed above and in Appendix 3. The changed management results in an increase in wood production by more than 7.2 tC/ha (+25%). The overall impact on the Scots pine forest is an increase in carbon stock in trees and wood products of more than 16 tC/ha (+28%). This 'gain' is equal to the total increase in carbon stock of all carbon pools combined (see the left-hand pair of bars in Figure 3.10), given that carbon stocks in deadwood, forest litter and soil will not change under this scenario. If the increase in carbon stocks is assumed to occur entirely over the transition period in which rotations are changed (which is assumed to last for 90 years), this gives an annual rate of carbon sequestration during this transition period of 0.18 tC/ha/yr (0.65 tCO_2/ha/yr).

Under the best-case scenario in Figure 3.10, increases in carbon stocks in deadwood, forest litter and soil are also included. The combined increase in these three carbon pools is more than 18 tC/ha (+9.4%). In reality, such changes are likely to occur over decades and possibly centuries in some of these carbon pools, but if the whole change is assumed to occur during the transition period (assumed to last for 90 years), this gives a rate of increase in the pools of 0.20 tC/ha/yr. In all carbon pools together (trees, products, deadwood, forest litter than soil), the total carbon stock in the system is 249 tC/ha before and 283 tC/ha after changes in management — an increase (or 'carbon gain') of almost 14%, equivalent to 125 tCO_2/ha. If all the carbon stock changes are assumed to take place during the transition period, this equates to an annual rate of carbon sequestration during this period of 0.38 tC/ha/yr (1.4 tCO_2/ha/yr).

The ultimate results for the complete calculation of the carbon gain associated with this example of improved forest management to produce extra biomass (including bioenergy) are shown in Figure 3.11. Only the best-case scenario considered above is illustrated in the figure, but the worst-case scenario is also discussed below.

Best-case scenario

To summarise the outcome of the example for the best-case scenario described above:

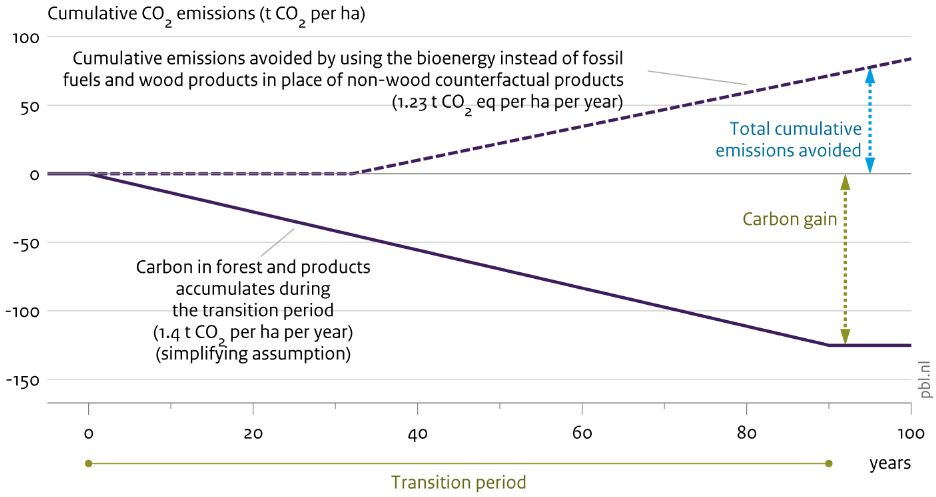
- The fluxes of biogenic CO_2 in and out of the forest (either directly from forests or when biomass is burnt or when non-energy wood products are destroyed) are in balance before management is changed.
- Initially, during the transition period, the improvements to forest management cause an imbalance in the system, so that there is net carbon sequestration. In the example in Figure 3.10 (left-hand pair of bars), the additional carbon sequestration during the transition period amounts to 1.4 tCO_2/ha/yr, which accumulates over the 90 years to a total of 125 tCO_2/ha. This quantity of additionally sequestered carbon is an example of what could be referred to as a 'carbon gain' that can occur in some circumstances when changing forest management to increase the supply of biomass.
- As described in Appendix 3, eventually as a result of the changed management, when the faster growing trees start to be harvested, an additional 3.8 GJ/ha/yr of bioenergy is supplied by the forest during the transition period and continuing after the transition period. Furthermore, an additional 0.27 tC/ha/yr of non-energy products are also supplied from the forest.
- Eventually, when all the forest areas are managed according to the improved regime, fluxes of CO_2 in and out of the system come back into balance as the system reaches a new equilibrium. Under this new equilibrium, the rate of wood harvesting and the supply and consumption of timber and bioenergy continue at a higher rate than before the improvements to management.
- Although the system eventually comes back into balance, the magnitude of the forest carbon stocks is increased by the improved management.

Assuming there is still a demand for the extra energy and other products, then, under the counterfactual scenario in which forest management is not improved to produce more biomass, these products need to be supplied from other sources. If the energy is supplied through burning a mixture of natural gas and coal instead of the bioenergy, and non-wood materials are used instead of the non-energy wood products, then, the annual CO_2 emissions from generating the 3.8 GJ/ha/yr using fossil fuels will amount to 0.29 tCO_2eq/ha/yr, while the emissions from the other non-wood products are 0.95 tCO_2eq/ha/yr. Hence, the use of the bioenergy and non-energy products avoids a total of 1.23 tCO_2eq/ha/yr. The extra bioenergy and non-energy products do not become available immediately after implementation of the forest management changes, but will begin to contribute around the time of the first thinning in the improved forest stands. Here, this is assumed to occur around 30 years after the start of the transition period.

During the transition period, the additional carbon sequestration due to the improved forest management and the use of the bioenergy and non-energy products to displace emissions act in synergy to provide immediate reductions in net CO_2 emissions, and in fact effectively provide 'net negative emissions'. After the transition period, the carbon in the forest and products stops accumulating but the bioenergy and products supplied after this time are effectively carbon-neutral, while the emissions from burning fossil fuels and manufacturing non-wood products will continue, assuming these energy sources and materials would continue to be used while there is no extra biomass produced. Hence, the extra bioenergy and products will continue to provide net emissions reductions. After 100 years, the cumulative net emissions avoided through these wood product and bioenergy substitution effects are 84 tCO_2/ha. After 100 years, the combined accumulated additional carbon sequestration in the forest (125 tCO_2/ha, see discussion of Figure 3.10 above) and emissions avoided through wood product substitution effects (84 tCO_2/ha) will amount to 209 tCO_2/ha, as illustrated in Figure 3.11.

Figure 3.11

Carbon gain arising from extra biomass by improving the productivity of forest areas



Source: Forest Research UK

Worst-case scenario

Under the worst-case scenario developed for this example, the greenhouse gas emissions avoided by using non-energy products and bioenergy instead of non-wood alternatives are assumed to be the same as under the best-case scenario. The key difference considered here is the size of the carbon gain resulting from forest carbon stock changes. The carbon gain is significantly smaller under this scenario, at 0.18 tC/ha/yr or 0.65 tCO_2/ha/yr (see discussion of Figure 3.10 above). After 100 years, the combined accumulated additional carbon sequestration in the forest (59 tCO_2/ha, see discussion of Figure 3.10 above) and emissions avoided through wood product substitution effects (84 tCO_2/ha) will amount to 143 tCO_2/ha.

Achieving these kinds of synergistic outcomes to enable a carbon gain may often involve conscious planning beyond what would be done routinely as part of 'Sustainable Forest Management'. Opportunities to manage biomass supply from forests whilst also enhancing carbon stocks are likely to be quite site-specific, for example where forest growth rates can be enhanced by diversifying tree species composition, where management can help restore damaged or degraded forests, or where forests can be managed to mitigate the effects of major natural disturbances. Such activities are also likely to face significant constraints, for example the introduction of fast growing exotic tree species may be considered undesirable, whilst opportunities to create new productive forest areas are limited by land availability and suitability. The key is to be conscious of the principle of changing forest management practices to sustain or enhance biomass supply and carbon stocks at the same time, and to always actively consider possibilities for achieving this when developing new biomass supply chains and plans for future forest management. Therefore, it is pertinent to pose the following question: *Could improved forest management as outlined above be implemented in practice, and could it really increase the supply of biomass as well as maintaining or even enhancing forest carbon stocks?*

There is some literature suggesting that changes in forest management have contributed in part to the accumulation of carbon stocks and enhanced carbon sinks in forests around the world, over the period from the mid-20th century to the present day (see Box 3.6). Some changes to forestry practice have involved active improvements to forest growing stock, while others have involved abandonment of practices that have led to forest degradation and loss of forests. In some countries, this has occurred in response to the introduction of legislation governing forest management and/or the adoption of principles defining good practice in forest management. The possibilities for managing biomass harvesting and carbon stocks in a planned way across a population of forest stands is explored further in Chapter 5.

Box 3.6 Evidence of increasing carbon stocks linked to enhanced forest carbon stocks

There is some evidence to suggest that the maintenance or enhancement of forest carbon stocks and sinks can be achieved in some situations through improvements in forestry practices. For example in Kauppi et al. (2022) synthesises detailed information from national forest inventories and other published sources to investigate trends in annual carbon sinks of forests in Finland, Norway and Sweden, compared with trends in annual harvesting rates. The study found that the annual rate of harvesting from forests in the three countries increased significantly over the period from 1960 to 2017, while the growth rate of the forest and carbon stocks also increased over the same period.

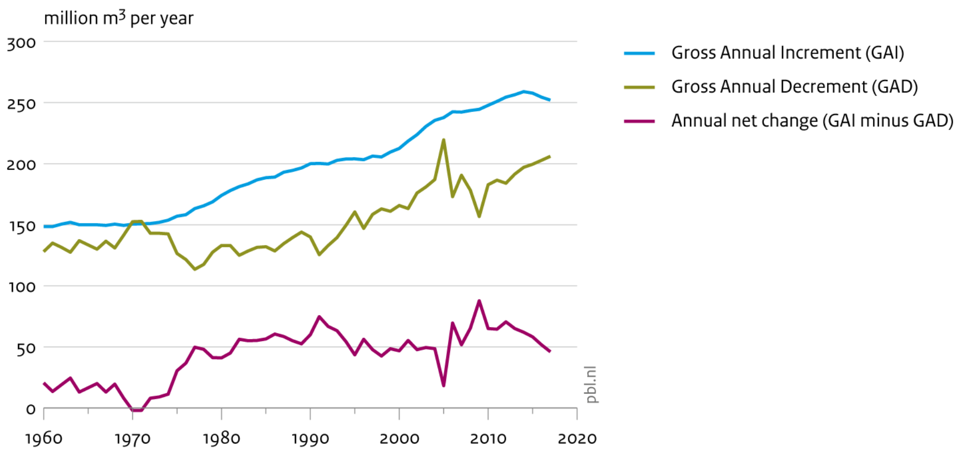
The results presented in Kauppi et al. are illustrated by the estimated annual changes in tree stem volume in the combined area of productive forests of the three countries between 1960 and 2017, as shown in Figure 3.12. The productive forest area was defined as the area of forested land where tree stands have the capacity to produce more than 1 m³/ha/yr of stemwood volume.

Figure 3.12 shows three measures of stem volume change:

- Gross Annual Increment (GAI) of stem volume: the total annual accumulation of stem volume in the productive forest areas of Finland, Norway and Sweden as a result of tree growth, before allowing for losses of stem volume as a result of tree mortality and harvesting.
- Gross Annual Decrement (GAD) of stem volume: the total annual losses of stem volume in living trees as a result of tree mortality and harvesting.
- The annual net change in standing stem volume in living trees in the productive forest areas of Finland, Norway and Sweden; this is the net result of GAI minus GAD and is equivalent to the stem volume stock change of forests.

Figure 3.12

Annual stem volume changes in productive forests in Finland, Norway and Sweden



Source: Kauppi et al. 2022; adapted by Forest Reseach UK

It is apparent from the figure that GAD in productive forests in Finland, Norway and Sweden has increased progressively over the period from 1960 to 2017, mainly driven by increased harvesting. However, GAI has also increased steadily over the same period. Note that a transient peak in GAD in 2005 and a smaller one in 2008 (and associated dips in net stem volume change) are related to the significant storms that severely damaged forests in parts of the region, in those years.

The net impacts of the trends in GAI and GAD over the period from 1960 to 2017 on the stock of standing stem volume in living trees (black line in Figure 3.12) are:

- A significant increase in the rate of standing volume gain between 1970 and 1976, correlated with a period in which GAD declined while GAI increased.
- A broadly constant rate of gain in the standing stock of stem volume over the period from 1977 to 2017.

These findings require careful interpretation. On the one hand, illustrations in Sections 3.2 and A2.5.1 show how observing a continuing rise in total carbon stocks in a forest area over time does not necessarily indicate that a carbon debt is being avoided. The accumulation of carbon stocks might have been even higher, if harvesting had not been increased. On the other hand, illustrations in Section 3.5 and Appendix 3 show how improved forest management practices could allow the rate of harvesting to increase while also maintaining or enhancing the growing stock of forests and hence these activities can actively enhance forest carbon stocks (i.e. the changed management and increased biomass supply are associated with a carbon gain, avoiding a carbon debt).

The question, therefore, is which of these situations is occurring in the forests over the period analysed by Kauppi et al., and how and why. The authors suggest that the forests in the region have undergone a carbon gain as a result of forest management measures introduced intentionally to restore and improve the productivity of the growing stock in the region. This is at least partly responsible for increasing biomass supply from forests in the region also resulting in a carbon gain.

The authors explain that wood harvesting from forests in the three countries considered involved unsustainable practices up to the end of the 19th Century and, to an extent, in the early 20th Century (see Enander (2011) for discussion of historical management in Sweden). In particular, harvesting during this period prioritised removing the better growing and better formed trees in forest stands, leaving behind the weaker trees with relatively poor growth rates and stem form. Moreover, little or no effort was made to ensure the regeneration of successor trees when trees or whole areas of forests were felled. The result of these practices was a degraded total growing stock of trees in forests and depressed forest growth increment.

In the 20th Century, national policies were introduced in the region explicitly aimed at ensuring sustainable management practices. Kauppi et al. attribute some of the steady increase in GAI between 1960 and 2017 to improved sustainable forest management practices, stimulated by these policies. The main relevant practices identified by Kauppi et al. are (in descending order of importance):

- Changes in forest management involving the withdrawal of the exploitive harvesting practices described above and stronger efforts to ensure the development of fully stocked and fast-growing stands of trees (note that this also involves a move towards more even-aged stands of trees).
- Ensuring full and fast regeneration of successor trees to replace those harvested.
- Conversion of land from a combination of sparse forest areas with cattle grazing to fully stocked forests, partly as a result of the abandonment of cattle grazing.

- Control of forest fires.
- Draining waterlogged (i.e. peatland) soils under forests.
- Application of fertilisers in some areas of forest.

Kauppi et al. also observe some actions towards planting stands of genetically improved trees with enhanced growth rates and stem form, produced through tree breeding programs. However, they note that these activities were not widespread during the early study period and did not contribute significantly to the observed positive trend in GAI.

Kauppi et al. recognise that the improvements in forest management are not the only reason for the increasing GAI: Elevated atmospheric CO_2 and associated climate warming (such as longer growing seasons) are also recognised by Kauppi et al. as contributing towards enhanced forest growth (Henttonen et al., 2017), but they did not assess the relative contributions of these effects to enhanced GAI. Another possible influence on forest increment could be nitrogen deposition from atmospheric pollution during the study period, but Kauppi et al. suggest that nitrogen deposition levels are relatively low in the region (Ackerman et al., 2019).

A period of increasing GAI in forests can also occur as part of longer cycles in increment related to the distribution of tree ages in a forest, such as when the distribution is skewed towards younger and faster growing stands of trees approaching the period of full-vigour growth (see Figure A2.1 in Section A2.1 and Section A2.4.1). Such a situation may happen for reasons that may or may not be related to how forests have been and are being managed. Kauppi et al. do not comment on whether this is relevant to their observations on the Scandinavian forests.

It may also be noted that the rate of harvesting dropped for a few years in the 1970s, reflected in a short-term reduction in GAD during that period. The reasons for this are not related to policies introduced to improve forest management (P.E. Kauppi, personal communication). Rather, unfavourable economic circumstances during the 1970s caused a drop in demand for wood. There was also a commercially driven initiative to improve the efficiency of wood supply chains from forests to processing mills, aimed at reducing stockpiles of harvested wood at mills. This resulted in a short-term drop in demand for freshly harvested wood. This development is interesting: Is this an example of a market-mediated or commercially mediated activity with a positive impact on the forest growing stock?

It must also be acknowledged that certain management practices introduced to enhance the productivity of forests involved negative impacts on total forest carbon balances. The main practice in this regard was the draining of peatland forest soils. This practice can increase the growth rate of trees through the increased aeration of the soil, but this also results in oxidation of soil organic matter, which is generally considered to result in increased emissions of CO_2 from the soil (IPCC, 2014b). Draining waterlogged soils can also lead to lower methane emissions from soil, which can compensate to an extent for the increased CO_2 emissions. However, the magnitude of such emissions is still being debated (for example, see Minkkinen et al., 2018; Simola et al., 2012). In addition to soil drainage, forest fertilisation can involve increases in greenhouse gas emissions, notably when nitrogen fertiliser is applied, resulting in emissions of nitrous oxide.

The findings of Kauppi et al. for a real situation across a significant region of Northern Europe give some credence to the idea that improvements to the management of existing forests can allow the extraction of biomass from forests to be increased while maintaining or enhancing forest carbon stocks and sequestration rates, that is, contributing towards a carbon gain. However, their study also highlights the challenges to achieving such outcomes and to verifying that this can be attributed to improved forest management:

- It would appear that in the case considered by Kauppi et al., improvements to forest management did not 'just happen', rather, it was necessary for robust national policies to be introduced and followed in practice.
- Increasing carbon uptake by forests (GAI) and maintained or enhanced forest carbon stocks can occur for several reasons, which may or may not be related to improvements to forest management or may only be partially related.
- It may be difficult to demonstrate or verify the extent to which improved forest management is contributing towards, or possibly detracting from, the maintenance or enhancement of forest carbon stocks.

The opportunities to introduce improvements to forest management, and the kinds of forestry practice involved, are likely to depend strongly on context and regional circumstances. In the example considered here, changes to forest management were introduced after a preceding period of forest exploitation, presenting an 'opportunity' to remediate the impacts of historical practices. The institutional frameworks were also in place in the region to develop policies to support more sustainable forest management and ensure their implementation. These specific circumstances cannot be assumed to exist currently in all regions of the world or Europe.

A further point arises, given the interest in further increasing the supply of biomass from forests. Taking the example of Scandinavia, efforts have already been made to improve forest management in the last century, and biomass supply has already been increased. Thus, it could be questioned whether there is further potential to increase biomass supply in the region while maintaining a carbon gain. This question is pertinent, given that, according to Figure 3.12, GAI has declined in the last few years of the study period (2015 to 2017), while the rate of wood harvesting (GAD) has continued to rise. As a result, the margin between GAI and GAD appears to be starting to narrow, and the rate of increase in forest stem volume growing stock is diminishing towards the end of the study period.

It may be speculated that forest management options for further enhancing GAD in this region might include:

- Closer matching trees (species or seed origins) to sites and climate (including as part of adapting to climate change) when replanting after harvest.
- Further actions towards breeding and planting genetically improved trees.
- Adaptation of forest management to prevent or remediate the impacts of natural disturbances (i.e. fires, storms, pest and disease outbreaks).

In the current context of societal expectations about forests, management may variously prioritise different objectives and in some situations climate change adaptation, biodiversity protection, recreation and/or conservation of carbon stocks could take precedence over wood supply.

The full benefits of these activities, assuming they are incentivised, would only be realised over long timescales and implementation would likely involve significant technical investment.

Is the example of Kauppi et al. unique?

It is worth considering whether the ultimately positive development of historical forestry practices and resulting impacts on forest carbon stocks in the Nordic region as described by Kauppi et al. is a result of unusual and possibly unique circumstances, or if there are further examples in other regions. Another paper by Kauppi et al. (2020) reviews the development of forestry practice in case study regions of Ireland, France, Eastern Europe and East Asia, and identifies a range of actions taken over many decades to restore and expand the area of forests. A pattern of declining forest areas and condition up to the twentieth century, followed by a period of active restoration and expansion is commonly observed in European countries (the United Kingdom is a further example, see Aldhous (1997), Gambles (2019), Mason (2007), and Ryle (1970)).

A pertinent study in the context of this report by Dale et al. (2017) has shown that forests within land areas containing wood-pellet producing mills in the South-eastern United States have expanded in terms of area and standing tree stocks, during the period when the mills have been operating since 2009. However, there are very few formal assessments of the existence of causal relationships between the development of forest areas and tree stocks and positive actions towards forest expansion and restoration, such as in the study of Kauppi et al. There have been some recent studies in the United States that investigate likely future trends of hypothetical scenarios, using methods involving complex analyses or modelling that depend on many assumptions and generally lack transparency (see Section 4.5). Nevertheless, it may be concluded that there is evidence from several regions that improved forest management can enhance both carbon stocks and biomass supply simultaneously. But because forest management has already been improved in many regions, notably in Europe, it is uncertain whether there is remaining potential for further improvement. As forest management improves, further improvements may become more challenging, or their benefits may take some decades to be realised. Examples include diversifying tree species composition in forests for greater resilience and improved growth, tree breeding to improve forest productivity, and expanding forest areas where land is available and not needed for food production.

3.6 Key insights

A number of key insights can be drawn from the discussion in this chapter. The theoretical examples illustrate how activities to produce biomass from forests for energy use can result in a carbon debt or carbon gain, or be carbon-neutral in certain circumstances. The likelihood that bioenergy from forests actually involves positive activities resulting in carbon gains or low emission levels is doubted and challenged by bioenergy sceptics, while proponents from the forestry and biomass sectors will point to the positive aspects of their forest management activities and utilisation of biomass feedstocks. However, the question of whether or not bioenergy supply will result in low or high greenhouse gas emissions is perhaps not the main point. The salient insight is that producing forest bioenergy may involve either negative, low or high emissions, depending on local circumstances and the type of forest management and biomass feedstock involved. The key questions, therefore, are whether the positive and negative practices can be distinguished and whether it is possible to support the positive practices and minimise or mitigate the negative ones. These questions apply equally to agricultural biomass sources. These issues are explored further in Sections 4.1 and 4.2 of Chapter 4 and possible practical approaches to managing the carbon impacts of biomass harvesting and use are considered in Chapter 5.

4 Variability in carbon impact study results

Chapter 3 has described how managing forests to supply biomass for bioenergy and/or for wood products can have variable effects on greenhouse gas emissions, categorised into the three broad classes of 'carbon debt', 'carbon neutral' and 'carbon gain'. It should, therefore, come as no surprise that published scientific assessments report a wide range of results, variously concluding that biomass and especially bioenergy supplied from forests:

- Can provide immediate reductions in CO_2 emissions.
- Leads to an initial increase in CO_2 emissions, followed by emissions reductions after a period that can vary from a few years to centuries.
- Causes emissions to be increased effectively indefinitely.

The factors that influence the magnitude and duration of carbon stock changes in forests resulting from forest management activities to supply biomass have been identified and quantified in studies using Life Cycle Assessment (LCA)-based models (Laganière et al., 2017; Matthews et al., 2015; Serra et al., 2019) and synthesised in literature reviews (Buchholz et al., 2016; Cowie et al., 2021; EZK & I&W, 2020; JRC, 2014; Khanna et al., 2017; Lamers & Junginger, 2013; Matthews et al., 2019; Matthews, Sokka, et al., 2014). There are two broad reasons for the divergent assessments of the carbon impacts of bioenergy systems found in the scientific literature.

Firstly, published studies can arrive at particular conclusions because they study different kinds of forest being managed in different ways to produce biomass, that is, because of factors inherent in the forest system(s) and biomass supply chains under study. Relevant factors include the dynamic and complex nature of forest ecosystems, the biomass feedstock being supplied for bioenergy, diverse biomass supply chains, the range of conversion pathways through which biomass is transformed into usable energy products (heat, electricity, solid, liquid, and gaseous fuels), and the alternative energy products being displaced.

Secondly, variability in results also arises from different choices made in studies when determining the assessment methodology, including the calculation methods such as the selection of a counterfactual scenario (see Section 2.2, Chapter 2), the detailed choice of calculation parameters such as the values of emissions factors, and the metrics used to assess carbon impacts and report results. One consequence is that it is possible for published studies to report very different results for the CO_2 emissions from biomass supply and use, even when similar forest systems and biomass supply chains are being studied, which can frustrate interpretation. This can create a perception that the CO_2 emissions from using biomass sources, especially for bioenergy, are extremely wide-ranging and the causes are complex and uncertain. A clear understanding of the scientific literature on the CO_2 emissions from the use of forest bioenergy requires a detailed analysis of all the factors involved. The purpose of this chapter is to provide such an analysis.

The key factors inherent in forest systems are reviewed in Section 4.1, along with a description of their typical influence on CO_2 emissions. Factors inherent in biomass supply chains are discussed in Section 4.2. Examples of assessments investigating combinations of factors and their influence on forest carbon balances are described in Section 4.3. The influence of methodological choices when assessing the CO_2 emissions of biomass sources is considered in Sections 4.4 and 4.5.

4.1 Factors inherent in forest systems

There are certain characteristics of forests that can affect the carbon balance of biomass supplied from them (see for example the review in Chapter 3 of Matthews, Sokka, et al. (2014)). These characteristics can be described as a set of factors such as shown in Table 4.1. The relevance of each factor is discussed briefly below.

Table 4.1
Inherent characteristics of forests

Characteristic	Description
Condition of forests	Defined for this purpose in broad terms, e.g. intact primary, managed (regenerated forests or plantations), damaged/disturbed and degraded[20].
Natural disturbances and forest degradation	Can vary in terms of frequency, intensity and type, e.g. fire, storms, pest and disease infestations.
Tree and stand growth rates	Can be defined in terms of the annual rate of stem volume growth, usually expressed in cubic metres per hectare per year.
Distribution of tree/stand ages	Can be characterised in terms of the relative areas of young, middle-aged and old trees and stands.
Management practices	Considered in terms of existing practices already established in forest areas, particularly those involving harvesting, and any changes to practices that may be involved in increasing the supply of biomass from forests.

4.1.1 Condition of forests

The condition of forest areas, at the time action is taken to extract biomass, can have a very significant influence on the consequent development of forest carbon stocks. This is related to the carbon stocks typically found under different conditions.

At one extreme, intact primary forests, and other forests with high conservation value, generally maintain carbon stocks close to the maximum carrying capacity of the land where they are located. If management involving harvesting to supply biomass is introduced in these kinds of forests, usually this will diminish the carbon stocks, even if the management is otherwise regarded as sustainable (see for example Box 3.1), although most likely the carbon stocks will eventually stabilise again at a lower level.

At the other extreme, severely naturally disturbed and degraded forests typically have significantly depleted carbon stocks. If these kinds of forests are managed for biomass supply, by restoring their stocks of trees and productivity, this can enhance the carbon stocks.

[20] The definition suggested for forest areas undergoing degradation is based on the IPCC definition of land degradation (IPCC, 2019b) but narrowed for the context of this report: Forest areas undergoing a negative trend in condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as a long-term reduction or loss of at least one of the following: biological productivity, ecological integrity, or value to humans. Degradation in terms of any of these factors could have a negative impact on forest carbon stocks (such as reduced rate of forest growth, compromised resilience, or likelihood of neglect or abandonment by forest owners with subsequent land use change).

Between these extremes, forest areas already under management for biomass supply, including managed plantation forests, can maintain stable carbon stocks under appropriate conditions, for example as illustrated in Section 3.1 of Chapter 3. However, carbon stocks can be diminished or enhanced when management of these forests is adjusted to increase biomass supply. The specifics depend on how management is adjusted, as illustrated in Chapter 3, discussed further below in this section, and explored in detail in Chapter 5 (Sections 5.1, 5.2 and 5.4).

4.1.2 Natural disturbances and forest degradation

Opportunities to supply biomass from forests in conjunction with a positive influence on carbon stocks depend on the frequency and intensity of natural disturbances in the absence of management. On the one hand, forest areas that experience very frequent and severe disturbances, such as regular fires, will tend to have relatively low carbon stocks, which may present opportunities for management to restore and maintain higher carbon stocks. There may be less potential in forests with lower disturbance regimes, where carbon stocks are higher. On the other hand, actions to improve forest carbon stocks and productivity may also be disrupted on high disturbance sites, and less so when there is low disturbance. Hence, opportunities to restore carbon stocks and increase the supply of biomass from disturbed forests are variable, depending on the site, climate and type of disturbance. There may be more potential for restoration activities in forests that have been degraded by past and present unsustainable practices, provided that the socioeconomic drivers of the present practices can be addressed.

In cases where there is significant, large-scale incidence of forest disturbance, such as due to a major storm, fire or disease outbreak, the affected trees can be left on site to decay or they can be harvested, an activity referred to in this context as 'salvage logging'. If the biomass is used for short-lived wood products and bioenergy, this is likely to hasten the return of the carbon in the biomass to the atmosphere, unless the alternative practice would be to burn the biomass on site, as part of assisting the regeneration of replacement trees, in preparation for tree planting, or to reduce wildfire risks in fire-prone areas. Conversely, leaving damaged and fallen trees to decay in the forest may delay the loss of carbon stocks for some years or decades, but the presence of this material on site is likely to present obstacles to the establishment of a successor stand, and so delay the restoration of carbon stocks in living trees. The impacts of salvage logging on the forest carbon balance, positive or negative, thus depend on local circumstances (see for example Bradford et al. (2012), Köster et al. (2011) and Thürig et al. (2005)).

4.1.3 Tree and stand growth rates

The potential growth rate of trees forming forest stands is an important factor in determining the effects on forest carbon stocks of decisions about forest management (e.g. when deciding whether to harvest trees, and, if so, by what management approaches) and the utilisation of harvested wood (see for example Marland & Schlamadinger (1997), Marland & Marland (1992), Nabuurs et al. (2008), Schlamadinger & Marland (1996)). There are several reasons why potential growth rate can be so important:

- Generally speaking, the faster the growth rate, the quicker carbon can be sequestered, e.g. when an area of non-forest land is converted to forest land through afforestation.
- When forest carbon stocks are disturbed, by natural processes or by harvesting, generally they can be replenished to pre-disturbance levels more rapidly where growth rates are higher.

- The faster the growth rate, the more wood can be harvested from a given area and the greater the subsequent potential for reducing emissions through use of wood products and bioenergy substitution effects.

As discussed in Appendix 2, mean forest growth rates over typical rotations can range from 1 m^3/ha/yr up to 40 m^3/ha/yr, generally with slower growth rates in boreal regions and the fastest growth rates in tropical regions, although with certain exceptions. It is very likely that options for managing forests to meet climate change mitigation targets (i.e. reducing emissions through biomass use and/or sequestering carbon) will be sensitive to growth rates over this range, suggesting a site-by-site approach for the evaluation of management options.

4.1.4 Distribution of tree and stand ages

The distribution of ages of trees and stands within forest areas present opportunities for management to increase biomass supply with positive or neutral effects on carbon stocks, but also place constraints on management options.

For example, if the age distribution is skewed towards young trees and stands, the majority of trees may be too small to be worth harvesting, whilst high levels of thinning in young stands could diminish longer-term growth rates in the forest. However, very young stands could be improved by 'cleaning thinnings', to remove poorly formed trees and leave some more space between better quality trees, freeing them from competition and enabling them to grow faster, so that there is negligible impact on overall stand growth rates and carbon stocks. The trees removed in these thinnings will be small and may lack stemwood suitable for conversion into wood products such as smaller sawnwood products or wood-based panels. Instead, the trees could be utilised for bioenergy. In general, younger stands are more suitable for thinning, but the small dimensions of the harvested trees make them unsuitable for conversion into longer-lived products such as structural sawnwood, limiting options for co-production of wood products and bioenergy.

Conversely, if the age distribution is skewed towards older trees and stands, then more stands will be available for harvesting. The generally larger dimensions of the trees make them more suitable for conversion into longer-lived wood products, with bioenergy as a by-product. Older stands have higher carbon stocks, however, so that significant harvesting in these stands would most likely result in a period of declining carbon stocks.

Overall, the influence of unevenly distributed tree and stand ages in forest areas may drive cycles in levels of biomass harvesting and the development of carbon stocks, as illustrated by the examples in Appendix 2 (Section A2.4.1). This can present challenges to managing forests to supply constant amounts of wood products and bioenergy, whilst also avoiding negative impacts on carbon stocks. It is, therefore, apparent that studies of the carbon balance of biomass supply chains may produce variable results, depending on the distribution of tree and stand ages in the forest areas under study.

4.1.5 Existing and planned forest management practices

The carbon balance of forest areas depends on the forest management practices already established in them, and also on any changes in practices introduced to increase supplies of biomass. This point has been illustrated by simple examples in Chapter 3 and Appendices 2 and 3. The options for forest management, and their typical effects on the development of forest carbon stocks, are very wide-ranging, but it is possible to define some broad classes, such as the examples shown in Table 4.2. Previous examples of this kind of assessment have been made by JRC (2014); Lamers and Junginger (2013); Matthews et al. (2018) and Giuntoli et al. (2022).

It is evident that variability in published results for the carbon balance of biomass supply chains can easily arise from studies considering systems that involve different types of forest management intervention to supply biomass.

Table 4.2
Examples of forest management to produce more biomass and their effect on forest carbon stocks.

Option	Effect on carbon stocks	Comments
Reversing deforestation	+++	
Creating new forest areas (afforestation).	+++	Sites with high soil carbon stocks and risks of indirect land-use change need to be avoided (see Sections 5.2.1 and 5.6).
Improving the condition of disturbed/degraded stands.	+/++	Outcomes are likely to be very site-specific (see earlier discussion in this section).
Improving the growth rates of stands.	0/+	See example in Section 3.5, Chapter 3
Continuation of pre-existing management/harvesting levels.	0	Forest management practices are assumed to be sustainable (see definition in footnote in Chapter 1).
'Cleaning thinnings' in very young stands.	0/-	Depends on density of young trees before thinning and extent of trees removed.
Extraction of woody residues from forest harvesting where these were previously left to decay on site.	-/--	Depends on site conditions (see further discussion in Section 5.5).
More thinning in managed forests than previously practiced.	-/--	See example in Section A2.5.1.
More frequent final felling in managed forests than previously practiced.	--	See Section 3.2 and example in Section A2.5.1.
Harvesting in previously undisturbed and unmanaged forests.	---	'Undisturbed' and 'unmanaged' forests require definition.
Deforestation	---	As noted in Chapter 1, biomass supplied as a result of direct or indirect permanent loss of forest areas (i.e. deforestation), violates the EU sustainability criteria as laid down in the RED (EC, 2023a).

4.2 Factors inherent in biomass supply chains

Biomass supply chains consist of all the elements and steps involved in producing biomass from forests or crops, or some other source, then transporting and processing and ultimately utilizing the biomass for various products, including for bioenergy. For biomass derived from forests, the first step in the chain usually consists of the forest areas where the biomass is harvested, as already discussed above. Factors inherent in other stages of forest biomass supply chains can also have an important influence on the carbon balance of biomass sources, including:

- How different types of biomass 'feedstock' (see definition below) are used for different products.

- Supply chain emissions from fossil fuels and materials consumed in growing, harvesting, extracting and processing the biomass.
- For bioenergy supply chains, the technology used to convert the biomass into useful bioenergy products of various types.
- The extent to which the biomass 'substitutes for' or 'displaces' the use of other higher emissions products (wood product and bioenergy substitution effects, see Appendix 1).

These factors are discussed briefly below, with a particular focus on forest biomass used as bioenergy.

4.2.1 Biomass feedstocks used for bioenergy

For the purposes of this report, a 'feedstock' is a raw material used in an industrial process. In the case of forest biomass supply chains, feedstocks consist of parts of harvested trees or biomass produced as co-products, for example during the sawing or milling of tree stems. The carbon balance of biomass supply chains can be influenced by how individual biomass feedstocks are allocated to different end uses, including for bioenergy.

To better understand the impact that choices regarding the use of biomass feedstocks can have, definitions are required for the different feedstocks. It is also important to understand how feedstocks are generated in supply chains. This is because there is sometimes confusion around the definitions and/or misinterpretation on the most probable use of feedstocks, or their usual fate in the absence of their use for bioenergy. Table 4.3 gives definitions for different forest biomass feedstocks typically used for bioenergy, and their likely alternative fate if not utilised for bioenergy. An assessment is also included of the carbon payback time (see definition in Section 2.4) typically associated with each feedstock, based on consideration of the alternative fate, which is discussed further below. The assessments in Table 4.3 are simplified from Matthews et al. (2018). A more detailed definition and assessment of forest biomass feedstocks when used for bioenergy is given in Sections 5.1 and 5.3.

Industrial and forest harvest residues

The use of industrial residues for bioenergy is generally found to generate mitigation benefits in the short term, particularly where the material would otherwise be burnt (incinerated) as waste (Serra et al., 2019). The same is true for forest harvest residues if they would normally be piled and burnt to reduce fire hazard or left to decay in the forest (Giuntoli et al., 2015). These two feedstocks are therefore associated with nil or small carbon debts in many studies and with greenhouse gas benefits usually realised within a decade. An exception is when residues left in forests decay slowly, and the use of residues for energy is associated with a relatively small substitution effect. If the removal of residues has a negative impact on site fertility, tree growth can be reduced with a very long-term negative effect on the forest carbon balance.

When trees from salvage logging (see Section 4.1.2) are extracted as forest residues and used as a feedstock for bioenergy, and the counterfactual scenario is that the trees are not logged, net greenhouse gas savings are usually achieved in the medium to long-term due to the slow decomposition of standing dead trees and coarse woody debris left in the forest (Laganière et al., 2017). However, the outcome depends on species and environment, and substitution effect of the biomass use. In some cases net greenhouse gas savings are seen in the short term (Lamers and Junginger, 2013).

Table 4.3
Examples of forest bioenergy feedstocks

Feed stock	Definition	Synonyms	Likely alternative fate	Payback Time[a]
Post-consumer wood waste	Wood from products that have come to the end of their useful lives.		Available for re-use, repurposing, recycling, or otherwise land filled or burnt without energy recovery. Can be used in some types of wood-based panels.	Short
Industrial residues	Wood generated as a by-product by the wood processing and associated industries, including offcuts, sawdust, sawmill chips, etc.	Mill residues, processing residues.	Used in wood-based panels, burnt without energy recovery, landfilling.[b]	Short
Forest harvest residues	The woody biomass of trees left in the forest following tree harvesting as being unsuitable/uneconomic to collect for wood products, typically consisting of branchwood, stem tops, defective tree stem pieces and stem offcuts but excluding tree stumps and roots.	Forest, harvest or logging residues/waste, slash.	Decay, pile and burn	Short to Very long
Stumps	The stemwood left above ground after a tree is felled, generally still attached to and including the roots.		Decay	Long
Lower quality stemwood	Woody material forming the above ground main growing shoot(s) of a tree or stand of trees, including wood in major branches, unsuitable for conversion to high quality wood products, such as sawnwood. Includes salvaged trees killed by natural disturbances such as wildfire, windthrow, insects and disease.	Roundwood, whole/ complete/ green trees, thinnings, pulp wood, rejected logs, salvaged trees.	Used in wood-based products, decay, pile and burn, left standing (uneconomic), unharvested (protection).	Short to Very long

[a] See Section 2.4 for the definition of the concept of carbon payback time and Table 2.4 for the definitions of classes of carbon payback time referred to in this report.
[b] Some industrial residues are already used for energy at sawmills to provide process heat and for drying timber in sawmills.

Stumps

Stumps are often associated with a higher carbon debt than other forest residues because their removal disturbs the soil and reduces organic matter inputs to the soil and, when left in the forest (counterfactual), they decay and release their carbon more slowly. This is especially the case in temperate and boreal environments (JRC, 2021b; Persson et al., 2017; Repo et al., 2011). Forest biomass harvesting guidelines of many jurisdictions discourage stump removal due to concerns over potential risk of land degradation (Hannam, 2012; Titus et al., 2021). On the other hand, stump removal can facilitate faster regeneration of the next rotation of trees and help control root disease. These beneficial impacts can counteract the warming effect of using slowly decaying forest residues for energy (Persson et al., 2017; Persson and Egnell, 2018). In some countries, such as Sweden, Finland and the UK, legislation and recommendations regulate the extraction of stumps and other forest residues, to prevent or limit negative impacts on forest productivity, biodiversity and other environmental values.

Lower quality stemwood

The definition of lower quality stemwood in Table 4.3 is very broad. It can, therefore, include a diversity of products in the form of tree stemwood, such as various types of thinnings, the smaller diameter part of larger tree stems (small roundwood), and the stems of trees of various sizes considered to be defective for some reason (heavily branched, twisted, snapped, diseased, dead and decaying). These feedstocks have a wide range of end uses and alternative fates, with the result that their use for bioenergy has very variable effects on greenhouse gas emissions. Even subclasses of these feedstocks, such as thinnings, are themselves diverse (see Box 5.2 in DESNZ, 2023).

Where stemwood feedstocks are not suitable for products other than bioenergy, they may often be regarded as forest residues. This could include smaller thinnings containing little stemwood, larger trees with excessive defects, and trees of a species unsuitable for utilisation for high quality wood products. Hence, even feedstocks potentially falling into the category of forest residues are diverse, with variable carbon payback times if utilised for bioenergy. This situation arises partly because of the innate variability of these feedstocks and partly because of their alternative fates if not used for bioenergy. For example, in some cases trees might be left to grow rather than being harvested, in other cases low quality stemwood might be left to decay in the forest and the decay rate will be highly dependent on the size of the material (the larger the diameter of the wood, the longer the decay time and potential carbon payback time if used for bioenergy). In a circumstance where the most likely outcome in the absence of a demand for bioenergy is to not harvest trees, or to harvest them at a later stage of stand development, stemwood used for bioenergy generally leads to medium to very long carbon payback times (see for example Section 3.2, and Bernier and Paré, 2013; Birdsey et al., 2018; JRC, 2021b; Laganière et al., 2017). In contrast, stemwood sourced from dedicated biomass plantations could provide bioenergy with very short carbon payback times, if planted on, for example, abandoned or degraded cropland or pastureland and does not displace food production (Lamers and Junginger, 2013).

In some areas, the 'value' of a stemwood feedstock may be determined by the location where it is grown and harvested, in relation to where the markets for its use are located. For example, pulp quality stemwood can be used for paper production, but in regions where the pulp and paper industry has declined, it is possible that this stemwood could become available for other products, including for bioenergy. In general, the relatively short residence time of pulp and paper products such as packaging, means that using pulp-quality stemwood for bioenergy is likely to lead to short carbon payback times.

It is acknowledged that using stemwood for bioenergy that is otherwise suitable for conversion into higher quality and longer-lived products such as plywood, sawnwood, or cross-laminated timber, can lead to significant negative impacts on the carbon balance (Birdsey et al., 2018; Smyth et al., 2014). However, this is highly unlikely because of economic considerations and market forces since long-lived wood products are the best economic use of high-quality stemwood.

The increased use of lower value stemwood for bioenergy can also have indirect effects on CO_2 emissions and carbon payback times. For example, diverting feedstocks useful for making wood products to useful bioenergy could lead to a loss of wood product substitution benefits, if those wood products are replaced by other greenhouse gas-intensive materials (see Section 3.3 and Cintas, Berndes, Hansson, et al., 2017; L Gustavsson et al., 2021; Leif Gustavsson et al., 2015; Schulze et al., 2020; F. de A. Ximenes et al., 2012).

4.2.2 Supply chain emissions

The emissions released along the steps in the supply chain (i.e. collection/retrieval, processing, and delivery to end users), sometimes called 'upstream' emissions, are highly variable but generally have only a small impact on the carbon balance of forest biomass supply chains. Fossil fuel emissions from harvesting operations (harvest machinery, site preparation and regeneration, and road construction/maintenance) are small and usually contribute little to overall emissions (McKechnie et al., 2011; Pa et al., 2011). The transportation of biomass (from the harvest site to the processing/storage facility and then to the end user) may, depending on methods and distances, in some cases represent more than half of supply chain emissions (Pa et al., 2011). Understandably, local supply chains tend to have lower transport emissions per unit of biomass-based fuels delivered relative to longer-distance routes. However, emissions per ton and per distance travelled differ significantly for different modes of transport (truck, rail, shipping). In the case of oceanic transport, even supply chains involving thousands of kilometres usually have a small contribution to the overall carbon balance of a bioenergy system, when efficient bulk transport is deployed (Jonker et al., 2014; Lamers et al., 2014). High emissions from transporting biomass, for example by road over long distances, may not be critical in determining the carbon impacts of using the biomass if the alternative non-biomass products also need to be transported over long distances by road. For example, a recent case study in northern Canada showed that the supply of wood pellets to a remote community (over 1,000 km) could provide net greenhouse gas savings within two years (Buss et al., 2022). Nevertheless, supply chains with large fuel use may be undesirable even if they represent an improvement compared to previous supply chains, because emissions are still relatively large, and there can be local impacts on pollution and congestion. In such cases, there may be options to optimise supply chains that aggregate and densify biomass to increase efficiency.

4.2.3 Biomass conversion technologies and bioenergy products

Biomass is a versatile resource in that it can be processed in different ways to produce power, heat and liquid transport fuels. These different fuel types and their processing and conversion technologies have different efficiencies (the net useful energy yield from a given amount of forest biomass). However, this diversity of products and conversion processes is a further source of variability and uncertainty.

Energy inputs and conversion losses during processing are low when forest industry residues (e.g. bark, sawdust, black liquor) are used on-site to meet the industry's own internal energy needs and to produce electricity and heat for nearby users (for example district heating). The production of solid fuels for use outside the industry can also involve relatively low conversion losses and energy input/output ratios (Hansson et al., 2015). However, biomass drying can be an energy intensive stage which can require fossil fuel input, depending on how well the material is ambiently dried, and what fuel is used for drying (Martín-Gamboa et al., 2020; Silva et al., 2021). Production of wood chips is associated with relatively low energy inputs (de la Fuente et al., 2018; Pecenka et al., 2020), compared to production of wood pellets, which requires further processing, involving size reduction, drying, pelleting and cooling (Manouchehrinejad et al., 2021). Many of these stages require electricity inputs and therefore the greenhouse gas intensity of the pelleting process is dependent on the local electricity grid emission factor (Laschi et al., 2016). In some instances, biomass can be used as an input fuel during the processing stages (e.g. drying), which could have a positive effect by decreasing the fossil input to the drying process, but can also decrease the net energy yield from the studied biomass supply chain.

The process of converting biomass to liquid or gaseous fuels is far more energy intensive and can lead to larger conversion losses (Lönnqvist et al., 2021), which will affect the net energy yield. The efficiency of biomass processing can be enhanced through process design and association with other energy/industrial infrastructure. For example, surplus heat from other industrial processes can provide some of the process energy needed for the biofuel conversion, or the biofuel conversion facility can be connected to a district heating system to make use of low temperature heat that would otherwise be lost (Thunman et al., 2018). These enhanced designs result in lower greenhouse gas emissions from processing, and can also help conserve more of the original energy in the biomass, which can lead to greater substitution effects, as discussed below.

Electricity generation from biomass has varying performance, depending on system configuration and association with other systems. A common example, electricity generation in combined heat and power (CHP) plants connected to district heating systems, improves the total system efficiency by making use of some of the heat generated in the electricity generation process. As discussed further in the next section, the co-production of several bioenergy products results in the displacement of several other energy products, and this can improve the net greenhouse gas savings per unit biomass significantly. Similarly, when bioenergy is produced as a by-product along with other bio-based co-products such as sawnwood and paper, the climate change benefits per unit of biomass can be greater (see Appendix 1). However, the fact that bioenergy products can be associated with integrated systems producing multiple products also complicates assessments of greenhouse gas emissions, and studies may adopt different approaches to assessing such systems. For example, the allocation of supply-chain emissions among several co-products can be done in different ways. This methodological issue partly explains divergence in results and conclusions about carbon balances and net greenhouse gas savings.

4.2.4 Bioenergy substitution/displacement effects

The use of forest biomass as an energy source can be advantageous as it can avoid the use of fossil fuels and the resulting emissions of fossil CO_2. The extent to which this displacement is beneficial to the net greenhouse gas balance depends on two main factors: the conversion efficiency and the types of energy sources being displaced (fossil or otherwise). If biomass supply chains produce more than one energy output (for example heat and power) then more than one fossil fuel displacement could be occurring. These aspects of bioenergy substitution effects, as briefly discussed below, may be represented more or less thoroughly in studies of the emissions of biomass supply chains.

The *volume* and *type* of energy source displaced is important in determining the net greenhouse gas savings from the forest bioenergy system (see Appendix 1), and hence the duration of the carbon debt and time to payback. The greenhouse gas emissions released during the combustion of fuel to supply a unit of energy (i.e. the gross emission factors) are similar for bioenergy and coal, but gross emissions factors for bioenergy are higher than for oil and substantially higher than for natural gas (IPCC, 2006). However, the emissions saved by using bioenergy also depend on the relative conversion efficiencies with which fuels (bioenergy or fossil fuel are combusted). As a result, a bioenergy system substituting for coal at a similar conversion efficiency will have an even higher greenhouse gas saving than a system substituting natural gas, where the natural gas counterfactual conversion system is also more efficient than the coal system (Laganière et al., 2017; Lamers and Junginger, 2013). Therefore, the conversion efficiency of both the forest bioenergy and displaced fossil fuel systems under comparison will influence the carbon debt and timing of greenhouse gas emissions mitigation. Higher conversion efficiencies of the bioenergy system relative to the fossil counterfactual scenario can reduce the duration of any carbon payback time.

The potential for one energy system to displace another depends on their suitability for serving similar applications. For example, thermo-electric plants such as biomass CHP have a different functionality in terms of flexibility, dispatchability, and inertial response compared with solar PV installations or wind power plants. So, these technologies are not natural substitutes for each other, whereas the expansion of electricity generation capacity with the same functionality as biomass would more likely rely on other carbon-based fuels, i.e. fossil fuels.

4.3 Combined effects of factors inherent in forests and supply chains

It is apparent from the discussion so far in this chapter that numerous factors are involved in determining the CO_2 emissions impacts of biomass supply chains. It can be challenging to grasp the contributions of these individual factors to the overall outcome for a particular example of a biomass source. Matthews, Sokka, et al. (2014) therefore attempted to summarise the influence of these factors in graphical form (see Figure ES1 in the Executive Summary of Matthews, Sokka, et al., 2014). This figure illustrates how the effectiveness (or otherwise) of the harvesting and use of forest bioenergy (in terms of achieving low CO_2 emissions and/or reductions in emissions compared with other options) may depend on a number of factors. However, the figure is now slightly out of date in places, for example, it does not allow for situations where a new biomass conversion technology with relatively high efficiency might replace an older less efficient fossil fuel-based technology.

Furthermore, the figure does not show the relative importance of the various factors or any effects due to interactions between them. Nevertheless, it is apparent from such a summary assessment that the results of a particular study of the emissions of forest bioenergy systems will depend on the comprehensiveness and accuracy with which the forest bioenergy production and conversion system is represented, notably with regard to the factors identified in this chapter. It is also important that such studies include a clear and complete statement describing the forest bioenergy production and consumption system(s) actually under study, otherwise the applicability and relevance of any results is likely to be ambiguous and potentially confusing.

Below, two examples are considered of published assessments of forest bioenergy systems in two world regions. These assessments attempt to allow for all the complexities of real-life situations where measures are taken to encourage the management of forests to supply more bioenergy, and where results may depend on multiple changes in underlying factors.

Both example studies consider scenarios involving biomass at relatively large scale from a significant area of forests. The first study (Section 4.3.1) allows for how forest management in existing forest areas may evolve in quite complicated ways in response to increased demand for biomass. The second study (Section 4.3.2) allows for dynamic changes in forest composition and area, that is, changes in tree species in existing forests, and in afforestation and deforestation activities, in response to varying levels of demand for biomass. The methodologies applied in the studies, including the assumed counterfactual scenario, are consistent with a research question of the type 'Pathways to change' (see Section 2.2 in Chapter 2). Both studies discussed below are also included in the broader assessment of published studies following in Section 4.5.

4.3.1 Example study: Assessing possible bioenergy use in Sweden

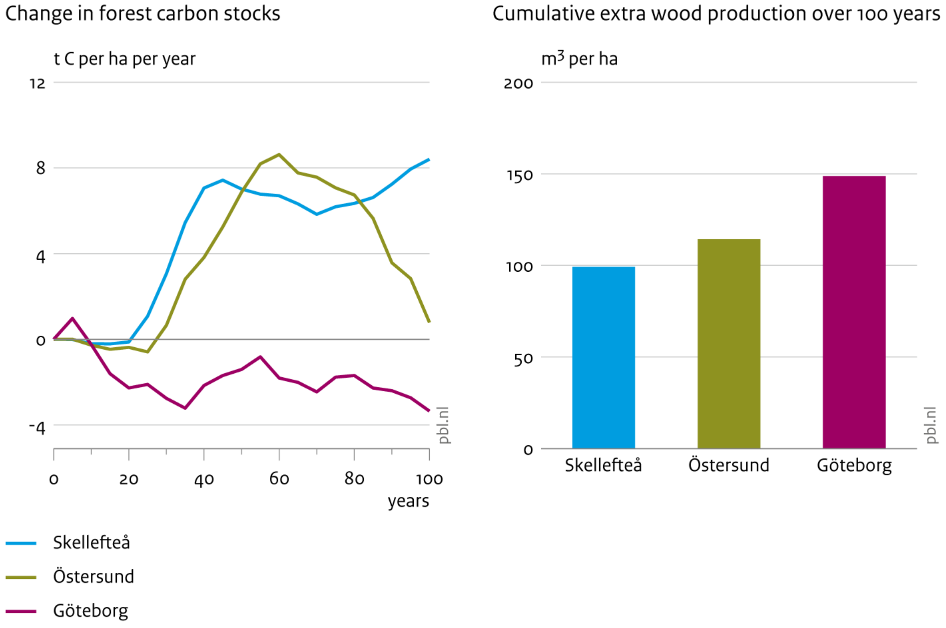
The first example is a study from Sweden by Cintas et al. (2016), which assesses the potential impacts of increased forest bioenergy use on greenhouse gas emissions in Sweden. In it, the authors consider the problem from several perspectives to show how results can depend on the scale at which the assessment is carried out, and on whether 'theoretical' or 'real-life' forest systems are assessed. Their analysis of theoretical forestry systems is consistent with the examples described in Chapter 3 and in Appendices 2 and 3. However, their paper presents further analysis that assesses the potential forest sector responses to increased incentives to supply bioenergy in three regions of Sweden: Skellefteå, Östersund and Göteborg. The assessment involves a simulation of how carbon stocks in the 'real' forest landscapes in these regions would develop, over time, under two scenarios:

1. A 'reference (counterfactual) scenario' in which forest management has the aim of mainly producing sawnwood and pulpwood.
2. A 'bioenergy scenario' with equal priority for the production of forest bioenergy, sawnwood and pulpwood.

The difference in carbon stocks in the forest landscape under the two scenarios was calculated, to determine whether carbon stocks would be increased or diminished, over time, as a result of a policy to encourage increased use of forest bioenergy. The results of this assessment, for the three regions of Sweden, shown in Figure 4.1, were taken from Cintas et al. (2016). The left-hand graph in the figure shows the projections of net change in carbon stocks in the forest over 100 years, in response to incentives to produce more bioenergy relative to the counterfactual scenario. The right-hand graph shows the estimated cumulative extra wood production (harvest) over 100 years from the three areas in the bioenergy scenario.

Figure 4.1

Carbon stock changes in forest landscapes in three Swedish regions in response to producing more bioenergy



Source: Cintas et al. 2016; adapted by Forest Research UK

Figure 4.1 shows that carbon stock changes in 'real-life' forest landscapes generally vary over time, according to quite complex trends and cycles, and so can the response of carbon stocks to changes in forest management, such as those that might be implemented to produce more bioenergy. This variability is in contrast to the simple trends in forest carbon stocks exhibited by the simpler examples illustrated in Chapter 3. The complexities in real-life situations arise because forests are not homogenous or regular, contrary to the simple examples. Rather, real-life forests usually consist of a collection of stands of different species, growth rates, ages and densities, growing on different types of sites. Forest management across an entire landscape is also rarely regular. Any assessment of the effects of actions to produce more bioenergy from forests therefore needs to distinguish between the effects of those actions and other influences on trends and cycles in the development of forest carbon stocks, as already discussed in Section 3.2.

Usually, models need to be applied to project how forest carbon stocks develop under different scenarios, so that the effects of a decision to produce more bioenergy can be identified amongst the many sources of variation in rates of increase or decrease in forest carbon stocks. Model-based assessments need good quality data on the composition of the forest areas studied and their current management. It is important that the modelling methods and input data and assumptions are fully documented and explained, as the results of the assessment are highly sensitive to these methodological details.

A key insight from the study of Cintas et al. is that changes in forest carbon stocks in response to actions to produce more bioenergy may vary, depending on the characteristics of the particular forest and on how management is assumed to change to supply more bioenergy. In the regions assessed in their study:

- Projected total forest carbon stocks in the Skellefteå region were unaffected for the first 20 years, followed by a sustained increase in carbon stocks over a period of 80 years, when compared to the reference scenario.
- A pattern similar to that of Skellefteå was obtained for the Östersund region, except that the increase in carbon stocks relative to the counterfactual scenario declined again from about 60 years after the introduction of changes to management.
- In the Göteborg region, projected forest carbon stocks were diminished for the greater part of a 100-year period, from the time when changes to forest management started to take place.

These variable effects on forest carbon stocks resulted from a combination of several changes to forest management and wood production in the three regions, each of which can have positive, negative or neutral impacts on the development of forest carbon stocks.

The forest management activities considered in the study of Cintas et al. included changes to rotations applied to forests stands and the frequency of thinning operations. Adjustments to silvicultural practice when establishing stands were also represented, such as changing tree planting densities. Their study does not consider other options for changing forest management, such as fertilising forest stands or introducing faster growing tree species.

The modelling approach applied by Cintas et al. involved determining economically optimal forest management in a region, given assumed economic values for various forest products. Under the bioenergy scenario, the production of bioenergy was ascribed to increased economic value, compared to under the counterfactual scenario. The economic modelling in the study took a long-term perspective, involving maximizing net present value using a discount rate of 2%.

Although regional-scale modelling simulated a diverse response of forest management under the bioenergy scenario, a key change involved retaining stands on longer rotation periods, which gave more opportunities for thinning the stands before clear-felling. This type of change occurred because the increased priority given to producing bioenergy under the bioenergy scenario made it more economical to continue thinning forest stands and clear-felling later, once stands were older, compared to under the counterfactual scenario.

The tendency to increase thinning at regional level does not mean that there would be more thinning in all forest stands. However, it was apparent that the aim of producing more forest biomass for energy was an incentive for more thinning when considering large scales.

Options for adapting forest management to produce more bioenergy, particularly extending rotation periods and carrying out additional thinning, depended on the state of the forest stands in each region:

- The forests in the Skellefteå and Östersund regions are often already managed for production, with stands tending to be relatively young and faster growing. There are many forest stands where adjusting thinning regimes and extending rotation periods has contributed to the increase in carbon stocks in their region. In the longer term, forest carbon stocks in the two regions develop differently, because Östersund is a relatively mountainous region, and forest stands have a relatively slow growth rate, whereas Skellefteå is more maritime in climate and forest stands grow relatively rapidly.
- In the Göteborg region, the forests have been managed very extensively for quite a long time and the age structure has shifted towards older stands with relatively low rates of annual net

carbon sequestration, but with relatively high carbon stocks in forest stands. There are only few forest stands where rotation periods can be extended so as to contribute to increasing carbon stocks.

The changes in management directly influence the development of carbon stocks in trees but there are also interactions with other forest carbon pools. For example, the extraction of biomass through thinning and clear-felling results in smaller losses of carbon from the forest from dead biomass that is otherwise left to decompose on site. Effectively, the losses of carbon which would occur anyway from these processes are diverted by harvesting so as to generate useful energy.

The above discussion shows how the precise nature and causes of changes in the development of forest carbon stocks in 'real' forest landscapes can be complicated and require very careful analysis. Cintas et al. highlight that their results '*…should be considered context-specific and should not be understood as representative of varying conditions across the world. Rather, the varied outcomes of the three [bioenergy] scenarios underline the need for empirical data and [local] knowledge, supporting a valid representation of forest ecosystems and management systems in the specific locations investigated*'.

4.3.2 Example study: Assessing wood pellet production in the southeast United States

The environmental impacts of producing wood pellets from US forests used as an energy feedstock in European countries has been a hot topic for some time, and there are numerous papers and reports on this and related subjects, such as the economic response of the US agriculture and forestry sectors to an increasing demand for wood pellets (see for example Abt et al., 2012; Aguilar et al., 2020, 2022; Duden et al., 2023; Galik & Abt, 2016; Kanieski da Silva et al., 2019; Wang et al. 2015).

The example study considered in this section, by Duden et al. (2023), which assesses the carbon dynamics in a realistic representation of forests and agricultural land in the Southern United States during the period 2010-2030, in response to varying scenarios for structural timber for housing and for wood pellets. An economic model was used to estimate changes in land use in the Southern US region, according to varying scenarios for housing and wood pellet demand. Scenarios were defined that represent 'low' and 'high' demand for housing, in combination with 'low' and 'high' demand for wood pellets. The low demand scenario for wood pellets assumed demand remained as observed in 2010 (0.5 million tons), with the high demand scenario assuming an increase to 12.1 million tons in 2030. The economic modelling was based on supply, demand and price cost data, and data on existing land uses, notably national forest inventory data that provide information on the growing stock of US forests (such as forest type group, stand origin and carbon stocks). Projections were made of transitions between different land uses, such as afforestation of pasture land, and conversion of regenerated forest areas to industrial pine plantations. A novel feature of this study involved the spatially explicit modelling of land use changes in the Southern US region, as described in Duden et al. (2017). Carbon stock changes were modelled by determining estimates of mean carbon stocks in different forest and agricultural land types (separately for aboveground biomass, belowground biomass, dead organic matter and soil), and using these to calculate carbon stock differences when one land type is changed to another.

At the scale of the complete South-east US region, Duden et al. find that terrestrial carbon stocks in 2030 under scenarios involving higher demand for wood pellets are increased overall, compared to scenarios in which wood pellet demand remains stable at the level of 2010 (see Figure 4.2). In contrast, total carbon stocks are diminished, compared to those in 2010, in a scenario of low demand for both housing and wood pellets.

Figure 4.2

Projected changes in terrestrial carbon stocks in the southern USA, 2010 – 2030

Source: Duden et al. 2023; adapted by Forest Research UK

Underlying the overall changes in carbon stocks for the high wood pellet demand scenarios are a combination of transitions between land uses, with variable effects on carbon stocks. The main effects on projected terrestrial carbon stocks in high wood pellet demand scenarios between 2010 and 2030 are related to (in order from largest positive to largest negative impacts):

- A shift from non-forest land to forest land, including some afforestation with pine plantations (increased carbon stocks).
- The retention of 'natural' forest areas that would otherwise be converted to non-forest land uses if there was less demand for wood (increased carbon stocks).
- Changes in the composition of forest areas in terms of constituent forest types (variously increased and decreased carbon stocks).
- Conversion of 'natural' forests to fast-growing pine plantations (decreased carbon stocks).
- Conversion of land (including forest land) to urban areas (decreased carbon stocks).

For all scenarios, the relative change in carbon stocks is small, being no more than 3.5% of total carbon stocks in above and below ground biomass and dead organic matter, and even smaller when soil carbon is included, at less than 2% in all cases. This is partly because the scenarios assume quite modest changes in wood supply. However, the absolute amounts involved are significant, ranging from a loss of 106 MtC for the lowest demand scenario to an increase of 268 MtC for the highest demand scenario. Duden et al. also found that increases and decreases in carbon stocks are variously projected to occur at finer spatial scales across the South-east US region. Duden et al. speculate as to whether higher levels of demand for wood pellets from the region might ultimately lead to a 'levelling off' or diminishing of total terrestrial carbon stocks in the region, compared to lower demand scenarios.

4.4 Factors related to methodology

The detailed methodologies and assumptions adopted in scientific studies can have a strong influence on assessments of the carbon impacts of biomass supply chains, and therefore on the conclusions reached by individual studies (Cowie et al., 2021; Favero et al., 2020; Jonker et al., 2014; Junginger, 2021). Important factors include:

- The *general methodological framework* applied (if any).
- The *spatial and temporal scales* over which assessments are made, such as a single stand of trees, or alternatively a population of tree stands within a landscape, and the time over which scenarios for forest management are assumed to develop.
- *Static or dynamic representation of forest areas and land use*, that is, whether or not methods allow for dynamic policy- and market-mediated responses in land use and land management.
- The *representation of forest management practices and uses of wood feedstocks* involved in biomass supply, including how scenarios for forest management and wood use are developed (based on assumptions, data and/or economic modelling).
- The specifics of the *'counterfactual' or 'reference' scenario*, in particular, how land use, land management and how the use of biomass and non-biomass resources is represented, assuming the biomass supply scenario being assessed is *not* enacted.
- The *'system boundary'* adopted, that is, the comprehensiveness with which activities and processes involved in biomass supply chains (directly and indirectly), and their associated emissions, are included in assessments.
- *Choice of metrics*, that is, the metrics selected for presenting results for emissions and/or climate warming impacts of biomass supply chains.

The above factors are briefly reviewed below.

4.4.1 General methodological framework

Scientific studies of forest biomass supply chains often apply formal methodological frameworks for developing scenarios and assessing emissions, although not always. Two common frameworks are 'consequential' and 'attributional' life cycle assessment (LCA), which serve different purposes and involve different approaches to assessing emissions, particularly regarding the system boundary used for the assessment, as summarised in Table 4.4. Further discussion and comparison of these two important LCA methods can be found in Section 4.3 of Matthews, Sokka, et al. (2014).

Table 4.4
Outline description of main LCA methodologies

LCA methodology	**Attributional**	**Consequential**
Suitable applications	Understanding the emissions associated with the life cycle of a product. Also appropriate for consumption-based emissions accounting.	Assessing the change in total emissions (and resulting impacts on climate) arising from a proposed or actual decision or action, such as buying a product or setting a policy.
Unsuitable applications	Not an appropriate approach for quantifying the change in total emissions resulting from policies or other decisions that change the output or consumption of certain products.	Not appropriate for consumption-based emissions accounting, because it quantifies changes in emissions associated with changes in activities, rather than total emissions attributable to a specific product or service.
Processes included (system boundary)	The processes and material flows identified as used in the production, consumption and disposal of the product.	All processes and physical flows directly or indirectly affected by a change in the output of a product, through market effects, substitution effects, use of constrained resources, etc.

It must be stressed that both attributional and consequential LCA are valid methods, depending on the purpose intended for an individual study, but the two methods will often produce very different results for greenhouse gas emissions. Hence, individual studies may legitimately use different methods and arrive at different results, depending on the intended purpose of each study. However, the results of studies employing attributional LCA, for example, for the purposes of product-based accounting, are unsuitable for informing understanding of the changes in emissions that may result from the introduction of policies or other decisions that give incentives to consume more biomass.

When reviewing evidence available from scientific studies, it is therefore important to identify the purpose and methods employed in each study. However, this can be challenging, because published studies do not always include an explicitly stated purpose, or may only state the purpose in very general terms. Furthermore, studies may sometimes use methods that are inconsistent with their stated or implied purpose. These points are explored further in Section 4.5. Whilst some methodology choices are clear once the objective of the study is articulated, others are subjective as discussed below, and there is limited guidance available to support these choices.

4.4.2 Spatial and temporal scales

Both the spatial and temporal scale considered in assessments of emissions from biomass supply chains can affect the results and conclusions of individual studies.

Spatial scale

The carbon balances of forests can be studied at different scales, generally falling into two broad classes:

- Stand-scale assessments typically look at carbon stocks in an individual stand of trees, often represented by a notional 1 hectare patch. Often, the stand consists of a single species of tree, usually all of the same age ('even-aged'). Examples of this kind of assessment can be found in Appendices 2, 3 and 5.

- Landscape-scale assessments consider carbon stock changes in a population of stands, often consisting of several tree species, growth rates and a range of tree ages. The various stands may also be managed in different ways for different objectives, while some stands may be un-managed. Some assessments consider theoretical populations of stands, such as the illustration in Sections A2.4, A2.4.1 and A2.5.1. Often, a real forest landscape is represented, such as, for example, a forest estate managed by a company, the forests and other land uses within an administrative region, or the entire forest or land area in a country or the world. Examples are discussed in Sections 4.3 and 4.5.

Stand-scale and landscape-scale assessments are suitable for different applications and have differing limitations, as shown in Table 4.5.

Table 4.5
Applications and limitations of stand-scale and landscape-scale assessment

	Stand-scale assessment	**Landscape-scale assessment**
Suitable applications	Simple illustrations of the growth dynamics of stands, how carbon stocks develop in stands and can be affected by management (Appendices 2, 3 and 5). Calculating estimates of long-term mean carbon stocks in a stand, depending on tree species, growth rate and management, which can then be applied at larger scales (Appendices 2, 3 and 5 and example applications in Section 5.2).	Understanding how development of forest carbon stocks may be affected over decades or centuries, in response to evolving management across a large forest area, for example to increase biomass supply (see examples in Section 4.3). Representing complexity in forest areas supplying biomass, such as variable tree species, growth rates, age distributions, management practices (existing and adjusted).
Limitations	Likely to over-accentuate the size of carbon stock changes resulting from adjustments to forest management practices being implemented across a large area of forest. Results are very sensitive to assumptions about when forest harvesting to supply biomass starts (in a pre-existing mature stand, or in a stand that is first grown for this purpose before harvesting). Unable to represent long-term impacts on carbon stocks resulting from adjustments to forest management evolving over time in a large population of stands. Cannot represent complexity in large forest areas (variable tree species, growth rates, age distributions).	Dependent on availability of data on detailed composition of forest areas (see above). Often requires numerically complex and intensive modelling or statistical analysis. This can also present challenges to transparency when presenting methods. Results can be the outcome of many complex changes over time and can be difficult to understand unless a supporting explanation is provided (see examples in Section 4.5).

In broad terms, stand-scale assessments are useful for illustrating aspects of the carbon dynamics of forests, particularly with regard to age-related aspects of tree growth and interactions between carbon stocks and management interventions such as harvesting. Landscape-scale assessments are more appropriate for understanding the impacts on carbon stocks and CO_2 emissions of policies or operational decisions intended to change levels of biomass supply from forests. However, landscape-scale assessments are often complex, involving multiple changes in forest management and land use practices that evolve over time. They also involve many underlying assumptions, for example about the kinds of forest practices involved or socioeconomic drivers of these practices (such as the prices of different wood products including energy products). Hence, transparency is important when presenting methods for landscape-scale assessments.

A stand-scale assessment has limitations in that it cannot show how forest management interventions evolve over time across a forest landscape. Stand-scale studies can also give sharply contrasting results, depending on assumptions made about which stage in the sequence of forest management practices in a stand to start the assessment. For example, starting when a single mature stand is harvested will commonly be associated with a rapid CO_2 emission to the atmosphere. Conversely, starting the assessment at the time when an area is planted with trees will observe the uptake of CO_2 (or cooling) during tree growth, which ceases when the site is harvested.

In general, assessments made at the stand scale, which also assume that an existing stand is harvested as the starting point and then the stand regrows, tend to indicate a larger carbon debt in response to biomass harvesting than assessments made at the landscape scale (Cherubini, Strømman, et al., 2011; Holtsmark, 2015; Pingoud et al., 2012; Walker et al., 2013). The landscape is the appropriate scale for assessments, when the purpose is to analyse the climate effects of policies affecting forest management decisions, such as to determine the effect of a policy incentivizing bioenergy, as this is the scale at which forests are managed (Cintas, Berndes, Cowie, et al., 2017), and for reasons discussed above.

Temporal scale

Another relevant consideration is the time over which an assessment is made of changes in forest areas in response to biomass harvesting, and the related changes in carbon stocks. Different studies consider different timescales, ranging from decades to centuries. Forest management practices, and patterns in the utilisation of biomass, are likely to evolve over time in response to increased demand for biomass or more specifically for bioenergy. For example, increased harvesting would not happen simultaneously across a large forest landscape, rather, this would happen progressively, to provide a steady and consistent supply of biomass. Interactions between forest management and the age-related development of carbon stocks in forests will also often take decades or centuries to be fully realised, effects that will not be captured in studies that only consider shorter timescales.

The assessment of policies on the contribution of biomass or more specifically bioenergy use towards emissions reduction targets, will often be linked to targets for emissions levels to be achieved in specified years, such as 2030, 2050 or 2100, or a specific, more subjective timescale, such as the lifetime of a bioenergy facility. It should be realised, however, that limiting or narrowing the timescale of modelling may not give a complete assessment of the climate effects of bioenergy, as it may leave out future benefits or risks. However, a need to understand whether policies or operational decisions will support or detract from near-term climate change targets may be a valid reason to focus on shorter timescales.

Another temporal aspect relates to how the carbon debt, if any, is assigned to the biomass products (so that the carbon footprint of the individual products can be quantified, for example to compare with alternatives). In systems where there is a carbon debt this may be shared amongst the products as an additional supply chain emission. The period of production over which the debt is shared is a subjective choice, and has a large influence on the calculated emissions intensity of the product. The period selected could be: the expected life of the bioenergy facility; the project life for example in the case of a carbon finance or development project; the rotation period of the forest; a nominated period such as 100 years.

The important point in the context of this current discussion is that studies of the emissions from biomass supplied from forests can refer to different timescales for assessment, depending on their specific purpose, and this has a strong influence on the results. This can sometimes lead to confusion when reviewing, interpreting and comparing results from published studies.

4.4.3 Static or dynamic representation of forest areas

The methods used to assess carbon stock changes in forest areas can represent these areas statically or dynamically:

- A static representation considers a fixed and unchanging forest area, for example a theoretical forest with a constant area, such as illustrated in Sections A2.4, A2.4.1 and A2.5.1, or an unchanging area of actual forest such as illustrated by the study discussed in Section 4.3.1.
- A dynamic representation allows for changes in forest composition and area in response to policy or economic incentives to produce more or less biomass from forests, such as the introduction of new tree species in the existing forest area, or expansion of the forest area through afforestation activities, or loss of forest area through deforestation. An example of a study allowing for dynamic changes in forests is discussed in Section 4.3.2.

Studies that assume a static (unchanging) forest area and composition can only represent a limited range of forest management responses to incentives to produce more biomass, such as increased thinning and felling or changes to forest rotations (see, for example, Bernier & Paré, 2013; Funk et al., 2022; Holtsmark, 2015; Peng et al., 2023). However, such incentives may encourage forest owners and managers to adopt practices to increase biomass production that also enhance carbon stocks, such as through use of fertiliser, more intensive site preparation or planting improved seedling stock. They may also influence decisions over land use, encouraging landholders to plant new forests or to retain forests rather than converting to agricultural uses (Abt et al., 2012; Abt et al., 2022; Baker et al., 2019; Daigneault et al., 2022; Favero et al., 2020, 2023; Galik and Abt, 2016; Kanieski da Silva et al., 2019; Kim et al., 2018; Wade et al., 2022). In either case, this would counteract any losses in carbon stock in existing forests resulting from greater biomass removal.
Thus, the effects of bioenergy incentives on atmospheric CO_2, and in terms of size of carbon debt or carbon gain, are more variable than suggested by studies that assume a static forest system.

4.4.4 Representation of forest management and wood use

Studies take more or less sophisticated approaches to representing forest management and the use of harvested wood, including how management may be changed to increase the supply of biomass, and how various feedstocks are used for bioenergy or other purposes:

- Some studies make simple assumptions, often considering more or less activity involving a single management practice, such as more frequent or more prevalent thinning of stands, or increased extraction of forest harvest residues. Generally, these studies also make simple assumptions about more or less use of a single wood feedstock as a source of bioenergy.
- Studies may develop more complex scenarios, involving multiple changes in forest management practices and/or the use of wood feedstocks; these may be based on assumptions, for which there may or may not be supporting evidence (for example from forest inventories or surveys of wood consumption).
- The most sophisticated studies may employ economic models of the forest sector, for example relating forest management practices, notably harvesting and biomass extraction, to the demand for various wood products and the resultant prices of wood feedstock types. Note that these studies also involve assumptions, but at a fundamental process level.

Studies that assess forest carbon at the stand scale tend to make simple assumptions about forest management and wood use, whereas the methods employed in landscape-scale studies can vary significantly, with all of the above methods represented in the scientific literature. The different types of methods vary in the accuracy with which they can represent realistic scenarios for biomass supply from forests, and the transparency of the methods and their results. Table 4.6 gives a summary of the main features of the three broad methods above.

Table 4.6
Potential accuracy and transparency of representation of management and wood use in scenarios for biomass supply from forests

Method	Accuracy of representation	Transparency
Simple assumptions	Very unlikely to represent real situations; actions to increase consumption of biomass, for energy or other purposes, are likely to involve multiple responses in terms of forest management practices and uses of wood feedstocks.	Very transparent; usually it is easy to see the relationships between carbon stock changes or CO_2 emissions and the generally simple management practices and uses of wood assumed.
Scenarios based on assumptions	Can potentially represent real situations but depends on reliability of assumptions and the detail with which complexity in the forest and wood products sectors is represented in scenarios. Assumptions may be or may not be founded on evidence from forest inventories, statistical surveys or other sources of information about practices in the forest and wood products sectors.	Can be transparent, but this depends on the thoroughness with which assumptions underlying scenarios are described, and the detail and clarity with which the consequent extent of forest management practices and uses of wood feedstocks in scenarios are explained.
Scenarios based on economic modelling	Can potentially represent real situations but depends on the completeness and accuracy with which economic linkages are represented. Also depends on the reliability of assumptions about economic variables such as wood feedstock prices. These may be more or less based on actual evidence.	Not always transparent; highly dependent on the thoroughness with which assumptions underlying economic modelling are described, and the detail and clarity with which responses in the forest and wood products sectors in scenarios are explained.

Forest management

Published studies can produce variable results for the carbon impacts of developing biomass supply chains, depending on how forest management is represented, which may sometimes simply reflect differing assumptions made by the study authors, whilst in other cases this is determined by economic modelling. In reality, changes in forest management could lead to a positive, negative, or neutral influence on the development of forest carbon stocks and net greenhouse gas emissions compared with a no-bioenergy scenario (Berndes et al., 2016). It is therefore critical that outcomes of individual studies are not assumed to apply in general to all situations, but instead are assessed for each specific context.

Use of wood feedstocks

Published studies of the carbon impacts of biomass supply can also produce variable results, depending on how woody biomass feedstocks are utilised for different purposes, especially in the case of bioenergy use. In a detailed analysis of 69 published studies, Matthews et al. (2019) found that 8 different types of wood feedstock were involved in scenarios for supplying bioenergy including, for example, forest harvest residues, industrial residues, small roundwood, small/young/pulpwood thinnings and/or complete trees (see Box 5.3 for definitions). Some of these studies represented only one feedstock type in bioenergy scenarios, whilst others considered combinations of feedstocks. Co-production of bioenergy as a by-product with other wood products was represented in some studies but not others. These differences sometimes simply reflect differing assumptions made by the study authors, whilst in other cases economic modelling determines feedstock uses.

4.4.5 Counterfactual scenario

Usually, the counterfactual scenario should describe the system that would exist or develop if no changes are made to pre-existing practices to supply bioenergy or biomass for other purposes, and include representation of all the associated elements outlined above. Fundamentally, both the scenario selected for describing the biomass/bioenergy system, and the counterfactual scenario describing a world without the biomass/bioenergy system, need to be relevant for the specific situation under study and the specific research question being posed (see Section 2.2). The specifics of the counterfactual scenario for land management, especially forest management, but also for the utilisation of harvested woody biomass, can have a big influence on the estimated carbon impacts.

Counterfactual land/forest management scenario

The counterfactual scenario for forest management (or land use in general) referred to in scientific studies of the impacts of woody biomass harvesting on forest carbon stocks and sequestration is one major cause of divergent results reported in scientific studies. A review of approximately 700 publications on attributional LCA studies (see Section 4.4.1) showed that a minority of studies explicitly applied (or proposed) a counterfactual scenario for land use, despite land use being recognised as highly relevant in most of the reviewed publications (Soimakallio et al., 2015).

Most of the studies did not make any clear statement for/against the use of a counterfactual scenario for land use, but in a few publications, it was argued that only absolute (observable) flows should be inventoried in attributional LCA. Attributional LCA methods are usually unsuitable for assessing policies or actions involving changes in biomass use to reduce net greenhouse gas emissions, or meet a goal of net zero greenhouse gas emissions. However, this is not always recognised when reviewing the extensive scientific literature assessing aspects of the emissions associated with bioenergy use, which can be a source of confusion.

Consequential LCA is the appropriate method for assessing the potential for bio-based products, including bioenergy, to contribute towards reducing greenhouse gas emissions. However, a detailed analysis of 69 published consequential LCA studies (see Section 4.4.1) by Matthews et al. (2019) found that less than half employed counterfactual scenarios representing continuation of pre-existing policies or practices (including forest management), consistent with addressing a research question of the 'Pathways to Change' type defined in Section 2.2. Slightly less than a quarter of the studies adopted a scenario of 'no harvesting', consistent with addressing a question of the 'Natural Alternative' type defined in Section 2.2. A further quarter adopted various other scenarios, such as simplistic assumptions about 'standard' forest management practices. Ten percent did not refer to a counterfactual scenario (meaning that results were for absolute greenhouse gas emissions, consistent with addressing a question of the 'Here and Now' type defined in Section 2.2) or did not specify whether a counterfactual scenario was applied.

The inappropriate use of a 'no harvest' counterfactual in assessments of forest bioenergy systems can give very misleading results when the biomass comes from forests already under long-established management for wood production. Results of such studies can underestimate the near-term mitigation benefits of forest biomass use and/or overestimate any carbon debt. Hence, these types of study frequently arrive at much more pessimistic conclusions about the mitigation potential of biomass and especially bioenergy use, compared with those studies that refer to a counterfactual scenario of continuation of pre-existing policies and practices, consistent with a research question of the 'Pathways to Change' type. The lack of a common understanding of the appropriate land use counterfactual scenario has contributed to misunderstanding and disagreements about the climate effects of bioenergy (Koponen et al., 2018).

Counterfactual scenario for resource use

The counterfactual scenario represents the energy sources and (bio)materials that would be consumed if the biomass consumed in the 'scenario of interest' (Section 2.2) is not supplied. The comparison of process emissions from manufacturing the products consumed under the two scenarios is the basis for estimating the wood-product and bioenergy substitution effects, as discussed in Section A1.2. Studies of the carbon impacts of biomass use make differing assumptions about the kinds of materials and energy sources that would be displaced by harvested biomass.

For bioenergy, determining the displaced energy source may depend on the context of the energy system, and therefore the greenhouse gas emissions displacement factor may take a range of values, depending on the specific scenarios considered in studies. For example, biomass power plants may be dispatched as either baseload or marginal running, which in the wider energy system may be displacing different fossil fuels that would have alternatively provided that power. Likewise, if biomass is used for heat, it would need to be determined if it replaced natural gas, fuel oil, coal, or other renewable energy sources, all of which have different impacts on greenhouse gas emissions. Estimation of wood-product substitution effects involves significant uncertainty and often studies rely on generic emissions displacement factors, which can vary quite widely in value, as much as a factor of 4 or more (see Section A1.3).

Some studies do not allow for the emissions associated with counterfactual products, effectively excluding the calculation of any emissions savings resulting from the supply and use of biomass for bioenergy and other products. Sometimes this may be a legitimate methodological choice, depending on the research question addressed (assuming this is clearly stated).

4.4.6 System boundary

The system boundary is an imaginary line drawn around the system under study, to define what is in or out of scope for assessment. A 'system' can be defined in different ways, depending on the purpose of an individual study. For example, in studies of forest and biomass carbon balances, the system might consist of an area of forest, or a wood processing factory manufacturing a product, or all human activities that might be affected by a policy decision, such as introducing incentives to produce more biomass. The choice of system boundary is closely linked to the research question being addressed, as shown for some example applications in Table 4.7.

A wide, often global, system boundary is needed to capture the effects on the carbon balance of policies or decisions that influence the amount of biomass supplied from forests. For example, the increased use of biomass for bioenergy can have impacts on the supply of wood products (see for example Section 3.3), influencing carbon stocks in wood products and material substitution benefits. These effects are only captured by studies that include the building sector within the system boundary (Cintas, Berndes, Hansson, et al., 2017; Gustavsson et al., 2021; Gustavsson et al., 2015; Schulze et al., 2020; Ximenes et al., 2012).

Changes in markets and behaviours in response to policies, incentives or regulation can occur outside forest ecosystems and significantly beyond the wood products and bioenergy sectors. For example, studies that include market and behavioural effects have identified a possible 'rebound effect', where increased supply and use of bioenergy could lower the price of fossil fuels. This in turn could lead to increased consumption of such fuels, and so reducing the fossil fuel substitution benefits of the bioenergy (Smeets et al., 2014). While impacts can occur across many sectors, and interactions can be complex, both negative and positive, applying a narrow system boundary tends to give results indicating higher emissions associated with biomass use, because substitution benefits in the energy and other sectors are not included. In practice, individual studies apply differing system boundaries:

- Including forest carbon stock changes with varying levels of detail, or sometimes excluding them.
- Including or excluding interactions with emissions 'beyond the forest gate' in other sectors (energy, transport, construction).

Table 4.7
Examples of system boundaries applied in studies of forests and biomass carbon balances.

<table>
<tr><th>Application</th><th>Included in system boundary</th><th>Excluded from system boundary</th></tr>
<tr><td rowspan="2">Understanding the carbon balance of a forest ecosystem.</td><td>Area of forest of interest, including trees, deadwood, litter and soil.</td><td>Land outside the area of interest.

Interactions with emissions in other sectors (energy, transport, construction).</td></tr>
<tr><td colspan="2">May include or exclude carbon stocks in wood products supplied from the forest of interest, depending on the purpose of the study.</td></tr>
<tr><td>International (UNFCCC) reporting of emissions and removals of CO_2 in Forest Land.</td><td>Area of forest of interest, including trees, deadwood, litter and soil.

Carbon stocks in wood products supplied from the forest area on interest.</td><td>Carbon in wood products disposed of in landfill is covered in another sector under UNFCCC reporting (Waste).

Interactions with emissions in other sectors (energy, transport, construction) are reported in the relevant sector under UNFCCC reporting, with no clear link to use of wood products.</td></tr>
<tr><td rowspan="2">Environmental Product Declaration (EPD), for a timber or bioenergy product (methods are essentially consistent with attributional LCA, see Section 4.4.1).</td><td>The complete supply chain, comprising the facilities and the processes involved in manufacturing and supplying a product to the point of use, installation, or consumption.</td><td></td></tr>
<tr><td colspan="2">May include or exclude the forests supplying the biomass, depending on the purpose of the study, so studies may or may not represent carbon stock changes related to forest management and harvesting material to manufacture the product.

May or may not include disposal of the product at end of life (in landfill or incineration etc.).</td></tr>
<tr><td>Understanding the impacts on emissions of a decision to encourage more use of biomass, for bioenergy or other purposes (very wide system boundary, effectively global, consistent with the methods of consequential LCA, see Section 4.1.1).</td><td>Includes all resources, facilities, activities and processes that may be affected by the decision, such as:
• forest areas (trees, deadwood, litter and soil);
• wood product carbon stocks;
• emissions involved in wood supply from forests and wood product manufacture;
• disposal of products at end of life;
• interactions with emissions in other sectors (energy, transport, construction).</td><td></td></tr>
</table>

4.4.7 Choice of metrics

Published studies refer to a range of possible metrics for expressing the impacts of biomass supply and use on greenhouse gas emissions and/or atmospheric warming. Examples of simple metrics are:

- Increases or decreases in emissions resulting from using the biomass, reported annually over the timescale considered by the study.
- The cumulative or annual average increase or decrease in emissions over the study timescale.

Other metrics sometimes used in studies include indices that implicitly compare emissions from bioenergy with fossil fuels (Zanchi et al., 2012), indicators of the estimated impact of bioenergy use on atmospheric warming (Cherubini, Peters, et al., 2011; Holtsmark, 2013) or accounting methods that aim to quantify climate benefit of temporary carbon sequestration (Brandão et al., 2013, 2019).

Metrics may be used to aggregate emissions of different greenhouse gases, to estimate the net effect on climate of emissions and removals of several greenhouse gases. The most commonly used metric is global warming potential (GWP), usually quantified over a 100-year timeframe. Because alternative metrics differ greatly in the warming impact assigned to methane relative to CO_2, the choice of metric is also influential if the bioenergy system affects methane emissions. For example, the use of mill residues for bioenergy, that would otherwise be landfilled or used for mulch, can avoid release of methane. On the other hand, woodchips for bioenergy that are stored for long periods in humid environments can release significant amounts of methane (Kuptz et al., 2020; Röder et al., 2015).

Other metrics are sometimes used: GWP quantified over longer or shorter periods, or other metrics, such as global temperature change potential or impact assessment methods that take into consideration the timing of emissions and removals (Brandão et al., 2013, 2019). Examples of the latter include "ton-year" approaches that estimate climate benefits of temporary sequestration, attributing a small climate benefit for each year that carbon is retained in the forest or in wood products. Approaches such as the 'Lashof method' and 'dynamic LCA' assign a climate benefit to temporary sequestration based on the estimated reduction in warming during a fixed period of assessment (e.g. next 100 years), if emissions are delayed. The influence of these choices is illustrated by Brandão et al. (2019), who show that the choice of impact assessment metrics and methods has a large impact on estimates of the climate change effects for bioenergy systems that involve a substantial change in land carbon stock.

The various metrics discussed above can involve underlying assumptions that may not be apparent to readers, and they can be difficult to interpret when considering implications for policies on limiting emissions. They can give drastically different results for the same case study, which can add to confusion when reviewing results from different studies. It might be argued that the proliferation of different types of metrics referred to in scientific studies has brought more confusion than clarity to understanding the potential benefits and risks of biomass use in the context of climate change mitigation.

In this report, estimates of the carbon impacts of biomass use have been expressed as directly as possible, without adjustments for the timing of emissions and removals. Usually, estimates are given in this report as annual or long-term carbon stock changes or as net changes in emissions to the atmosphere, expressed annually or averaged over time.

4.5 Sources of variation in example studies

Why is it proving so difficult for stakeholders, or even experienced researchers, to arrive at a common interpretation and understanding of available scientific evidence? One reason is that different published studies consider narrowly defined examples of forestry systems, management practices and/or biomass supply chains (particularly feedstocks), with strongly contrasting properties. This is not necessarily a problem, unless the results of such studies are used to make generalised conclusions about all harvesting of forest biomass, used for wood products or for bioenergy. A further complication can arise because different studies apply different methodologies that give contrasting results. Again, this is not necessarily a problem, if the methods are appropriate for the research question being addressed, and the questions being addressed by studies are clearly stated. However, significant problems can occur if inappropriate methodologies are applied, and the findings are used to offer generalised conclusions about the role of forest management and biomass use in increasing or reducing CO_2 emissions. The analysis in Table 4.8 of a small number of published studies illustrates the kinds of issues that can arise when trying to review and interpret evidence from scientific publications. The study by Tian et al. (2018) appears twice in the table, representing scenarios involving an assumed static and dynamic forest area, respectively (see Table 4.7).

It must be stressed that the studies in Table 4.8 do not represent a random sample from available literature. Rather, they have been selected purposefully to give contrasting examples of methods, outcomes and issues that can be encountered in published studies. The studies are grouped according to whether they suggest positive, variable or negative outcomes for CO_2 emissions resulting from forest management and biomass use, and within each group, are listed alphabetically according to the first author. A 'negative' outcome in this context implies increased emissions, whilst a 'positive' outcome implies reduced emissions. A 'variable' outcome means that the study presents both positive and negative outcomes, depending for example on the forest types, management practices and biomass feedstocks considered in different scenarios. The studies are assessed with respect to eight factors, which are described in more detail in Table 4.9. The assessments in Table 4.8 are colour-coded as an aid to comparison across the studies. This is explained in Table 4.8 and further details are given in Table 4.9. The assessments are based on a more detailed analysis of each study, which is included in Appendix 4.

The analysis in Table 4.8 reveals the diversity in the systems considered and methodological approaches of individual studies. There are also some broad tendencies for studies arriving at particular outcomes (positive, negative, variable) to share some common features. The example studies that report *positive outcomes* tend to involve methods that:

- Represent dynamic changes in forest areas in response to policy measures or demand for biomass, including changes in afforestation and deforestation rates and changes to tree species composition in existing forest areas (tree species, growth rates).
- May consider short or medium timescales (but not exclusively).
- Are likely to include comparison with a counterfactual scenario consistent with a research question of the type, 'Pathways to Change'.
- Report simple results for carbon stock changes and/or emissions, either annual or cumulative/averaged over time.

Of these, the study of Aguilar et al. (2022) is based on a very complicated statistical analysis, the results of which depend on the robustness of the methodology and underlying assumptions. Two studies (Magelli et al., 2009; Kilpeläinen et al., 2011) are attributional LCA studies, one of which implicitly assumes that forest biomass is carbon neutral. Neither study represents the development of carbon stocks in forest areas under a counterfactual scenario to the 'biomass supply' scenario. Another study is concerned with the special case of very specific afforestation scenarios (Forster et al., 2021).

The example studies that report *negative outcomes* tend to involve methods that:

- Assume a static representation of forest areas, that is, no response to policy measures or demand for biomass, including changes in afforestation and deforestation rates or changes to tree species composition in existing forest areas (tree species, growth rates).
- Make simplistic assumptions about carbon stock changes in existing forest areas.
- Include comparison with a 'no harvesting' counterfactual scenario consistent with a research question of the type, 'Natural Alternative'.
- May involve manipulations of results for carbon stock changes and/or emissions (such as weighting towards shorter term effects).

One of these studies (Bernier and Paré, 2013) considers an unusual case in which 'no harvesting' scenario may be appropriate for addressing a 'Pathways to Change' question and the bioenergy feedstock may consist of all stemwood.

The example studies that report *variable outcomes* tend to involve methods that:

- May consider theoretical single stands or landscapes, or may consider real forest landscapes.
- May assume a static or dynamic representation of forest areas, depending on the scenarios considered.
- May consider multiple scenarios for forest management and biomass use, may represent a range of forest management practices, and may include a sophisticated representation of forest carbon stock changes.
- Consider longer timescales.
- Include comparison with a counterfactual scenario consistent with a research question of the type, 'Pathways to Change'.
- Allow for wood product and bioenergy substitution effects (possibly assuming low or high estimates for emissions displacement factors).
- Report simple results for carbon stock changes and/or emissions, either annual or cumulative/averaged over time.

Table 4.8
Analysis of scope and methods of 16 selected published studies evaluating the effects of use of forest biomass for bioenergy and/or wood products. The meaning of assessment factors and the colours used are further explained in Table 4.9.

Assessment factor / Study region (study source)	Southeastern USA (Aguilar et al., 2022)	Southern USA (Duden et al., 2023)	United Kingdom (Forster et al., 2021)	Finland (Kilpeläinen et al., 2011)	British Columbia (Magelli et al., 2009)	USA (Tian et al., 2018)	Ontario (Chen et al., 2018)	Sweden (sub-regions) (Cintas et al., 2016)	Hypothetical region (Schlamadinger & Marland, 1996)	British Columbia (Smyth et al., 2020)	North America (Stephenson & MacKay, 2014)	USA (Tian et al., 2018)	Austria (Zanchi et al., 2012)	Canada (Bernier & Paré, 2013)	USA/Global (Funk et al., 2022)	Nordic region? (Holtsmark, 2015)	Globe (Peng et al., 2023)
Spatial scale. Dark green: real landscape; Mid green: theoretical landscape; Light green: theoretical stand;	Dark green	Dark green	Mid green	Light green		Dark green	Dark green	Dark green	Light green	Dark green	Light green	Dark green	Mid green	Mid green	Dark green	Light green	Dark green
Forest area dynamics. Dark green: dynamic; Mid green: scenario dependent; Light green: static	Dark green	Dark green	Dark green	Light green		Dark green	Light green	Light green	Mid green	Light green	Mid green	Light green	Mid green	Light green	Light green	Light green	Mid green
Temporal scale. Dark green: Long; Mid green: Medium; Light green: Short	Light green	Light green	Dark green	Dark green	Light green	Dark green	Dark green	Dark green	Dark green	Mid green	Dark green	Dark green	Dark green	Dark green	Mid green	Dark green	Mid green
Management/C stock changes. Dark green: no issues; Mid green: no invalidating issues; Light green: special case (afforestation); Red: major issues	Mid green	Mid green	Light green	Mid green	Red	Mid green	Dark green	Dark green	Mid green	Dark green	Mid green	Mid green	Mid green	Mid green	Red	Mid green	Red
Counterfactual management. Dark green: consistent with 'Pathways to Change'; Mid green: other type (appropriate); Red: other type (unsuitable)	Mid green	Dark green	Dark green	Red	Red	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Mid green	Mid green	Red	Red
Bioenergy feedstocks. Dark green: detailed; Mid green: simplistic (appropriate); Red: simplistic (unsuitable)			Dark green	Dark green	Mid green		Mid green	Dark green	Dark green	Dark green	Dark green		Red	Mid green		Red	Light green
Product substitution. Dark green: with mid-range emissions displacement; Light green: with low or high emissions displacement			Light green				Light green	Light green	Light green	Light green			Dark green	Dark green			Light green
Metric of CO_2 emissions comprehensible?. Dark green: simple/easy to understand; Red: complicated	Red	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Red	Dark green	Dark green	Red	Red
Outcome. Dark green: positive/beneficial; Mid green: variable; Red: negative/detrimental	Dark green	Dark green	Dark green	Dark green	Dark green	Dark green	Mid green	Mid green	Mid green	Mid green	Mid green	Mid green	Mid green	Red	Red	Red	Red

Table 4.9
Key to Table 4.8

Assessment factor	Colour code and meaning
Spatial scale: Does the study consider the forest system at the scale of an individual stand or forest landscape, and is the stand/landscape theoretical or based on a real example? Where a study considers several types of spatial scale, the most complex type is recorded for the purposes of this assessment.	Real landscape Theoretical landscape Theoretical stand
Static or dynamic forest area: Does the study allow for changes in forest area (rates of afforestation and deforestation), and changes in the composition of existing forests (such as replacing tree species and improving growth rates) in response to policy measures or biomass demand?	Dynamic Static/dynamic, dependent on scenario Static Forest system not represented
Temporal scale: Does the study consider change in forest systems, forest management and related emissions over a 'Short', 'Medium' or 'Long' timescale? Where a study has considered several timescales, the longest timescale is recorded for the purposes of this assessment.	Long (80 years or longer) Medium (around 40 years) Short (20 years or shorter)
Forest management and effects on carbon stock changes: How simple or sophisticated is the modelling or analysis of forest carbon stock changes and forest management practices? Specifically, are there any issues (see Table A4.16)?	No issues Issues, do not necessarily invalidate study Special case (afforestation only) Major issue(s)
Counterfactual forest management: Is the counterfactual for forest management consistent with a research question of the type, 'Pathways to Change' or another type ('Here and Now', 'Human Footprint' or 'Natural Alternative', not represented). See Section 2.2.	'Pathways to Change' Other type (special case where 'no harvesting' is counterfactual for 'Pathways to Change' question) Other type (unsuitable for research question or not represented)
Bioenergy feedstocks: Is the representation of bioenergy feedstocks simplistic or detailed?	Explicit in some detail Simple, but appropriate for scenario Simple, but unrealistic or inappropriate for research question
Wood product substitution: Are emissions saved through wood product substitution represented, if so, how?	Yes, with emissions displacement consistent with mid-range estimates currently reported (see Appendix 1) Yes, with either relatively high or low emissions displacement compared with mid-range estimates currently reported
Metric: Are results for CO_2 emissions presented using a simple metric, such as annual emissions, or is the metric based on a more complex manipulation of results for emissions?	Simple and/or easy to understand Complicated statistical results or metric
Outcome: the paper concludes that the effects on CO_2 emissions of the studied forest biomass supply chain(s) are positive/beneficial, variable, or negative/detrimental	Positive Variable Negative

The *key observations* are that:

- Studies reaching consistently negative conclusions about the possible role of forest management, wood products and bioenergy in contributing towards climate change goals typically have narrow scopes, and/or assume simplistic, unrealistic or special-case scenarios for forest management or wood utilisation, and/or they employ some elements of incorrect methodology for addressing such subjects.
- Studies reaching consistently positive conclusions may not adequately represent impacts of biomass harvesting on forest carbon stock changes and/or they employ some elements of incorrect methodology for addressing such subjects (this is more likely in older studies). More recent studies reaching positive conclusions typically assume that dynamic responses in forest management practices occur in response to increased demand for biomass, such as increased afforestation, reduced deforestation, or improvements to growth rates in existing forest areas. Although representing often quite complex dynamic responses, the representation of individual forest management practices may still be simplistic in some cases.
- In contrast, studies that consider a broader range of scenarios for forest management and biomass use, that include a relatively detailed representation of forest management practices and resultant carbon stock changes, and that apply appropriate methodologies, tend to conclude that no particular option for forest management and biomass use, including forest conservation, is universally the best in terms of carbon impact. Rather, outcomes are variable, depending on local conditions and circumstances, the detailed choices made about forest management practices and wood use to meet objectives, such as to supply certain levels of biomass, and decisions about how wood feedstocks are utilised (such as for bioenergy or non-energy purposes).

These observations can help to understand the variability of results and conclusions displayed in published scientific literature about the CO_2 emissions of forest management and biomass use. Studies addressing relevant questions, employing robust methods, suggest that the impacts on CO_2 emissions of expanding the use of biomass, for energy or non-energy purposes, can be very variable. This would present significant challenges to developing simple policies and measures regarding forest management and biomass use if the variability reflected randomness or uncertainty. However, based on the discussion in this chapter, it is suggested that the variability is likely to be systematic, and attributable to identifiable factors related to forest types, forest management practices, and how biomass is utilised for different purposes. A systematic analysis of these factors could help inform policies on forest biomass production and use.

4.6 Discussion and key insights

4.6.1 Variability in study results is systematic and can be understood

Arguably, the science of the carbon cycles of vegetation systems is relatively simple, little more than 'carbon book-keeping'. However, it is proving challenging to reach consensus on its implications for increasing the use of biomass as an energy source or for other bio-based products. There is a good scientific understanding of the interactions between carbon stocks and sinks in terrestrial vegetation and soil and the management of these systems to produce biomass. This is based on a considerable body of research and many published scientific papers. However, conclusions drawn about the carbon impacts of increased biomass production vary considerably. A bewildering array of results is reported in the scientific literature on the carbon impacts of biomass and bioenergy systems. At one extreme, studies find that using biomass, for bioenergy and/or for other purposes, can immediately deliver net reductions in greenhouse gas emissions. At the other extreme, studies conclude that biomass use involves indefinite net increases in emissions, particularly when used as bioenergy. Between these extremes, almost every conceivable outcome is reported in scientific studies, in terms of net impacts on emissions over time. As a result of the wide range of conclusions drawn in studies, there can be a perception that the available scientific evidence is confusing and self-contradictory. However, based on the analysis in this chapter and similar findings in earlier published reviews, it is concluded that there are clear and understandable reasons for the diversity displayed in the findings of different studies.

4.6.2 Study approaches depend on the question being addressed and underlying motivation

It must be stressed that the differing scenarios considered, and the approaches adopted by individual studies do not necessarily imply that some studies have been carried out 'correctly', whilst others have used the 'wrong methods' or have studied the 'wrong scenarios'. The scenarios studied, methods used, and assumptions and parameters made can all legitimately vary, depending on the *purpose* of an individual study, that is, the particular *research question* being addressed by each study. If the question to be addressed is framed with care, and the assumptions defined with precision, then it should be possible to obtain results that are generally in agreement. Unfortunately, frequently, the motivation and intended purpose of individual studies are not explicitly stated. This can lead to difficulties and confusion when trying to make sense of the available published scientific evidence.

4.6.3 Beware of confirmation bias and simplistic interpretations

The possibility has been raised of 'confirmation bias' having an influence in some, possibly many, scientific studies of (forest) biomass supply chains (Abt and Abt, 2018). This is the notion that researchers might (consciously or unconsciously) select scenarios for biomass supply chains for study (and their counterfactuals), or choose methods, assumptions and parameters, that produce results for carbon impacts that reflect personal or corporate viewpoints. If this practice is occurring, this is performing a great dis-service to efforts towards sustainable development.

Sometimes, the selection of bioenergy and counterfactual systems by researchers may reflect their genuine experiences of bioenergy systems, but which may nevertheless represent a rather restricted set of cases or possibilities. This is not necessarily a problem, as long as the purpose of such studies is clearly stated (see above), and it is clear that results and conclusions refer to specific cases and should not be considered generally applicable to biomass or bioenergy.

There is an ongoing debate between proponents and sceptics regarding the potential of biomass as a renewable resource that can contribute towards reducing greenhouse gas emissions, with particular concerns over forest bioenergy sources. Contributors to this debate frequently cite differing studies and evidence sources to support their position, and sometimes use bold but simplistic statements to get their points across. Some of these statements have been discussed and analysed in Chapter 3 and Appendix 2. Examples of statements sometimes made by proponents of forest bioenergy include (text in square brackets added for clarification):

- "[Sustainable management of forests for wood production] will keep, even improve, the CO_2 uptake capability [of forests]; while … decreased harvesting will lead to reduced … CO_2 uptake capability of the forest … the CO_2 uptake in old forests is low, and in very old stands the CO_2 is even negative."[21]

- "A properly managed forest can boost carbon stock as the younger, faster growing trees that are replanted after felling absorb more CO_2 than older, over-mature trees."[22]
- "…utilization of thinned trees for bioenergy is beneficial both to the carbon balance of the forest-product system and also to future production of high-value timber (harvested stemwood)."[23]
- "[A] continued [increase in] forest carbon [stocks] across the landscape, means that products [from the forest], including wood bioenergy, are not adding carbon emissions to the atmosphere. As a result, when wood pellets [from the forest] are used to generate energy, we can set stack emissions to zero."[24]

Examples of statements sometimes made by forest bioenergy sceptics include:

- "It seems like it's got to be better to burn a tree than to burn coal, because the trees can grow back. So, that's true, they can grow back, but it takes a really long time for that to happen, and in the short run you're putting more carbon in the air, and that makes climate change worse."[25]
- "When burnt, trees generate more CO_2 emissions per unit of energy generated than fossil fuels … In terms of electricity generation, smokestack emissions from combusting wood can be more than three times higher than those of natural gas, and 1.5 times those of coal per MWh."[26]
- "These forms of accounting [for forest carbon dynamics at the landscape scale, see for example Section A2.4] do not accurately capture the effects of new forest harvests for the basic reason that the forest growth and regrowth used to offset the effects of new harvests would happen anyway. As hundreds of scientists in letters and many scientific bodies have written, any growth or regrowth of forests that would occur anyway cannot logically alter the climate consequences of new harvests" (Peng et al., 2023).
- "There is a carbon sequestration opportunity cost [when using forest bioenergy]. Harvesting trees for energy releases carbon that would otherwise have remained stored in the forest. It also forgoes future carbon sequestration that otherwise would have occurred had the trees been allowed to continue growing."[27]

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[21] See discussion of Figure 3 on page 3 in Hektor et al. (2016).

[22] Quotation from Drax website, see discussion of Principle 1, "Forest biomass for bioenergy should be sourced from sustainable forests", under "7 principles of a sustainable forest biomass policy".

[23] Quotation from IEA Bioenergy Technology Collaboration Program website, see discussion, "Forest management and market responses".

[24] Quotation from Enviva website, see discussion, "How is carbon accounted for in forests?", under "Carbon accounting: A standardized approach".

[25] Quotation from Panorama documentary, "The Green Energy Scandal Exposed", broadcast on 8th October 2022 on BBC Television (BBC One) in the UK.

[26] Quotation from World Resources Institute website, see discussion, "INSIDER: Why Burning Trees for Energy Harms the Climate: Why aren't trees a climate-friendly energy source?".

[27] Quotation from World Resources Institute website, see discussion, "INSIDER: Why Burning Trees for Energy Harms the Climate: Why aren't trees a climate-friendly energy source?".

- "If whole trees are burnt to replace coal for electricity of heat production, it has a disastrous impact in the climate … even in the best-case scenario, it would take seven decades to reach carbon parity with coal."[28]

There is obvious merit in offering simple and understandable explanations of a sometimes confusing body of scientific evidence. This is particularly the case, given the need for clear messages to help shape policies and actions involving forest bioenergy that will contribute towards climate change goals and support sustainable forest management and land-use practices.
Unfortunately, simple statements and interpretations rarely offer an objective, impartial, accurate or balanced view of the benefits and risks involved in mobilising forest biomass resources for use as an energy source (or for other products). The statements are all the more pernicious for usually having some basis in scientific fact, albeit selectively presented. Examples given in Chapter 3 and Appendix 2, and in Section 4.5 above, illustrate how narrowly defined assessments and simplistic interpretations can present a distorted picture and lead to false conclusions about bioenergy and biomass more generally, either too negative or too positive. Contradictory results will be less likely, and their causes more readily identified, if researchers ensure that:

- The purpose of an assessment is clearly articulated;
- Assumptions made and methods used in calculations are consistent with the specified purpose;
- The purpose, assumptions, methods and parameters are documented transparently.

4.6.4 Dynamic responses to policies in the forest and biomass sectors are important

The examples of studies assessing forestry systems and supply chains at large scales and allowing for dynamic responses illustrate how the response from the forestry and wood products sectors to demand for more bioenergy can involve an ensemble of changes in activities. Some of these activities can have negative effects on terrestrial carbon stocks whilst others can have positive effects. These effects may also vary in magnitude and can range from positive to negative over time, because of the heterogeneous composition of forest areas in terms of tree species, growth rates, age distributions and densities, and because of the non-linear growth dynamics of tree stands. It can be challenging to fully understand and characterise all the changes that are happening or are likely to happen in forests and to the use of wood products, and the consequences for carbon stocks and greenhouse gas emissions. However, the example studies highlight the importance of recognizing the likely complexity of responses in real-life situations, rather than assuming simple changes in forest management and wood utilisation, such as a single response of more thinning in forest stands or the harvesting of whole trees to produce bioenergy.

The pre-existing state of forest areas in terms of the above factors also strongly influences the potential to implement different forest management practices and/or produce particular types of biomass feedstocks (such as small roundwood or sawlogs). The possibilities of bioenergy supplies being associated with negative impacts on forest carbon stocks and increased greenhouse gas emissions depend on *inter alia* the pre-existing state of forest areas and pre-existing forest management practices. Similarly, the opportunities for introducing activities that will ensure carbon gains

[28] Quotation from FERN website, see discussion, "European biomass industry confirms it is burning large amounts of low-quality stemwood (tree trunks)".

and/or low greenhouse gas emission levels can be either relatively easy, difficult or impossible to implement, depending on these factors.

Simple analyses, typically based on considering the carbon stock changes in a single stand, are useful for illustrating aspects of the carbon dynamics of forests, but these cannot capture the complexity of dynamic responses in the forest, wood products and other sectors. Landscape-scale assessments with a wide system boundary are more appropriate for understanding the impacts on carbon stocks and CO_2 emissions of policies or operational decisions intended to change levels of biomass supply from forests.

Strengths and weaknesses of large-scale dynamic studies

Studies that attempt to comprehensively represent real forestry systems at large scales, and economic circumstances, such as illustrated in Section 4.3 have been undertaken for several regions of the world, including some global scale studies (Daigneault et al., 2022; Favero et al., 2022, 2023). These types of studies have certain advantages:

- The varying conditions of forest areas, in terms of tree species, growth rates, age distributions and current and future carbon stocks can be represented.
- Impacts of scenarios of forest management on all relevant carbon pools can be modelled, including tree biomass, deadwood, forest litter, soil and carbon retained in wood products.
- Dynamic changes in land use and management can also be represented, including afforestation, deforestation and changes to forest management including transitions from one forest type to another.
- Dynamic changes in sectors of the economy such as construction, furniture, energy and transport in response to varying levels of biomass production can be modelled.
- Market-mediated effects influencing land use, land management and resource use are also represented as part of the modelling.

The above issues are all important in determining the overall impacts of changes in levels of biomass use for various purposes on future terrestrial carbon stocks and net greenhouse gas emissions to the atmosphere, and these are not always captured accurately by the methods employed in more simple studies.

However, it must be acknowledged that there are significant uncertainties in the results of this kind of modelling. The methods also rely on numerous assumptions, for example about the costs of various activities and products and how these may develop in the future, and how land and forest managers may change their behaviour in response to changing demands for biomass. These assumptions may be supported to a greater or lesser extent by available data and evidence sources, depending on the geographic region and systems under study. The models involved are complex and it can be difficult to understand how studies that employ them produce the results. Often, it is difficult to fully document methods in scientific publications, leading to a general lack of transparency in the presentation of these studies and their results. Nevertheless, it is also certain that (i) such economic effects occur, so it is definitely incorrect to ignore them and so (ii) assessments that do not allow for these effects are incomplete and are potentially inaccurate. The application of complicated economic modelling methods may therefore be necessary and unavoidable. Uncertainties in economic modelling and underlying assumptions can be addressed by carrying out a sensitivity analysis. Published studies may include these to show that variations in assumptions and input parameter estimates do not substantively change the results and conclusions. Given the potential complexity and sophistication of landscape-scale, dynamic assessments, transparency is important when presenting methods and results and offering conclusions.

Implications for supporting effective practice in the forestry and biomass sectors

The scientific research literature has many examples of studies addressing questions of the kind, “what would be the consequences for CO_2 emissions of increasing the supply and use of forest biomass, for use as bioenergy or for other bio-based products, by employing specific examples of forestry practices?” However, an alternative question for supporting effective forest management and biomass use, and related policies could be: “what forest management practices and uses of forest biomass are consistent with supporting a goal of reducing CO_2 emissions or atmospheric warming (and which practices and uses would not be consistent with this goal)?” There are no obvious examples of studies that have explicitly addressed this question, and it is suggested that this represents a significant research gap. Nevertheless, the available scientific evidence, from both comprehensive landscape-scale and simpler stand-scale studies, can be analysed to identify ‘good’ and bad ‘practices’, as already discussed in Sections 4.1 and 4.2. This is discussed further in Chapter 5, where the possibility of managing the carbon impacts of biomass supply and use is explored.

5 How to encourage options that lead to greenhouse gas savings?

The purpose of this chapter is to address the extent to which science may offer policy principles and recommendations to support the supply and use of forest biomass, especially for bioenergy, consistent with the goal of reducing greenhouse gas emissions. In Section 5.8, a brief consideration is also given to agricultural biomass sources.

5.1 Options for managing the carbon balance of forest resources

Possible solutions to the challenge of managing the effects on the carbon balance of harvesting and using forest biomass consist of two elements:

1. The policy framework supporting actions to use forest biomass while ensuring positive effects on the carbon balance, or at least minimising negative effects.
2. The technical methods used to assess and manage the supply and use of forest biomass while ensuring beneficial effects on the carbon balance or limiting negative effects.

Overview of policy frameworks

The main kinds of policy framework are shown in Table 5.1, with brief comments on their relevance to forest biomass sources, especially when used for bioenergy. Some of the main examples of existing frameworks are also given in the table, with an emphasis on those with a worldwide or European focus. An in-depth discussion of the workings and effectiveness of existing policy frameworks is beyond the scope of this report. Ramirez-Contreras and Faaij (2018) have reviewed international biomass and bioenergy sustainability frameworks and certification systems and their application. Titus et al. (2021) have critically reviewed environmental guidelines covering harvesting of forest residues applying in regions of Europe and the USA. Annex 2 (CCC, 2018a) of the report of the UK Climate Change Committee (CCC, 2018b) has presented a broader review and analysis of best practice in international biomass governance.

It may be noted from Table 5.1 that there are several linked policies in the EU to address biomass sustainability directly or indirectly, involving:

- Directly addressing major issues of concern (deforestation).
- Specifying in standards the verifiable requirements for biomass to be considered sustainable.
- Supporting collective international actions to reduce greenhouse gas emissions.
- Providing financial support for actions to protect and restore ecosystems with high carbon stocks amongst other benefits.

The direct coverage of biomass and bioenergy in EU legislation is outlined in Box 5.1.

Table 5.1
Overview of policy frameworks supporting sustainability of forest biomass supply and use

Policy framework type	Notable examples	Relevance to biomass/bioenergy
Regulations directly proscribing certain actions.	EU Regulation on Deforestation-free Products.[1]	Aim to explicitly prevent unsustainable practices linked to biomass supply and use or the consumption of biomass derived from such practices.
Regulations setting out mandatory sustainability standards.	EU Renewable Energy Directive (RED III).[2]	Aim to support the use of biomass but only allowing supply and consumption consistent with criteria-based sustainability standard.
Voluntary sustainability standards.	SBP[3,4] FSC[5] PEFC[6] Gold Standard[7,8]	Aim to provide certification ('eco-labelling'), allowing suppliers to assure consumers of the sustainability of their products or services.
Voluntary schemes encouraging certain environmental actions.	Gold Standard[7,8] UK Woodland Carbon Code (UK domestic scheme)[9]	Aim to provide assurance to consumers that certain environmental activities are providing genuine benefits. Enable the generation of quantified and exchangeable units such as 'carbon credits'. Main relevant examples are forest carbon sequestration credits.
'Cap and trade' systems encouraging collective actions towards a defined outcome	EU Emissions Trading System (EU ETS)[10,11]	Provide a framework for actors to cooperate in meeting targets for environmental benefits such as emissions levels (those doing better than the target can sell the excess 'credits' to those falling short)[12].
Financial incentives directly supporting certain actions.	EU Common Agricultural Policy (CAP)[13]	Make direct payments to actors in return for implementing measures that provide environmental benefits such as protection of wetlands and 'carbon farming' (e.g. reforestation and agroforestry).

[1] https://environment.ec.europa.eu/topics/forests/deforestation/regulation-deforestation-free-products_en
[2] https://energy.ec.europa.eu/topics/renewable-energy/renewable-energy-directive-targets-and-rules/renewable-energy-directive_en
[3] https://sbp-cert.org/about-us/
[4] https://sbp-cert.org/documents/normative-documents/version-2/standards-v2/
[5] https://fsc.org/en/fsc-standards
[6] https://pefc.org/standards-implementation/standards-and-guides
[7] https://www.goldstandard.org/ and https://www.goldstandard.org/gold-standard-for-the-global-goals/our-standard
[9] https://woodlandcarboncode.org.uk/
[10] https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en
[11] The EU ETS has at one time allowed contributions from international carbon credits including those generated by afforestation activities, but this is not envisaged to continue in future developments of the EU ETS.
[12] Note that emissions from biogenic sources are counted as zero in the existing EU ETS, on the understanding that these are counted as part of reporting/accounting for LULUCF, for example in greenhouse gas inventories.
[13] https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en

Box 5.1 Coverage of biomass and bioenergy under EU legislation

EU legislation of principal relevance to biomass and bioenergy at the time of writing this report comprises The *Renewable Energy Directive 2018/2001* or *REDII* (EC, 2018), the *amendment to the REDII*, also called 'REDIII' (EC, 2023a), an *implementation regulation on establishing operational guidance on the evidence for demonstrating compliance with the sustainability criteria for forest biomass laid down in Article 29 of the REDII* (EC, 2022), *the revision of the LULUCF Regulation 2023/839* (EC, 2023b), and the *Waste Framework Directive 2008/98/EC* (EC, 2008).

REDIII

The REDIII, that came into force on 19 April 2023, addresses the contributions made by renewable energy sources towards the European Union's climate and energy goals. It is an important revision of the previous directive, REDII, in the context of the Green Deal and the fit-for-55 package, also with respect to sustainability and carbon sequestration (referred to as 'CO_2 *removals*') of forestry activities.

The sustainability criteria are described in Article 29, which has 14 paragraphs. Article 30 deals with the verification of compliance with the sustainability and greenhouse gas emissions saving criteria. The REDIII does not define biomass sources in further detail, such as the classes of forests and biomass feedstocks discussed in this chapter, nor does it explicitly refer to carbon debt.
Amendments to paragraphs 3 and 6 in article 29 are of particular importance to the use of forest biomass for biofuels, bioliquids, and biomass fuels in the context of the discussion in this chapter. Paragraph 3 of article 29 states that Member States 'shall take into account the waste hierarchy set out in Article 4 of Directive 2008/98/EC and shall ensure the application of the principle of the cascading use of biomass' to ensure that 'woody biomass is used according to its highest economic and environmental added value in the following order of priorities: (a) wood-based products; (b) extending the service life of wood-based products; (c) re-use; (d) recycling; (e) bioenergy; and (f) disposal.' Member States may derogate from that principle where 'the local industry is quantitatively or technically unable to use forest biomass for an economic and environmental added value that is higher than energy production, for feedstocks coming from: (a) necessary forest management activities, aiming to ensure pre-commercial thinning operations or carried out in accordance with national law on wildfire prevention in high-risk areas; (b) salvage logging following documented natural disturbances; or (c) the harvest of certain woods whose characteristics are not suitable for local processing facilities.
Furthermore, 'Member States shall not grant direct financial support for the use of saw logs, veneer logs, industrial grade roundwood, stumps and roots to produce energy' or 'grant new support or renew any support for the production of electricity from forest biomass in electricity-only installations' (unless it is produced in a region identified in a 'territorial just transition plan' or 'produced applying biomass CO_2 capture and storage').

Paragraph 6 of article 29 includes sustainability criteria to minimise the risk of using forest biomass derived from unsustainable production. In the REDIII, the amendment to point (iv) of paragraph 6(a) reads: '…that harvesting is carried out considering maintenance of soil quality and biodiversity in accordance with sustainable forest management principles, with the aim of preventing any adverse impact, in a way that avoids harvesting of stumps and roots, degradation of primary forests, and of old growth forests as defined in the country where the forest is located, or their conversion into plantation forests, and harvesting on vulnerable soils, that harvesting is carried out in compliance with maximum thresholds for large clear-cuts as defined in the country where the forest is located and with locally and ecologically appropriate retention thresholds for deadwood extraction and that harvesting is carried out in compliance with requirements to use logging systems that minimise any adverse impact on soil quality, including soil compaction, and on biodiversity features and habitats'.

Link to LULUCF and the LULUCF Regulation

Land use, land-use change, and forestry (LULUCF) is a sector in greenhouse gas inventories, defined by the Intergovernmental Panel on Climate Change (IPCC), which covers anthropogenic emissions and removals of greenhouse gases resulting from changes in terrestrial carbon stocks. It covers the carbon pools of living biomass (above and below ground), dead organic matter (dead wood and forest litter) and soil organic carbon for specified land categories (forest land, cropland, grassland, wetland, urban land and other land).

The greenhouse gas fluxes reported in LULUCF are mainly carbon dioxide (CO_2) from carbon stock changes. Generally, net emissions are reported by EU Member States from cropland, grassland, wetland, urban land, and other land, while forest land and harvested wood products contribute net emission removals (i.e. carbon sequestration) that outweigh the emissions from other land uses. The LULUCF Regulation addresses the contributions made by the LULUCF sector towards meeting future greenhouse gas emission levels. Matthews (2020a) discusses the 2018 version of the regulation in detail.

The ambition of the revised regulation is to reverse the current trend of declining LULUCF net removals and deliver, in 2030, 310 Mt CO_2 equivalent removals. To do so, the title of Article 4 is changed from 'Commitments' to 'Commitments and targets', and targets are introduced relating to each of the periods towards 2035: i) 2021 to 2025 – 'no-debit' rule; ii) 2026 to 2030 – binding minimum national 2030 net-removal targets per Member State (see table in annex IIa to the proposal); iii) 2031 to 2035 – climate-neutrality commitment (nationally) for the land sector by 2035 and negative emissions thereafter.

The REDIII refers explicitly to the revised LULUCF Regulation. Paragraph 7a of Article 29 states that 'the production of biofuels, bioliquids and biomass fuels from domestic forest biomass shall be consistent with Member States' commitments and targets laid down in Article 4' of the revised LULUCF-regulation.
Increased harvesting rates have been identified as contributing to a negative trend in net removals in forest land in the European Union, although other factors are also recognised, namely ageing forests and natural disturbances, such as storms, forest fires, droughts, and bark beetle damage. The requirement to meet targets for net removals therefore implicitly places constraints on rates of harvesting from EU forests, unless increased harvesting also involves measures to maintain and enhance carbon forest stocks. This is loosely consistent with the class of existing forests in Table 5.3 categorised as involving 'management to maintain or enhance carbon stocks or sinks' (see discussion in Box 5.2).

Main conclusions
The REDIII and revised LULUCF Regulation do not refer explicitly to carbon debt or payback times in the context of biomass use for energy. Nevertheless, impacts on greenhouse gas emissions related to biomass harvesting and use are a central concern for both pieces of legislation. Generally, the revisions being made to the RED and the LULUCF Regulation tighten rules addressing environmental sustainability of biomass use and aim to increase carbon sequestration in EU forests. The relevant changes are likely to limit the risks of biomass harvesting and use in EU forests resulting in net reductions in carbon removals or increases in emissions. However, the REDIII and LULUCF Regulation do not guide actors in how to implement measures to manage forests and utilise biomass to meet renewable energy and greenhouse gas emission goals. In principle, Member States are allowed to impose additional sustainability criteria to achieve this. Hence, it appears that the main challenges are those of developing a practical framework for planning, deciding, and implementing actions 'on the ground' in forests to deliver both carbon sequestration and sustainable biomass supply.

Technical methods underpinning policies

Policy frameworks generally refer to a set of supporting technical methods to enable policies to be put into practice and to verify compliance. Table 5.2 gives some suggested options for technical methods addressing biogenic CO_2 emissions, also indicating the kinds of actors who might use the methods, and the policies they may be most relevant for. It must be stressed that all the options presented here are proposed as tentative solutions. More work would be needed to develop fully workable solutions applied in conjunction with specific policies. The ideas are derived from the analysis presented in Chapters 2 to 4 and also draw on existing examples of methods where relevant.

Table 5.2
Technical methods supporting sustainability of forest biomass supply and use

Method	Likely users	Relevant policies or schemes
Forest-based: Site-by-site assessment (Section 5.2)	Forest areas entirely under one ownership. Forest areas entirely managed by one management company, charity etc. Forest areas with different owners who 'buy in' to a collective scheme.	Voluntary or mandatory forest carbon management scheme. Voluntary or mandatory emissions trading system (covering land sector only or all sectors).
Forest-based: Regional-scale assessment (Section 5.3)	Biomass consumer or supply chain operator, sourcing material from a defined area of forest not under their ownership or direct management.	Criteria forming part of biomass sustainability standard (forest management/stocks).
Forest-based: National/regional-scale monitoring (Section 5.4)	National/regional government Agency monitoring compliance through analysis of reported statistics. Support to international cooperation amongst national governments.	National/regional scale monitoring/reporting/accounting Component of biomass sustainability standard.
Feedstock-based: Biomass feedstock decision tree (Section 5.5.1)	Biomass consumer in situations where forest inventory data are lacking or very limited.	Voluntary biomass sustainability standard. Operational method to ensure compliance with biomass sustainability standard.
Feedstock-based: List of biomass feedstock criteria (Section 5.5.2)	Agency monitoring compliance through analysis of reported statistics.	Criteria forming part of biomass sustainability standard.
Full life cycle assessment (Section 5.6).	Company quantifying carbon footprint of products (attributional LCA). Researchers evaluating policy options (consequential LCA). Independent auditor called in as required.	Detailed assessment of options and existing practices to check consistency with requirements of policies/schemes. Spot checks on accuracy of data reported by other approaches Light touch unless problems identified

The methods can be divided into three classes:
1. 'Forest-based' methods aim to support the management and/or monitoring of forest carbon stocks, to provide assurance that forest management, including biomass harvesting, is having a reducing or neutral effect on biogenic CO_2 emissions.
2. 'Feedstock-based' methods are more concerned with the extraction and use of forest biomass for bioenergy. They aim to classify tree biomass feedstocks according to the likelihood of low or high associated biogenic CO_2 emissions, and screen them to prioritise the use of 'low-emissions' feedstocks for bioenergy.
3. 'Full LCA methods' aim to enable the comprehensive assessment of greenhouse gas emissions resulting from a new policy or business initiative to invest in the supply and use of biomass, for bioenergy, and/or other bio-based products (see also Section 4.4.1).

As a general point, as stated in Section 1.1, here we assume that forest biomass generally originates from forest areas managed according to wider principles of Sustainable Forest Management (SFM) (Forest Europe, 1993). In this context, article 29(6) of the EU RED III on sustainability criteria stipulates that, '…harvesting is carried out considering maintenance of soil quality and biodiversity in accordance with sustainable forest management principles' (see Box 5.1 for more details).

5.2 Site-by-site assessment

Site-by-site assessment is the most rigorous of possible forest-based methods, but is also the most complex and data-intensive. The main steps in the method involve:
1. Identifying the region of forest where the method is to be applied.
2. Dividing the forest region into homogenous units (individual sites) in terms of their composition and management.
3. Classifying each site to indicate how the trees within the site have been managed historically, and the planned future management.
4. Using the above analysis to estimate the effects the planned management will have on forest carbon stocks and biomass supply.

The implementation of Steps 1 to 3 is illustrated by an example given in Section 5.2.1, with a supporting discussion of how forests may be classified in Section 5.2.2. The estimation of effects on carbon stocks and biomass supply in Step 4 is illustrated for the example implementation in Section 5.2.3.

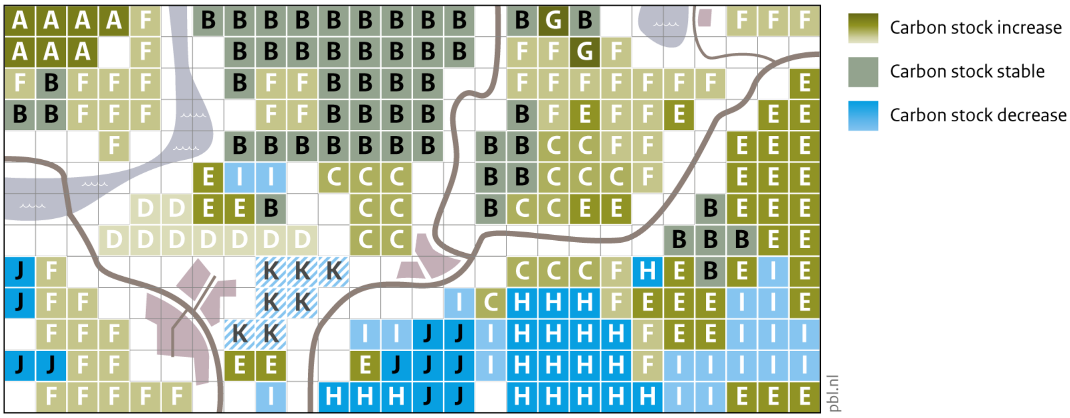
5.2.1 Site-by-site assessment: identifying and classifying forest sites (Steps 1 to 3)

The example in Figure 5.1 illustrates how, hypothetically, a region can be defined, and the forest units within that region can be classified. Suppose the large rectangle shown in Figure 5.1 represents a region. This region may consist of a few tens or hundreds of hectares owned by an individual, or millions of hectares within a country's national borders. It could also represent a region of land that is managed by a forestry company. The land represented by the region does not need to be contiguous, but it must be possible to clearly delineate the complete extent of the land that, taken as a whole, contains all relevant forests involved in the supply of forest biomass. More specifically, this comprises the existing forests within the defined region, land undergoing afforestation, and forests undergoing deforestation within the defined region.

The squares in Figure 5.1 represent homogenous forest units (in terms of their composition and management) contained within the region. The land areas occupied by the different types of forest unit given in the table below the figure are in arbitrary units. Each type of forest unit is given a label (class) that indicates how the forests have been managed historically, and the planned future management. The various classes of pe-existing and planned management are described in the key to Figure 5.1.

Figure 5.1

Hypothetical region of land including units of forest managed in different ways



Area	Class	Historical or planned action
7	A New afforestation	Creation of a mixture of forest areas, either for wood production or for accumulation of maximum carbon stocks.
Existing forests		
50	B Continuing production	Existing forest areas managed according to pre-existing plans, where levels of wood production are consistent with historical levels.
18	C Carbon management	Enhancement of wood production in single-species forest areas by restocking with genetically improved trees in place of unimproved trees.
9	D Carbon management	Enhancement of wood production in forest areas by restocking with tree species better suited to sites and climatic conditions, compared with existing tree species.
36	E Carbon management	Increased resilience of single-species forest areas at risk of disease outbreaks by restocking with species mixtures.
50	F Carbon management	Enhanced carbon stocks in forest areas by extending rotation periods, while avoiding significant reductions in wood production.
2	G Carbon management	Enhanced carbon stocks in forest areas with low productivity by minimising harvesting and other disturbances.
20	H Increased production	Management of forest areas for increased wood production by increasing frequency of thinning interventions.
21	I Increased production	Management of forest areas for increased wood production by optimising rotation periods, generally involving shortening of longer rotations.
11	J Increased production	Extraction of residues left behind after forest harvesting where previously these would have been left to decay in the forest; decay rates estimated as moderate.
7	K Deforested areas	Forest areas converted to non-forest land because of unavoidable development.

Source: Forest Research UK

Referring to classes of forest, such as those used in Table 5.3, has the advantage of covering all woody biomass produced from the forest areas, regardless of how that biomass is utilised (such as for structural applications, paper, chemical feedstocks or for bioenergy). For example, as long as the biomass comes from forest areas associated with short or medium carbon payback times, there is reasonable assurance that using the biomass should contribute to reducing greenhouse gas emissions within a time horizon of 0 to 30 years, regardless of what the biomass is used for. This is advantageous because reference to classes of biomass feedstock can be avoided. Prescribing how biomass feedstocks can and cannot be used for different purposes can be problematic, as discussed in Section 5.5. Referring to classes of forest also avoids giving bioenergy special treatment in relation to other possible uses of forest biomass. However, a possible drawback is that biomass feedstocks especially suitable for the manufacture of very long-lived wood products or with potentially high substitution benefits may not be prioritised for such end uses (which would require supporting measures). There are also other challenges to such an approach. Most obviously, it would be necessary to classify forest areas supplying biomass according to a scheme such as in Table 5.3, and to be able to verify that the management of defined forest areas is consistent with the assigned classes. This presents some issues, as discussed below. Furthermore, it would be necessary to establish a reliable chain of custody for biomass sources, to provide assurance that biomass originates from preferred forest areas (in terms of classes such as defined in Section 5.2.2).

5.2.2 Is it possible to define 'classes' of forests?

A complete set of suggested possible 'classes' of forest is given in Table 5.3. Each forest class is defined in more detail in Box 5.2. Also in Table 5.3, an indicative assessment of carbon payback time is assigned for biomass originating from each forest class. The metric of carbon payback time is defined in Section 2.4 and example calculations are given in Sections 3.2 and 3.4 and in Section A2.5. The assessments in Table 5.3 are semi-quantitative, according to 4 categories from 'Short' to 'Very long', as defined in Table 2.4. The relevance and applicability of carbon payback time estimates in this context are discussed in Section 2.4.

Table 5.3
Classification of scenarios for forest biomass (as a source for all types of products) in terms of classes of forest and carbon debt payback time.

Biomass source (forest type), see Box 5.2		Payback time	Feasibility
Landscaping and urban trees		Short	
New afforestation		Short–Medium	
Existing forests	Continuing supply at established harvesting rates	Short–Medium	
	Management to maintain or enhance C stocks or sinks	Short–Medium	
	Increased biomass extraction/supply	Short–Very long	
	Salvage logging	Short–Very long	
Deforestation		Very long	
Forests undergoing degradation negatively affecting carbon stocks		Long–Very long	

Key to feasibility assessments in Table 5.3

	Feasibility (of implementation and verification)
	Relatively easy to implement and verify the use or non-use of this biomass source.
	Likely that some issues would need to be addressed when implementing and verifying the use or non-use of this biomass source.
	Could be complicated to implement or verify the use or non-use of this biomass source.

Most of the biomass sources in Table 5.3 cannot be assigned to a single class of payback time; most are assigned ranges, such as 'Short–Medium'. Besides possible variation related to variation in the size of substitution effects of wood products and bioenergy (see Appendix 1 and Section 4.2.4), this reflects the various outcomes possible for each class of biomass source, resulting from, for example:

- Variability in forest growth rates between regions;
- Variations in the details of forest management interventions (such as the numbers and sizes of trees harvested when thinning forest stands);

- Variability in how certain biomass sources would be treated if not utilised for bioenergy;
- Variability in climatic conditions affecting the rate of decay of the residues from conventional forest harvesting (if they are not extracted and used for bioenergy).

The length of payback times depends on the magnitude and duration of any carbon debt (as defined in Section 2.4), and on the magnitude of greenhouse gas emissions avoided through wood product substitution effects, as frequently described using greenhouse gas emissions displacement factors (see Appendix 1). The carbon payback times given in Table 5.3 are consistent with:

- Carbon debts of a magnitude and duration (where these occur) relevant for forests in temperate and boreal regions. They may be less relevant for tropical regions, where both tree growth rates and rates of wood decay and soil carbon turnover are generally faster. It should be noted that a carbon debt, as defined in this report, can result from lower rates of carbon sequestration in forests, just as much as from reductions in forest carbon stocks (see Sections 2.2 and 3.2.1). Payback times estimates given in this report make no allowance for the possibility of CO_2 emissions from wood consumed as bioenergy being recovered and avoided by deploying carbon capture and storage (CCS) technologies.
- Greenhouse gas emissions displacement factors for bioenergy when assumed to displace other energy sources (generally fossil fuels), with values ranging from 0.4 to 1.1 tCeq/tC. Where bioenergy is being produced as a co-product with timber and other wood-based products such as panels, the displacement factor for these non-energy products is assumed to be typically in the range of 1 to 1.5 tCeq/tC. The basis for these estimates is discussed in Appendix 1, where their application in studies of biomass and bioenergy greenhouse gas impacts is also considered.

The payback times given in Table 5.3 do not explicitly indicate which biomass sources are suitable or unsuitable to use as part of actions to meet greenhouse gas emissions reduction targets and net zero emissions but, implicitly, sources classified as having 'Short' or 'Medium' payback times are more consistent with such goals, while generally biomass source categories are progressively less suitable, the longer the payback time.

Table 5.3 also includes feasibility assessments that indicate how easy or challenging it might be to identify whether biomass sources originate from one or more particular forest classes. These assessments are based on the discussion in Box 5.2.

Box 5.2 Definitions for classes of forest areas

Landscape and urban trees
'Landscape and urban trees' refers here to the management of individual trees, small groups of trees and small woodlands, and forests, where management has nothing to do with wood supply as the primary objective. Typically, this biomass originates from felling or pruning trees along roadsides and railways, or on farms, or in gardens, parks and urban areas, generally to meet safety objectives (clearing power lines, removing dangerous branches or improving visibility on roads, including 'tree surgery') or landscaping objectives (such as accessibility for the public or as part of designing parkland). The biomass produced from these sources can go to waste and may be burnt on site or incinerated without energy recovery or is sometimes disposed of in landfill sites.

However, it may also be chipped and used for animal bedding or for horticultural purposes, such as mulch (e.g. wood chips spread under trees that have been pruned). The biomass may also be utilised as bioenergy. Situations where this potential bioenergy source would otherwise be incinerated without energy recovery or landfilled with resultant methane emissions are particularly advantageous in terms of net impacts on greenhouse gas emissions. Identifying whether woody biomass originates from such sources could be relatively straightforward, because the supply chains and actors involved are quite discrete and usually separate from those involved in the forestry and wood products industries.

New afforestation

This class represents 'new' afforestation activities (i.e. afforestation carried out 'now' or in the 'recent past', which needs defining). For example, for the purposes of the Kyoto Protocol (UNFCCC, 1998), afforestation refers to the direct human-induced conversion of non-forested land to forested land that has taken place since 1989, where the land has not been forested for a period of at least 50 years previously. The reason for a definition of afforestation is to avoid confusion with land that has been forested for a long time, and also to exclude situations where trees are planted or natural regeneration occurs on recently deforested land. The Kyoto Protocol also defines reforestation, which can occur on land that has not been forested for a period shorter than 50 years; reforested land is not covered in this current discussion. It is assumed that afforestation is carried out without displacing essential food production and thereby causing indirect land-use change and that afforestation on soils with high organic carbon stocks (such as peatlands) is avoided. Local guidelines could be needed to support decisions about where and how to afforest non-forest land.
Initially, new afforestation generally involves additional carbon sequestration from the atmosphere, mitigating CO_2 emissions in this way, rather than through the provision of forest biomass. In some situations, the removal of pre-existing vegetation and the disturbance of soil as part of ground preparation for afforestation can result in some initial net losses of carbon, rather than gains. Sometimes, it can take longer than a decade for newly established forests to offset initial carbon losses, so that the forest may not start to accumulate carbon stocks until after that point is reached. For this reason, the carbon payback time associated with afforestation is sometimes more correctly categorised as 'Medium' according to the classification used in Table 5.3, rather than 'Short'.

Newly afforested areas will take time to reach the age when thinning or felling of trees can be carried out, so the biomass supplied from these forests only becomes available some years after land is afforested. Also, we assume here that areas afforested in the 'distant past' are not counted in this category.
The origin of wood as produced from newly afforested areas could be verified as part of a certification process. In principle, it should be possible to demarcate land areas that have newly or very recently been afforested, provided a record of these land areas is maintained. Some issues with land tracking can arise, for example when newly afforested areas are subsequently deforested again, or when areas that were deforested in the recent past are reforested. There could be technical or logistical issues in setting up an appropriate chain of custody for the woody biomass sources.

Existing forests: 'continuing supply at established harvesting rates'

This class represents forest areas where management involves harvesting rates that are consistent with long-term historical rates of sustainable biomass supply. More specifically, 'an established harvesting rate' has the following characteristics:

- Biomass harvesting is not increasing above the rates observed in the past (preferably over 20 years or more).
- Biomass harvesting does not exceed the rates consistent with sustainable yield management (see Box 3.1).

It must be recognised that actual forest management is influenced by the strength or weakness of markets for wood products, which can work against efforts to produce a steady supply of woody biomass from forests, particularly on smaller, local scales. In some regions of the world, forests are owned by numerous private landowners and decisions about the management of forest stands are less likely to be coordinated, but rather driven by circumstances and the business aims of each landowner. Nevertheless, it remains the case that a carbon debt associated with biomass production can be avoided or minimised, as long as annual wood supply from a forest area is kept close to the 'established' rate, and, in particular, is not increased significantly above the 'established' rate or increased gradually but consistently over many years.

There is an important exception to the above statement: if the age distribution of the stands forming a forest is very skewed to younger or older ages, there may be periods when it is not possible to continue harvesting at historically observed rates consistently with the principle of sustainable yield management. This situation could occur if there is a period during which the area of stands in a forest with ages suitable for final harvesting is relatively small. This illustrates how there may be situations in which harvesting may need to be adjusted to ensure that wood supply is always consistent with sustainable yield, i.e. the second characteristic of forest areas within this class, as defined above. Current net forest increment in stem volume is routinely calculated in national and regional forest inventories, and often as part of business planning and performance monitoring by forest estate management companies. Estimates of increments are an important benchmark for determining an upper limit to the rate of sustainable-yield harvesting.
Natural disturbances, such as storms and tree disease outbreaks, can sometimes work against efforts to maintain an even rate of wood harvesting. Certain measures may help to mitigate these effects (see discussion of Existing forests, 'salvage logging').

In practice, characterising a forest area as belonging to the class considered here would require the relevant forest area to be clearly delineated, and for information on rates of harvesting and forest increment to be available, to verify the consistency of the management of the forest area with the two characteristics defined above.

The broad terms 'forest' and 'forest area' can be applied to different scales and situations, including:
- A population of forest stands within the national boundaries of a country or an administrative region;
- A discrete group of forest stands owned by an individual or institution (such as a charitable organisation);
- A collection of stands with an administrative or commercial connection – examples include the forest stands managed by the same forest management company (on behalf of various owners) and areas covered under a forest certification scheme.

In principle, forest areas delineated in any one of these ways could be characterised as belonging to the class of forests discussed here, as long as it could be demonstrated that the specified forest area is being managed consistently with the characteristics defined earlier. The rate of wood supply from forest areas is often routinely monitored and reported in national and regional statistical reports. Such information is also collected for business purposes by forest management companies. As already discussed, rates of forest increment are also frequently monitored and the methods for assessing forest increment are well established. It is assumed that an appropriate chain of custody could be established with a supporting verification protocol to determine that biomass sources have been extracted from the delineated forest areas.

Existing forests: 'management to maintain or enhance carbon stocks'

The possibilities for this kind of management and outcomes are explored in Section 3.5 and Appendix 3. The studies discussed in Section 4.3 give examples of scenarios in which this could occur. However, achieving the dual goals of increasing biomass supply from forests while maintaining or enhancing their carbon stocks is likely to require conscious efforts to ensure such an outcome. This would involve the introduction of a relevant set of forest management measures to explicitly address these aims.

Relevant forest management measures are a diverse group of specific and often unrelated practices, and it is doubtful that a complete list can be compiled. This is partly because forestry practitioners may develop new and innovative types of management interventions, if incentives exist to deliver 'forest carbon management'. Several reviews have been made of active forest management measures aimed at maintaining and enhancing forest carbon stocks and/or increasing biomass supply from forests (for example, see Matthews, 2020b; Schelhaas et al., 2007). However, not all of these measures can achieve both objectives at the same time; many involve trade-offs between the two objectives of enhancing carbon stocks and increasing the rate of biomass harvesting.

A non-exhaustive list of examples of measures potentially relevant to achieving both aims includes:

- Protecting forest areas against present risks of deforestation or degradation, while also managing these areas for some biomass supply.
- Ensuring complete and rapid restocking of felled forest areas with productive replacement trees.
- Avoiding the clear-felling of forest areas, involving a range of forestry practices whereby at least some trees are always retained, either evenly spread across sites, in clumps, or both; collectively, these methods are sometimes referred to as 'continuous cover forestry'. However, note that these silvicultural practices can have variable applicability as well as differing impacts on rates of wood supply and forest carbon stocks, depending on the detailed methods, location-specific conditions including forest structure, and the management practiced previously.
- Diversifying the tree species composition of forests to create species mixtures, potentially as part of efforts to ensure the resilience of forests to future climate – there is also some evidence to suggest that the productivity of forest stands formed of species mixtures have higher productivity than pure-species stands.
- Adapting forest management to enhance the resilience of forests to natural disturbances, such as storms, fires, and disease outbreaks. Relevant activities may include those covered in the previous two points, as well as 'pre-emptive clear-felling' of some forest areas to avoid larger scale disturbances (which could also cause some losses to wood supply and carbon stocks), such as to create 'fire breaks' to avoid extensive wildfires.
- Introducing trees with superior growth rates into forest areas; this may involve new tree species or existing tree species but with specimens selected for higher growth rates or improved stem form (such as for conversion into sawlogs). Situations where long-established biodiverse

forest areas would be replaced by plantations would not count as a relevant activity, because it would not meet the wider principles of Sustainable Forest Management.
- Fertilisation of forest stands growing on nutrient-limited soils.

Other measures are possible that can enhance carbon stocks, but which may result in reduced rates of biomass harvesting. Examples include:
- Extending rotation periods in stands managed with clear-felling (see Section A2.5).
- Managing forest areas primarily for the protection of natural ecosystems with a minimum of harvesting activities.
- Adoption of 'continuous cover forestry' methods (in some situations, see earlier in this discussion).

Measures may involve coordinated actions across a population of forest stands. For example, one approach might involve:
- Dividing forest stands in an area into those that are more productive and those that are less productive (in terms of growth rate and higher value wood supply);
- Reducing harvesting from the less-productive areas (where changing management would have less impact on the rate of wood supply), to enhance carbon stocks and sequestration (including creating protected 'carbon reservoirs');
- Increasing harvesting from the more productive areas, to increase biomass supply but potentially involving a trade-off with forest carbon stocks in these areas, which could be minimised if also accompanied by measures such as fertilisation or restocking with trees with superior growth rates.
- Over the whole forest area, this approach might allow for biomass supply to be increased while maintaining or possibly enhancing forest carbon stocks. The possibilities for managing biomass harvesting and carbon stocks in a planned way across a population of forest stands is explored further in the main text.

In practice, characterising a forest area as belonging to the class considered here would require the relevant forest area to be clearly delineated, as already discussed for the class of existing forests under 'continuing supply at established harvesting rates'. An appropriate chain of custody could be established with a supporting verification protocol to determine that biomass is being extracted from the delineated forest areas.

Demonstrating and verifying that the forest areas are being managed consistently with the concept of 'management to maintain or enhance carbon stocks or sinks' described above and in Box 3.6 could be technically challenging. In particular, there could be challenges in making the case that forest management is being changed actively from 'baseline' practices. An approach to this could involve:
- Documenting the existing management practices and the planned changes. Some flexibility might be allowed, to include changes in forestry practice which started to be introduced in the recent past, for example in the preceding 10 years, in acknowledgement of pre-existing efforts to manage forest carbon stocks.
- Estimating the improvements in forest carbon stocks and/or sequestration rates expected to result from making the changes to forest management (this exercise could involve the use of forest models), with estimates expressed on a per-hectare basis.

- Documenting the areas of forest within the delineated region where each new forest management practice is planned to be introduced (this might initially involve simply stating the intended total area within the forest, but ultimately would involve mapping the relevant areas).
- Combining the estimates developed above to quantify and document the expected total increase in total carbon stocks and/or sequestration rates associated with the planned changed management practices in the forest.
- The expected increases in biomass supply would also be documented with supporting evidence (which might also involve the application of models), to show the level of increased wood supply expected as part of the changes in forest management consistent with conserved or enhanced carbon. The assessment could go into some detail about changes in biomass supply, by analysing the material produced, notably biomass suitable for use as sawlogs versus biomass only suitable for use as bioenergy. This is illustrated by the example calculations in Appendix 5, which accompany the description of the application of the methods described in this section.

It is assumed that an appropriate chain of custody could be established with a supporting verification protocol to determine that biomass sources have been extracted from the delineated forest areas.

Existing forests: 'increased biomass extraction/supply'
This class represents forest areas where management involves harvesting or biomass extraction rates that are increasing significantly compared with long-term historical rates of biomass supply, and where this is also resulting in diminished carbon stocks and/or sequestration rates in forests. More specifically, forest areas in this class are defined as being managed with harvesting with the following characteristics:

- Biomass harvesting/extraction is increasing or has increased above rates observed in the past (for example over the previous 20 years) and this is not a temporary change.
- The increased biomass harvesting/extraction does not exceed rates consistent with sustainable yield management (see Box 3.1).
- The changes in management practices to produce the additional biomass result in a finite reduction in carbon stocks in forest areas.
- Section 3.2 and Appendix 2 explain in detail how some changes in forest management practices can have these kinds of impacts on forest carbon stocks and/or sequestration rates, even when these practices are otherwise consistent with the wider principles of sustainable forest management and sustainable yield management in particular.

A non-exhaustive list of examples of relevant forest management practices would include:

- Shortening of rotations applied to forest stands to enhance annualised wood supply (see Sections A2.3, A2.5, and A2.6).
- Increased frequency of thinning and/or felling of forest areas, where this is not relevant to measures to reduce risks or impacts of natural disturbances (such as fires or outbreaks of pests and diseases)
- Increased quantity of biomass removed when thinning forest areas, most likely involving harvesting more trees in an individual thinning event.
- Increased extraction of wood harvesting residues, where these would otherwise have been left to decompose in the forest and decay rates are slow (for example, multiple decades).

Ideally, the supply of biomass from this class of forest would be minimised. Hence, in practice, the aim would be to ensure that the bulk of forest biomass supplies come from forest areas in the three classes of forest described earlier, i.e. New afforestation, Existing forests: 'continuing supply at pre-existing harvesting rates', and Existing forests: 'management to maintain or enhance carbon stocks or sinks'. In this context, a precautionary approach could be adopted of assuming that areas of forest not demonstrated as belonging to one of these three classes are allocated by default to this class.

There are some cases in this class of forest associated with short carbon payback times, but these are quite specific. The main examples involve extraction of wood harvesting residues or salvage logging, where the residues and/or dead trees would be burnt on site as part of preparation for forest restocking or regeneration under existing practice, rather than being left to decompose in the forest.

Existing forests: 'salvage logging'
The (IPCC, 2014a) defines salvage logging as the practice of harvesting and physically removing trees or parts of trees (living or dead) from disturbed areas. This management activity is also known as salvage cutting, salvage harvesting, sanitation cutting, and other designations.
Storms, wildfires, and outbreaks of pests and diseases can disturb forest areas, damaging and killing some or all of the trees. Such disturbances are sometimes significant, affecting thousands or millions of hectares and millions of cubic metres of potential timber. In these situations, there is a choice between leaving the dead or damaged trees in the forest and allowing the ecosystem to recover eventually through natural regrowth, or intervening to remove some or all of the affected trees, to make use of some of the wood products and bioenergy. At least some of the extracted timber can be kept in storage areas if needed, to smooth out wood supply to wood-based industries over several years. The presumption is made here that salvage logging is usually accompanied by active efforts to support forest regeneration and regrowth where needed, to avoid degradation of affected forest areas and ensure rapid restoration of productive potential.
The impacts of salvage logging on forest carbon balances will vary significantly, depending on the context. For example, carbon payback times for extracted biomass can be short if:

- Biomass otherwise left in the forest would decay very quickly (for example, over 10 years or sooner).
- The biomass would otherwise be extracted and burnt as waste as part of restoring forest areas and risk management.
- Clearance of deadwood and/or active support for restocking with new trees enhances carbon sequestration in the regenerating forest.

Alternatively, payback times can be long if:

- Biomass otherwise left in the forest would decay slowly (for example, over decades) and its presence in the forest does not impede the regeneration of new trees.
- Clearance of the deadwood interferes with natural regeneration processes (for example through further site disturbance).

It appears, therefore, that decisions about whether to salvage log disturbed forest areas, and if so, to what extent, need to be made on a case-by-case basis. Local guidelines could be developed to support such activities. It is likely that disturbed forest areas can be clearly identified and delineated, with supporting information about the nature of the disturbances and their impacts. It is assumed that an appropriate chain of custody could be established with a supporting verification protocol to determine that biomass sources have originated from the delineated forest areas.

Deforestation and forests undergoing degradation
In principle, the class of deforestation is easy to define as consisting of areas of land that undergo a permanent change from forest cover to non-forest cover such as grassland, agricultural land, and urban land. The definition suggested here for forest areas undergoing degradation is based on the IPCC definition of land degradation (IPCC, 2019b), but narrowed for the context of this report: Forest areas undergoing a negative trend in condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as a long-term reduction or loss of at least one of the following: biological productivity, ecological integrity, or value to humans. Degradation in terms of any of these factors could have a negative impact on forest carbon stocks (such as reduced rate of forest growth, compromised resilience, or likelihood of neglect or abandonment by forest owners with subsequent land use change).

Generally, the supply of biomass from these classes of forest would be avoided. Only in exceptional circumstances might biomass from such sources be relevant in the context of ensuring short carbon payback times. For example, there may be situations where deforestation is unavoidable (possibly as part of essential urban development, or where trees need to be removed to conserve non-forest ecosystems such as heathlands or peatlands, or to protect the water supply in places where it would be affected by evapotranspiration of forests upstream). In these situations, the alternative to utilising the felled biomass would be to burn it as waste.

5.2.3 Site-by-site assessment: estimation of effects on carbon stocks and wood supply (Step 4)

The following discussion describes how information on forest units within a defined region can be used to estimate the effects of planned management on the carbon stocks in the forest and the level of wood supply. This is illustrated by building on the hypothetical example of a forest region described in Section 5.2.1. The main method proposed below is quantitative, that is, estimated values are derived for carbon stock changes and levels of wood supply. Brief consideration is also given to a possible qualitative method, based on the classifications with respect to carbon payback times.

In Table 5.4, estimates are given for the likely changes in long-term mean carbon stocks resulting from the implementation of the planned management in the forest classes shown in Table 5.3. The rationale behind this simplified method is derived from the theoretical consideration of forest carbon stock dynamics at the landscape scale, as explored in Sections 3.1, 3.2, and 3.5 and Appendices 2 and 3.

These methods are consistent with those described in IPCC Good Practice Guidance on the preparation of national greenhouse gas inventories (IPCC, 2006) for estimating carbon stock changes in terrestrial vegetation, known as 'Tier 1' and 'Tier 2' methods. Similar systems have also been suggested in earlier discussions on related issues (Canadell et al., 2007; Kirschbaum et al., 2001; Orr et al., 2017). The basic method involves:

i. Identifying a per-hectare estimate of the long-term mean carbon stock of the pre-existing (i.e. initial) land use (such as, cropland, grassland, or forest managed in a particular way).
ii. Identifying a per-hectare estimate of the long-term mean carbon stock of the planned land use and management.
iii. Estimating the change in per-hectare long-term mean carbon stock as the difference between the above two estimates.

iv. For each class of forest (A to K in the example considered here), multiplying the carbon stock change estimated for each class, as calculated above, by the total area for the class of forest (the relevant areas are indicated in Figure 5.1 in this example), then multiplying by the probability of carbon stock change assigned to that management class (see below) .
v. Adding together the results of the above step for each class of forest in the region, to obtain an estimate for the total net change in carbon stocks in the forests resulting from implementation of the plan for forest management within the region.

Table 5.4
Estimation of effects on forest carbon stocks resulting from the implementation of the planned management illustrated in Figure 5.1.

Class of forest & management	Area[1]	Mean carbon stock per ha[2]			Probability	Total[2]
		Initial	Resultant	Difference		
A	7	2.5	81.4	78.9	0.8	442
B	50	45.5	45.5	0.0	1.0	0
C	18	50.0	75.0	25.0	0.8	359
D	9	56.0	64.3	8.3	0.8	60
E	36	0.0	37.0	37.0	0.1	133
F	50	50.4	59.0	8.6	0.9	387
G	2	50.4	215.9	165.5	0.7	232
H	20	90.0	57,0	-33.0	1.0	-660
I	21	71.8	57.0	-14.8	1.0	-311
J	11	51.9	36.3	-15.6	1.0	-171
K	7	45.5	2.5	-43.0	1.0	-301
Total	**231**	-	-	-	-	**171**

[1] The areas in this column could be for example ha or kha, depending on context.
[2] The quantities here could be for example tC or ktC, depending on context.

The estimates of per-hectare carbon stocks in Table 5.4 were obtained from simulations made using the CARBINE forest carbon accounting model, in a similar way to examples discussed in Sections 3.1, 3.2, and 3.5 and Appendices 2, 3, and 5. The specific results referred to are consistent with tree species and management practices relevant to forests and forestry practice in the United Kingdom. The estimates of mean carbon stocks are for carbon in tree biomass (above and below ground) only. Estimates for carbon in forest litter, soil, and wood products harvested from forests could also be included. An exception in Table 5.4 is 'Class J', which involves the extraction of residues from harvesting in managed forests, where previously these would have been left to decompose in the forest. In this case, the estimates of 'initial' and 'resultant' carbon stocks represent the long-term mean stocks in deadwood and forest litter in forests, for the scenarios of extracting and not extracting the residues. Appendix 5 includes a summary description of the assumptions behind the calculation of estimates for all the forest classes in Tables 5.4 to 5.6.

It must be stressed that the 'initial' and 'resultant' carbon stocks in Table 5.4 represent mean per-hectare carbon stocks, characterised for forest stands with defined tree species composition, growth rate, and prescribed management, or for vegetation under a non-forest land use, where relevant. In practice, these carbon stocks would only be observed for each land use or forest class at landscape scale (rather than for individual stands). Furthermore, it would take time for the long-term mean carbon stock for a particular vegetation or forest class to become established. For example, when establishing forests on former grassland, it is apparent that the carbon stocks in the new forest will take decades or longer to accumulate. This also applies when considering changes in long-term carbon stock occurring as a result of forest management changes. For example, a decision to adjust rotations applied to a particular class of forest would usually require careful restructuring of the existing forests over a period of decades or longer. The estimates in Table 5.4 only assess total carbon stock changes resulting from forest management (or land-use change), without allowing for the various timespans within which these changes occur. In principle, the methods proposed here could be extended to allow for timing (see Appendix 5), but the aim has been to design a pragmatic system, and to only add complexity if it is needed to ensure that the system produces desired outcomes (i.e. biomass supplied from forests with small, zero, or negative net emissions from land use).

In Table 5.4, it is also apparent that initial and resultant carbon stocks as well as carbon stock changes can vary considerably. These differences reflect the underlying classes of forest and the types of interventions made when changing management or land use. For example, extending rotation periods by 10 years (forest units in Class F) results in a relatively modest change in long-term mean carbon stocks, while ceasing harvesting and minimising disturbance (forest units in Class G) can result in the accumulation of relatively high per-hectare long-term mean carbon stocks. The detailed calculations of the carbon stocks and stock changes (Steps i to iv) for these two forest classes are described in Appendix 5. These results illustrate how the size of a forest area that is available for implementing a particular change in forest management can be as important as the potential per-hectare change in carbon stocks. To be more explicit, it is possible to achieve big impacts on overall forest carbon stocks by implementing changes in forest management that result in big carbon stock changes in relatively small areas or more modest changes in relatively expansive areas.

A further refinement to the calculations In Table 5.4 involves multiplying the estimates of carbon stock changes by a ‘probability’. The idea is to allow for the possibility that, in practice, not all of the carbon stock changes based on the simple estimates may be realised. For some of the forest classes, the assigned probability of positive carbon stock changes is set to less than 1. This is consistent with a precautionary approach to allow for positive impacts on forest carbon stocks that are associated with planned changes in forest management. The specific reasons for assigning a probability of less than 1 for certain forest classes in Table 5.4 vary and depend on context; details are given in Table 5.5. Probabilities have been selected subjectively in this example but could be derived from assessments of local circumstances, such as experience of the growth rates of different tree species and recent trends in episodes of disturbance events.

The effects of changes in forest management on long-term woody biomass supply can also be estimated, and results for the example considered here are shown in Table 5.6. The calculation methods are similar to those used for long-term carbon stocks and stock changes; further details are given in Appendix 5. Note that the table only shows the long-term mean annual rate of wood supply for the forests before and after changes to forest management. The rate of wood supply during the transition period when forest management changes are being implemented may be different (see for example discussion in Section 3.4.1).

Table 5.5
Rationale for probabilities assigned in Table 5.4

Class	Description
A	Probability of 0.8 assigned, to allow for the possibility of the carbon sequestered in new forests being less than estimated; for example, growth rates of new forests may be slower than anticipated or forests may be managed differently than planned (may involve more thinning than originally anticipated).
C	Probability of 0.8 assigned, to allow for the possibility of the growth rates of genetically improved trees being slower than anticipated.
D	Probability of 0.8 assigned, to allow for the possibility of the growth rates of replacement tree species being slower than anticipated.
E	Probability of 0.1 assigned, to reflect low risk or relative infrequency of disease outbreak actually occurring.
F	Probability of 0.9 assigned, to reflect possible operational/practical constraints on extending rotations in some forest stands.
G	Probability of 0.7 assigned, to allow for the possibility of forests that are managed minimally to enhance carbon stocks experiencing an increased risks of disturbance (such as from fires or storms). However, a probability of 1.0 assigned for calculating a reduction in biomass supply (Table 5.6), to assume conservatively that any biomass arising from thinning or felling is not utilised (see Section A5.3).

Table 5.6
Estimation of effects on woody biomass supply resulting from the implementation of the planned management illustrated in Figure 5.1.

Class of forest & management	Area[1]	Woody biomass supply (odt/ha/yr)			Probability	Total difference per year[2]
		Initial	Resultant	Difference		
A	7	0.0	2.4	2.4	0.8	13.2
B	50	3.5	3.5	0.0	1.0	0.0
C	18	4.1	7.1	3.0	0.8	42.7
D	9	4.1	6.6	2.5	0.8	17.8
E	36	0.0	2.6	2.6	0.1	9.2
F	50	3.0	3.0	-0.02	0.9	-1.0
G	2	3.0	0.0	-3.0	1.0	-6.0
H	20	4.4	4.7	0.4	1.0	7.2
I	21	4.7	4.7	0.0	1.0	0.3
J	11	0.0	0.5	0.5	1.0	5.7
K	7	3.5	0.0	-3.5	1.0	-24.8
Total	**231**	-	-	-	-	**64.3**

[1] The areas in this column could be for example ha or kha, depending on context.
[2] The quantities here could be for example odt/yr or kodt/yr, depending on context.

It is apparent from Tables 5.4 and 5.6 that long-term carbon stocks and biomass supply can go up or down as a result of changed management, depending on the class of forest, as defined above. However, considering the region in Figure 5.1 as a whole, if it is assumed that areas are given in thousands of hectares, the overall effects of the various changes to the management of forest areas are a net increase in long-term forest carbon stocks of around 171 ktC, and an increase in biomass supply of 64.3 kodt/yr.

Using the results in Table 5.6 on forest areas and initial woody biomass supply, the total pre-existing biomass supply from forests is calculated to be 657 kodt/yr. The pre-existing long-term carbon stock in forests was calculated in a similar way, from Table 5.3, at 10.5 MtC. The total long-term woody biomass supply from the region after changing management, thus, comes to 721 kodt/yr, and the total long-term carbon stock amounts to 10.7 MtC. It therefore follows that the forests in the region can be managed to achieve a 10% increase in the overall annual supply of woody biomass and a 2% increase in overall regional forest carbon stocks.

Several main points can be drawn from the example presented in Figure 5.1 and Tables 5.4 to 5.6:

- The estimated carbon stock changes in Table 5.4, for the individual classes of forest and for all forests in the region as shown in Figure 5.1, do not represent the total changes in forest carbon stocks that would be directly observed, if these forests were to be monitored (such as by repeated forest inventories). Rather, the estimates represent the changes in carbon stocks that would be expected to occur as a result of implementing the planned management practices, relative to any underlying trends in forest carbon stocks in the region. This is entirely intentional, because pre-existing trends in forest carbon stocks can mask the impacts of changes to forest management practices, either positively or negatively (for example, involving negative marginal changes, see Sections 3.2 and A2.5.1). By defining the planned management practices (and any changes), and estimating their specific impacts on forest carbon stocks, it is possible to 'factor out' carbon stock changes in the region that may be occurring for other reasons (such as the distribution of tree ages that exists in the forests).

- In the example considered here, estimated net carbon stock changes in the various classes of forest are either positive, zero, or negative, but, when combined together for the complete region, the overall result is positive (Table 5.4), with a value of 171 'units' of carbon. The main point here is that overall, at the landscape scale, for the forests in the region, any wood products or bioenergy supplied from the forests are associated with management practices that are enhancing the region's carbon stocks. It follows that the wood products or bioenergy produced from the region can be regarded as 'carbon neutral' or better. It should be emphasised that it is not necessary for the carbon stock change in each forest unit to be positive or zero (some can be negative as in the example above), as long as the overall result for the complete region is positive or zero. Conversely, an overall negative result for a region would indicate that wood products or biomass produced from the region are risky in terms of net impacts on carbon stocks and greenhouse gas emissions.

- Other outcomes for overall carbon stock changes are possible if this method were to be implemented, depending on the specific region involved. In particular, the assessment may indicate that the impacts on carbon stocks are difficult to determine and therefore uncertain. Alternatively, practical constraints or obstacles may make it impossible to develop or characterise the kind of plan envisaged above for individual forest units, or to characterise the likely impacts of plans for their management. In these cases, as well as for assessments that indicate negative impacts on carbon stocks, a 'fallback option' could be to assess biomass sources from forest *intended for use as bioenergy* by considering the classes of biomass feedstock involved, as discussed in Section 5.5.

- As already discussed earlier, Table 5.4 shows that magnitudes of changes in per-hectare carbon stocks may vary significantly, depending on the initial state of the forest unit and the planned change in its management. This would be important to consider when implementing the approach described here in a real-life situation. However, the opportunities for adopting particular changes in forest management practices depend strongly on regional and local circumstances and practical and social constraints.

- It is also apparent from the example presented above that changes to forest management generally have an impact on both carbon stocks and the long-term supply of wood products and bioenergy, with changes in supply, in turn, affecting the potential for substituting greenhouse gas-intensive materials and fossil fuels. Choices therefore have to be made between continuing to consume non-renewable 'geological carbon' (fossil fuels), sequestering and protecting carbon in forests, and managing forests on a sustainable basis to produce wood to enable substitution. When making these choices, it is important to be aware of the differing properties of geological carbon and carbon in terrestrial vegetation systems such as forests (see Box 2.1.)

- The methods developed here depend critically on the availability of reliable estimates of long-term mean carbon stocks for all relevant classes of forest. Assessments may require a large selection of estimates, representing a range of tree species, growth rates, and, importantly, various forest management options. Relevant default values for forest carbon stocks (known as 'Tier 1' values) are available in Good Practice Guidance on preparation of national greenhouse gas inventories produced by the IPCC (2006), but these cover far too few possible options. The types of detailed carbon stock estimates needed, representing a sufficient set of options, would represent 'Tier 2' values as defined in IPCC guidance. Generally, Tier 2 values have not been determined for most regions of the world, so these would need to be developed. However, a comprehensive set of Tier 2 values would only need to be produced once, and an existing forest carbon accounting model could be used to calculate these (there are several examples available, see Sections A2.1 and A5.2). The results could then be available for general use. When making assessments, such an approach might be simpler and more practical than directly applying a complicated forest carbon accounting model, which would, for example, require far more detailed information about forests, such as data on the distribution of stand ages.

- In addition to implementing measures to support positive effects on forest carbon stocks as illustrated above, avoiding the use of some biomass feedstocks for bioenergy could also still be considered. For example, if wood suitable for manufacturing long-lived products were to be disfavoured as a feedstock for bioenergy, this could provide further assurance that biomass supplied from the forests gets utilised effectively from the viewpoint of potential impacts on net greenhouse gas emissions.

Qualitative assessment

A qualitative site-by-site assessment could be considered if the information needed for estimating effects on carbon stocks and wood supply is unavailable or limited. This is illustrated in Table 5.7 below for the example hypothetical forest region in Figure 5.1. The classification of forest units is carried out as described in Sections 5.2.1 and 5.2.2.

Qualitative assessments of carbon payback time and changes in wood supply are then assigned to each forest class, according to the system in Table 5.3 and Box 5.2. In this example hypothetical region, 172 units of area assigned a carbon payback time class of 'Short-Medium', 52 units are assigned to 'Short-Very long' payback times, and 7 units to a class of 'Very long', as shown in Table 5.8. These areas can be expressed in percentage terms as also shown in the table. The areas and percentages can then be calculated allowing for the risk-based probabilities attached to each forest class, as described above (Tables 5.4 to 5.6). These results are equally shown in Table 5.8. Similar calculations can be made for the qualitative assessments of effects on wood supply, as also shown in Table 5.8.

Table 5.7
Qualitative assessment of effects on carbon stocks and woody biomass supply resulting from the implementation of the planned management illustrated in Figure 5.1.

Class of forest & management	Area[1]	Carbon payback time class[2]	Change in wood supply[2]	Probability[3]
A	7	Short–Medium	Increase	0.8
B	50	Short–Medium	No change	1.0
C	18	Short–Medium	Increase	0.8
D	9	Short–Medium	Increase	0.8
E	36	Short–Medium	Increase	0.1
F	50	Short–Medium	Decrease	0.9
G	2	Short–Medium	Decrease	0.7/1.0
H	20	Short-Very long	Increase	1.0
I	21	Short-Very long	Increase	1.0
J	11	Short-Very long	Increase	1.0
K	7	Very long	Decrease	1.0
Total	**231**	-	-	-

[1] The areas in this column could be for example ha or kha, depending on context
[2] Based on classification of forest classes in Table 5.3 and Box 5.2.
[3] See Table 5.5, the two values for Class G refer to carbon payback time and change in wood supply, respectively.

Table 5.8
Summary results of qualitative assessment of effects on carbon stocks and woody biomass supply resulting from the implementation of the planned management illustrated in Figure 5.1

		Area (arbitrary units)		Area (%)	
		Unweighted	**Weighted[1]**	**Unweighted**	**Weighted[1]**
Carbon payback time	Short–Medium	172	127.2	74.5	68.3
	Short-Very long	52	52	22.5	27.9
	Very long	7	7	3.0	3.8
Wood supply	Increase	122	82.8	52.8	44.5
	No change	50	50	21.6	26.9
	Decrease	59	54	25.5	29.0

[1]Areas weighted by probabilities given in Table 5.7.

In summary, for this hypothetical example, it is estimated that 68-75% of the forest area in the region is assigned to 'Short-Medium' carbon payback times, while 3-4% is assigned to 'Very long' payback times. A less certain class of 'Short-Very long' is assigned to 23-28% of the forest area. For wood supply, 45-53% of forest area is assessed to a class of 'increase', with 'decrease' assigned to 26-29% of the area, and 'no change' in the remaining area (22-27%). These kinds of assessments could be referred to when evaluating plans for the future management of a region of forest, or in deciding whether to invest in a quantitative assessment.

5.2.4 Verification of site-by-site assessment

The methods considered here depend critically on effective and transparent verification that the desired outcomes are being achieved. This could involve two elements:

1. Monitoring to check that the planned management is actually being implemented.
2. Monitoring to confirm that the changes in carbon stocks associated with specific management practices are being realised.

It is suggested here that the first element above is *necessary*, while the second element is *highly desirable*. If the second element is not carried out, then implementation could be supported by other evidence (such as from experimental trials) demonstrating the magnitudes of carbon stock changes resulting from the various individual management practices. A process of formal external technical review and validation or audit would be appropriate to verify the plan as accurate, realistic, and achievable. Methods involving classifying forest areas in terms of pre-existing management practices, and planned changes to those practices, such as illustrated above, require justification and verification that the classifications applied are valid, including 'on the ground'. Otherwise, the implementation of such a system could be open to gaming, or to risks of counterclaims from different stakeholder groups about the kinds of forest management being practiced.

For example, it is conceivable that increased harvesting of forests might be justified spuriously by 'seeing risks of forest disturbance everywhere'. Equally, there may be significant challenges to objectively assessing the positive impacts of management interventions to reduce forest disturbance, where outcomes could be very uncertain. Thorough, objective, and impartial scrutiny and validation of plans for management of forest areas may be needed for avoiding such perverse responses and outcomes. A risk-based approach could also be considered, as illustrated in the example presented above.

A further process of monitoring and verification would check that the plan was being implemented. This might involve confirming that the planned changes to forest management are happening. It would be significantly more challenging and expensive to show that commensurate carbon stock changes were occurring in the forest, if this level of assurance were to be needed. These review, audit, and verification processes imply the existence of an administrative framework for overseeing the validation of forest areas as being managed consistently with the principle of 'carbon management' as outlined above. Such an approach is not without precedent, having been explored previously in frameworks supporting the Clean Development Mechanism and Joint Implementation under the Kyoto Protocol (for example, see UNFCCC, 2021) and, to a lesser extent, in forestry certification systems.

It must be acknowledged that high costs of implementation would be a serious barrier to adoption in the forest sector. The further development of cost-effective and practical methods for managing and verifying forest carbon stocks and the use of wood feedstocks are subjects for essential further research. Some aspects may be addressed by current efforts to translate the principles of Climate Smart Forestry into practical methods and tools to support forest management, consistent with climate change goals.

Large-scale monitoring to explicitly assess the effects of forest management and harvesting on carbon stock changes in forests could be costly and present technical challenges. Sophisticated methods are needed, such as the example presented in Section 5.2. The main problem is that the objective would be to verify the marginal impacts on forest carbon stocks *directly attributable to the forest management practices*. As explained elsewhere in this report (see Sections 3.2.1 and A2.5.1), generally this is not the same as the total carbon stock changes that would occur over time in the forests. Rather, the changes arising from the forest management practices would be a *component* of the observed total changes, making it necessary to separate them out as part of monitoring. It may be of interest to note that 'Forest Reference Level accounting', as developed for the EU LULUCF Regulation (Regulation (EU) 2018/841), is in effect an attempt to address this challenge at large scales in the context of national and international accounting for the contributions of forest management activities to greenhouse gas emissions to, and removals from, the atmosphere. There is some debate about whether the Regulation is effective in addressing this issue (see for example Matthews, 2021). The methods described in Sections 5.3 and Section 5.4 are intended to provide a practical framework for managing forests at relatively large spatial scales, whilst assessing the likely effects on carbon stocks and carbon sequestration, as well as enabling a pragmatic approach to verifying that changes actually occur.

5.3 Regional-scale assessment

This method does not require the complexity of analysis or detailed data for site-by-site assessment. The method works with data that might typically be collected as part of a comprehensive national forest inventory program. The main steps in the method involve:

1. Identifying the region of forest where the method is to be applied.
2. Obtaining inventory data on the areas of forest within the region.
3. Analysing the inventory data to estimate parameters related to existing forest management.
4. Estimating forest carbon stocks and potential wood supply in relation to existing management.
5. Using the results of the above analysis to decide which forest areas are suitable for supplying biomass.
6. Obtaining statistics on forest harvesting and/or wood supply from the forests within the region.
7. Using the statistics on forest harvesting/wood supply to confirm that harvesting rates are not increasing in the region at a significant rate.

The implementation of Steps 1 and 2 is illustrated by examples given in Section 5.3.1. The analysis of inventory data in Step 3 is illustrated for these examples in Section 5.3.2. The estimation of carbon stocks and biomass supply in Step 4 is illustrated in Section 5.3.3. The application of these results of this analysis to planned forestry practice (Step 5) is discussed in Section 5.3.4. Steps 6 and 7 are outlined in Section 5.3.5.

5.3.1 Regional-scale assessment: identifying and classifying forest areas (Steps 1 and 2)

The region where the method is applied may consist of a defined area of land containing forests, similar to Figure 5.1. This would define a region where a supplier is harvesting woody biomass, or is planning to. This could also represent the region falling within the catchment area of a biomass processing facility. Unlike the method of site-by-site assessment, the total area of forest in the region is considered, not necessarily all under the ownership or management of a single operator or consortium of operators. Various unrelated actors could be involved in owning the forests or in their management, including decisions about harvesting. Data for similar forest areas outside the region may also be included to ensure statistical robustness, as long as these areas are consistent with those within the region, in terms of species composition, growth rates, and management.

This method does not require knowledge of individual forest sites or units, but it depends on reliable, statistically representative inventory data being available for the forests within the defined region. The essential requirement is to be able to classify forest areas according to tree species and age, and ideally also growth rate. This kind of data is collected and publicly reported in many countries, including Canada, the USA, and many European nations. However, there are also many countries where such data are not available with sufficient detail, making this method difficult and often impossible to apply.

Two illustrations of the kind of data required are given in Tables 5.9 and 5.10. These are hypothetical examples for notional regions of land, but they are based on actual forest inventory data reported for two regions of the world. Only simple modifications have been made to the reported data (selecting specific tree species groups and growth classes and scaling the total area younger than 201 years to 100,000 ha). The first example (Table 5.9) is from a region where the great majority of forests have been under relatively 'intensive' management for wood supply for many years. The available inventory data allow forest areas to be classified according to tree species, growth rate class, and tree age class. The growth rate classes in Table 5.9 are defined as:

- Very slow (up to 4 m^3/ha/yr stem volume production on an optimal rotation).
- Slow (4 to 8 m^3/ha/yr).
- Moderate (8 to 14 m^3/ha/yr).
- Fast (14 to 20 m^3/ha/yr).
- Very fast (higher than 20 m^3/ha/yr).

The second example (Table 5.10) is from a region where some forests are under intensive management but there are also substantial areas under relatively 'extensive' management.

Table 5.9
Forest area inventory data in hectares for a notional region containing 100,000 ha of relatively 'intensively' managed forest (classification by species group, tree age class, and growth rate classes of slow, moderate, fast and very fast, where relevant for tree species).

Age class (years)	Spruces				Pines			Oaks
	Slow	Moderate	Fast	Very fast	Slow	Moderate	Fast	
0-10	97	2,193	1,675	32	226	326	5	168
11-20	432	3,801	2,669	826	308	883	121	229
21-30	1,387	5,463	5,208	2,782	412	1,480	183	1,336
31-40	1,585	6,352	5,532	2,154	553	2,302	284	1,218
41-50	1,126	5,192	4,008	819	809	2,461	314	1,307
51-60	814	2,190	1,585	221	1,387	2,580	197	1,835
61-70	355	1,169	657	55	1,210	1,612	67	1,785
71-80	108	319	115	7	565	473	27	1,930
81-90	69	189	51	3	403	279	17	2,462
91-100	42	24	21	1	217	84	3	2,056
101-120	18	6	4	0	125	55	0	1,910
121-140	80	2	0	0	53	5	0	759
141-160	0	2	0	0	9	3	0	449
161-180	1	0	0	0	35	1	0	424
181-200	5	4	0	0	10	4	0	586
Total	**6,120**	**26,906**	**21,526**	**6,901**	**6,323**	**12,550**	**1,220**	**18,454**

Table 5.10
Forest area inventory data in hectares for a notional region containing 100,000 ha of relatively 'extensively' managed forest and over 157,000 ha of relatively unmanaged forest (classification by species group, tree age class, and two ecological sub-regions within the main region).

Age class (years)	Hemlock		Firs		Douglas Fir		Spruces	
	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2
0-20	1,210	53	291	443	620	489	0	2,631
21-40	2,069	90	755	956	528	680	269	3,484
41-60	1,850	283	215	1,225	1,312	880	304	1,470
61-80	1,222	173	169	1,361	1,289	1,113	11	1,777
81-100	1,093	311	132	2,049	588	3,101	62	2,881
101-120	664	321	191	2,887	609	3,913	27	4,066
121-140	713	323	237	3,652	454	4,286	29	5,621
141-160	388	283	241	4,355	281	3,508	26	5,500
161-180	684	268	225	4,349	169	1,332	49	3,034
181-200	342	300	235	3,559	193	1,005	49	2,192
201+	18,344	2,768	6,108	14,124	1,171	3,893	578	10,883
Total	**28,578**	**5,174**	**8,801**	**38,960**	**7,213**	**24,201**	**1403**	**43,539**
Sub-total[1]	**10,234**	**2,406**	**2,693**	**24,836**	**6,042**	**20,308**	**825**	**32,656**

[1] Sub-total excludes forest areas older than 200 years.

The terms 'intensive' and 'extensive' applied to forest management have been discussed in Box 4.2 in Matthews et al. (2015). The available inventory data allows forest areas to be classified according to tree species and tree age class. Forest areas are also classified as falling within one of two ecological sub-regions within the defined region.
The total area of managed forests in both hypothetical example regions (Tables 5.9 and 5.10) is 100,000 ha. Additionally, there are over 168,000 ha of older forests in the second region (Table 5.10) that may be regarded as unmanaged including not typically being harvested for wood supply.

5.3.2 Regional-scale assessment: analysis of inventory data (Step 3)

The purpose of this analysis step is to look for evidence in the inventory data of how the forests in the defined region are being managed. When concerned with biomass supply, the management activities of main interest are the frequency of clearfelling in forest areas and the prevalence and intensity of thinning.

Frequency of clearfelling

The results in Table 5.11 show how the inventory data for the example of an intensively managed forest region (Table 5.9) might be analysed to assess the frequency of clearfelling in forest areas. This is determined by estimating the likely age at which forest stands are clearfelled, that is, the typical or characteristic rotation age. The method proposed below involves:

- Calculating the change in area between successive age classes in the inventory data.
- Identifying the age class in which the biggest drop in area occurs compared with the adjacent younger age class.

For example, for spruces in the 'moderate' growth class in Table 5.9, the difference between the reported areas for the age classes of 41-50 and 51-60 years is 5,192 – 2,190 = 3,002 ha (see value in bold text Table 5.11). This is the biggest drop in area for the sequence of results for this forest class.

It is thus inferred that the likely clearfell rotation for forests in this class is 51-60 years. Similar results are calculated for the other forest classes as highlighted by the values in bold text in Table 5.11. Note that adjustments are needed to results, such as in Table 5.9, before calculating differences, when age classes have different class intervals (e.g. 10 and 20 years).

Table 5.11
Analysis of forest area inventory data in hectares with respect to age class for a notional region containing 100,000 ha of relatively 'intensively' managed forest.

Age class (years)	Spruces				Pines			Oaks
	Slow	Moderate	Fast	Very fast	Slow	Moderate	Fast	
0-10	-	-	-	-	-	-	-	-
11-20	335	1,608	994	794	82	556	116	61
21-30	955	1,663	2,538	1,956	104	597	62	1,107
31-40	198	888	324	-628	141	823	101	-118
41-50	-459	-1,160	-1,524	**-1,335**	256	159	30	89
51-60	-312	**-3,002**	**-2,423**	-598	578	119	-117	528
61-70	**-459**	-1,021	-928	-166	-177	-968	**-129**	-50
71-80	-247	-850	-542	-48	**-645**	**-1,139**	-41	145
81-90	-40	-131	-64	-4	-162	-194	-10	532
91-100	-27	-164	-29	-2	-186	-195	-14	-406
101-120[1]	-33	-21	-20	-1	-155	-56	-3	**-1101**
121-140[1]	31	-2	-2	0	-36	-25	0	-576
141-160[1]	-40	0	0	0	-22	-1	0	-155
161-180[1]	0	-1	0	0	13	-1	0	-13
181-200[1]	2	2	0	0	-12	2	0	81

[1] Calculations for older age classes adjusted to allow for wider class interval (20 years) compared to younger classes (10 years).

It may be challenging to apply the same method as above to the example of a relatively extensively managed forest area. Forest inventory data for more extensively managed regions can be quite heterogenous, with the influence of managed rotations on age distributions less clear. Hence, an alternative method is suggested in this case, which involves:

- Calculating a cumulative probability distribution for the forest areas in each species group and sub-region.
- Identifying percentile for the cumulative probability distributions giving the age or age range likely to represent the typical rotation ages applied to forest areas.

This method is illustrated in Table 5.12 for the example of a region of forest under relatively extensive management. The table shows cumulative probability distributions for the forest types in each sub-region, calculated from the inventory data in Table 5.10. Areas of older forest, specifically areas in the oldest age class in the inventory data, are excluded from the analysis, as they may be assumed to be beyond typical rotation ages, perhaps including areas of relatively unmanaged forest and primary forest.

Table 5.12
Analysis of forest area inventory data with respect to age class for a notional region containing 100,000 ha of relatively 'extensively' managed forest.

Age class (years)	Hemlock		Firs		Douglas fir		Spruces	
	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2	Sub-region 1	Sub-region 2
0-20	11.8	2.2	10.8	1.8	10.3	2.4	0.0	8.1
21-40	32.0	5.9	38.9	5.6	19.0	5.8	32.6	18.7
41-60	50.1	17.7	46.9	10.6	40.7	10.1	69.5	23.2
61-80	62.1	24.9	53.1	16.0	62.0	15.6	70.7	28.7
81-100	72.7	37.8	58.0	24.3	71.8	30.8	78.3	37.5
101-120	79.2	51.2	65.1	35.9	81.8	50.1	81.5	49.9
121-140	86.2	64.6	73.9	50.6	89.4	71.2	85.1	67.2
141-160	90.0	76.4	82.9	68.2	94.0	88.5	88.2	84.0
161-180	96.7	87.5	91.3	85.7	96.8	95.1	94.1	93.3
181-200	100	100	100	100	100	100	100	100
201+[1]	-	-	-	-	-	-	-	-
P_{70}[2]	95	149	131	162	96	139	68	143
P_{75}[2]	107	158	142	168	106	144	91	149

[1] Areas in the oldest age class have been excluded from the assessment.
[2] P_{70} and P_{75} are the 70th and 75th percentiles of the age distributions, respectively.

A value or range now needs to be selected for the percentile assumed to be representative of the typical rotation ages applied to forest stands. If the method is applied to the inventory data for the example of an intensively managed forest area (Tables 5.9 and 5.11), the percentile giving the best match to the rotation ages identified earlier is found to be 95% (range 85% to 95%). These calculations are based on the area in Table 5.9 but are not presented here. A percentage as high as 85% to 95% is understandable for forests under intensive management, where the great majority of forest areas will be felled quite precisely around the rotation age. However, this is unlikely to be the case for the extensively managed forest considered in Tables 5.10 and 5.12. Instead, it is likely that significant forest areas will not be under management and will be older than the typical rotation. Furthermore, rotation ages are likely to be less systematic and so broader in terms of age range and less distinct in the data. However, compared to an intensively managed forest area, a percentile lower than 85% is likely to be representative of the rotation ages in these extensive forest areas. For this example, the 70th and 75th percentiles are selected in the cumulative probability distributions of the forest areas with respect to age, excluding the oldest age class. Values are selected around the upper quartile in the absence of better information about probable rotation ages. The ages given by these percentiles are shown at the bottom of Table 5.12.

Thinning practice

There is no obvious way of inferring whether thinning is being carried out in forests from the area data reported in forest inventories, such as in Tables 5.9 and 5.10. However, many forest inventories also report information on the standing stem volume or biomass in forests. If data are reported for volume or biomass in age classes, similarly to the area data in Tables 5.9 and 5.10, it may be possible to estimate the standing volume or biomass per hectare in each age class for each forest type. Calculations along the following lines could then be made:

- Identify the mean growth rate of forests in the class (see examples in Section A2.2). Growth rates may be available from published studies or local operational information.
- For each age class, derive an expected value of standing volume or biomass per hectare, by multiplying the mean growth rate by the mid-range value of age for the age class.

- Estimate the actual standing volume or biomass per hectare in each age class from the forest inventory data.
- If the estimates of actual standing volume or biomass per hectare are significantly lower than the projected values based on mean growth rate, this suggests thinning is practiced in this forest class.

It may be possible to elaborate on these calculations to assess the prevalence or intensity of thinning in more detail. However, consideration of how this method might be fully specified and implemented is beyond the scope of this report.

5.3.3 Regional-scale assessment: estimation of carbon stocks and wood supply (Step 4)

The estimation of carbon stocks and wood supply is not essential for the implementation of this method, but some broad calculations are possible. The method is illustrated in Table 5.13 for two example forest classes in the hypothetical region of intensively managed forest: spruces with a moderate growth rate and pines with a slow growth rate. The method consists of the following steps:

i. Calculate the total area in the forest class with ages up to and including the age class identified as consistent with the typical rotation age.
ii. Use a model to estimate the long-term mean carbon stock and rate of wood supply for this forest class (defined in terms of tree species, growth rate, and management), as already illustrated in Section 5.2.3 and by examples in Appendices 2, 3, and 5.
iii. Estimate the total carbon stock (long-term mean) for forests being managed assuming the typical rotation age by multiplying the per-hectare mean carbon stock from step ii by the area calculated in the first step.
iv. Estimate the total wood supply (long-term mean) from forests being managed assuming the typical rotation age by multiplying the per-hectare rate of wood supply from step ii by the area calculated in Step i.

Forests in age classes older than the assumed rotation age are not included in the above estimation of carbon stocks and wood supply, on the assumption that they are excluded from management for wood supply (including harvesting). Estimates of carbon stocks could also be derived for these areas if of interest. The calculations in Table 5.13 involve the assumption that all the stands in the two example forest classes are regularly thinned. If stands are not thinned, different per-hectare carbon stock and wood supply estimates would apply. The method would need to be refined if some forest areas are being thinned whilst others are not thinned. The detailed elaboration of these methods is beyond the scope of this report.

Where estimates of actual carbon stocks are reported as part of forest inventories, these may show quite large differences from the long-term mean estimates derived by this method. This is highly likely if the age distribution of the forests is very uneven, as is the case for the examples in Tables 5.9 and 5.10 (see also examples in Section A2.4.1). Reported estimates may nevertheless be useful as a sense check on the long-term mean estimates.

Table 5.13
Estimation of long-term mean carbon stocks and wood supply for two forest classes (see Table 5.9).

	Spruces, moderate growth rate	Pines, slow growth rate
Characteristic rotation age range (years)	51-60[a]	71-80[a]
Total area with ages up to characteristic rotation age range	25,191[b]	5,470[b]
Long-term mean carbon stock in trees (tC/ha)	45.5[c]	39.1[d]
Long-term mean rate of wood supply (odt/ha/yr)	3.5[c]	2.3[d]
Total long-term mean carbon stock in trees (MtC)	1.15	0.21
Total long-term mean wood supply (kodt/yr)	88.2	12.4

[a] From Tables 5.11 and 5.12.
[b] Sum based on data in Tables 5.9 and 5.10.
[c] Based on long-term mean carbon stocks and wood supply in a stand of Sitka spruce, growth rate 12 m3/ha/yr, rotation age 56 years (see results for forest type B in Tables 5.4 and 5.6).
[d] Based on long-term mean carbon stocks and wood supply in a stand of Scots pine, growth rate 6 m3/ha/yr, rotation age 78 years (see results in Figure A3.2 and Table A3.1).

5.3.4 Regional-scale assessment: application of results to decision-making (Step 5)

The results of the assessments in Sections 5.3.2 and 5.3.3 could be used as a guide to decisions about harvesting forests by thinning or clearfelling. The case of clearfelling is illustrated in Tables 5.14 and 5.15. In Table 5.14:

- Each forest class is assigned a 'characteristic' rotation age range. Clearfelling stands within this age range is likely to be consistent with existing management practices within the region and thus at low risk of potential negative effects on carbon stocks.
- The age classes immediately adjacent to the characteristic rotation age range (one class younger and older than this class) are assigned an assessment of 'caution'. This implies that some limited clearfelling of stands may occur in these classes, as long as the majority is in the characteristic rotation age range.
- Forest areas in all other age classes are assigned an assessment of 'not recommended'. Clearfelling in younger age classes strongly implies significant shortening of rotations compared to the characteristic rotation age. Clearfelling in older age classes implies risks of harvesting in stands not previously under management for wood supply (for example, see illustration in Sections 3.2 and A2.5).

Table 5.14
Assessment of rotation ages in relation to potential impacts on forest carbon stocks for an example region of relatively intensively managed forests (see Tables 5.9 and 5.11).

Forest class		Rotation age (years)				
Species group	Growth class	Not recommended	Caution: short	'Characteristic'	Caution: long	Not recommended
Spruces	Slow	< 51	51-60	61-70	71-80	> 80
	Moderate	< 41	41-50	51-60	61-70	> 70
	Fast	< 41	41-50	51-60	61-70	> 70
	Very fast	< 31	31-40	41-50	51-60	> 60
Pines	Slow	< 61	61-70	71-80	81-90	> 90
	Moderate	< 61	61-70	71-80	81-90	> 90
	Fast	< 51	51-60	61-70	71-80	> 80
Oaks	All	< 91	91-100	101-120	120-140	> 130

Table 5.15
Assessment of rotation ages in relation to potential impacts on forest carbon stocks for an example region of relatively extensively managed forests (see Tables 5.10 and 5.12)

Forest class		Rotation age (years)				
Species group	Sub-region	Not recommended	Caution: short	'Characteristic'	Caution: long	Not recommended
Hemlock	1	< 80	80-89	95-110	111-120	> 120
	2	< 135	135-144	145-160	161-170	> 170
Firs	1	< 120	120-131	130-145	146-155	> 155
	2	< 150	150-160	160-170	171-180	> 180
Douglas fir	1	< 85	85-94	95-110	111-120	> 120
	2	< 125	125-134	135-145	146-155	> 155
Spruces	1	< 55	55-64	65-95	96-105	> 105
	2	< 130	130-139	140-150	151-160	> 160

5.3.5 Regional-scale assessment: obtaining and interpreting statistics on forest harvesting/wood supply (Steps 6 and 7)

For the regional-scale assessment method suggested in this chapter to work, in addition to managing forest areas by containing consistent rotation ages, it is also important to ensure levels of harvesting (in terms of areas thinned and felled or stem volume extracted) are stable, or only increasing at a rate of no more than a few percent compared to a historical baseline level. The reasons for this have been discussed at length in Chapter 3 and Appendix 2. The method thus also requires data on the extent of forest harvesting taking place in the defined forest area, both historically and going forward from the present. This data may be available from forest inventories as reported forest 'removals', meaning in this context the amount of standing tree stem volume felled each year in tree harvesting activities. Alternatively, statistics may be compiled on the supply of harvested wood to local wood processing plants in the region (sawmills and board, paper and pellet mills). This data is often reported in units of standing stem volume expressed in cubic meters but may sometimes be reported as stem or tree biomass (fresh or dry) or carbon. These statistics would need to be available as a time series, to enable confirmation that harvesting rates are not increasing rapidly above historical levels.

A fully elaborated system would allow for certain exceptions, such as extraction of biomass as part of salvage logging, or management to adapt forests to increase their resilience and reduce the risk for larger carbon losses from long-term climate change and natural disturbances later in time. It may also be possible to extend the method to allow for assessment of possible changes to forest management at large scale, to support planning decisions aiming towards achieving an overall carbon gain over a forest landscape. The general approach has been illustrated when applied on a site-by-site basis in Section 5.2. These are very important aspects of a fully developed method that are not explored above and further development is beyond the scope of this report.

Verification
Published silvicultural guides may provide evidence to validate/verify parameters such as rotation ages and thinning practice. Future forest inventory reports can be analysed to confirm the stability of these parameters over time. Comparison of estimates of long-term mean carbon stocks with estimates reported in forest inventories has already been discussed in Section 5.3.3. Regional administrations and/or commercial companies could collect operational data on rotation ages and thinning practice where biomass is sourced.

5.4 National/regional-scale monitoring

This method would typically be applied at a large scale and could form a component of a programme for compiling and reporting national statistics on forests. It could also work with forest inventories collected for operational purposes by forest management agencies and commercial forestry companies. The method is complementary to regional-scale assessment described in Section 5.3. The main steps in the method involve:
1. Identifying the region of forest where the method is to be applied and obtaining relevant forest statistics.
2. Analysing the statistics to derive indicators that can be used to monitor effects of management on carbon stocks.
3. Possibly using the indices to inform decisions about forest management, especially harvesting.

The method aims to work as far as possible with data collected routinely as part of forest inventories, but some additional statistics may need to be measured, depending on the thoroughness of the current scope of inventories being referred to. Step 1 is discussed briefly in Section 5.4.1. The derivation of useful indicators from inventory data and their application to monitoring and planning forest management (Steps 2 and 3) are described in Section 5.4.2.

5.4.1 National/regional-scale monitoring: obtaining relevant forest inventory data

This method works as much as possible with data usually collected in forest inventories. The first step is to find inventory data for a relevant region. For example, suppose there is an interest in understanding the effects of forest management and harvesting in areas of forest within quite a large region, perhaps even a whole country. The forest management and harvesting activities in this region are likely to be carried out by multiple actors. Hence, typically, this method provides information about the combined effects on forests of all the actors operating within the region. It may be less suitable for assessing the effects contributed by the operations of an individual actor. If forest inventory data are reported spatially, or broken down into different sub-regions, then it may be possible to select data for sub-regions which have most relevance for the locations where a particular actor is operating, whilst excluding less relevant areas. Several types of inventory data are required for this method:

- The standing 'tree stock', measured as the stem volume of standing trees.
- Forest increment, measured as the annual growth of tree stem volume.
- Forest 'removals' (tree volume harvested, see Section 5.3.5).

These data are often reported in units of standing stem volume expressed in cubic metres but may sometimes be reported as stem or tree biomass (fresh or dry) or carbon. The method also requires some data that is not commonly reported according to current forest inventory procedures, specifically, the mean age of trees felled in harvesting activities. Collecting this data is likely to involve an extension of existing forest inventory procedures. There are several possible ways such data could be obtained, depending on how pre-existing inventory procedures might most easily be adapted, and on whether statistics are also collected on wood flows in timber and biomass supply chains. Further discussion about possible methodologies is beyond the scope of this report.

5.4.2 National/regional-scale monitoring: analysis and interpretation of forest indicators

The forest inventory data described above can be used in combination to monitor for effects on forest carbon stocks of forest management activities in the region of interest:

- Standing stem volume can be used as a proxy indicator of tree (and forest) carbon stocks.
- The amount of stem volume being felled ('removals') can be used as an indicator of the intensity of tree volume and biomass harvesting and extraction.
- Standing stem volume can be used in combination with increment and removals (see above) to calculate the 'harvest fraction' and the 'growth:drain ratio' (see discussion below).
- The mean age of trees removed in harvesting can be used as an indicator of rotation age and the intensity of thinning.

Harvesting fraction represents the proportion of standing tree stem volume felled each year, which may also be expressed as a percentage. Growth to drain ratio is defined as the ratio between annual tree stem growth (increment) and tree stem volume felled each year. These statistics are two further indicators of the intensity of volume and biomass harvesting. Management consistent with sustainable yield (see Box 3.1) requires the harvest fraction to be small, typically no more than a few percent, and growth to drain ratio needs to greater than or equal to 1 (harvesting does not exceed growth).

Biomass supplied from forests is unlikely to be associated with practices that cause sustained carbon losses if the forest areas producing the biomass meet the criteria based on the above indicators as listed in Table 5.16.

Table 5.16
Criteria for biomass to be considered sustainable in carbon terms based on indicators derived from national/regional-scale monitoring.

Indicator	Criterion
Standing stock of stem volume	Ideally stable or increasing. Where decreasing, need to demonstrate link to very uneven forest age distribution. Long-term decreases in stocks indicate high risk of diminishing carbon stocks.
Annual stem volume harvest	Stable, or at most small increase compared with historical harvesting rates (a few percent). Linked to growth:drain ratio criterion (see below).
Harvest fraction	No more than a few percent at most.
Growth:drain ratio	Generally greater than or equal to 1, or with only short episodes where ratio drops below 1.
Mean age of removals (harvested trees)	Stable, showing no trend to younger or older ages. However, cycles in mean age may occur when the forest age distribution is uneven and thinning is commonly practiced (there may be a variable balance between younger thinnings and older final harvests).

It is very important to stress that the above indicators of the effects of forest management and harvesting on carbon stocks are used most effectively when considered together 'in concert'. Referring to any one individual indicator, or any one criterion listed in Table 5.16, is unlikely to be sufficient (see for example discussion in Section 3.2.1). This is supported by theoretical simulations (not presented in this report) which explore the sensitivity of results for these indicators to forest age distribution and different scenarios for forest management.

Similarly to the regional-scale assessment method, a fully elaborated system would allow for certain exceptions in which the above criteria were not always followed. Examples include biomass extraction as part of salvage logging, or management for resilience to reduce the risk of carbon losses from long-term climate change and natural disturbances. It may also be possible to extend the method to allow for assessment of possible changes to forest management at large scale, to support planning decisions aiming towards achieving an overall carbon gain over a forest landscape. These are very important aspects of a fully developed method that are not explored above and further detailed development is beyond the scope of this report.

Verification

As already highlighted earlier in this chapter, the proposed methods require further development. In the case of the method described above, significant testing is needed to verify that the method works reliably across a range of circumstances.

5.5 Feedstock-based methods

The methods described in Sections 5.2 to 5.4 are founded on the analysis and interpretation of reliable forest inventory data. However, such data is not collected systematically or comprehensively in all parts of the world. In these situations, relevant data may be incomplete or entirely lacking. The methods also require political and administrative cooperation amongst public agencies, landowners, and biomass producers and consumers. Cooperation between different countries may be needed in some contexts. It could prove challenging to put in place the frameworks needed to work with the methods because of these requirements.

An alternative approach avoiding the requirement to directly assess or monitor forest areas would involve biomass consumers monitoring and controlling the use of different types of forest biomass feedstocks for different purposes. A specific objective could be to ensure that harvested wood grades that meet the quality requirements for certain wood products (e.g. durable structural products) are directed to such uses, while other wood grades can be directed to the production of pulp, chemicals, biofuels, etc. It should be noted that harvested wood is often already prioritized in this way because it makes economic sense to do so.

Two broad methods for screening forest biomass feedstocks in this way have been suggested, the first involving detailed decision flowcharts and the second involving a simpler list of feedstock criteria. These methods are explored in Sections 5.5.1 and 5.5.2, respectively.

A first step involves classifying biomass sources according to different types of woody biomass feedstock, such as 'industrial residues' and 'small roundwood/pulpwood'. A set of suggested possible 'classes' of forest biomass feedstocks is given in Table 5.17. Each feedstock class is defined in more detail in Box 5.3. Also in Table 5.17, an indicative assessment of carbon payback time is assigned for biomass originating from each forest class (see discussion of payback times in Section 5.2.2 above and Sections 3.2, 3.4, and A2.5).

Because biomass consumption is considered here, it is necessary to define its intended use. In the context of this report, the main concern is the use of biomass as a feedstock for energy generation (i.e. bioenergy). Hence, the classification of biomass feedstocks in terms of carbon payback times in Table 5.17 relates specifically to these feedstocks being used for bioenergy. The classification is based on those proposed in assessments by JRC (2014), Lamers and Junginger (2013), Matthews et al. (2018) and Giuntoli et al. (2022). However, the classification of particular forest biomass feedstocks is not always consistent across these assessments and the classification proposed in Table 5.17 is also not completely consistent with these earlier assessments. Various definitions exist for the biomass feedstocks in Table 5.17; the specific definitions assumed in this report are given in Box 5.3.

Table 5.17
Classification of forest biomass feedstocks (for bioenergy use only) in terms of classes of wood products and carbon debt payback time. Classes of biomass feedstock are defined in detail in Box 5.3.

Biomass feedstock	Payback time: range (most likely value)	Feasibility
Wood from post-consumer wood waste	Short–Very long (Short)	
Wood from industrial residues	Short–Very long (Short)	
Stem tips/tops and branch wood left after stemwood harvesting ('forest harvest residues')	Short–Very long (Short)	
Complete trees or parts of stems not wanted for fibre (sometimes forming part of 'forest harvest residues')	Short–Very long (Medium)	
Small roundwood ('pulpwood') produced as a side product of sawlog harvesting	Short–Very long (Short)	
Complete trees ('pre-stemwood thinnings')	Short	
Complete trees or stems ('pulpwood thinnings')	Medium–Long (Medium)	
Complete trees or stems ('sawlog thinnings')	Long–Very long (Very long)	
Wood suitable for use as structural timber	Long–Very long (Very long)	
Wood from tree stumps including roots	Short–Very long (Long)	

Box 5.3 Definitions assumed for biomass feedstocks and related quantities

Complete trees: The woody parts of the above-ground biomass of a tree, i.e. stemwood plus branches and bark but usually excluding foliage.
Forest harvest residues: The woody biomass of trees discarded in the forest following the harvesting of the stemwood of trees that is unsuitable for technical or economic utilisation for the manufacture of sawnwood, wood-based panels, or paper. Forest harvest residues typically consist of branchwood, stem tops, defective tree stem pieces, and stem offcuts, but excluding tree stumps and roots.
Industrial residues: Wood generated as a by-product by the wood processing and associated industries, including offcuts, sawdust, and sawmill chips, which may be disposed of or used as a feedstock for wood-based panels or bioenergy.
Pre-stemwood size thinnings: Small, very young trees cut down during the early growth of dense regenerating stands, to prevent trees from overcrowding one another (suppressing growth), and to improve the spatial distribution of trees. The trees may have very little or no wood of stemwood dimensions (see 'Stems/stemwood').
Pulpwood: See small roundwood.
Small/young/pulpwood size thinnings: Trees harvested as thinning, generally early in the life cycle of forest stands, with a total stemwood volume of less than, for example, 10% material of sawlog dimensions. It must be stressed that this class is intended to represent trees that, if harvested, have stems that are of a size suitable for utilisation principally as pulpwood. A separate class of 'pulpwood' represents harvested stemwood converted to pulpwood (see above and the definition of small roundwood below).
Roots: In the context of this discussion, the main/coarse structural roots of a tree.
Roundwood: All stemwood, with or without bark, including wood in its round form, or split, roughly squared, or in other form, which is extracted during harvesting operations in a forest. For the purposes of this project, roundwood can be regarded as the same as stemwood, as defined below.
Sawlog: Roundwood of sufficient dimensions to be sawn lengthways for the manufacture of sawnwood.
Sawlog size thinnings: Trees of bigger dimensions harvested as thinnings, with a significant proportion of material of sawlog dimensions (compare with 'Small/young/pulpwood size thinnings').
Sawn timber/sawnwood: Solid wood sawn into straight lengths of varying shapes, generally for structural applications, including roof beams, fencing, doors, and frames, also some shorter-lived products such as pallets.
Small roundwood: Small roundwood may be defined as stemwood of small diameter, which does not fall into the category of sawlog, but which may typically be used to make fencing, or chipped to make wood-based panels, pulped to make paper, or used in bioenergy applications.
Stems/stemwood: While other definitions exist, in this context, this is woody material forming the above ground main growing shoot or shoots of a tree or stand of trees, including all woody volume above ground with a diameter greater than 7 cm over bark, and wood in major branches where there is at least 3 m of 'straight' length to 7 cm top diameter.
Stem tips/tops: The top of the main stem of a tree, with a diameter smaller than 7 cm over bark, not meeting the definition of stemwood.
Stumps/tree stumps: The stemwood left above ground after a tree is felled, generally still attached to the roots.

Wood-based panels: A set of products manufactured from a composite of wood veneer sheets, chips, particles, and/or sawdust, generally combined with resins, including plywood, particle board, oriented strand board, and fibreboard.

A classification system based on biomass feedstocks has the advantage that biomass consumers are able to identify which types of biomass source they are using relatively easily. It could be used where it is challenging to track biomass sources back to the precise forest areas from which they originate, and document how those forest areas are being managed. Hence, in principle, monitoring the biomass used for bioenergy could be relatively straightforward to implement. However, the carbon payback times associated with a given biomass feedstock can be very variable. For example, if forest harvest residues are not extracted for use as bioenergy, they may be burnt as waste as part of preparing the forest site for regeneration and replanting of successor trees. Alternatively, the residues may be left to decompose, either on the site or piled up at the roadside. From the perspective of carbon payback time, the former possibility would involve little impact on the net forest CO_2 balance, while the latter could involve a carbon payback time of varying duration. The payback time may be quite short if the forest harvest residues are small sized (such as branches and small stem defects) and climatic conditions are conducive to rapid decomposition of biomass (generally warmer and wetter conditions).

Alternatively, a long payback time would be associated with residues of large dimensions (such as large lumps of defective tree stems left on site) or climatic conditions too dry or too cold for rapid decay to occur. In some situations, removing forest harvest residues could prevent the cycling of nutrients back to the soil, leading to a depletion of site fertility and reduced forest productivity. Any carbon debt created in these circumstances would never be fully repaid, implying a 'Very long' carbon payback time (although the unpaid debt may be small). These different scenarios for one example feedstock illustrate how an approach to identifying carbon impacts resulting from using bioenergy sources classified in terms of biomass feedstocks can be unhelpfully simplistic.

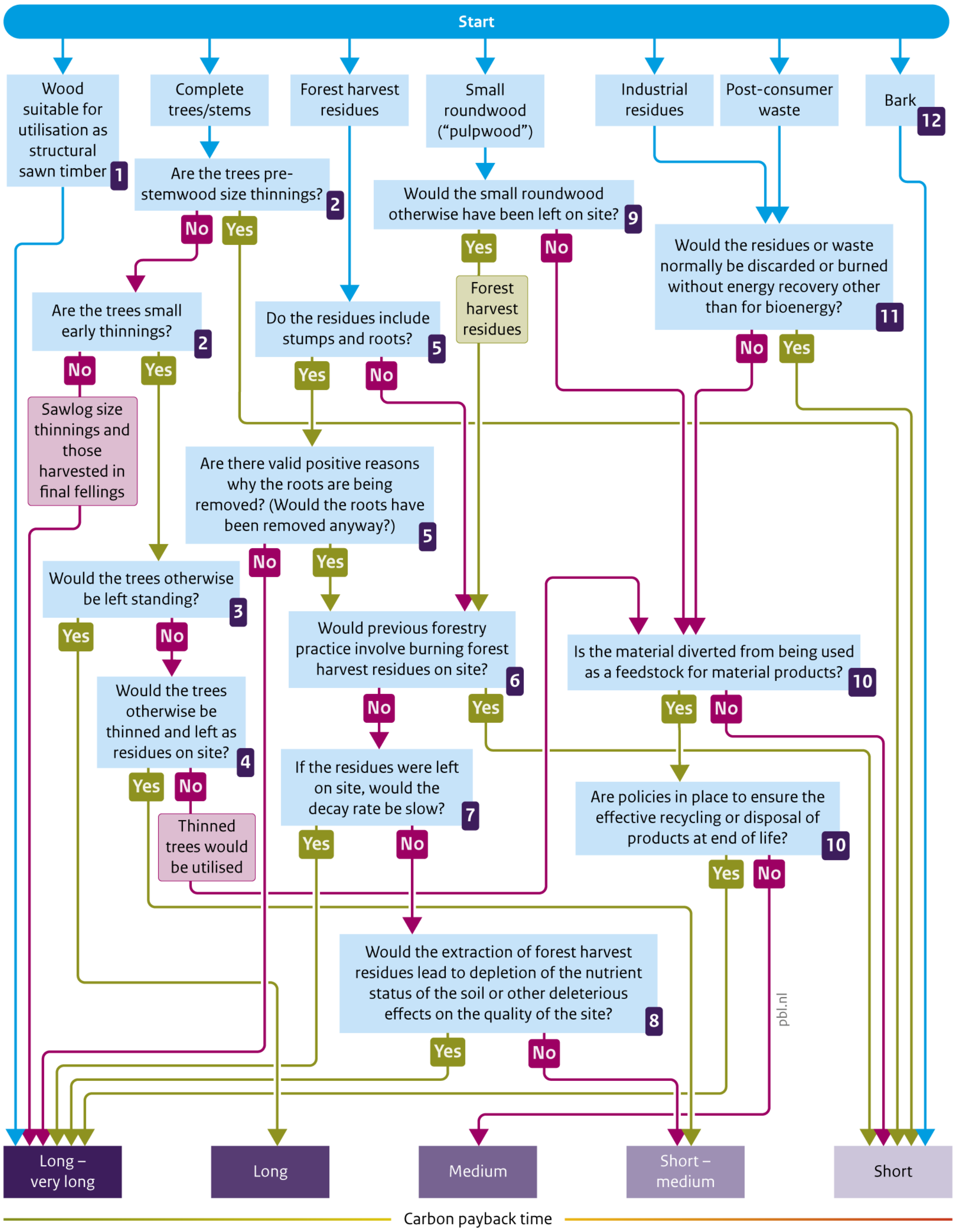
A further important example is the general class of 'primary woody biomass' referred to in EU legislation, as discussed earlier. More generally, examples in Sections 3.1 to 3.5 and Appendices 2 and 3 show that the carbon payback time associated with harvesting and utilising forest biomass for any end use can be very variable and is related strongly to the kinds of interventions made in forest management to produce the biomass, regardless of the primary biomass feedstock involved. This is reflected in the generally wide ranges in payback times shown for classes of biomass feedstock in Table 5.17. JRC (2021b) arrived at similar conclusions about the variability in carbon payback times for biomass feedstocks, observing that, given the wide variety of situations across Member States, it was difficult to univocally define and meaningfully implement such restrictions in EU legislation — the risk would have been to complicate compliance without necessarily fostering further sustainability or biodiversity conservation.

5.5.1 Biomass feedstock 'decision tree'

The most refined and elaborated method for characterising biomass feedstocks in terms of carbon payback times involve decision flowcharts such as the example illustrated in Figure 5.2. This example is adapted from a previous assessment by Matthews et al. (2015). The decision flowchart is supported by a set of numbered notes in Box 5.4, the numbers referring to labels at various points in Figure 5.2. The flowchart is relatively detailed and places what might be regarded as maximal constraints on the use of forest biomass feedstocks for bioenergy. It is uncertain whether some of the details are necessary to ensure that bioenergy derived from forest biomass sources involves short or medium carbon payback times. For example, including checks on whether certain low value feedstocks might be diverted from possible use for other purposes, such as for wood-based panels or paper, could be viewed as addressing hypothetical scenarios. However, testing for these situations could be kept relatively simple, for example possibly by looking at relative prices attracted by biomass used as inputs to different supply chains.

Figure 5.2

Assessing carbon payback times of forest bioenergy sources



Source: Forest Research UK

Box 5.4 Notes to Figure 5.2

1. A presumption is made here that harvested wood suitable for use as structural sawn timber in long-lived products should not be used for bioenergy (see Section 3.3). From a practical perspective, the definition of sawn timber is generally well established and relevant feedstocks should be relatively straightforward to identify.

2. These questions are aimed at identifying situations in which forest bioenergy is being produced from 'Pre-stemwood size thinnings', 'Small/young/pulpwood size thinnings', and 'Sawlog size thinnings'. Removal of the first two categories of thinnings from growing stands of trees can be important for the improvement of stands later in their rotations. Thinning may be conducted for environmental reasons (such as avoiding overstocking and the suppression of understory vegetation or potential loss of habitats), and/or from the perspective of wood supply (such as favouring the subsequent growth of better-quality trees for wood supply). The growing stands of trees can recover quickly from the removal of Pre-stemwood size thinnings, so that negative impacts on carbon stocks from thinning are likely to be short term. The removal of Small/young/pulpwood size thinnings is likely to diminish carbon stocks in forest stands, compared to the option of not thinning, at least temporarily. However, stands left unthinned can become overgrown and unstable, and the supply of sawlogs later in the rotation can be suppressed. Thinnings of older and bigger trees, and those harvested in final fellings, usually contain a significant proportion of stemwood suitable for conversion to sawn timber for longer-lived wood products as well as pulpwood; utilisation of these trees for bioenergy instead of non-energy wood products with long service lives can have significant negative impacts on carbon stocks (see Section 3.3). Definitions would be needed for 'Pre-stemwood size thinnings', 'Small/young/pulpwood size thinnings', and 'Sawlog size thinnings', which may require local interpretation (see suggestion in Box 5.3). It can be complicated to evaluate the effects of thinning on carbon stocks, particularly in the medium and longer term. This is because of the interactions between removal of trees in thinnings and the subsequent growth of the remaining trees, as outlined above. In addition, it may be necessary to allow for factors such as risks from fire and disease which may sometimes be mitigated by thinning. See also Box 2 in DESNZ (2023).

3. In some situations, lack of markets for Small/young/pulpwood size thinnings may simply result in thinning not being undertaken and the trees being retained in forest stands and continuing to grow. This question is aimed at identifying such situations. This can have consequences for the subsequent development of stands as outlined in Note 2. See also discussion under Note 4.

4. In some situations, early thinning of small trees (Pre-stemwood or Small/young/pulpwood size) may be carried out to improve forest stands, even when there are no markets for the thinnings, and the trees may be discarded on site in the forest, rather than leaving stands unimproved by not thinning. This question is aimed at identifying such situations. There may be some practical challenges to identifying what the alternative (or counterfactual) action might be to the felling and extraction of the thinnings (such as trees left standing, or 'thinned to waste' and left to decompose in the forest). Data on recent/current thinning practices in the forest region producing the trees might support such an assessment.

5. A presumption is made here that the extraction of tree stumps and roots should be avoided, because of the disruption this would cause to the site and soil, and resultant impacts on soil

carbon stocks. However, there may be situations in which tree roots are removed as part of conventional practice. An example might involve actions to control an endemic tree disease affecting certain sites. These questions are aimed at identifying relevant situations. However, the definition of 'valid positive reasons why roots are being removed' would need to be carefully stated and justified. Ensuring adherence to wider principles of Sustainable Forest Management is relevant in this context (see Section 5.9).

6. In some forest areas, it is conventional practice to burn harvest residues on site, as part of preparation for restocking through tree regeneration or replanting. If this practice is changed so that harvest residues are extracted instead of burnt, this should have negligible impacts on net CO_2 emissions. This question is aimed at testing for such cases. There could be some practical challenges to identifying what the alternative or counterfactual fate would be for the forest harvest residues (discarded and left to decay in the forest or possibly burnt on site). Data on recent/current practices on the treatment of residues in forest regions might support such an assessment.

7. If the most likely alternative or 'counterfactual' fate for forest harvest residues is to be left to decompose in the forest, instead of being utilised for bioenergy, then two main factors influence the carbon payback time: the physical dimensions of the pieces of biomass material and the rate at which dead biomass is broken down by processes of decay. A key factor to be considered is the time it takes for biomass to decay, often described as the 'half-life' of the dead biomass. A slow rate of decay equates to a long half-life and a 'Long' or 'Very long' carbon payback time, whereas a fast rate of decay equates to a short half-life and a 'Short' or 'Medium' payback time. Essentially, the use of biomass with a long half-life for bioenergy needs to be avoided, where 'long' requires definition. Several factors influence the half-life value, notably related to climate (temperature and rainfall/moisture).

8. Forest productivity can be diminished by the excessive removal of harvest residues, particularly if this includes tree foliage. The nutrient status of the soil can be affected, as can soil acidity. The physical structure of the soil may be damaged if harvest residues (such as mats of branch wood) are not present to protect it from heavy machinery, and erosion risk is increased if soil is left bare. This question is aimed at testing for such situations. There are likely to be practical challenges to assessing and managing such wider sustainability impacts of extracting forest harvest residues. Locally applicable protocols (if developed) would support decisions on whether to extract forest harvest residues, and in what quantities. Ensuring adherence to wider principles of Sustainable Forest Management is relevant in this context (see Section 5.9).

9. There may be circumstances in which trees are felled primarily for the supply of sawlogs, while local uses do not exist for any associated small roundwood, which is, therefore, discarded and left in the forest, effectively forming part of the residues of forest harvesting. This question is aimed at identifying where these situations are occurring. There may be some practical challenges to identifying what the alternative or counterfactual action might be to utilising the small roundwood other than for bioenergy (used for another purpose, discarded and left to decay in the forest or possibly burnt on site). Data on recent/current thinning practices in the forest regions producing the wood may support such an assessment.

10. It is assumed here that opportunities to avoid greenhouse gas emissions through wood product substitution effects are higher in magnitude when: (a) forest bioenergy is supplied as a co-

product alongside other non-energy wood products (see Appendix 1); and (b) the use of harvested wood to manufacture non-energy wood products is not diverted for use as bioenergy (see Section 3.3). However, there are likely to be some exceptions. In particular, it is assumed that the use of non-energy wood products may not lead to significantly higher avoided greenhouse gas emissions if the products are not recycled carefully at their end of life (Matthews et al., 2014b). The answers to these questions may identify the various relevant situations.

11. There could be circumstances in which industrial residues or post-consumer waste could be utilised as a feedstock for the manufacture of certain wood products, such as particle board, rather than being landfilled or burnt as waste without energy recovery. This question is aimed at identifying situations where this might occur (see also Note 10). There may be some practical challenges to identifying what the alternative or counterfactual fate of industrial residues might be if not utilised for bioenergy (landfilled, burnt as waste without energy recovery, used for non-energy wood products). Data on recent patterns of wood utilisation might support such an assessment.

12. A presumption is made here that the use of bark for bioenergy is non-contentious in terms of greenhouse gas emissions and carbon payback times, even in situations where bark is being diverted from non-bioenergy uses.

5.5.2 Biomass feedstock criteria

The simplest method for managing greenhouse gas emissions from forest biomass utilised for bioenergy involves constructing a list of criteria for the consumption of forest biomass feedstocks. Table 5.18 gives an example, adapted from a set of criteria originally developed for the European Climate Foundation (Matthews et al., 2018). It must be stressed that these criteria were intended as an initial proposal, rather than a fully developed and tested solution. Further work would be needed to produce a generally applicable and accepted method.

The feedstock categories in the original European Climate Foundation (ECF) report were defined some years ago and do not align exactly with those in Table 5.17. The feedstock classes in Table 5.18 have been renamed or adapted to show how they relate to Table 5.17 and Box 5.3. Two additional criteria are included in Table 5.18, covering the scale of wood supply from a defined forest area and woody biomass supplied as part of salvage logging. The importance of managing the scale of biomass harvesting has already been discussed for the methods described earlier in this chapter. Specifically, it is important to ensure levels of harvesting (or biomass) supply are stable, or only increasing at a rate of no more than a few percent compared to a historical baseline level (see discussion in Chapter 3 and Appendix 2). Primary biomass feedstocks derived from salvage logging are an example of where a criterion may require careful further development. In the original ECF report, the criterion was defined very openly as, 'favour supplies of wood biomass from salvage logging where a simply calculated but robust estimate of greenhouse gas emissions meets a defined minimum threshold'. For the adapted version in Table 5.18, it is suggested that feedstocks of this origin are treated no different to those from harvesting of standing trees. This is quite conservative, since there is a consequent implicit stipulation that large diameter stemwood be treated in the same way as, 'sawlog thinnings' or wood suitable for use as structural timber. This prevents the use of this material for bioenergy, even if otherwise the material may be burnt as waste on site as part of restocking disturbed forest areas. Salvage logging is discussed further in Section 4.2.1 and Box 5.2.

Table 5.18
Example of criteria for biomass feedstocks utilised for bioenergy, adapted from Matthews et al. (2018). Classes of biomass feedstock are defined in detail in Box 5.3.

Feedstock	Criterion/action
Scale of forest bioenergy use (all feedstocks).	Aim for levels of forest bioenergy use that are well within the long-term sustainable-yield capacity of the supplying forest areas. When setting levels for bioenergy use, take account of the consumption of biomass for other uses (materials).
Wood from tree stumps including roots.	Strongly disfavour supplies of forest bioenergy from stumps including roots.
Wood from post-consumer wood waste.	Strongly favour supplies of forest bioenergy from post-consumer waste wood. Particularly favour such sources where the waste wood would otherwise be burnt or put in landfill without energy recovery. Also favour use of waste wood at levels that do not compete with current levels of consumption of such feedstocks for material uses (e.g. wood-based panels).
Wood from industrial residues.	Strongly favour supplies of forest bioenergy from industrial residues. Particularly favour such sources where the residues would otherwise be burnt as waste without energy recovery. Also favour use of industrial residues at levels that do not compete with current levels of consumption of such feedstocks for material uses (e.g. wood-based panels).
Forest harvest residues, includes complete trees or parts of stems not wanted for fibre.	Strongly favour supplies of bioenergy from fast-decaying forest residues (i.e. apart from stumps including roots or other large residues) provided this avoids levels of extraction of forest residues that lead to high risks of degradation of site/soil quality (e.g. carbon stocks, nutrient status, water balance).
Salvage logging	Treat material derived from salvage logging in the same way as material derived from harvesting of standing trees, according to feedstock type.
Whole tree stems: • Pre-stemwood thinnings' • 'Pulpwood thinnings')	Restrict supplies of forest bioenergy from whole tree stems to small/early thinnings, with the aim of improving the quality of the remaining growing stock. Favor situations in which, otherwise, there would be limited incentives to thin and improve forest stands. Alternatively, favour supplies of wood biomass from small/early thinnings where a simply calculated but robust estimate of greenhouse gas emissions meets a defined minimum threshold.
Small roundwood: • 'Pulpwood' produced as a side product of sawlog harvesting	Favor supplies of forest bioenergy from small roundwood at levels that do not compete with current levels of consumption of such feedstocks for material uses. Particularly favour such sources where the small roundwood would otherwise be burnt without energy recovery or sent to landfill.
Sawn timber: • 'Sawlog thinnings' • Wood suitable for use as structural timber	Strongly disfavour supplies of forest bioenergy from wood feedstocks suitable for use for sawn timber products.
Co-production • Wood from industrial residues • 'Pulpwood' produced as a side product of sawlog harvesting	Strongly favour the supply of forest bioenergy as a by-product of wood harvesting for the supply of long-lived material wood products. However, it is very important to ensure that flanking measures are in place to ensure that other feedstock criteria above are met and to encourage the disposal of material wood products at end of life with energy recovery and/or in a way that ensures low greenhouse gas emissions.

5.6 Full LCA methods

Life cycle assessment (LCA) methods have been introduced in Section 4.4.1. The development of a complete and widely accepted LCA methodology is well beyond the scope of this report. There is a vast body of literature on LCA methods applied to forest management and biomass use and there are already several reviews, as discussed in Chapter 4. It remains the case that, while there are established and widely accepted general methodologies for LCA studies, there is no such widely accepted standard for application to questions related to biomass and bioenergy supply such as considered in this report. Any such methodology is likely to be complex and could be very costly to implement in the forestry and biomass sectors. LCA studies of clearly identified case studies of forest biomass supply chains could support the other methods described in this chapter, providing spot checks as part of verification.

5.7 Assessment of technical methods

It has already been stressed several times that the technical methods described in this chapter are proposed tentatively and further development and wider discussion is needed before they can be confirmed as suitable for use. However, a preliminary assessment of the methods is possible in terms of their:

- Effectiveness for informing understanding and decisions about the use of forest biomass sources and the effects on biogenic CO_2 emissions.
- Efficiency in terms of the administrative burden placed on biomass suppliers and consumers to demonstrate correct application of the methods and compliance with good practice.
- Readiness for putting into practice, for example, how fully developed methods are and whether data and expertise are generally available, or more technical investment is required.

Such an assessment is provided in Table 5.19, and overview of the key conclusions about methods is given in Table 5.20. The main conclusions that may be drawn from the assessment are:

- The methods are at varying stages of development and readiness for supporting policies aimed at encouraging biomass use with low associated biogenic CO_2 emissions. All require at least some further development.
- There are trade-offs between the effectiveness of methods in supporting the above aims and the administrative burdens and costs likely to be placed on biomass suppliers and consumers.
- There may be some challenges to achieving general acceptance of any particular method if it were to be proposed for general use. These can be partially addressed by transparent reporting of data, calculations and results.

Table 5.19
Preliminary assessment of technical methods described in this chapter (Sections 5.2 to 5.6)

Method	Assessment
Site-by-site assessment	*Effectiveness: Exceeds requirements*. Enables detailed assessment of the current status of forest stands/areas, options for adjustments to management and likely effects on carbon stocks. Directly provides data to assess opportunities for increasing biomass supplies in conjunction with a carbon gain, as well as where there are risks of incurring a carbon debt. Timing of carbon stock changes can be allowed for if required. Verification is straight-forward if implementation is fully documented and on-site checks are performed. *Efficiency: Significant administrative burden.* Requires detailed and most likely spatially explicit data on the composition and management of individual forest stands/areas. Assessments involve site-by-site calculations of projected biomass supply levels and related carbon stock changes, implying the need to develop detailed and transparent forest management plans. However, management may not always be fully under the control of those responsible for the biomass supply chains. Transparent documentation and stakeholder consultation is also likely to be necessary to gain acceptance of the assessments. Strictly, verification would require site visits to check that management on the ground is consistent with the documented plans. A registry of data, analysis, and verification would need to be maintained. *Readiness: Significant further development required.* This method has not been fully developed and trialled to establish whether it is feasible. An administrative system would be needed for managing a large, detailed, spatially explicit data set. At present, a generally accepted calculation methodology has not been developed, and little work has been done to produce robust and generally accepted default values for use in calculations. The whole process requires strong forestry and carbon expertise.
Regional-scale assessment	*Effectiveness: Fully meets requirements.* Enables assessment of pre-existing forest management of defined forest areas and levels of biomass supply. Also permits significant changes to management to be identified and the assessment of likely effects on forest carbon stocks. Provides some information to inform decisions about planned management of forest areas. *Efficiency: Moderate administrative burden.* Requires the collection of reliable forest inventory data sets to be routinely performed, maintained over time and made publicly available. Transparent documentation and stakeholder consultation is also likely to be necessary to gain acceptance of the assessments. A registry of data, analysis, and verification would need to be maintained. *Readiness: Significant further development required.* The description of data and methods provided in this report is tentative and further work is needed to produce robust and generally accepted methodology. Although forest inventory data is collected routinely in some regions, current coverage is not comprehensive at global scale. Field sampling intensities may need to be enhanced to provide sufficient data for robust analysis and estimation of management parameters such as rotation ages. The whole process requires strong forestry and some carbon expertise.

Method	Assessment
National/regional-scale monitoring	*Effectiveness: Fully meets requirements (monitoring), partially meets requirements (decision making).* Enables monitoring of forest areas at relatively large scale to check whether key parameters such as levels of harvesting, growth:drain ratio and mean age of harvested trees are stable, or exhibit step changes or trends. Stable or very slowly changing parameters provide assurance that there is a low risk of a carbon debt occurring; significant changes in parameters suggest risks and should trigger further investigation. The method also provides broad indicators that can guide management decisions at a large scale (e.g. typical tree harvest ages and existing levels of wood supply). However, the method does not help inform decisions on how to manage forest areas for positive effects on carbon stocks in conjunction with increased biomass supply. *Efficiency: Small to moderate administrative burden.* The method involves relatively straightforward analysis of conventional forest inventory data, most of which is collected as part of established inventory protocols. The method could thus be implemented as part of established forest inventory reporting, provided data *is* available and sufficient for analysis. Transparent documentation and stakeholder consultation is likely to be necessary to gain acceptance of the assessments. However, if the data and analysis are documented and published, this may be sufficiently transparent to serve as verification, because it is relatively easy to understand and check the methods and details. A system for public reporting of data, analysis, and verification would need to be maintained. *Readiness: Moderate further development required.* The method can be implemented, at least at large scale, in regions where forest inventory data are already collected. Application of the method at sub-national scale may require field sampling intensities to be increased to ensure robust characterisation of parameters. Some additional field or operational data collection may be needed to enable reliable estimation of harvest ages. The process builds upon existing forestry expertise, with some understanding of forest carbon dynamics.

Method	Assessment
Feedstock-based methods	*Effectiveness: Just about fit for purpose.* Does not provide an explicit assessment or check of the effects on forest carbon stocks in response to supplying biomass from forests. Instead, restricting the use of harvested wood for bioenergy to certain feedstocks implicitly reduces the likelihood of significant carbon stock losses in forests from bioenergy supply and use. The method also implicitly provides guidance to support decisions about which biomass feedstocks to use and which to avoid for consumption as bioenergy. *Efficiency: Relatively small administrative burden.* Requires biomass feedstocks used for bioenergy to be monitored and reported. Also requires verification that levels of supply of biomass from forests are not rapidly increasing. This data may already be collected as part of forest inventories or as operational data collected by biomass suppliers and consumers. There are existing examples of registries for reporting relevant data, analysis, and verification. *Readiness: Modest further development required.* Likely to involve some extensions to existing examples of protocols for regulating use of biomass feedstocks for bioenergy. Some improvements or refinements may be needed to definitions of feedstocks in existing protocols.
Full LCA methods	*Effectiveness: Fully meets or exceeds requirements if applied correctly.* LCA methods can provide a wealth of transparent information about the carbon or greenhouse gas balance of an existing or planned biomass supply chain, including effects on carbon stocks in forests supplying the biomass. For example, LCA can reveal where the 'big numbers' and sensitivities occur in supply chains, and inform decisions about future forest management and biomass feedstock processing and use. However, it is essential that the correct methods are applied, for example the LCA goal and question must be defined appropriately, and the LCA methods are consistent with the goal and question. *Efficiency: Significant administrative burden.* LCA studies of forest biomass supply chains are complex and costly to carry out. They require large and detailed data sets on forest composition and management, on the details of biomass processing and supply chains and reliable emissions factors to support calculations. Modelling of forest carbon dynamics (in response to decisions about biomass harvesting/extraction) can be complex. Transparency is vital in LCA but requires significant effort to fully document assumptions, calculations, and ultimate results. *Readiness: Well developed but no consensus on a widely applicable methodology.* General LCA methods have been in existence for decades and are at an advanced stage of development. However, currently, there is no widely accepted and general method for allowing for carbon dynamics in vegetation systems forming part of biomass supply chains, notably regarding the timing of when emissions and sequestration occur. This is still under discussion, see Section 4.4.7. There is a diversity of views on how to do this and, so far, a consensus on a standard methodology is proving elusive. LCA studies of forest biomass supply chains require expert knowledge and skills that are not widely available, particularly concerning biogenic carbon dynamics and how to include them in LCA calculations.

Table 5.20
Overview of preliminary assessment of technical methods described in this chapter (Sections 5.2 to 5.6).

Method	Effectiveness	Efficiency	Readiness
Site-by-site assessment	Exceeds requirements	Significant administrative burden	Significant further development required
Regional-scale assessment	Fully meets requirements	Moderate administrative burden	Significant further development required
National/regional-scale monitoring	Fully meets requirements (monitoring)[1] Partially meets requirements (decision making)[2]	Small to moderate administrative burden	Moderate further development required
Feedstock-based methods	Just about fit for purpose (monitoring and decision making)[1,2]	Relatively small administrative burden	Modest further development required
Full LCA methods	Fully meets or exceeds requirements if applied correctly	Significant administrative burden	Well developed but no consensus on a widely applicable methodology for application to bioenergy systems

[1] Application to monitoring effects of management and biomass harvesting on carbon stocks.
[2] Application to supporting forest management decisions including harvesting and supply of biomass feedstocks to processors.

5.8 Biomass sources: classes of agricultural biomass

The focus of this report is on understanding the potential carbon impacts of utilizing forest biomass sources. However, some discussion of agricultural sources of biomass is appropriate, particularly to identify the similarities and differences between agricultural and forest biomass sources in terms of potential impacts on carbon stocks and net CO_2 emissions.

Quantifying the carbon impacts from use of agricultural biomass for bioenergy is generally simpler than for forestry biomass. Agricultural crops are generally non-woody annual species, with residues that decompose quickly, unlike forests, that grow over decades or centuries and whose residues can take decades to decompose. Thus, the temporal dynamics of carbon fluxes are much less complex in agricultural systems. Nevertheless, impacts on soil carbon stocks (positive or negative) can continue for decades or even centuries, until new equilibrium is reached. Additionally, agricultural biomass feedstocks are far more diverse than forest biomass sources, and the bioenergy products and the conversion processes involved are also more diverse than for forest bioenergy, so counterfactual scenarios can be complex to characterise.
Table 5.21 gives a summary of the main types of agricultural biomass sources and their potential or typical carbon impacts.

Table 5.21
Main types of agricultural biomass sources and their typical impacts

Biomass type	Examples	Typical carbon impact
On-farm residues otherwise retained in field.	Crop straw, dairy manure	Debt
On-farm residues otherwise burnt.	Crop straw	Neutral
Purpose-grown annual crop.	Canola, maize	Neutral
Purpose-grown perennial crop.	Miscanthus, eucalyptus	Gain
Purpose-grown perennial crop on marginal land.	Miscanthus, eucalyptus	Gain
Post-farm gate residues otherwise incinerated or applied to land.	Nut shells, abattoir waste	Neutral
Post-farm gate residues otherwise landfilled.	Food waste	Possible small debt, counteracted by avoided methane (CH_4) emissions, with a net result of reduction in emissions.

A diverse range of biomass types associated with agriculture can be used for bioenergy. These include by-products of crop and livestock production systems, such as straw and manure, and by-products of processing, such as nut shells, abattoir waste, and dairy effluent. Additionally, biomass can be purpose-grown, such as sugar, starch, and oilseed crops used for ethanol and biodiesel production, or perennial grasses and short-rotation woody crops that can be combusted for heat and electricity or used as feedstock for producing liquid and gaseous fuels. The likelihood of a carbon gain or carbon debt differs between these feedstock types as well as depending on local factors such as soil properties, climate, and historical land use.

Even though manure, straw, and compost decompose quickly when used as soil amendments, diversion to bioenergy will reduce the organic matter input to soil, so can deplete soil carbon stocks (e.g., Blanco-Canqui, 2013). Organic matter inputs play a critical role in supporting the chemical, physical, and biological fertility of soils, increasing water-holding capacity and reducing erosion risk, so diversion of organic inputs to bioenergy can also indirectly reduce soil carbon levels through lower plant growth and topsoil loss. However, some bioenergy options can be integrated with agriculture in ways that minimise carbon losses. For example, anaerobic digestion of manures to produce biogas, while also producing a digestate by-product that can be applied to soil as a nutrient-rich organic amendment (Nyang'au et al., 2022). Pyrolysis or gasification of biomass to produce bioenergy also produces biochar; when biochar is used as a soil amendment or in long-lived products such as asphalt and concrete, the biomass carbon persists for decades to thousands of years, and biochar applied to soil can increase plant productivity (Joseph et al., 2021). As already discussed in detail for forest biomass sources, the difference in soil carbon stocks between the 'biomass/bioenergy scenario' and the 'counterfactual scenario' for land use/management determines the magnitude of the carbon debt or gain. Returning digestate or biochar to the site of biomass removal will reduce any carbon debt. Furthermore, anaerobic digestion or pyrolysis of manures can avoid emissions of methane and ammonia, and biochar application to soil can reduce soil emissions of nitrous oxide, thus providing additional climate benefits.

In the case of purpose-grown biomass crops, the carbon debt or gain is determined by the effect on carbon stocks in vegetation and soil, which varies depending on the specific biomass crop, the land use history, and management practices (Davis et al., 2013). Converting annual cropland to perennial grass crops such as miscanthus or switchgrass can enhance soil carbon because it increases the organic matter inputs and reduces soil disturbance, decreasing the mineralisation rate of soil organic matter. Similarly, planting biomass crops on degraded land raises soil carbon levels through increased organic inputs to soil. In contrast, draining peatlands for planting bioenergy crops such as oil palm can lead to large losses of soil carbon (Wicke et al., 2008). Thus, biomass production can lead to a carbon debt or carbon gain, depending on whether the soil carbon stocks decrease or increase. Planting short rotation tree crops, such as willow, poplar, or eucalyptus, in place of annual crops or on degraded land, is likely to lead to carbon gain, through an increase in carbon stocks in above and below-ground biomass, as well as an increase in soil carbon (Don et al., 2012; Robertson et al., 2017). Similarly, integrating trees with cropping or grazing by planting shelter belts or riparian buffers, for example, can provide biomass for bioenergy and wood products while increasing the carbon stored on farmland in vegetation and possibly in soil (Hübner et al., 2021; Panwar et al., 2022).

The use of post-farm-gate processing residues for bioenergy will not affect carbon stocks in vegetation or soil if this biomass would otherwise be incinerated without energy recovery, so its use for bioenergy poses no risk of a carbon debt. If the counterfactual fate is landfill, some of the carbon will be released as CO_2 or methane, but a fraction may be stored for at least several decades (Ximenes et al., 2017, 2019). The climate effect of diverting biomass from landfill to use for bioenergy depends on the avoided carbon storage in landfill, as well as avoided methane emissions. As agricultural residues such as food waste decompose quickly and to a much greater extent than woody biomass in landfill, there is likely to be a net climate benefit from diversion away from landfill. If the residues previously had other uses, there may be indirect effects with (negative or positive) consequences for land carbon stocks.

In general, while changes to agricultural practice to enhance biomass production for bioenergy could be introduced relatively quickly, the soil carbon levels can take many years to reach a new (higher or lower) equilibrium. Therefore, supplying biomass for bioenergy from agricultural sources involves similar opportunities and risks to those explored in detail in this report for forest biomass. Although not considered further in this report, we suggest that the carbon impacts of agricultural biomass sources could be quantified and managed using similar approaches to those described for forest-based bioenergy in this chapter.

5.9 Discussion of technical methods

The emphasis in the discussion of technical methods in this chapter has been on the essential technical aspects of any such system, while the policies that would encourage and/or regulate implementation of such systems, and the issues that might be encountered, have not been considered. Some of these issues are briefly discussed below, along with some insights that may be drawn from the discussion of methods above.

Firstly, one of the purposes of this report stated in Chapter 1 and repeated at the start of this chapter should be recalled: to identify the extent to which science offers policy principles/recommendations to minimise the risk of (unacceptably) high carbon debts and net greenhouse gas emissions that occur as a result of using biomass from forests primarily to generate energy. The methods outlined in this chapter aim to characterise forest biomass sources according to their carbon payback times, or directly according to their effects on development of carbon stocks so that, potentially, choices can be made about whether or not to produce and use the biomass, or about what specific purposes to use the biomass for. The method described in Section 5.5, expressed in terms of biomass feedstocks, are intended to offer a technical solution relevant to directly addressing the initial question, particularly with regard to biomass used for energy. The methods based on monitoring and managing forest areas described in Sections 5.2 to 5.4 also offer potential solutions. However, these methods are more general with regard to biomass, and also permit another alternative question to be addressed, specifically: how can forests in a defined region of land be managed to maintain or enhance carbon stocks and carbon sequestration? If plans for forest management are developed with this main objective in mind, then, as a co-benefit, this assures that biomass produced from the forests involves short carbon payback times when considered overall. This offers an alternative focus more broadly on forest management for climate change mitigation, rather than narrowly on understanding the impacts of mobilising biomass resources.

A broader-perspective approach emphasising climate change mitigation through forest management has other potential advantages. Notably, if a narrower focus is taken on carbon impacts of activities involved in producing forest biomass, this is likely to complicate assessing and verifying the nature and magnitude of any impacts. As already discussed, the carbon stock changes related to management in an area of forest will occur in response to a combination of demands made on land and the forests within the region of land. Hence, the carbon stock changes cannot be attributed to a single cause or single actor operating in the region. Even if one actor is able to demonstrate that their specific demands on land and forest are unlikely to cause negative impacts on forest carbon stocks, this would not guarantee that overall negative impacts resulting from the combined demands of all actors will be avoided. The methods outlined in Sections 5.2 to 5.4 get around this problem by focusing on the more holistic objective of managing forests to mitigate climate change through maintaining and enhancing forest carbon stocks, while also mobilising biomass resources, where this is consistent with that principal objective.

Forest management: not just about carbon

Taking a broader perspective ultimately suggests considering impacts of forest management on other ecosystem services in addition to carbon sequestration. Conserving biodiversity is recognised as a key objective alongside climate change mitigation (Giuntoli et al., 2022). Orr et al. (2017) have proposed a system similar to that considered above, but one that addresses several other criteria in addition to carbon. However, multi-criteria assessment of biomass sources is a work in progress.

The methods outlined in Sections 5.2 to 5.4 are appropriate for managing carbon impacts, but would be challenging to extend to apply to biodiversity as well. In this report, forest biomass is assumed to generally originate from forests managed according to the wider principles of Sustainable Forest Management (SFM). Formal standards for SFM did not cover forest carbon stocks and sequestration when originally developed. More recently developed concepts, such as Climate-Smart Forestry and Natural Climate Solutions, explicitly consider both mitigation and adaptation to climate change as well as biodiversity and ecosystem services and may form viable approaches when combined with existing SFM standards. It important to recognise that SFM is intended, *inter alia*, to support the conservation of biodiversity in managed forests. Addressing the need to conserve or enhance biodiversity can involve synergies but also trade-offs with other environmental and socio-economic targets, which need to be considered when developing or implementing climate policies, including providing incentives for greater use of biomass for bioenergy and/or wood products.

Indirect effects on land use

It is also important to recognise the finite scope of the methods described in this chapter. Specifically, the methods are designed to support forest management and woody biomass supply from forests in a clearly defined region of land. Forests outside the defined region are thus not supported, unless similar approaches are being implemented outside the region as well. This could be important because it is possible that efforts to implement forest management measures within one region could indirectly affect how forests outside the region are managed. These indirect effects, generally taken to be market-mediated, are often referred to as 'leakage' and/or 'indirect land-use change' (iLUC).

An example of leakage is a situation in which efforts to protect carbon stocks by restricting tree harvesting from a defined region of forest result in more pressure on wood supply in a different, unprotected region (i.e. not covered by the methods considered here). The resulting additional harvesting from these forests could involve some losses of carbon stocks which detract from efforts to conserve carbon in the protected forests.

An example of iLUC is a situation in which creating new forests on cropland within a defined region through afforestation creates a demand for cropland elsewhere, to make up for the lost supply of food or feed. The cropland area could then expand outside the region, possibly on former forest land, with related negative impacts on carbon stocks.

The possibility of leakage and iLUC effects cannot be ignored. However, risk of these effects occurring is a weak argument against the methods considered in this chapter. It is important to recognise the limits of what can reasonably be done and controlled for by individual actors or groups of actors. In this respect, it seems difficult to justify holding actors who make positive forest management efforts responsible for other actors elsewhere, even if the management choices of those actors could be regarded as indirectly related. Rather, there could be an aspiration to encourage as many actors as possible to implement the kinds of methods considered here across as much land area as possible. The specific issue of deforestation for the expansion of agriculture could also be addressed explicitly by adopting strong governance measures to tackle this.

Furthermore, if some actors are successful in demonstrating the effectiveness and benefits of the methods described above, these activities may act as an example and encourage more actors to adopt similar approaches. It may also be observed that the methods suggested in this chapter support synergies between woody biomass supply and the conservation or enhancement of forest carbon stocks and minimise and/or mitigate for trade-offs between these two goals, making leakage effects less likely.

No system can be completely flawless or foolproof. The methods obviously involve significant simplifications. For example, the methods described in Sections 5.2 and 5.3 only assess total changes in carbon stocks resulting from forest management, without any consideration of the time taken for these changes to occur, which will be variable. In principle, the methods proposed here could be extended to allow for timing (e.g. see Appendix 5), but the aim has been to design a pragmatic system, and to only add complexity if it is needed to ensure that the system should work.

Integration into policies

The above methods could be integrated into policies in different ways (see Section 5.1), and the specific policy choices may depend on context. For example, regulation may work in regions where forest land is under the control of a few management companies, or in situations where communities have an existing culture of land and forest stewardship. Financial incentives, mediated through the monetising of carbon sequestration and possibly involving a trading system, might be more workable in regions where there are numerous individual owners of relatively small land-holdings.

6 Conclusions and main findings

6.1 Reflections on biomass

At the conclusion of this report, it seems appropriate to reflect on 'what biomass is', the reasons why biomass is important, and on why there is so much discussion about its future role.

Biomass: a nature-based renewable resource

Biomass is a naturally occurring renewable resource – we can literally grow and re-grow what we use, for a diversity of possible applications, ranging from wood-based products in construction to burning biomass as an energy source ('bioenergy'). Examples include crops grown for their fibrous or woody stems and branches, residues from agricultural crops such as straw and seed husks, wood harvested from forests, 'waste' biomass such as offcuts of wood and sawdust produced by forest industries, post-consumer waste products derived from biomass, and animal manure and sewage.

Renewable biomass potential is finite but uncertain

While biomass is renewable, the capacity to produce it is finite but very uncertain. For example, Nabuurs et al. (2022) conclude that estimates of the global technical potential to supply biomass constrained by food security and environmental considerations fall within previous ranges corresponding to *medium agreement*, roughly 5–50 and 50–250 EJ/yr by 2050 for residues and dedicated biomass crops, respectively. They indicate that the magnitude of the biomass resource potential depends on the priority given to bioenergy products versus other products obtained from the land—notably food, fodder, fibre and conventional forest products such as sawn wood and paper—and on how much total biomass can be mobilized in agriculture and forestry. This in turn depends on natural conditions (climate, soils, topography), on agronomic and forestry practices, and on how societies understand and prioritize nature conservation and soil/water/biodiversity protection and on how production systems are shaped to reflect these priorities.

Biomass has a multitude of uses

Biomass is unique as a natural resource in that it has a wide variety of applications, including for food, structural materials, paper, chemicals, plastics, pharmaceuticals, and various types of fuel. Sustainable biomass offers unique opportunities to rapidly reduce emissions as it can be used to produce a wide range of alternatives to non-renewable and carbon-intensive products and fossil fuels. In the longer term, biomass has potential to reduce emissions in hard-to-abate sectors, such as construction and transport, including aviation and shipping. These potential roles of wood products and bioenergy are usually referred to as 'wood product substitution (or displacement)' and 'bioenergy substitution (or displacement), respectively. The resultant reductions in net greenhouse gas emissions may be referred to as 'greenhouse gas emissions displacement'. In the short term, biomass can replace non-renewable resources in existing technologies and infrastructures, such as when used as bioenergy for generating power and heat. Biomass is also a natural store of energy, making it valuable as a complement to other intermittent renewable energy sources.

Biomass is key to developing a 'circular economy'

Biomass can be reused, repurposed, recycled, and, ultimately, burnt with energy recovery. As such, it has a vital contribution to make to a 'circular economy', an economy that prioritises the use of renewable resources and aims to reduce overall resource consumption. A circular economy is essential to facilitate the transition away from fossil fuels and to achieve net-zero emission goals. Developing a circular economy could help ensure the most effective and efficient use of finite renewable biomass resources. Capturing the carbon emissions from bioenergy could enable then to be stored in geological formations (a process known as bioenergy with carbon capture and storage, or 'BECCS'), contributing net negative emissions when using bioenergy. The captured carbon can also be used in, for example, the food, beverage, and manufacturing industry, or to produce fuels. However, discussion of applications relying on carbon capture was outside the scope of this report.

Biomass production can be a friend to sustainable development, but can also be a foe

Expanding biomass production can support progress towards sustainable development goals in a number of ways. Creating new areas of biomass crops and trees can help to restore degraded land, and the economic value of managing land to produce biomass can also sometimes encourage improvements in the management of farmland and forests. Some biomass production systems can diversify land use and offer a range of benefits, such as when perennial grasses and short rotation woody crops are introduced in agricultural landscapes (within crop rotations or through localisation, for example as contour belts, along fence lines and riparian buffers), providing shelter for livestock, retention of nutrients and sediment, erosion control, pollination, pest and disease control, and flood regulation (Babiker et al., 2022). This includes agroforestry systems with a more complex vegetation composition, which reduce the overall pressure on soil and provide a mixture of food and biomass products. Diversifying crops and trees can also increase their resilience to the negative effects of climate change. Biomass supply chains can support rural economies, creating and diversifying job opportunities.

But it must always be remembered that the capacity for terrestrial ecosystems to supply sustainable biomass and other products is not unlimited, and that some practices involved in biomass production can be detrimental. For example, there are significant negative impacts if biodiverse forest ecosystems are converted to biomass plantations, and increasing the rate of sustainable biomass harvesting from agricultural land and managed forests can diminish carbon stocks in vegetation and soil in some circumstances. Fast growing biomass crops and forest plantations can relieve the pressure on forests with high conservation value but may put pressure on soils and water resources. Moreover, expanding biomass crops and forests can displace food production and local communities. In general, the production of biomass implicitly makes demands on land use and requires decisions about priorities when managing the finite land resource. The potential impacts of increasing biomass supply on carbon stock dynamics, particularly in forests, are the principal concerns discussed in this report.

6.2 Main findings

The science behind the carbon impacts of biomass harvesting use is relatively straightforward, but its interpretation and implications for policy and practice have proved challenging, and a consensus needs to be reached. The following conclusions and recommendations are drawn from the assessment in this report.

Understanding biomass and the effects of its use on the carbon cycle

- There are similarities and essential differences in the geological and biological carbon cycles, and this has important implications for the production and consumption of fossil fuels and biomass, particularly as an energy source (Section 2.1).
- Carbon 'debt', 'gain', and 'neutrality', as defined in this report (Section 2.4), are all real and all are possible, as discussed in detail for forest biomass sources (Chapter 3) and in summary for agricultural sources (Section 5.8).
- The magnitude and duration of any increase or decrease in emissions resulting from biomass production, processing, and use ultimately need to be understood in terms of their effects on atmospheric warming (Section 2.3).

Recommendation 1: When developing or reviewing policies directed towards supply and use of biomass, for bioenergy or non-energy purposes including for wood products the following points should be taken into account:

- Openly acknowledging and addressing the risks that supplying biomass can incur a carbon debt.
- Recognising the possibility for biomass to be carbon neutral.
- Actively considering the potential opportunities for synergies between producing biomass and conserving or enhancing carbon stocks in terrestrial vegetation and soils.

Understanding the results of scientific studies of biomass carbon impacts

Variation in carbon impacts, and divergent research findings, can be understood and explained, notably in terms of diversity in biomass supply chains and also diversity in assessment methodologies (Chapter 4). The different methodologies are all relevant for assessing the CO_2 balances of forestry and biomass supply chains, depending on the context and the purpose of an individual study. However, methodologies consistent with a question type defined in this report as "Pathways to Change" (Section 2.2) are pre-eminent when investigating whether managing forests to supply wood products and bioenergy could contribute towards, or detract from, a goal of reducing CO_2 emissions in a specified timeframe.

Some researchers have advocated, explicitly or implicitly, that the correct counterfactual scenario for forest management should always be the option of leaving forests unharvested, and assuming that the trees would grow on and reach maximum carbon stocks for that location, sometimes omitting consideration of disturbances from diseases, fires, or storms. This methodology addresses a question of the type defined in this report as "Natural Alternative" (Section 2.2). The difference in carbon stocks and sequestration rates for the managed forest, compared to what would occur in the unharvested forest, is sometimes referred to as the 'carbon sequestration forgone' or 'opportunity cost' attributable to managing forest areas for wood supply, even if the current management regime has been long established. Although such a comparison is valid in certain situations, often the comparison with 'no harvesting' or 'no management' is entirely hypothetical and the implied research question is inappropriate and misleading when informing policy and practice to ensure that the supply and use of wood products and bioenergy contribute towards a goal of reducing CO_2 emissions (Section 2.2).

Because of the diversity of methodologies in published studies, it is possible for studies to report very different results for the CO_2 emissions from biomass supply and use, even when similar forest systems and biomass supply chains are being studied, which can frustrate interpretation. This can create a perception that the CO_2 emissions from using biomass sources, especially for bioenergy, are extremely wide-ranging and the causes are complex and uncertain. A clear understanding of the scientific literature on the CO_2 emissions from the use of forest bioenergy requires a detailed analysis of all the factors involved (Chapter 4). In general, it *is* possible to identify the reasons why a carbon debt, carbon neutrality, or carbon gain can occur when growing, harvesting, and utilising biomass for any purpose, including for use as bioenergy (Chapter 3 and Sections 4.1 and 4.2).

Recommendation 2: Significant caution is advisable when considering whether published scientific studies of the greenhouse gas emissions associated with biomass use, particularly those concerned with biogenic carbon emissions, are relevant for informing policies on biomass sustainability. A set of key critical tests could be developed for referring to when reviewing studies, covering points such as whether a clear research question is stated, whether this question is relevant for informing policies, and whether the technical methods are appropriate for addressing the question.

Be wary of simplistic interpretations
Proponents and opponents of forest bioenergy sometimes use bold but simplistic statements to get their points across, but these kinds of statements and interpretations rarely offer an objective, impartial, accurate, or balanced view of the benefits and risks involved in mobilising forest biomass resources for use as an energy source or for other products (Section 4.6.3).

Recommendation 3: Simplistic statements and claims about the climate impact of biomass-based products including bioenergy, such as illustrated by examples in this report, should be avoided in communications about biomass policies and biomass sustainability.

Implications for measures to manage CO_2 emissions from biomass sources
Many climate-change mitigation measures outside the forestry and other land use sectors can be associated with a 'carbon debt', but the possibility that mitigation options are associated with a carbon debt is not in itself a sufficient reason to exclude them from the list of potentially relevant mitigation strategies. However, neither should up-front emissions occurring when deploying mitigation measures, including those involving the use of biomass, simply be ignored. Up-front emissions need to be assessed, and the drawback of such emissions needs to be weighed against the longer-term benefits of deploying mitigation measures (Section 2.3).

There are challenges to managing biomass carbon impacts (Chapters 2 to 4) but it is possible to develop methods for assessing options for managing land (particularly forests) and biomass supply and use. These methods could support management decisions to avoid or minimise net CO_2 emissions associated with a carbon debt, ideally also ensuring that the supply of biomass goes hand in hand with the conservation and enhancement of vegetation and soil carbon stocks at the landscape scale (Chapter 5).

Possible solutions to the challenge of managing the effects on the carbon balance of harvesting and using forest biomass consist of two elements (Section 5.1). The first element is a policy framework supporting actions to use forest biomass while ensuring positive effects on the carbon balance, or at least minimising negative effects. The second element comprises the technical methods used to assess and manage the supply and use of forest biomass while ensuring beneficial effects on the carbon balance or limiting negative effects. There are several kinds of policy framework potentially relevant in this context, as considered briefly in this report (Section 5.1). The technical methods outlined in this report can be divided into three classes:

1. 'Forest-based' methods aim to support the management and/or monitoring of forest carbon stocks, to provide assurance that forest management, including biomass harvesting, is having a positive or neutral effect on biogenic CO_2 emissions. Three types are discussed in this report: 'site-by-site assessment', 'regional-scale assessment', and 'national/regional-scale reporting'.
2. 'Feedstock-based' methods are more concerned with the extraction and use of forest biomass for bioenergy. They aim to classify tree biomass feedstocks according to the likelihood of low or high associated biogenic CO_2 emissions, and screen them to prioritise the use of 'low-emissions' feedstocks for bioenergy. Two types are discussed in this report: 'biomass feedstock decision trees' and 'biomass feedstock criteria'.
3. 'Full LCA methods' aim to enable the comprehensive assessment of greenhouse gas emissions resulting from a new policy or business initiative to invest in the supply and use of biomass, for bioenergy and/or other bio-based products. These are discussed briefly in this report.

These methods are at varying stages of development and readiness for supporting policies aimed at encouraging biomass use with low associated biogenic CO_2 emissions (Sections 5.2 to 5.6). All require at least some further development. There are also trade-offs between the effectiveness of methods in supporting the above aims and the administrative burdens and costs likely to be placed on biomass suppliers and consumers. Furthermore, there may be some challenges to achieving general acceptance of any particular method if it were to be proposed for general use. These can be partially addressed by transparent reporting of data, calculations, and results.

Forest-based and feedstock-based methods described in this report have differing strengths and weaknesses. The feedstock-based methods are intended to offer a technical solution relevant to directly addressing the initial question, particularly with regard to biomass used for energy. The forest-based methods also offer potential solutions. However, these methods are more general with regard to biomass, and also permit another alternative question to be addressed, specifically: how can forests in a defined region of land be managed to maintain or enhance carbon stocks and carbon sequestration? If plans for forest management are developed with this main objective in mind, then, as a co-benefit, this assures that biomass produced from the forests involves short carbon payback times when considered overall. This offers an alternative focus more broadly on forest management for climate change mitigation, rather than narrowly on understanding the impacts of mobilising biomass resources.

More thorough scientific assessments (e.g. life cycle assessment studies) could also have a complementary role in informing policy development and perhaps in 'spot testing' examples of real supply chains, as part of verifying the sustainability of biomass supplies. We suggest that further development of practical frameworks to support planning and management of biomass use, possibly along the lines suggested above and discussed in this report, is essential.

Over-simplified approaches to managing the carbon impacts of biomass supply can result in sub-optimal and perverse outcomes (Sections 3.2 and A2.5.1).

Actions to mobilise biomass and bioenergy whilst sustaining or enhancing carbon stocks could be integrated explicitly into efforts towards Climate-Smart Forestry (Section 5.9).

The methods described in this report could be integrated into existing policies addressing biomass, bioenergy, and climate change in different ways (Sections 5.1 and 5.9).

Recommendation 4: Existing technical methods supporting policies, such as biomass sustainability criteria, should be compared with the refined and elaborated methods proposed tentatively in this report, to identify where they are consistent and where there may be gaps.

Recommendation 5: Consideration should be given to further development and testing of the technical methods described in this report, where needed to ensure the use of biomass contributes positively to climate change mitigation objectives.

Biomass and sustainable forest management: not just about carbon

Forest biomass is assumed to generally originate from forest areas managed according to the wider principles of Sustainable Forest Management (SFM), but formal standards for SFM did not cover forest carbon stocks and sequestration when originally developed. More recently developed concepts, such as Climate-Smart Forestry and Natural Climate Solutions, explicitly consider both mitigation and adaptation to climate change as well as biodiversity and ecosystem services and may form viable approaches when combined with existing SFM standards (Section 5.9). It important to recognise that SFM is intended, *inter alia*, to support the conservation of biodiversity in managed forests. Addressing the need to conserve or enhance biodiversity can involve synergies but also trade-offs with other environmental and socio-economic targets, which need to be considered when developing or implementing climate policies, including providing incentives for greater use forest biomass for bioenergy and/or wood products.

No single policy or system can address everything, but limitations of the methods described in this report can be addressed by effective and transparent verification and through flanking policies and measures addressing specific important issues affecting forests not directly related to biomass and bioenergy supply, such as deforestation caused by the expansion of agriculture for food production (i.e. iLUC, see Section 5.9). Supporting policies may also be needed to enable the effective use of biomass resources to ensure that optimal substitution benefits follow from increasing the supply of woody biomass from forests.

Recommendation 6: It must be recalled that biogenic carbon emissions represent one issue amongst several that need to be addressed by sustainability frameworks addressing biomass use. It is important to clarify the relationship between policies addressing the greenhouse gas emissions of biomass and wider sustainability frameworks, to ensure their effective and efficient integration.

Consensus on the assessment of carbon impacts of biomass use is needed urgently

The science behind the carbon impacts of biomass use is relatively straightforward, but its interpretation and implications for policy and practice have proved challenging, and a consensus needs to be reached. It must be recognised that there has been a long history of unsustainable forest exploitation around the world. In this context, there is understandable scepticism about a positive role for increasing the supply of wood products from forests. Indisputably, forest management practices need to accord with high sustainability standards and undoubtedly there is room for improvement in many areas.

The ongoing dispute in the mainstream media and scientific literature about biomass sustainability and its relevance to meeting net-zero greenhouse gas emissions is preventing the development of a generally accepted framework to support biomass use. Biomass is not unique in having potential positive and negative impacts. This is equally true when expanding the deployment of any new technology or practice, including other renewables (see end of Section 2.4). However, biomass has received particularly strong attention in discussions about how to achieve sustainable development and net-zero emissions goals.

Policymakers are unsettled by the lack of consensus in the interpretation of the available scientific evidence, and the opposing claims made by lobbying groups, which erode confidence in all scientific studies and all evidence. This itself presents risks: either policymakers will hesitate to support the use of biomass to its full potential, when it is a much-needed resource to support the development of circular, low-carbon economies, or there is a risk that biomass use will be expanded without adequate safeguards in place, undermining sustainable development. In contrast, if policymakers are provided with sufficient, objective, and balanced interpretations to make sense of the otherwise confusing scientific evidence, then they are more likely to have the confidence to utilise the information to develop policies that support or constrain biomass use as appropriate. Such an objective and balanced understanding of the benefits and risks of expanding biomass use is possible if there is a willingness amongst stakeholders to support its development.

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Appendices

Appendix 1. Wood product carbon stock dynamics and substitution effects

In Section A.1.1 the role of wood products as a pool of sequestered carbon is explained and the theoretical basis for so-called 'wood products substitution effects' in Section A1.2. The potential magnitude of wood products substitution effects on greenhouse gas emissions are considered in Section A1.3 and the arguments for and against the significance of these effects are also reviewed in Section A1.4. In the context of this report, wood products include woody biomass used as a source of bioenergy or as a feedstock for biochemicals and biomaterials such as bioplastics.

A1.1 Carbon stock dynamics of wood products

Wood products, such as paper, particleboard, or timber used in the construction industry, represent a reservoir or 'pool' of carbon sequestered from the atmosphere by forests. It follows that, when trees are cut down, not all of the carbon in the wood is released immediately. Rather, the release of some of the carbon back to the atmosphere is delayed, for the period during which the various wood products are in use. Even some wood used as fuel may be retained for one or two years before being combusted, whilst some wood products, such as construction timber, can remain in use for many decades and sometimes centuries. In terms of the carbon stock dynamics of forests, it is this role of wood products in potentially delaying the return to the atmosphere of carbon originally sequestered by trees that is critical.

This role of wood products as a carbon pool is well understood and widely accepted but sometimes there is confusion about the implications for the best use of harvested wood if the objective is to enhance carbon sequestration in wood products. For example, a conclusion frequently drawn is that harvested wood is best utilised for long-lived products in preference to short-lived products (see for example, Brunet-Navarro et al. (2017); Eriksson et al. (2007); Nabuurs et al. (2018)). However, the main drivers of the magnitude of carbon stocks in wood products are the amount of wood contained in specific finished products, and the numbers of units of specific finished products in use at any time. Hence, unlike forest ecosystems, socio-economic factors are the main determinants of carbon stocks in wood products, rather than biophysical factors, such as the durability of products. Product durability is still an important consideration, since this determines how frequently a product in use needs to be replaced. This in turn has implications for how much woody biomass needs to be supplied from forests (to provide the replacements). The importance of re-using, re-purposing and recycling wood products (regardless of their lifespans) is also apparent, as a way of extending the time with which carbon in harvested wood is retained out of the atmosphere in products (Cañete Vela et al., 2022; Stegmann et al., 2022).

For wood products to sequester extra carbon, the carbon stocks in the wood products pool must grow – simply replacing old products with new products does not increase the amount of carbon in the wood products pool (although total carbon stocks might increase if old wood products are re-used, repurposed or recycled, or carbon in old products going into landfill at end of life is also counted). However, society has much more control over what is done with harvested woody biomass than over the natural development of forest ecosystems, either in the presence of active forest management or otherwise. This suggests that consideration should be given to expanding the use of wood products, for example in the construction sector. This would need to allow for the capacity of forests to provide woody biomass sustainably, as well as considering the potential impacts of increasing woody biomass supply on carbon stock dynamics in forests, which is a principal concern of this report.

Any incentives to sequester carbon in wood products would need to be developed with care, or perverse outcomes could occur. For example, manufacturers and builders might simply increase the amount of wood included in products in ways that do not serve any useful purpose, i.e. is not needed for the products to fulfil their intended function. If this happened, the inclusion of the extra wood in the products would be superfluous and wasteful of a valuable renewable resource. These rather subtle observations about the role of wood products are not always recognised.

A1.2 Rationale behind wood product substitution effects

When any particular wood product is manufactured, this involves the consumption of energy and resources, with consequent greenhouse gas emissions, on top of possible issues with carbon debt. Any greenhouse gas emissions associated with the wood product can be avoided, if society can avoid using the product. However, if this option is adopted, perhaps as a policy decision by a country or region, then one or more other options must be pursued instead, even if implicitly:

- Society might try to manage with using less of the particular product, regardless of its origin or what it is made from (that is, overall consumption could be reduced).
- Society might find an alternative source for the particular wood product, imported and/or manufactured from biomass supplied from elsewhere, possibly from a region where forestry and other land uses are not subject to strong sustainability standards (any issues with carbon debt or emissions would be 'exported' to the producing countries or regions).
- Society might consume a product manufactured from materials other than woody biomass, in place of the wood product. As discussed below (Section A1.3), products made from materials other than biomass frequently have higher greenhouse gas emissions involved in their manufacture and use, although not always.

These possible alternative actions taken by society are often referred to as 'counterfactual scenarios' to the (actual) scenario in which the choice is made to produce and use a particular wood product. As a corollary, the above analysis suggests that, when choosing to use wood products, the potential exists to avoid greenhouse gas emissions, by ensuring that they are used in place of more greenhouse gas-intensive materials and fossil energy sources. In other words, the wood products could be used to 'displace' or 'substitute for' alternative products with higher greenhouse gas emissions involved in their manufacture and use. These possible contributions to greenhouse gas emissions reductions through use of wood products are generally referred to as 'displacement effects' or 'substitution effects'. Displacement effects do not only potentially occur when changes are made to supply and use wood products and forest bioenergy. They can occur more generally when any changes in the use of resources occur, for example when deciding to reduce (or increase) the consumption of non-renewable resources that may be more or less scarce. However, wider consideration of substitution effects is beyond the scope of this report.

A1.3 Potential magnitude of wood product substitution effects

The potential effects on greenhouse gas emissions of changes in the supply and consumption of wood products are usually estimated by comparing the greenhouse gas emissions of an alternative (counterfactual) non-wood product with those of a particular wood product, and expressing the result as a ratio with respect to a unit quantity of wood product, so as to derive a "greenhouse gas emissions displacement factor" (often abbreviated to "displacement factor"). Hence, this is calculated as:

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

Note that the formulation of the above equation is simplified for clarity, by assuming that the 'non-wood' product does not include any wood as a component of its manufacture. If necessary, the calculation can be elaborated to allow for both products containing a proportion of wood.

When calculating these kinds of results, the greenhouse gas emissions of the two products are often expressed in units of tons carbon equivalent (tCeq) and the mass of wood is expressed in units of tons carbon (i.e. the carbon content of the wood composing the product, with units tC). Thus, displacement factors are frequently reported with units of tCeq/tC. For example, a displacement factor for a wood product of 1.5 tCeq/tC would imply that supplying and using 1 extra ton carbon of a specified wood product leads to the displacement (or 'savings' or 'avoidance') of 1.5 tCeq of greenhouse gas emissions that would have been associated with the manufacture and use of an equivalent non-wood (counterfactual) product, or that reducing the supply and use of a specified wood product by 1 ton leads to an increase in greenhouse gas emissions of 1.5 tCeq, as a consequence of the increased manufacture and use of an equivalent non-wood (counterfactual) product.

A key reference in the estimation of such displacement factors has been the review of available scientific literature by Sathre and O'Connor (2010), which suggested a generic displacement factor for wood products of 2.1 tCeq/tC. However, there have been several more recent reviews which have suggested that median or mean displacement factors for wood products may be smaller (EFI, 2022; JRC, 2021a; Leskinen et al., 2018; Myllyviita et al., 2021). A synthesis of estimates from these reviews suggests median or mean values in the range 0.9 to 1.6 tCeq/tC (mid-range 1.3) for wood used in construction (structural and non-structural applications) and 0.4 to 1.6 tCeq/tC (mid-range 1.0) for wood used for other applications (furniture, packaging and biochemicals). Certain applications of woody biomass may involve larger displacement effects, for example, estimates for wood-based textiles range from 2.5 to 3.1 tCeq/tC (mid-range 2.8), although these estimates are based on very few studies. However, when considering potentials for reducing greenhouse gas emissions through using wood to displace other materials, it is important to consider the potential size of the market for the product, as much as the potential magnitude of the displacement factor.

A further review by Hurmekoski et al. (2021) has reported an even smaller mean estimate for the displacement factor of woody biomass used for material products, of 0.55 tCeq/tC (range 0.27-1.16 tCeq/tC). This estimate refers to fossil carbon avoided per ton of carbon contained in total harvest and is intended to reflect the pattern with which wood is used currently, with significant quantities utilised for paper, card and packaging, which are estimated to have low emissions displacement factors. The resultant weighted average of displacement factors, allowing for the proportions of wood allocated to different product types and end uses, therefore gives more weight to low estimates. In this context, Hurmekoski et al. (2021) note that some wood products such as graphic papers and hygienic papers are often assumed to provide limited to no substitution benefits, whilst others fall outside the scope of the analysis (such as textiles and chemicals). They further emphasise that their mean value reflects a very specific situation in terms of the ways in which wood is utilised within a national economy. The results are therefore context-specific and not necessarily appropriate for general application in other geographical regions or specific sectors.

All the reviews report very wide variability in individual estimates of displacement factors around the central values stated above, ranging from quite significantly negative (implying net greenhouse gas emissions increases resulting from utilizing a wood product) to positive and very substantial (up to 5 tCeq/tC). Leskinen et al. (2018) suggest that the main reasons for the differences are the inclusion of a large number of studies of a diverse set of possible products, and methodological differences between individual studies.

Typical displacement factors for woody biomass used as bioenergy are generally lower than the values for material products suggested above. Mean values of 0.67 and 0.75 tCeq/tC, can be inferred from the review of Myllyviita et al. (2021), with a range from -0.08 to 2.5 tCeq/tC. For solid woody biomass energy products (such as wood chips and pellets), calculations based on data and results presented in Table 1.1 of Matthews, et al. (2014a) and Tables 5.3 and 5.4 of Matthews et al. (2015), suggest displacement factors for wood pellets in the range 0.4 to 1.1 tCeq/tC (mid-range 0.75). The variability in the factor depends on the type of fossil fuel displaced and the magnitude of supply chain emissions. Higher displacement factors for bioenergy are possible, depending on the energy conversion systems involved. For example, a displacement factor of 1.3 tCeq/tC has been estimated for a new and relatively efficient biomass combined heat and power plant replacing an old coal fired heat boiler and electricity from a coal based condensing plant (Cintas, Berndes, Cowie, et al., 2017).

Greenhouse gas emissions displacement factors assumed in this report

Several theoretical examples given elsewhere in this report (Sections 3.2, 3.4, 3.5, A2.5 and Appendix 3) involving the calculation of carbon payback times require assumptions to be made about the greenhouse gas emissions displacement factors applying for material wood products and woody biomass used as bioenergy. A value of 1.2 tCeq/tC has been assumed for material wood products in these examples. This value was selected rather than the smaller estimate suggested by Hurmekoski et al. (2021), on the basis that a value of 1.2 represents a reasonable estimate from literature reviews of the potential magnitude of substitution effects, if the use of wood were to be encouraged to provide substitution benefits as an explicit aim.

Greenhouse gas emissions avoided through using woody biomass for bioenergy are calculated explicitly in the examples given elsewhere in this report. Implied displacement factors can be derived from these calculations: these are 0.93 where it is assumed that woody biomass used for bioenergy substitutes for coal (Sections 3.3, 3.4 and A2.5), 0.74 where bioenergy substitutes for a 50:50 mixture of coal and natural gas (Section 3.5 and Appendix 3), and a relatively conservative estimate 0.6 in cases where bioenergy substitutes for a mix of fossil fuels (calculation involving 'biomass cascading' in Section 3.4).

It is very important to highlight that the displacement factors for wood products discussed here and referred to in this report do not include any allowances for impacts on carbon stocks in forest areas, as a result of changes to forest management such as increased or decreased harvesting associated with changes in the supply of products. These effects are allowed for in the example calculations included in this report, but the estimates are presented separately from the estimates of greenhouse gas emissions avoided through wood product displacement effects, to show the interactions between the two contributions to net changes in greenhouse gas emissions associated with using woody biomass.

A1.4 Arguments for and against the positive contribution of wood products towards mitigating greenhouse gas emissions

Sometimes, doubts are expressed about the greenhouse gas emissions mitigation benefits of wood products in contributing to carbon sequestration, and particularly whether greenhouse gas emissions are actually avoided through wood products displacing greenhouse gas-intensive non-wood products (Harmon, 2019; Howard et al., 2021; Law and Harmon, 2011).

Howard et al. (2021) highlight that the actual products (such as metals, concrete, fossil fuels) displaced by wood products are uncertain and strictly unknown and therefore question the validity of published estimates of emissions displacement factors. However, whilst the magnitude of wood product substitution effects can be uncertain, nevertheless assuming that no substitution effects occur is certainly incorrect in most situations, and making an assumption of zero displacement of emissions is likely to result in significant inaccuracies in assessments of the contribution of wood products to mitigation of greenhouse gas emissions.

Harmon (2019) asserts that three phenomena could lead to scenarios in which wood products make no useful contribution to substitution effects; Harmon calls these phenomena ’displacement decline’, ’leakage losses’ and ‘replacement losses’.

Displacement decline

If the economy in general decarbonises, the point will be reached where there will be no high-emissions products or energy sources for wood products and wood fuel to displace (or ‘substitute for’). This suggests that the application of current estimates of greenhouse gas emissions displacement factors will be invalid when assessing substitution effects some years from now. This phenomenon is referred to as ‘displacement decline’ by Harmon. A similar view is the basis of an analysis by Brunet-Navarro et al. (2021).

The successful decarbonisation of the economy is of course a highly desirable outcome. If this is achieved, it is undeniably correct that there will no longer be any high-emissions resources being consumed, that can be substituted for. However, the logic of assuming that low-emissions resources then no longer contribute towards decarbonisation is questionable. For example, suppose that efforts are made now to deploy solar electricity generation capacity, with the aim of reducing emissions from energy supply and consumption. If the economy in general is decarbonised at some point in the future, the logic behind the displacement decline argument would suggest that solar energy no longer provides any benefit, because it is no longer displacing higher emissions energy sources. However, the use of solar energy has contributed towards the achievement of the decarbonisation of the economy, and allows this decarbonisation to be sustained going forward. The question then arises as to what would happen if the use of solar energy was to be stopped. (For example, would consumption of fossil fuels be resumed?) The same points could be made about wood products and bioenergy and their potential substitution effects.

For example, declining greenhouse gas savings from the displacement of alternative non-biomass products may be due to the increasing use of biomass in their production. For example, the greenhouse gas savings obtained from building with wood instead of concrete may decrease due to the cement industry investing in carbon capture and storage and switching to using biomass instead of coal in the cement production process, while the construction industry is starting to use biochar as a filler in concrete leading to additional carbon storage in concrete structures. It then does not follow that the greenhouse gas savings per hectare of harvested forest biomass will decrease, even if the use of construction timber produces a lower substitution effect.

The pathway to net zero greenhouse gas emissions is likely to involve complex changes in resource use and, in some situations, the greenhouse gas emissions of alternatives (counterfactuals) to bio-based products may increase in the future rather than decrease. For example, this can happen if a source of fossil fuels is switched from one geographical region to another (El-Houjeiri et al., 2019), or if oil is extracted from less accessible sources such as sands and shales. Furthermore, potentially, wind, solar and bioenergy could make complementary rather than competing contributions to decarbonisation of energy provision, because they can fulfil different functions. Power generation is the most likely application of wind and solar systems. In the case of bioenergy, the applications include transport biofuels, heat and thermal electricity generation. Often, fossil fuels will be the main counterfactuals for these applications. Additionally, for example, coal is often used in large condensing power plants producing only electricity, while biomass is used in smaller decentralised combined heat and power plants, making use of waste heat, which increases the overall energy efficiency. Biomass could also contribute to the decarbonisation of non-biomass resource supply chains, such as for smelting iron in place of coal.

If the economy is decarbonised, wood products and bioenergy can continue to provide materials, chemicals and energy with low or zero (and potentially net negative) greenhouse gas emissions. In these circumstances, estimates of emissions savings by using biomass, calculated using currently applicable displacement factors, represent the contributions that the biomass has made to decarbonisation, and continues to contribute to allow decarbonisation to be sustained. The key is to avoid situations in which supplying wood-based products results in a significant and long-lasting carbon debt, as discussed in detail in this report.

Leakage losses
Harmon's concept of leakage losses can be understood by considering the following hypothetical scenario: *Suppose harvested wood is used to manufacture a certain 'product A', displacing the use of an alternative substance, such as, concrete. In principle, under current manufacturing conditions, this should result in net avoided greenhouse gas emissions. However, now suppose that as a consequence, rather than less concrete being produced, an alternative use is found for some or all of the displaced concrete, in the manufacture of a new 'product B'. It may be argued that, if such a scenario occurs, the net greenhouse gas emissions avoided by using the harvested wood are diminished in magnitude and potentially negated ('lost'), even though using the wood made it possible to avoid using concrete to manufacture the original 'product A'.*

Whilst the rationale behind the concept of leakage losses is understandable from this scenario, the question might then arise as to how far the scenario should extend in considering such knock-on effects. For example, if wood had not been used to manufacture 'product A', would the alternative scenario be that concrete was used to manufacture both 'product A' and 'product B?'. It is possible to identify a range of possible kinds of 'leakage effects' related to the use of different product categories, which may variously contribute to or detract from the potential substitution benefits of wood products. Full discussion of this subject is beyond the scope of this report.

It must be conceded that simply making greater use of wood products and bioenergy cannot deliver a decarbonised economy if done in isolation. Rather, this would need to be done as one element of a set of coordinated and complementary actions, all supporting efforts towards decarbonisation in all industrial and wider economic sectors. As above, when considering the role of wood products and bioenergy, the key is to avoid situations in which supplying wood-based products results in a significant and long-lasting carbon debt.

Replacement losses

Harmon's concept of replacement losses can be summed up simplistically in the following statement: *New wood products do not sequester additional carbon or displace greenhouse gas emissions because they just replace old wood products at the end of their service lives.*

Arguably the phenomenon of replacement losses has been recognised and is almost universally allowed for in studies modelling carbon stock dynamics in wood products. Numerous references to scientific studies published over decades could be cited to support this assertion (Chen et al., 2008; Dewar, 1990; Harmon et al., 1990; Johnston & Radeloff, 2019; Perez-Garcia et al., 2005; Pingoud et al., 1996; Skog et al., 2004; Skog & Nicholson, 1998; Thompson & Matthews, 1989; Winjum et al., 1998). Methods defined in IPCC guidance for estimating emissions and sequestration in wood products for reporting in national greenhouse gas inventories fully allow for new wood products replacing old ones (IPCC, 2019a). Globally, the rate of consumption of wood products is increasing, rather than decreasing or stable, suggesting that new wood products are needed in addition to replacements for old wood products. Furthermore, the net effect on carbon stocks of replacing old wood products with new ones depends on the fate of the old products at end of life, which could involve reuse, repurposing or recycling, or disposal and long-term retention in landfill.

The situation with regard to wood product substitution effects and the relevance of replacement losses is debatable. The question arises as to what materials would need to be used to replace the old wood product, if a replacement wood product was not available. As previously, when considering the potential contributions of wood products and bioenergy, the key is to avoid situations in which supplying wood-based products results in a significant and long-lasting carbon debt.

Appendix 2. Carbon stock dynamics: Carbon neutrality and debt

This appendix introduces in some detail the fundamental science of carbon sequestration in forests. Firstly, carbon stock dynamics in an individual stand of trees are described. Then, some different ways of measuring carbon stocks are defined. Examples are then given of how management can influence forest carbon sequestration and carbon stocks, and how assessments of carbon dynamics in forests depend on the scale considered (individual stands of trees or whole forest landscapes). These examples are used to show how, in certain situations, woody biomass can be continuously harvested from forests without having negative impacts on carbon stocks. A further illustration is given of how managing forests to increase wood production can result in some loss of carbon stocks, and consequently a period of raised CO_2 emissions (or a 'carbon debt'), even when management is consistent with the principle of sustainable yield when a long-term view is taken.

The illustrations are based on theoretical examples of forests formed of stands of Sitka spruce trees, with a mean stem volume growth rate of 12 m^3/ha/yr when stands are managed on an optimum rotation. This tree species and growth rate are commonly encountered in commercially managed forests in the United Kingdom. Typically, growth rates of managed forests across Europe are lower, between 4 and 8 m^3/ha/yr (but with some faster growing areas). Growth rates can be lower or higher in other regions of the world, for example typically 1 to 4 m^3/ha/yr in boreal regions such as Canada and Northern Europe, to 16 m^3/ha/yr and higher in commercial pine forests in the USA, and potentially up to 30 to 40 m^3/ha/yr in tropical regions.

The Sitka spruce forest stands considered in most examples are assumed to be managed without thinning of trees during the rotation. Whilst this example is theoretical, this practice (and the approach to creating forest areas) can occur in Sitka spruce stands in the United Kingdom. More typically, forest stands are thinned periodically over a rotation, to improve the quality of the trees retained for final harvest at the end of the rotation.

Although the examples described based on UK Sitka spruce stands are for a particular type of forest, the principles described hold in general for all tree species and growth rates, and also for forest managed with thinning during the rotation. Detailed examples based on more representative examples of forests, growth rates and management in boreal and subtropical regions are described in Sections A2.4.1 and A2.5.1.

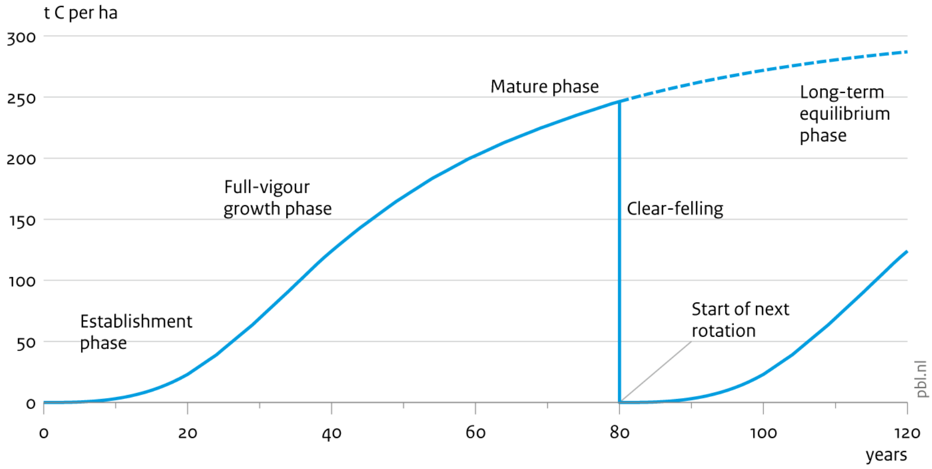
Note that a further simplifying assumption is applied in some examples below that all stemwood is used for energy and that tree stem tops, bark and stumps are retained on site, with same explanation as provided in Section 3.1 of the main report. The simplifications in examples do not generally reflect real practice but have been chosen for clarity when explaining the fundamental science of carbon balances and the potential impact of tree harvesting and bioenergy production. The examples also highlight where important sensitivities and uncertainties may occur in estimates of net CO_2 balances for bioenergy production from forests. These sensitivities can be related to the scenarios assumed for forest management and biomass utilisation, and/or differences in the completeness of calculations and underlying assumptions.

A2.1 Carbon dynamics in individual stands of trees

Cycles in carbon stocks over time can occur in individual stands of trees managed for production involving clear-felling, reflecting the periodic growth, felling and regrowth of stands. This is illustrated in Figure A2.1, which shows change in tree carbon stocks that can occur on a notional one hectare of land by planting and managing a stand of Sitka spruce trees as described above.

Figure A2.1

Development of tree carbon stocks in a Sitka spruce forest stand



Source: Forest Research UK

Harvesting is assumed to involve clear-felling of stands on a rotation of 80 years. Note that Sitka spruce stands with the growth rate considered here are usually managed on shorter rotations than 80 years, which are closer to the optimum rotation, with 50 to 60 years being more typical. For simplicity, the results shown in Figure A2.1 are for carbon stocks in trees only, i.e. no account is taken of carbon stocks in deadwood, litter and soil, or of the contributions from carbon retained in wood products. Four phases can be identified in the development of tree carbon stocks over time:

1. the establishment phase;
2. the full-vigour growth phase;
3. the mature phase, and
4. the long-term equilibrium phase (if the trees are not clear-felled, continuation of dashed line in Figure A2.1).

The rate of net carbon sequestration in the biomass of trees (the slope of the curve in Figure A2.1) can be significant in the full-vigour phase with a maximum rate of 5.6 tons carbon per hectare per year. However, after 100 years, rates of carbon sequestration have declined to less than 1.0 tC/ha/yr. This phenomenon is sometimes referred to as 'saturation' when (in unchanging environmental conditions) a steady state occurs in the balance of flows of carbon into and out of a forest. The magnitude and stability of the carbon stock at this saturation point, and the time taken to reach it, depend on various factors including tree species, the specific pattern of tree growth (and age-dependent growth rate), soil type, long-term management, disturbance events and climate, also including environmental changes such as atmospheric pollution and the fertilisation effect of enhanced atmospheric CO_2 concentrations. If trees in stands are not thinned or clear-felled, saturation will occur because the growth rates of trees slow down as trees get older. Underlying this is the balance between the processes of photosynthesis by trees, losses of carbon from respiration, tree mortality and disturbance, and transfers of carbon between the trees, other forest carbon pools and the atmosphere.

In managed stands, the maximum carbon stock is usually determined by the rotation age applied for harvesting trees. The carbon stocks in trees accumulate from the time of planting up to the end of each rotation, when clear-felling reduces carbon stocks in living trees to zero. Part of the felled above-ground biomass is extracted for the manufacture of wood products and for use as bioenergy, while the remainder and below-ground biomass are usually left on site, where they decay and release carbon to the atmosphere. After clear-felling, the carbon stocks then accumulate again following restocking with the result that, over repeated rotations, carbon stocks in living trees 'cycle' between zero and 246 tC/ha every 80 years.

The general pattern of carbon sequestration in stands of trees illustrated in Figure A2.1, including the slowing down of the rate of carbon sequestration with tree/stand age, is widely accepted (Maclaren, 2000; Morison et al., 2012). This understanding is the basis of 'Tier 1' methods for estimating carbon stock changes in Forest Land (and other vegetation systems) as described in IPCC Good Practice Guidance on methods for estimating and reporting national greenhouse gas emissions inventories. Specifically, methods are included in IPCC Guidance that represent land-use change as involving a change in carbon stocks from one constant level to another, over a specified period of years.

The pattern shown in Figure A2.1 is also a feature of the estimates of forest carbon stocks and rates of carbon stock changes over time produced by internationally applied forest carbon models (Beets et al., 1999; Böttcher et al., 2012; Cannell and Dewar, 1995; Dewar, 1990, 1991; Kindermann et al., 2008; Kindermann et al., 2006; Matthews, 1991, 1994; Mohren et al., 1999; Nabuurs, 1996; Richards, 2001; Schelhaas et al., 2007; Schlamadinger and Marland, 1996; Thompson and Matthews, 1989; Waterworth et al., 2007). Generally, these models rely on underlying forest growth models, calibrated using data on the forest growth patterns exhibited by trees and stands of trees, which have been the subject of centuries of research, see for example (Assman, 1970; Chapman and Meyer, 1949; Husch et al., 2003; Matthews et al., 2016a; Philip, 1994; Pretzsch, 2009; Pretzsch et al., 2019; Prodan, 1968). Some forest growth models displaying such growth patterns are based on explicit representations of ecophysiological processes driving forest carbon assimilation and resultant growth (see for example Landsberg and Waring, 1997).

Recently, some researchers have been suggesting that leaving forests unharvested and unmanaged is the most effective strategy for them to contribute towards reducing greenhouse gas emissions (Moomaw et al., 2019). Analyses of field measurements of CO_2 fluxes into forests, and modelling studies, suggest that carbon uptake can continue in older stands (Knohl et al., 2003; Luyssaert et al., 2008; Pugh et al., 2019), which may be partly caused by environmental changes such as enhanced atmospheric CO_2 concentrations and nitrogen deposition. These observations may sometimes lead to the conclusion that older forests can have the potential to sequester carbon in perpetuity (or, at least over very long timescales). However, flux methods measure the net carbon uptake by forests, consisting of the balance between gross uptake through photosynthesis and losses from respiration. Flux measurements of respiration involve some approximations that may lead to underestimation of losses and overestimation of net carbon uptake (Gundersen et al., 2021). It is important to distinguish carbon sequestration rates in unmanaged stands recovering from disturbances and rates in intact stands, where rates are typically much lower (Finzi et al., 2020; Paul et al., 2021), but interactions between disturbances, tree growth and mortality can be complex (Begović et al., 2023;

Pugh et al., 2019). Some of the evidence for carbon sequestration rates in older forests is based on observations of the growth of rates of individual old and very large trees (Begović et al., 2023; Stephenson et al., 2014). However, numerous studies have shown that the number of trees that can be supported on an area of land decrease according to the inverse of the size of the trees (such as the inverse of mean stem diameter or mean stem biomass; see for example Kikuzawa, 1999; Luyssaert et al., 2008; Reineke, 1933; Yoda et al., 1963).

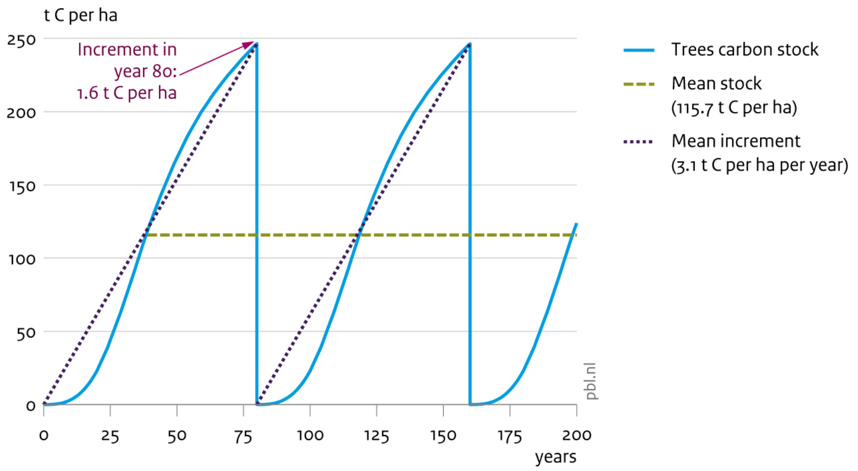
This interaction between the size of individual trees and the number that can be supported on an area of land may explain why estimates of carbon sequestration obtained in some studies of old, large individual trees may appear to be at odds with the carbon dynamics generally observed at the scale of a stand of trees. Gray et al. (2016) conclude that old-growth and large trees are important carbon stocks, but they play a minor role in additional carbon accumulation. Luyssaert et al. (2008) point out that high forest carbon stocks suggested by theoretical potentials may only rarely be achieved because of natural disturbance events. However, they also observe that conserving high carbon stocks in existing long-established very mature forests is a sensible measure.

A2.2 Measuring carbon stocks and carbon sequestration

To explain how managing forests to produce woody biomass can have variable impacts on carbon stocks and carbon sequestration, it is important to understand different ways of measuring carbon stocks, carbon uptake and carbon sequestration. Three different measurements of forest carbon stocks and carbon uptake are illustrated below, using the example of a forest stand in Figure A2.2, equivalent to the example in Figure A2.1.

Figure A2.2

Tree carbon stocks in a Sitka spruce forest stand managed on a clear-fell rotation of 80 years



Source: Forest Research UK

Mean forest (tree) carbon stocks

One measure of carbon stocks for a stand of trees is the mean carbon stock in the stand over a single rotation. For the example stand of trees in Figure A2.2, the mean carbon stock in trees is almost 116 tC/ha, as indicated by the dashed horizontal line. The cyclical variation in the carbon stock around this mean over time is considerable. One way of measuring carbon sequestration, or carbon losses, in vegetation systems including forests, is to evaluate changes in mean carbon stocks resulting from management interventions, such as afforestation activities and increased thinning in forests. This method is used extensively in examples given in this report.

Mean carbon increment

One way of measuring carbon uptake in a stand of trees is illustrated by the slope of the dotted black lines in Figure A2.2. These indicate the mean rate of accumulation of carbon in the growing trees forming the individual stand over the rotation of 80 years. This measure is referred to here as 'mean carbon increment', and it represents the net result of the flows of carbon indicated by fluxes A, B and L in Figure 3.1 in Section 3.1, noting that the measurement is usually confined to carbon in trees, rather than total carbon in all forest carbon pools. For the example stand of trees in Figure A2.2, the mean carbon increment over the 80 year rotation is 3.1 tC/ha/yr. The carbon 'lost' when trees are felled is usually calculated and reported as a separate result. In another context, there is a very good reason for doing this: Forestry practitioners refer to estimates of forest increment and related estimates for losses in felled trees (called 'removals') and compare them to establish the balance between 'increment' and 'removals'. Ensuring that removals do not exceed forest increment (certainly in the long run) is one of the basic tests of sustainable-yield management; this is one reason why these estimates are usually reported together prominently in forest statistics.

From a certain viewpoint, mean carbon increment might be interpreted as a metric of forest carbon sequestration. However, it is also apparent that mean carbon increment only represents part of the carbon balance of a forest. The full calculation of carbon sequestration requires the subtraction of the losses ('removals') from the gains, and also allowance for net carbon exchanges in other forest carbon pools.

Current carbon increment

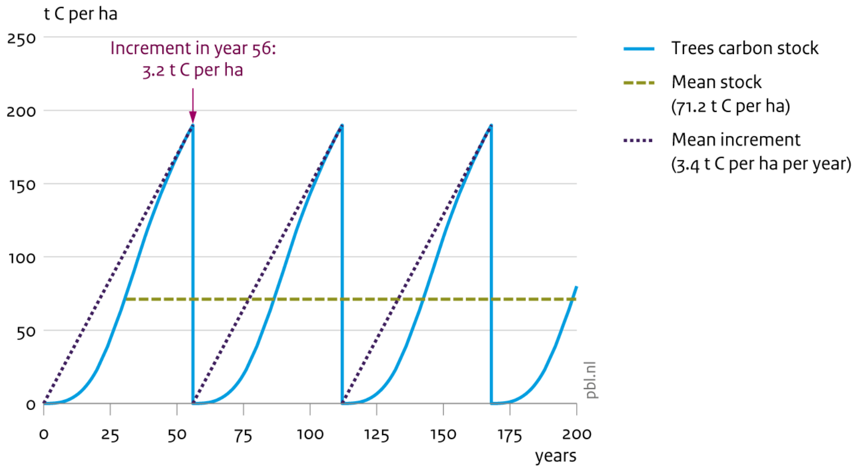
A further way of measuring carbon uptake in a stand of trees is to calculate current carbon increment. This is similar to the mean carbon increment defined above but represents the carbon increment in a given year. For example, the value of current carbon increment for the year at the end of a rotation, when the trees are aged 80 years, is the slope of the curve at the point indicated by the purple arrow in Figure A2.2, and is 1.6 tC/ha/yr. Like mean carbon increment, the value of this measurement is consistently positive but it only represents part of the carbon balance of a forest.

A2.3 Dependence of carbon measurements on rotation period

If the rotation period (time to clear-fell harvest) applied to stands forming a forest is changed, this affects both the mean tree carbon stocks in the forest and the mean carbon increment. This is illustrated in Figure A2.3. This shows the development of tree carbon stocks in a stand of trees that is the same as shown in Figure A2.2, except that the stands of trees are managed on a clear-fell rotation of 56 years, instead of 80 years.

Figure A2.3

Tree carbon stocks in a Sitka spruce forest stand managed on a clear-fell rotation of 56 years



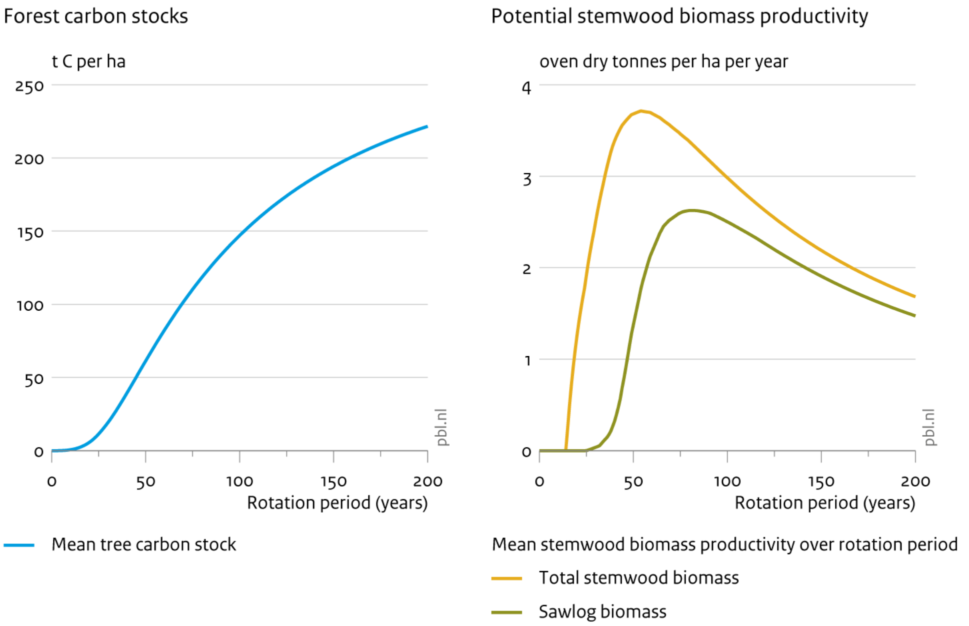
Source: Forest Research UK

Compared to the forest managed with an 80-year rotation in Figure A2.2, mean carbon increment in the forest on the shorter rotation is higher, at 3.4 tC/ha/yr instead of 3.1 tC/ha/yr, an increase of 10%. This happens because the growth rate of the trees managed on the longer rotation slows down at older ages. Current carbon increment at the end of an 80-year rotation is much lower than for a rotation of 56 years, at 1.6 instead of 3.2 tC/ha/yr, respectively. In contrast, the mean tree carbon stock in the forest managed on the shorter rotation is lower, at slightly over 71 tC/ha compared with almost 116 tC/ha. This reflects the fact that the mean age of the trees in the forest managed on the shorter rotation is 28 years, as opposed to 40 years for the forest managed on the longer rotation.

Figure A2.4 shows the relationship between the rotation applied to a stand of Sitka spruce such as described above and mean tree carbon stocks over the rotation (left-hand graph). The figure also shows how the stemwood biomass productivity over a rotation also varies with the applied rotation (right-hand graph). Biomass productivity is shown as mean growth rate in units of oven dry tons per hectare per year (odt/ha/yr). Two results for stemwood biomass productivity are shown in the right-hand graph in the figure. The first is for total stemwood biomass growth rate or production, and the second is for sawlog biomass production (i.e. biomass of relatively large diameter stemwood).

Figure A2.4

Influence of rotation period on carbon stocks and biomass productivity in a Sitka spruce stand



Source: Forest Research UK

The estimated carbon stock in the forest rises monotonically as the rotation period is increased. In contrast, biomass growth rate initially rises as the rotation period is increased but reaches a maximum value, and then declines for longer rotations. In terms of total stemwood biomass, managing the Sitka spruce stands forming the forest on a rotation of 55 years should achieve maximum production (3.7 odt/ha/yr). Note that the example given above in Figure A2.3 is based on a rotation of 56 years, just one year different from the optimum rotation age. Maximum production of biomass suitable for use as sawlogs occurs at a longer rotation of 80 years (2.6 odt/ha/yr). The mean growth rate of total stemwood biomass for a rotation of 80 years is slightly lower than for a rotation of 55 years (3.4 odt/ha/yr).

Figure A2.4 illustrates how the choice of rotations applied to forest areas involves trade-offs between achieving high biomass productivity for different types of wood product and high forest carbon stocks, for example:

- Choosing rotations to maximise production of biomass involves reduced potential for sawlog production.
- Choosing relatively long rotations to achieve high carbon stocks is likely to involve significantly reduced total biomass and sawlog productivity.
- Choosing relatively short rotations (such as less than 45 years in the case of Figure A2.4) generally involves significantly reduced total biomass and sawlog productivity, and also low forest carbon stocks.

Such points are very important when considering the adjustment of rotations in forest areas in order to increase the supply of forest bioenergy.

A2.4 Carbon dynamics in populations of stands

The discussion below serves two purposes, firstly, to illustrate how assessments of carbon dynamics in forests can depend on the scale considered and secondly, to describe an example of how, when large scales are considered, wood can be harvested from a forest without having negative impacts on forest carbon stocks.

Usually, not all of the stands of trees in a population forming a complete forest or landscape will be the same age or clear-felled at the same time, not least because a forest estate is usually managed to provide a regular supply of wood products. Hence, at the scale of a forest or landscape, losses of carbon stocks related to harvesting may be counterbalanced by carbon sequestration in the remaining stands which are still growing, as is the case if the relevant forest area is managed on the basis of sustainable yield (see Box 3.1, Section 3.1).

The pictures in Figure A2.5 illustrate how a forest could be created and then harvested according to sustainable yield principles, also showing the overall consequences for forest carbon stocks and carbon sequestration. This example is based heavily on earlier illustrations presented by Piers Maclaren (see for example Maclaren (2000, 1996)). It describes how a 5,600 hectare Sitka spruce forest can be created by establishing a population of even-aged stands at a rate of 100 hectares per year over a period of 56 years. Harvesting is assumed to involve clear-felling of stands on a rotation of 56 years, i.e. when stands reach an age of 56 years. Key parameters defining this forest creation scenario are given in Table A2.1.

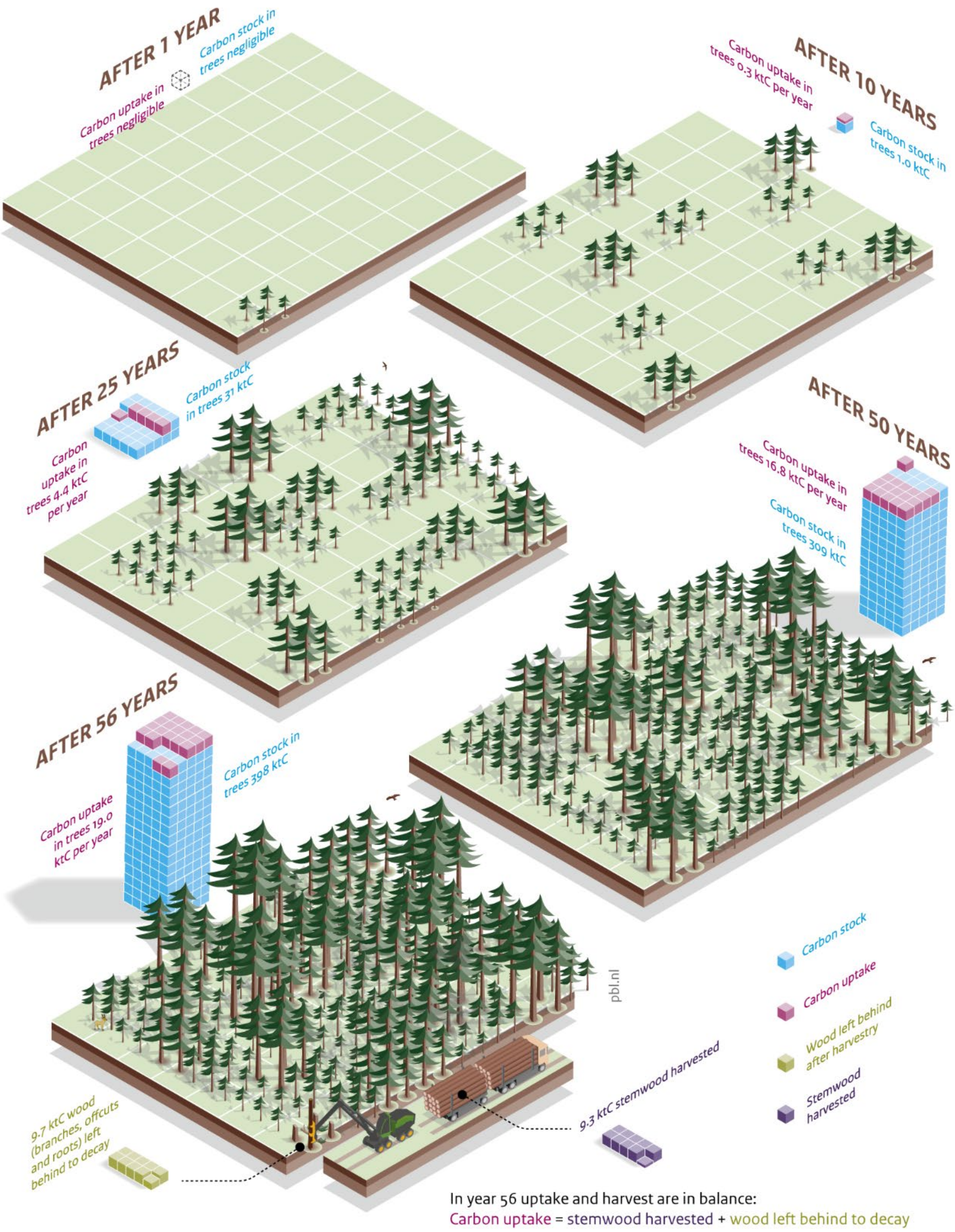
Table A2.1 Key parameters and assumptions underlying carbon stock calculations for example forest (Figure A2.5)

Parameter/assumption	Description/value
Notional country/region	United Kingdom
Forest area	5,600 ha
Tree species	Sitka spruce
Tree stem volume growth rate	12 m^3/ha/yr (4 odt/ha/yr) when grown on optimum rotation of about 55 years.
Tree planting program	100 hectares of trees planted per year over a period of 56 years.
Management	Even-aged planted forests, no thinning during the rotation, trees clear-felled on a specified rotation. Equal areas of forest are maintained for each forest stand age from 1 year up to the rotation age.
Rotation age	56 years
Wood utilisation	Stemwood extracted and utilised for bioenergy; residues (branchwood, roots, offcuts) left to decay in the forest.
Wood supply (estimates derived from Forest Research growth models, see Matthews, Henshall, et al. (2016); Matthews, Jenkins, et al. (2016)	11.2 m^3/ha/yr (3.7 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 10.1 m^3/ha/yr (3.3 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 56,700 m^3 (18.7 kodt/yr) for the complete 5,600 ha forest, once fully established.

After 25 years, 2,500 hectares of new Sitka spruce stands have been established, ranging in age from 1 to 25 years. The oldest stands are now growing relatively fast. Carbon stocks in trees have reached 31 ktC and the rate of carbon sequestration in year 25 has risen to 4.4 ktC/yr. After 50 years, 5,000 hectares of new Sitka spruce stands have been established, ranging in age from 1 to 50 years. Many stands are now in their most vigorous phase of growth, with the oldest in the mature phase. Carbon stocks in trees have reached 309 ktC and the rate of carbon sequestration has risen to almost 17 ktC/yr. After 56 years, the complete area of 5,600 hectares has been established with Sitka spruce stands, ranging in age from 1 to 56 years.

Figure A2.5

Creating a 5,600 hectare forest from even-aged Sitka spruce stands over 56 years and resultant impacts on carbon stocks and carbon sequestration



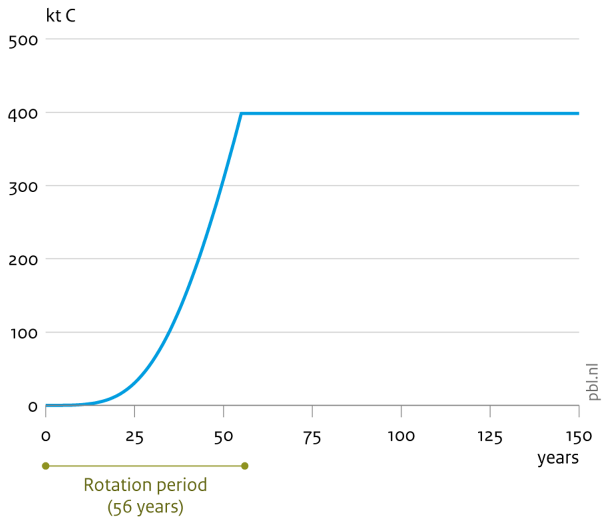
Source: Maclaren 1996, 2000 and Matthews 2020

The accumulation of carbon stocks continues up to year 56, at which point the first stands to be established (and therefore the oldest stands) are clear-felled. This results in the loss of 19.0 ktC in standing trees that are harvested, of which 9.3 ktC is extracted for use in products or for bioenergy, and almost 10 ktC is left in the forest as ‘residues’ (such as branches, offcuts of stem defects, tree roots). However, the lost carbon is exactly compensated for by the continuing growth and carbon sequestration in the remaining younger stands, so that, in year 56, carbon losses and gains in trees exactly balance. In year 57 another cohort of stands is clear-felled but the growth of the remaining forest stands again counterbalances losses of carbon stocks, as long as any felled stands of trees are re-established as soon as they are clear-felled.

The development over time of the carbon stocks in the trees comprising the stands forming the stands of a 5,600 hectare forest is shown in Figure A2.6. It shows how the accumulation of carbon stocks is initially slow, then becomes more rapid over the first 40 years from the start of forest establishment, as more stands of trees are planted, and the older stands enter their most vigorous phase of growth (see Figure A2.1). From year 56 onwards, the balance between the carbon losses when stands of trees are felled, and the continuing growth (and regrowth) of the remaining (and restocked) stands of trees results in the maintenance of an unchanging carbon stock in trees at the landscape scale, equal to almost 400 ktC for the whole forest, or more than 71 tC/ha, expressed on a per-hectare basis. Hence, provided that stands of trees are re-established as soon as they are felled, the *overall carbon stocks in the forest are not reduced by tree harvesting, but neither do they increase*, rather *a constant carbon stock is maintained over time*. The constant carbon stock means that there are no net emissions of carbon (as CO_2) to the atmosphere from the forest.

Figure A2.6

Tree carbon stocks in a 5,600 ha Sitka spruce forest managed on a clear-fell rotation of 56 years



Source: Forest Research UK

Notice that the per-hectare mean carbon stock in the Sitka spruce forest has exactly the same value as the mean carbon stock calculated for the individual stand managed on a rotation of 56 years in Figure A2.3. This is not a coincidence; these are two different ways of calculating the same result for the type of scenario considered here. Referring to results for mean carbon stocks can be one way to reconcile estimates based on stand-scale and landscape-scale assessments of forest carbon dynamics.

The example presented above is a simplified and idealised representation of a forest and its management, but it illustrates how continued harvesting of biomass from a managed forest can involve no net losses of carbon stocks from the forests, and therefore not result in net emissions of CO_2. This is not a subjective observation open to interpretation or argument – it is an undeniable physical fact. As already noted in the main report, it is also an undeniable fact that, ‘it takes seconds to cut down a tree, but it takes decades or centuries – 56 years in this case – to replace the carbon by growing another tree'. However, this observation is seen to be misleading when considering the sustainable management of a forest at the landscape scale, as illustrated here.

Although the example used in this section starts with the creation of a managed forest through afforestation (tree planting), the result is not limited to afforestation scenarios. Once a sustainable and stable set of management practices is established in an area of forest, it is possible to harvest wood for use as wood products or bioenergy while maintaining a stable carbon stock in the forest. This is represented by the flat portion of the trajectory in Figure A2.6. The initial increase in carbon stocks in the figure is the result of the afforestation activities and is an example of a 'carbon gain' as discussed more thoroughly in Appendix 3. In other scenarios, the introduction of new management practices to increase the supply of wood may result in a net reduction of carbon stocks, or a 'carbon debt', as discussed below and elsewhere in this report.

A2.4.1 Allowing for uneven stand age distributions

One important simplification of the above example is the assumption of a perfectly even distribution of tree stand ages over the assumed rotation of 56 years. Usually, real forests are composed of collections of stands with unevenly distributed tree ages. This has implications for the development of carbon stocks over time in forests, and for how forest areas are managed. These points can be illustrated by further modelled examples, as discussed below. Two examples are considered:

- A forest formed of stands of Scots pine, with a mean stem volume growth rate of 4 m^3/ha/yr over an optimal rotation period (see Section A2.3).
- A forest formed of stands of Corsican pine, with a stem volume growth rate of 16 m^3/ha/yr over an optimal rotation period.

The illustrations for these examples are based on UK growth and yield models and simulations produced using the Forest Research CARBINE model. These two forest types have been selected to be broadly representative of regenerated coniferous forests growing in the boreal region (such as Canada and the Nordic countries) and pine forests in subtropical climates (including the Southern USA) that are managed for wood production. Note that a mean growth rate of 16 m^3/ha/yr is commonly observed for regenerated pine stand in the Southern USA, but much faster growth rates are possible in plantations in the region formed of genetically improved pine trees managed intensively for wood production (such as with fertiliser application and intensive weed control, see Borders & Bailey, 2001). Key parameters defining these forest scenarios are given in Table A2.2.

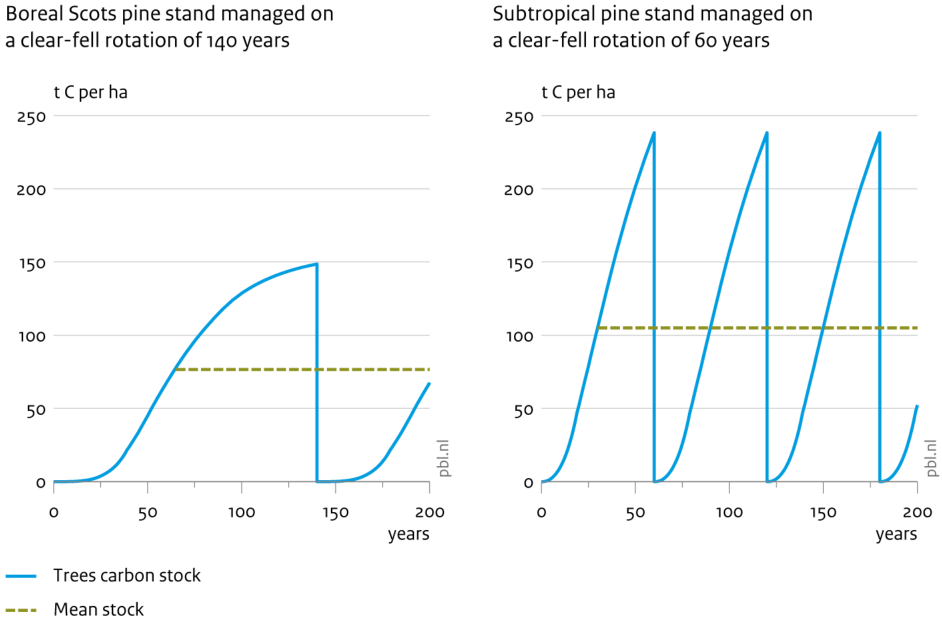
Table A2.2 Key parameters and assumptions underlying carbon stock and wood supply calculations for example forests (Figures A2.7 to A2.9)

Parameter/ assumption	Description/value	
	'Boreal'	'Subtropical'
Notional country/region	Canada, Nordic countries or more general boreal region	Southern USA or more general subtropical region
Forest area	140,000 ha	60,000 ha
Tree species	Scots pine (surrogate in Forest Research growth models/CARBINE model for coniferous forests in region)	Corsican pine (surrogate in Forest Research growth models/CARBINE model for pine forests in region)
Tree stem volume growth rate	4 m^3/ha/yr (1.7 odt/ha/yr) when grown on optimum rotation of about 90 years	16 m^3/ha/yr (6.4 odt/ha/yr) when grown on optimum rotation of about 50 years
Distribution of forest area with respect to stand age	Even distribution: Equal areas of forest for each forest stand age from 1 year up to the rotation age Uneven distribution: Forest stands with ages ranging from 1 year up to the rotation age. Majority of area of stands concentrated at mid-rotation stand ages, with relatively fewer stands with trees at younger or older ages	
Management	Even-aged regenerated forests, no thinning during the rotation, trees clear-felled on a specified rotation.	
Rotation age	140 years[1]	60 years
Wood utilisation	Stemwood extracted and utilised for bioenergy; residues (branchwood, roots, offcuts) left to decay in the forest	
Wood supply Estimates derived from Forest Research growth models, see Matthews, Henshall, et al. (2016); Matthews, Jenkins, et al. (2016).	3.0 m^3/ha/yr (1.2 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 2.7 m^3/ha/yr (1.1 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 372,000 m^3/yr (156 kodt/yr) for the complete 140,000 ha forest, once fully established.	13.7 m^3/ha/yr (5.5 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 12.3 m^3/ha/yr (4.9 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 738,000 m^3/yr (295 kodt/yr) for the complete 60,000 ha forest, once fully established.

Figure A2.7 shows the development of carbon stocks in the living trees over time in individual stands forming the two types of forest. The stands of trees are assumed to be created at time zero, managed without any thinning, and clear-felled at the specified rotation age, with immediate re-stocking and regrowth after clear-felling. The rotation age assumed for the boreal forest example is slightly longer than typical practice (100 to 120 years), but this has been assumed here to simplify calculations. As observed in previous examples in this appendix, carbon stocks in living trees cycle over a rotation between zero and a maximum value, which is 149 tC/ha for the boreal forest example, and 238 tC/ha for the subtropical example. The mean carbon stocks in the forest stands over a rotation are 76.6 tC/ha and 105 tC/ha respectively.

Figure A2.7

Tree carbon stocks in stands of trees in boreal and subtropical regions

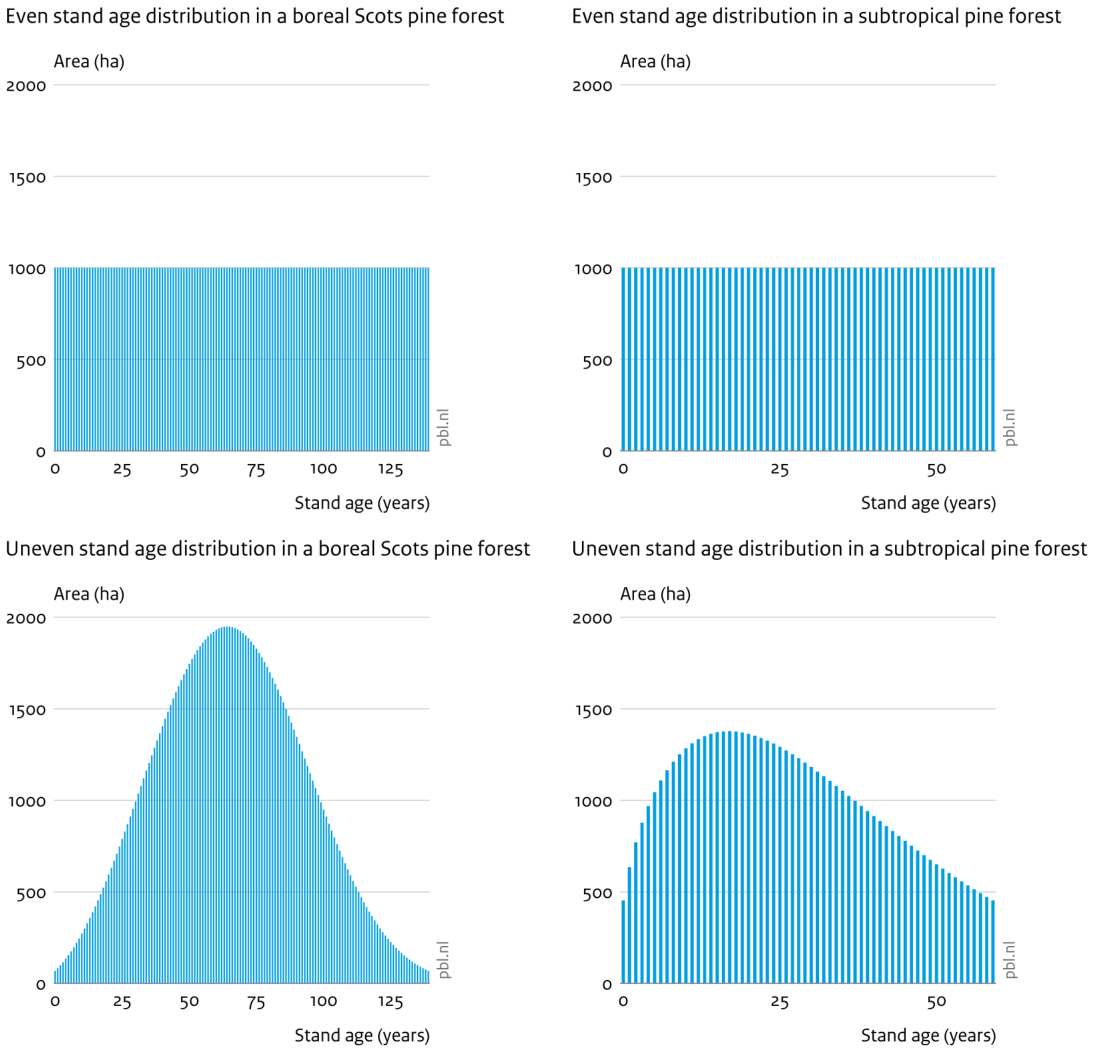


Source: Forest Research UK

Examples of possible distributions of stand ages forming a forest are shown in Figure A2.8. In two upper graphs in Figure A2.8, the age distributions are assumed to be perfectly even over the rotations applied to the boreal and subtropical forest examples. The two lower graphs in Figure A2.8 illustrate how forest areas might be distributed in an uneven way with respect to stand age over the rotations applied to the boreal and subtropical forest examples. In both cases, there is a bigger area of stands at mid-rotation ages, compared with the areas of stands at younger or late-rotation ages. The total area of forest is assumed to be 140 kha in the examples for the boreal forest and 60 kha in the examples for the subtropical forest.

Figure A2.8

Theoretical forest stand age distributions



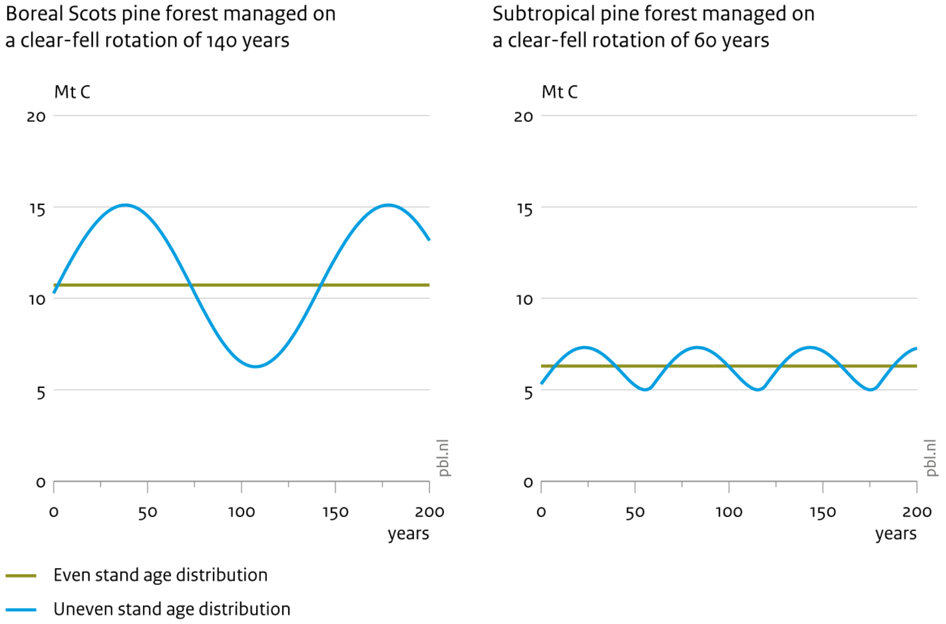
Source: Forest Research UK

Figure A2.9 shows the development of total carbon stocks in living trees in the example boreal and subtropical forests. The green horizontal lines show carbon stocks in the two example forests when the distributions of stand ages are perfectly even over the applied rotations. Under these special conditions, carbon stocks in the forest neither increase nor decrease, even though trees are regularly being harvested. The total carbon stocks in living trees in the boreal forest are almost 11 MtC, whilst those in the subtropical forest are 6.3 MtC. If these total stocks are divided by the respective forest areas, this gives mean carbon stocks of 76.6 tC/ha and 105 tC/ha, as already observed for the stand scale estimates in Figure A2.7. The blue lines in Figure A2.9 show the development of carbon stocks over time for examples of when the distributions of stand areas with respect to tree age are uneven. The carbon stocks show a cyclic development, undulating around the constant carbon stock observed for the situation when age distributions are perfectly even.

Two important points arise from consideration of the results. Firstly, the development of carbon stocks over time in the forests with uneven age distributions is driven by a combination of the specific age distribution present in the forest, the rates and patterns of growth exhibited by the individual stands of trees, and the way in which the stands are managed (such as the rotations applied). Hence, forest managers only have partial control over the development of forest carbon stocks.

Figure A2.9

Tree carbon stocks in forests with even and uneven stand age distributions



Source: Forest Research UK

Secondly, in the examples considered here, the forest management practices do not change over time (such as the rotations applied to stands are always the same), but carbon stocks nevertheless rise and fall over time because of the uneven age distribution and the particular growth patterns of individual stands of trees. Hence, when carbon stocks in the example boreal forest are increasing during the period between zero and 38 years, and between 108 and 178 years, this is not the result of ‘good’ or ‘improving’ forest management. Equally, when the carbon stocks are declining between 38 and 108 years, and after 178 years, this is not the result of ‘bad’ or ‘worsening’ forest management. Rather, the increases and decreases are principally a reflection of the uneven age distribution of the stands in the forest. Similar observations can be made about the rising and falling carbon stocks in the example subtropical forest. This point is very important, because it should be apparent from such illustrations that the impacts of forest management on forest carbon balances cannot be determined by simply monitoring the development of carbon stocks in forests, to see whether they are stable over time, or increasing or decreasing. This point is explored further in Section A2.5.1.

It should also be noted that the examples of uneven age distributions considered in these examples are relatively simple, for example involving continuous distributions. There are also no stands of trees with ages older than the rotations specified as part of management. Real forests generally have more complicated structures. The examples considered here also do not allow for the possibility that forests can be disturbed by fires, storms, pests, diseases, etc. All these factors would strongly influence the trajectory with which forest carbon stocks develop over time.

As already noted, the management of these example forests is assumed to remain the same, rather than evolving over time. For the cases involving perfectly even forest age distributions, this results in a constant rate of supply of harvested wood. However, when age distributions are uneven, rates of wood supply can go up and down depending on the area of forest available for clear-felling (at rotation age), in a given year. The rate of stemwood supply in the example boreal forest with an uneven age distribution varies between 12 and 339 kodt, depending on the year. Stemwood supply varies between 149 and 452 kodt in the equivalent example Southern US forest. Usually, large annual variations or cycles in wood supply are undesirable from an economic standpoint, and forest managers often adapt the management of stands to supply wood at a more stable rate. They often also try to modify the age distribution of forests so that ultimately it approaches the idealised even distribution, so that it is easier to ensure that forest management and wood supply rates can be kept consistent over time. Modifying the structure of forests in this way, and/or varying the details of the management applied to forest areas, will generally have impacts on the development of forest carbon stocks, as discussed further in Section A2.5.1.

A2.5 Carbon stock impacts of changing rotations

The above observations might lead to the suggestion that the harvesting of biomass from forests and utilising the biomass for bioenergy is always carbon neutral, as long as the rate of harvesting does not exceed the growth rate of the forest. However, this logic does not hold in general.
The following discussion illustrates how increasing biomass harvesting from an area of forest can lead to a period of raised CO_2 emissions (or a 'carbon debt'), even when the management of the forests is completely consistent with the principle of sustainable yield, when a long-term view is taken.

As discussed in Section A2.3 (see Figure A2.4), if the rotation period (time to clear-fell harvest) applied to stands forming a forest is changed, this affects both the mean tree carbon stocks in the forest and the carbon increments. The level of biomass production from the forest also depends on the applied rotation. For example, the 5,600 ha forest of Sitka spruce with a perfectly even age distribution, as described in Section A2.4, can supply almost 19 kodt/yr of stemwood (3.3 odt/ha/yr), when stands are managed without thinning on a 56 year rotation. If the stands forming the forest are managed on longer rotations, such as 80 years, the rate of stemwood supply is lower, at 17 kodt/yr (3 odt/ha/yr). It follows that, if the forest is initially being managed with an 80 year rotation, and the rotations applied to stands are shortened to 56 years, then wood supply can be increased by 1.67 kodt/yr, or 10%. However, shortening the rotations in this way also involves a reduction in carbon stocks in the forest.

Table A2.3 shows the results for total carbon stocks in a 5,600 ha forest such as described in Section A2.4, with equal areas of stands of trees over a full rotation of either 56 years or 80 years. In both cases, biomass production consists of stemwood only. All of the stemwood biomass is being used to produce energy by burning it as fuel. The remaining parts of the felled trees (foliage, branches, offcuts of stem defects, tree roots) are left to decay in the forest (assumed simply here to occur instantaneously). As stressed at the start of this appendix, these kinds of simplifications, which do not generally reflect real practice, have been applied in examples for clarity when explaining the fundamental science of carbon balances and the potential impact of tree harvesting and bioenergy production.

For management on either rotation, biomass harvesting matches the rate of biomass growth of the forest and so is consistent with the principle of sustainable yield. Carbon stocks are significantly higher in the forest managed on an 80 year rotation (almost 650 ktC or 2.4 $MtCO_2$), compared with the carbon stocks of the forest managed on the 56 year rotation (almost 400 ktC, or 1.5 $MtCO_2$, see Section A2.4).

Table A2.3
Carbon stocks and stemwood biomass production in an example 5,600 ha forest managed on rotations of 56 and 80 years

Measurement	Rotation 56 years	Rotation 80 years	Change (80 years to 56 years)	Change (%)
Total carbon stock in living trees (ktC; $ktCO_2$)	398; 1461[a]	648; 2376[a]	-250; -915[a]	-39%
Carbon stock change (ktC/yr; $ktCO_2$/yr)	-	-	-4.5; -16.3[a,b]	-
Stemwood biomass production (ktC/yr)	9.3	8.5	0.83	
Stemwood biomass production (kodt/yr)	18.7[c]	17.0[c]	1.67	+10%
Bioenergy production (TJ/yr)	336[d]	306[d]	30	

[a] CO_2 estimates calculate by multiplying carbon estimates by 44/12 (the ratio of the molecular masses of CO_2 and carbon).

[b] Calculated by dividing the total carbon stock change by the new rotation of 56 years (implicitly it is assumed that the forest undergoes the transition from being managed on longer rotations to shorter rotations over a period of 56 years).

[c] Calculated by dividing annual stemwood biomass production in units of ktC by an estimate of the carbon content of oven-dry wood (0.5; Matthews, 1993).

[d] Calculated by multiplying the annual stemwood biomass production in units of kodt by an estimate of the net calorific value of wood (MJ/odkg). The net calorific value of an energy source is sometimes also referred to as the lower heating value. Net calorific value represents the quantity of heat produced by the complete combustion of a given amount of a substance, allowing for any moisture content. The estimate referred to here (18 MJ/odkg). This is an estimate for woody biomass with a relatively low moisture content, expressed per unit of oven-dry biomass.

If an area of forest such as considered in this example was being managed with a rotation of 80 years, a decision could be taken to shorten the rotations to 56 years. This decision to shorten rotations should increase biomass production by almost 1.7 kodt/yr (Table A2.3). However, it is also apparent that this will involve a reduction of 250 ktC (915 $ktCO_2$) in the carbon stocks in the trees forming the forest. This reduction in carbon stocks will occur progressively over time, as the stands of trees in the forest are shifted from the longer rotation to the shorter rotation; here it is assumed that this transition happens over 56 years – consistent with the new rotation applied to the stands. If it is assumed that the carbon stocks are reduced at a constant rate over this period, this gives a rate of loss of carbon stocks (equivalent to net biogenic CO_2 emissions) from the forest of 4.5 ktC/yr.

It is evident that, during the 56-year transition period, the carbon stocks in the trees forming the forest cannot be assumed to be maintained at a constant level, and that the losses of carbon stocks must be allowed for when estimating the biogenic CO_2 emissions associated with using the biomass. More accurate calculations are possible but the aim here is to illustrate the principle of how a ‘carbon debt’ can occur as a result of producing biomass for energy from forests. Hence the example is theoretical and deliberately simplified.

The question arises as to whether changing the management of the forest to produce extra bioenergy would provide additional net reductions in CO_2 emissions. To answer this question, it is necessary to compare the outcome of the decision to take this action with the alternative of deciding not to take the action: the ‘counterfactual scenario’ (see Section 2.2). For the very simplified example considered here, it is clear how to define such a scenario: it involves continuing with the pre-existing management of the forest by maintaining the rotations of 80 years. However, note that in real-life situations it can be more difficult to clearly identify the counterfactual scenario for actions involving forest management to produce extra biomass.

For the 'extra-bioenergy' scenario, involving shortening rotations as considered above, the key outcomes are a supply of an extra 30 TJ/yr of bioenergy from the start of the transition period and continuing after the transition has taken place and a net biogenic CO_2 emissions of 16.3 ktCO_2/yr) during the transition period, which accumulate over the 56 years to a total of 915 ktCO_2. For the counterfactual scenario, energy supply and emissions continue as shown for a rotation of 80 years in Table A2.1. This means that there continue to be zero CO_2 emissions associated with the supply of bioenergy from the forest. However, the extra 30 TJ/yr of bioenergy does not become available (and therefore is not supplied) under the counterfactual scenario.

If it is assumed that there is still a requirement for this extra energy, then it is necessary to supply it from another source. Suppose that the consequence is that the extra energy is supplied by burning coal instead of the extra biomass. Then, given an emissions factor for coal of 95 gCO_2/MJ, the annual CO_2 emissions from generating the 30 TJ/yr using coal are 2.85 ktCO_2/yr). The cumulative emissions from coal over the transition period for the 'extra-bioenergy' scenario are significantly smaller, at 160 ktCO_2. However, after the transition period, the net biogenic emissions from the bioenergy stop accumulating, whilst the emissions from burning coal in the counterfactual scenario would continue (if it is assumed that coal is used as the alternative fuel indefinitely).

Because the net biogenic CO_2 emissions from the bioenergy only occur for a finite period, whereas the emissions from burning the coal (or other fossil fuels) would continue indefinitely, it follows that the point must come where the cumulative emissions from burning coal would exceed the total CO_2 emissions released by the forest-bioenergy system during the transition period. The time when this occurs in the example above and is 322 years after what would have been the start of the transition period for producing the extra bioenergy. The calculation of this result is illustrated pictorially in Figure 3.3. Key parameters and assumptions involved in these calculations are given in Tables A2.1, A2.3 and A2.4. The specific results for carbon debt and payback time in Figure 3.3 are sensitive to the simplifying assumptions made in the example and to the values assumed for key parameters used in calculations. This is discussed briefly in Section 3.4.1.

Table A2.4
Selected key parameters and assumptions underlying carbon debt calculations for this example of changing forest management to produce extra bioenergy

Parameter	Description/value
Forest type	As described in Table A2.1 (Sitka spruce plantations) 5,600 ha forest fully established after period of initial creation described in Section A2.4.
Rotation (initial state)	80 years
Rotation (eventual state)	56 years
Duration of transition period	56 years
Wood utilisation	As described in Table A2.1 (Section A2.4)
Wood supply before transition	10.2 m^3/ha/yr (3.4 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 9.2 m^3/ha/yr (3.0 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 51,600 m^3 (17.0 kodt/yr) for the complete 5,600 ha forest, once fully established.
Wood supply during transition	Assumed to be the same rate of supply as for wood supply after transition.
Wood supply after transition	As described in Table A2.1 (Section A2.4).
Energy value of wood	18 MJ/odkg
Carbon content of wood	0.5 tC/odt
Assumed counterfactual fuel source	Coal with emissions factor of 95 gCO_2/MJ.

A2.5.1 Interactions with stand age distributions

It should be apparent why a carbon debt occurs as a result of shortening the rotations in the Sitka spruce forest considered above. However, the occurrence of a carbon debt can be harder to discern in 'real' forests, where the age structure of stands is usually more complicated. This can lead to misunderstandings and confusion about whether management of particular regions of forest is having positive, neutral or negative impacts on forest carbon balances. This is a crucial issue that warrants closer attention.

To illustrate how confusion can arise, further analysis is presented based on the two theoretical examples of areas of forests already considered in Section A2.4.1 (a 'boreal coniferous forest' and a 'subtropical pine forest'). Scenarios in which the example areas of forest are managed according to unchanging prescriptions have already been described in Section A2.4.1. Additional scenarios are considered below, in which the management of the two example forest areas is adjusted, with the aim of supplying extra woody biomass from the forests, whilst complying with the principle of sustainable yield management. Illustrations are given for cases involving even and uneven distributions of stand ages in the forests, so that the two cases can be directly compared for each of the example forests. In essence, the scenarios considered involve:

- A significant shortening of rotations in a proportion of the example boreal coniferous forest, to increase total stemwood from the forest (this scenario is similar to the one illustrated Section A2.3 but for a different tree species, growth rate and rotation change).
- The introduction of regular thinning in stands forming a proportion of the example subtropical pine forest, to increase total stemwood supply from the forest, whilst also 'bringing forward'

some stemwood supply in the short term (through thinning during the rotation, rather than waiting for the time of clear-felling at the end of the rotation).

The key parameters defining these scenarios are given in Table A2.2 and Table A2.5 below.

Table A2.5
Key parameters and assumptions involved in calculation of increased stemwood biomass supply and consequent impacts on carbon stocks in theoretical examples of 'boreal' and 'subtropical' forests (Figures A2.11 to A2.14 and Table A2.6)

Parameter/assumption	Description/value	
	'Boreal'	'Subtropical'
Notional country/region	As described in Table A2.2.	
Forest area		
Tree species		
Tree stem volume growth rate		
Distribution of forest area with respect to stand age		
Initial management	As described in Table A2.2: even-aged regenerated forests, no thinning during the rotation, trees clear-felled on a specified rotation.	
Adjusted management	Shorten rotations in 30% of the area of stands forming the forest to be closer to the rotation age, so as to increase total annual supply of woody biomass. Specifically, the rotation age is halved in these forests as described in Box A2.1. Management is unchanged in the remaining 70% of area of stands.	Introduce regular thinning in 30% of the area of stands forming the forest. This slightly increases the total annual supply of stemwood biomass, because fewer trees are lost to mortality as a result of competition for space between trees. Thinning also 'brings forward' wood supply to an earlier time during the life cycle of stands. Management is unchanged in the remaining 70% of area of stands.
Initial rotation age	140 years	60 years
Adjusted rotation age	70 years	Unchanged
Wood utilisation	Stemwood extracted and sawlog-sized stemwood utilised for manufacturing sawn timber products. Other stemwood and offcuts from sawn timber manufacture utilised for bioenergy. Residues left to decay.	
Wood supply before transition	As described in Table A2.2.	
Wood supply after transition (estimates derived from Forest Research growth models, see Matthews et al., 2016ab.)	3.5 m³/ha/yr (1.5 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 3.1 m³/ha/yr (1.3 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 438,000 m³/yr (184 kodt/yr) for the complete 140,000 ha forest, once fully established.	15.8 m³/ha/yr (6.3 odt/ha/yr) when allowing for losses from tree mortality because of competition for space between trees in stands that are not thinned. 14.3 m³/ha/yr (5.7 odt/ha/yr) after allowing for efficiency of conversion of stemwood in standing trees to felled stemwood products. This is equivalent to 855,000 m³/yr (342 kodt/yr) for the complete 60,000 ha forest, once fully established.

Further details of how the adjustments to management have been modelled using CARBINE are given in Box A2.1 for the boreal forest example, and in Box A2.2 for the subtropical forest example. It must be stressed that the specific scenario considered for the boreal forest example is very unlikely to occur in practice. The initial rotation of 140 years is on the long side for the management of coniferous forests in the boreal region. Furthermore, application of a rotation of 70 years would result in a significant loss of sawlog production, which would not make commercial sense. The subtropical pine forest scenario may be broadly representative of one possible change in forestry practice in response to markets for wood pellets.

Box A2.1 Details of adjustments to management of boreal coniferous forest example

Objective. To increase long-term stemwood biomass supply from a forest area by roughly 5% compared to pre-existing supply levels.
Forest with even age distribution over rotation. Most of the of the forest area (70%) is managed in the same way, without change from the original scenario in Table A2.2. This involves clear-felling all areas of stands which have reached the rotation age of 140 years. Forest stands are left unthinned during the rotation. Management is changed in stands forming 30% of the forest area as described below. Note that the years quoted here are arbitrary, but the year in which management is changed (the start of the transition period) could be taken as the present, with earlier years representing the past and subsequent years the future.
Management in years 0 to 99 (30% of forest area, this also applies below). Management continues as in the original scenario described in Table A2.2.
Management year 100 (start of transition period). The stands that have reached the rotation age of 140 years are clear-felled. The regenerated stands in this area are then managed with a rotation of 70 years (referred to as 'area A'). The stands that have reached the adjusted rotation age of 70 years are also clear-felled ('area B'). Hence, the area of stands clear-felled in year 100 is increased, compared to clear-felling practice in the period before year 100. Stemwood supply is increased in this year because there are contributions from the stands clear-felled on the original (longer) rotation and from the stands clear-felled on the new (shorter) rotation.
Management in years 101 to 169 (year 169 is the end of a 70-year transition period). Management and wood supply follow the same pattern as in year 100.
Management in year 170. The stands that have reached the rotation age of 70 years are clear-felled. The area felled consists of the 'increased' area previously clear-felled in year 100 (area A plus area B). However, the stands in both A and B are now being managed with the shorter rotation of 70 years. Clear-felling the stands at 70 years produces less stemwood per hectare than would be obtained by harvesting at age 140 (because the trees are much younger). The overall effect of increasing the area clear-felled whilst reducing the per-hectare wood supplied by stands is a net increase in wood supply (see discussion of Figure A2.4; see also Figure A2.11). However, because the trees being clear-felled are now much younger, they are smaller in size and contain much less stemwood of sawlog dimensions, compared with trees in a stand aged 140 years. Hence, sawlog supply is negatively affected by the changed management.
Management after year 170. Management is according to the same pattern as in year 170. That is:

- All stands are now managed with a clear-felling rotation age of 70 years
- The total area of stands felled each year is increased
- The total stemwood supplied per hectare from clear-felling stands is diminished

- On balance, annual total stemwood supply is increased compared to how stands were managed previously, but sawlog supply is diminished.

Forest with uneven age distribution over rotation. The pattern of clear-felling and annual rate of wood supply are affected in a similar way to the forest with an even age distribution, but the variations over time are more complicated because the areas clear-felled vary in a complex way, depending on the year. In some years, the rate of wood supply is diminished compared to the case in which forest management continues without adjustment to rotation ages (see discussion of Figure A2.12).

Box A2.2 Details of adjustments to management of subtropical pine forest example

Objective. To increase long-term stemwood biomass supply from a forest area by roughly 5% compared to pre-existing levels supply.

Forest with even age distribution over rotation. Most of the forest area (70%) is managed in the same way, without change from the original scenario in Table A2.2. This involves clear-felling all areas of stands which have reached the rotation age of 140 years. Forest stands are left unthinned. Management is changed in stands forming 30% of the forest area as described below. Note that the years quoted here are arbitrary, but the year in which management is changed (the start of the transition period) could be taken as the present, with earlier years representing the past and subsequent years the future.

Management in years 0 to 59 (30% of forest area, this also applies below). Management continues as in the original scenario described in Table A2.2. This involves clear-felling all areas of stands which have reached the rotation age of 60 years. Stands are also managed without thinning.

Management year 60 (start of transition period). The stands that have reached the rotation age of 60 years are clear-felled. The regenerated stands in this area are then managed with a rotation of 60 years (hence the rotation age is unchanged). However, the regenerated stands are also managed with regular thinning every 5 years from age 20 to age 55 years ('area A'). The area of stands that has reached age 20 years is thinned. This is the age for the first scheduled thinning, if stands are managed with regular thinning consistent with the principle of sustainable yield ('area B'). Stemwood supply is increased in this year because there are contributions from the stands that are clear-felled and from the stands that are thinned.

Management in years 61 to 64. Management and wood supply follow the same pattern as in year 60.

Management in year 65. The stands that have reached the rotation age of 60 years are clear-felled. The regenerated stands in this area are then managed with a rotation of 60 years (hence the rotation age is unchanged). However, the regenerated stands are also managed with regular thinning every 5 years from age 20 to age 55 years.

The area of stands that has reached age 20 years is thinned. Additionally, the area of stands that has reached age 25 years is thinned. This is the second scheduled thinning in the stands that were first thinned at age 20 (in year 60). Thinnings are scheduled for every 5 years from age 20, until the rotation age (60 years) is reached. Stemwood supply is further increased in this year because there are contributions from the stands that are clear-felled and from the stands that are thinned, either for the first time (stands of age 20) or the second time (stands of age 25).

Management in years 66 to 69. Management and wood supply follow the same pattern as in year 65.

Management in years 70 to 99. Management and wood supply follow a similar pattern to that described for years 60 to 69, except that, from year 70 up to year 99, stands are thinned for a third, fourth, fifth, sixth, seventh and eighth time, depending on the ages reached by stands. The result is that wood supply progressively increases in 5 year steps (see discussion of Figure A2.11). One further consequence of the regular thinning is that there are much smaller losses of trees in stands because of competition between trees for growing space. Trees that would otherwise have died are either harvested in the thinnings or released from competition and able to keep growing.

Management in year 100. By year 100, all stands are being managed with regular thinning, so that wood is supplied from stands being thinned at different points during their life cycle (depending on whether the year coincides with the 5 year cycle for thinning in the stand). In addition to wood supplied from thinnings, the stands that have reached the rotation age of 60 years are clear-felled. However, by year 100, the stands being clear-felled have been regularly thinned during their life cycle. As a consequence the stemwood supplied from clear-felling is diminished, compared to the quantity that would be supplied from stands that have not been thinned. The overall effect of managing stands with regular thinning (as opposed to previously having not been thinned) is a net increase in stemwood supply (see discussion of Figures A2.10 and A2.11). Early thinnings generally involve the harvesting of small trees that are generally too small to provide sawlogs, whilst promoting the growth of the remaining trees so that they grow bigger and provide extra sawlogs. The net result is that the supply of stemwood suitable for use as sawlogs from all harvesting over a rotation is about the same, whether thinning or not thinning.

Management after year 100. Management is according to the same pattern as in year 100. That is:

- All stands are now managed with thinning on a 5 year cycle starting at age 20 and continuing to age 55 years, with clear-felling at age 60.
- The total stemwood supplied per hectare from clear-felling stands is increased.
- The total sawlog supply is about the same as before the practice of thinning was introduced.

Forest with uneven age distribution over rotation. The pattern of thinning and annual rate of wood supply is affected in a similar way to the forest with an even age distribution, but the variations over time are more complicated because the areas thinned and clear-felled vary in a complex way, depending on the year. In some years, the rate of wood supply is diminished compared to the case in which forest management continues without adjustment to rotation ages (see discussion of Figure A2.12).

Stand scale effects

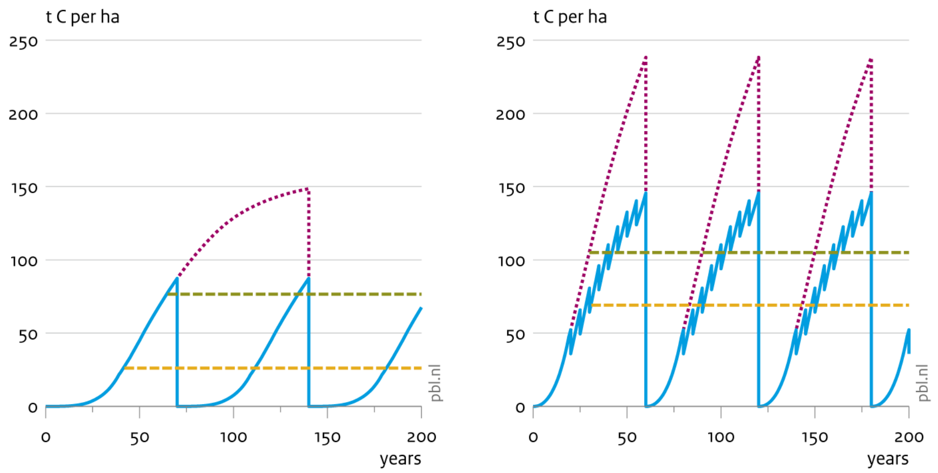
The effects of adjusting management as described above on carbon stocks in individual stands of trees are shown in Figure A2.10, for the boreal coniferous forest example and the subtropical pine forest example, respectively. The development of carbon stocks in these stands before management is changed has been described in Section A2.4.1. Further description about the changes to management is given in Boxes A2.1 and A2.2.

In the case of the boreal forest example, when the rotation age is shortened to 70 years, the carbon stock in living trees cycles during the rotation between 0 and 87 tC/ha, with a mean carbon stock over the rotation of 26 tC/ha (orange dashed line in left-hand graph in Figure A2.10). The mean carbon stock in a stand thus drops by 50 tC/ha, when compared with the mean carbon stock of almost 76 tC/ha when the stand is managed with a rotation of 140 years (green dashed line). The quantity of stemwood supplied when the stand is clear-felled at 70 years is 92 odt tC/ha, compared with 156 odt/ha, when the stand is age 140 years. The quantity of stemwood supplied when clear-felling a stand is significantly reduced when clear-felling on the shorter rotation. However, because two harvests can be made on the shorter rotation, for every single harvest on the longer rotation, the supply of stemwood from a stand managed on the shorter rotation over a comparable period of 140 years is 184 odt/ha.

Figure A2.10

Impact of adjusted management on carbon stocks in tree stands

Shortening of rotations from 140 to 70 years in a boreal Scots pine stand | Introduction of regular thinning in a subtropical pine stand



Trees carbon stock
- Rotation of 140 years
- Rotation of 70 years

Mean stock
- Rotation of 140 years
- Rotation of 70 years

Trees carbon stock
- Without thinning
- With thinning

Mean stock
- Without thinning
- With thinning

Source: Forest Research UK

In the case of the subtropical forest example, when regular thinning is practiced in the pine stand, the carbon stock in the living trees cycles during the rotation of 60 years between 0 and 146 tC/ha, with a mean carbon stock over the rotation of almost 70 tC/ha (see orange dashed line in right-hand graph in Figure A2.11). The mean carbon stock in a stand drops by 36 tC/ha, compared to when leaving the stand unthinned (green dashed line). Note also that the regular thinning of the stand during the rotation temporarily reduces the carbon stock, but this increases again as the remaining standing trees continue to grow, taking advantage of the extra growing space left by the trees that have been removed. It is assumed that 8 thinnings are carried out, starting when the stand is 20 years old and repeated every 5 years up to 55 years. Thinnings are carried out every five years according to standard prescriptions defined in British yield models. Standard British thinning prescriptions are likely to be different from normal practice in subtropical regions, where thinning may be less frequent and more intensive in terms of the numbers of trees removed. The quantity of stemwood supplied when the thinned stand is clear-felled is 189 odt tC/ha, compared with 295 odt/ha, when an unthinned stand is clear-felled. However, a further 19 odt/ha, is supplied from each of the 8 thinnings in the thinned stand, so that total stemwood production over a rotation is 342 odt/ha. Thinning the stand thus produces slightly more stemwood over the life cycle of the example stand of pine trees, compared with stands that are not thinned.

Forest scale effects

The effects of adjusting management as described for the example forests in Table A2.5, Boxes A2.1 and A2.2 are shown in Figure A2.11 (forests with perfectly even age distributions) and Figure A2.12 (forests with uneven age distributions). The figures show trajectories of stemwood biomass supply and carbon stocks in growing trees over time for two example forests, showing the effects of adjustments to forest management with the aim of supplying extra stemwood biomass.

Forests with even age distributions

The upper graphs in Figure A2.11 show how annual stemwood supply is increased when management is adjusted in the boreal coniferous forest (left-hand upper graph) and the subtropical pine forest (right-hand upper graph), when forest age distributions are perfectly even. Note that the years on the x-axis in the figure are arbitrary, but the year in which management is changed (the start of the transition period) could be taken as the present, with earlier years representing the past and subsequent years the future. In both examples:

- Annual stemwood supply is boosted during the transition period whilst management is being adjusted, by 17.6% in the boreal forest example, and up to 15.6% in the subtropical forest example.
- After the transition period, annual stemwood supply is sustained at a constant rate that is higher than under the previous management, by about 5% (see Boxes A2.1 and A2.2).

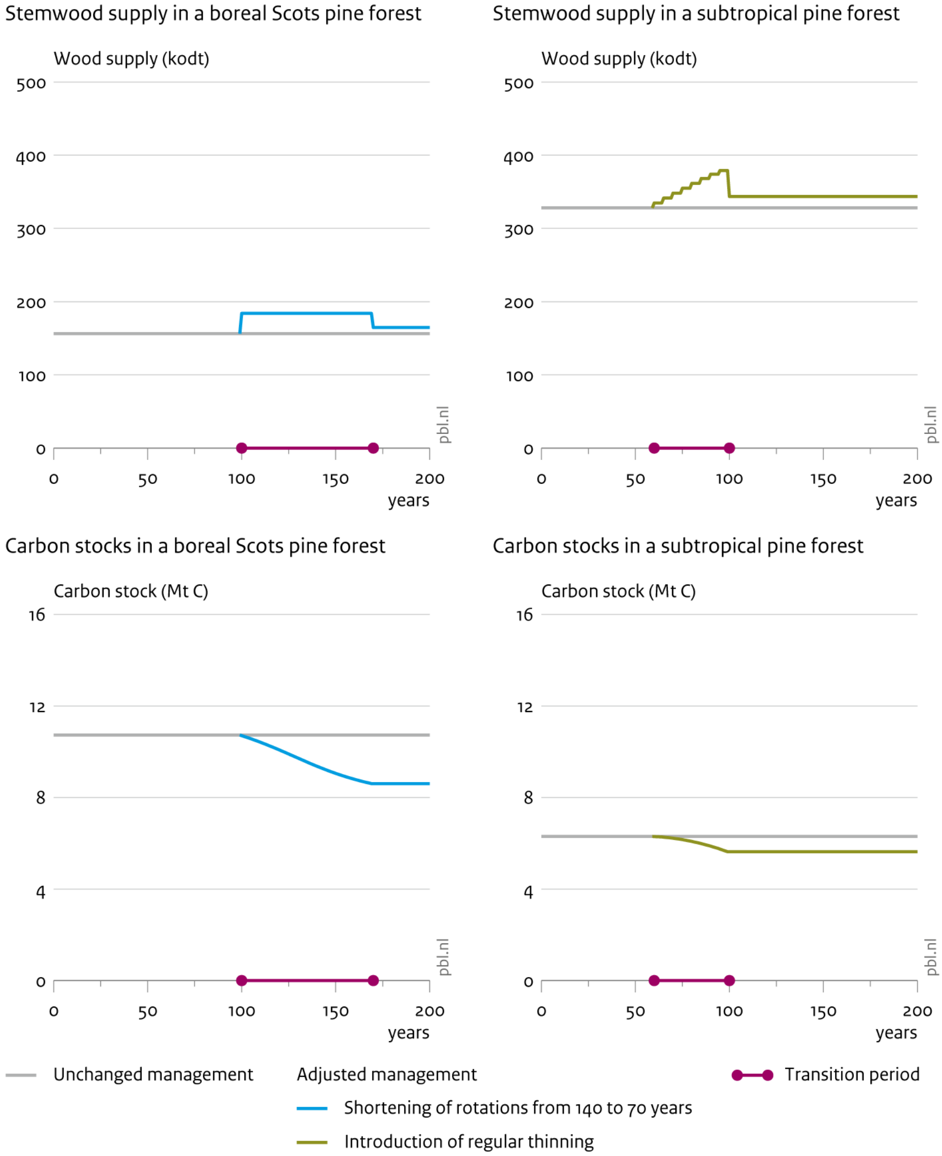
The lower figures in Figures A2.11 show how carbon stocks in living trees in the two example forests decrease during the transition period. For the boreal coniferous forest example (left-hand lower graph), carbon stocks drop by 2.1 MtC or 20%. In the case of the subtropical pine forest example (right-hand lower graph), the reduction is 0.7 MtC or 11%. In both examples, carbon stocks stabilise at a smaller magnitude after the transition period, compared to the situation before management is changed.

It is apparent in both these examples that forest management is sustainable in terms of impacts on carbon stocks when the forests are managed according to the original system, and also when managed under the changed system, in the time after the period of transition has occurred, in the sense that carbon stocks are stable. However, it is also apparent that carbon stocks in the forests are negatively affected during the transition period, whilst management practices are being adjusted to supply extra stemwood.

It is easy to see how carbon stocks develop in these examples, and to see the consequences of changing management, because these examples are highly simplified. In particular, the examples are based on simple, perfectly even forests in terms of stand age distributions, and involve assuming very simple examples of changes to stand management to supply extra stemwood. However, real forests are usually much more complex, and changes made to forest management in response to markets for timber and woody biomass can be complicated and difficult to determine. Potential interactions between simple changes in forest management when working with uneven age distributions in forests are illustrated below.

Figure A2.11

Impact of adjusted management on stemwood supply and carbon stocks in forests with even stand age distibution



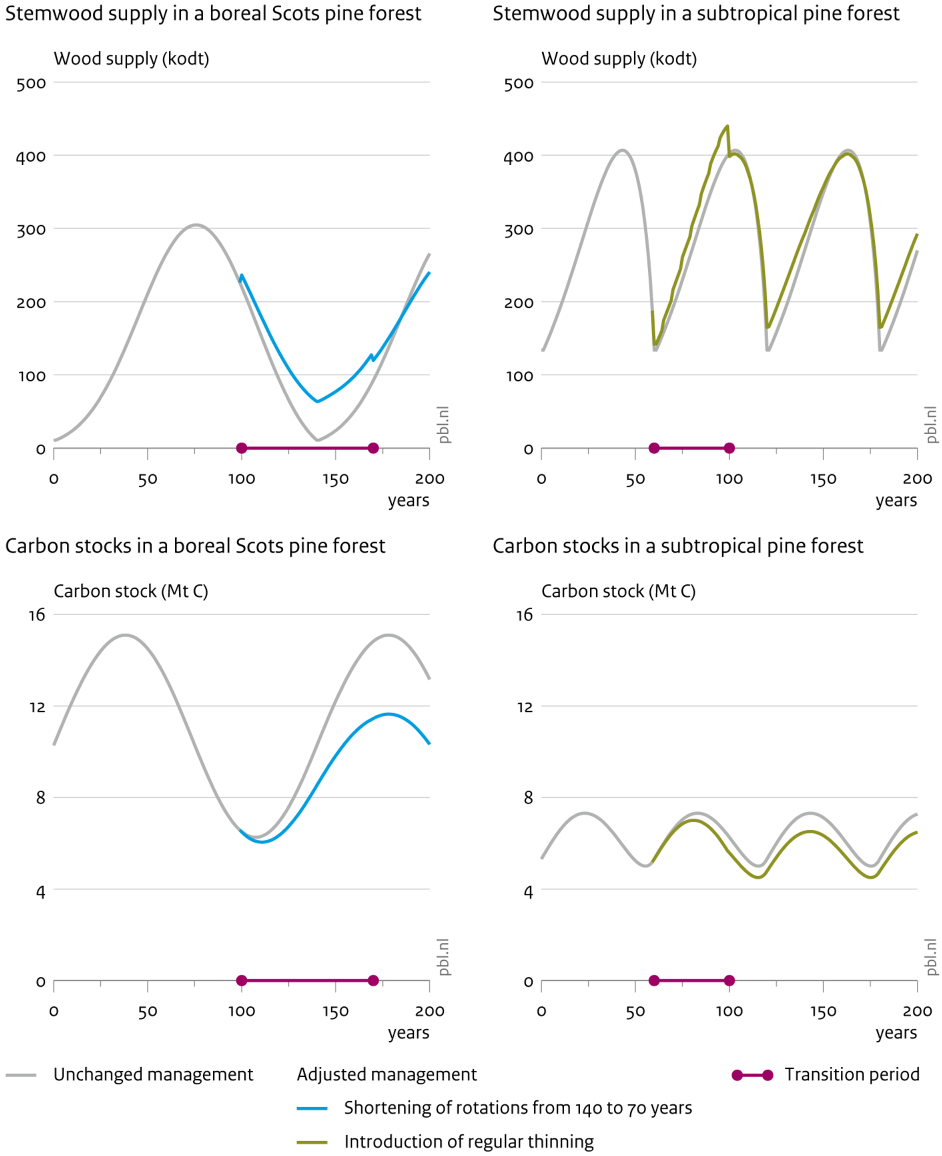
Source: Forest Research UK

Forests with uneven age distributions

The upper graphs in Figure A2.12 show, respectively, how the annual rate of wood supply is changed when management is adjusted in the boreal coniferous forest example (left-hand upper graph) and the subtropical pine forest example (right-hand upper graph), and when forest age distributions are uneven as described in Section A2.4.1. In both examples the long-term effects on wood supply are similar to the case when forest age distributions are simple (even). However, the effects on annual stemwood supply are variable over time and follow complicated trajectories, compared to the simpler examples discussed above.

Figure A2.12

Impact of adjusted management on stemwood supply and carbon stocks in forests with uneven stand age distribution



Source: Forest Research UK

In the case of the boreal coniferous forest example, annual stemwood is increased by between 16.2 and 53.7 kodt (mean 41.8). Stemwood supply already varies significantly over time because of the uneven age distribution in the forest, with the result that the relative increase in wood supply is very variable (7% to 493%), depending on the year. The adjusted management tends to smooth out annual stemwood supply, with the biggest increases in years where previously the rate of supply would have been at its lowest (around year 140 in Figure A2.12, left-hand upper graph). In the time after the transition period up to year 200, the increase in stemwood supply declines and by year 185 annual supply is diminished, compared to the rate that would occur if management is not adjusted.

In the case of the subtropical pine forest example (right-hand upper graph in Figure A2.12), annual wood supply is increased during the transition period (years 60 to 99), starting when the first scheduled thinnings occur in some stands (see Box A2.2). Annual supply increases in five-year steps, from 8 to 41 kodt. Wood supply is then slightly diminished for 12 years after the transition period (by about 1%). From year 112 onwards, changes in annual stemwood supply follow a cyclic pattern. Similarly to the boreal forest example, the adjusted management tends to slightly smooth out the cyclic variation in annual wood supply related to the age distribution of stands forming the forest. There are increases and decreases in individual years but on average annual wood supply is increased by 14 kodt.

The lower graphs in Figures A2.12 show how carbon stocks in living trees in the two example forests change over time as a result of the adjusted management. Carbon stocks deviate progressively from the pattern of development when management is unchanged. The magnitude of the difference varies depending on the point in the periodic age-related cycle, but the difference is consistently a decrease, with a mean magnitude effectively the same as observed for the examples involving even age distributions, once the transition period is passed (see lower graphs in Figure A2.11).

These examples, which allow for forests having an uneven age distribution, are still relatively simple representations of forest composition, structure and management. However, it is apparent from Figure A2.12 that the effects of forest management intended to enhance wood supply can be difficult to distinguish from 'background' carbon stock changes. To emphasise this point, consider the results for the carbon stock changes in the boreal forest example, for an even age distribution (Figure A2.11, left-hand graphs), and for the uneven forest (Figure A2.12, left-hand graphs). In the lower left-hand graph in Figure A2.11, the effects of changed management on carbon stocks over time are clear to see, even without comparing with the alternative (counterfactual) trajectory of carbon stocks when management is not changed. However, the effects of changed management on the trajectory of carbon stocks in the uneven forest (Figure A2.12, lower left-hand graph) are harder to discern. The effects are masked by the underlying cyclic development of forest carbon stocks related principally to the age distribution of the stands forming the forest. It is only when comparing this trajectory with the equivalent trajectory when management is unchanged that the effects are really apparent.

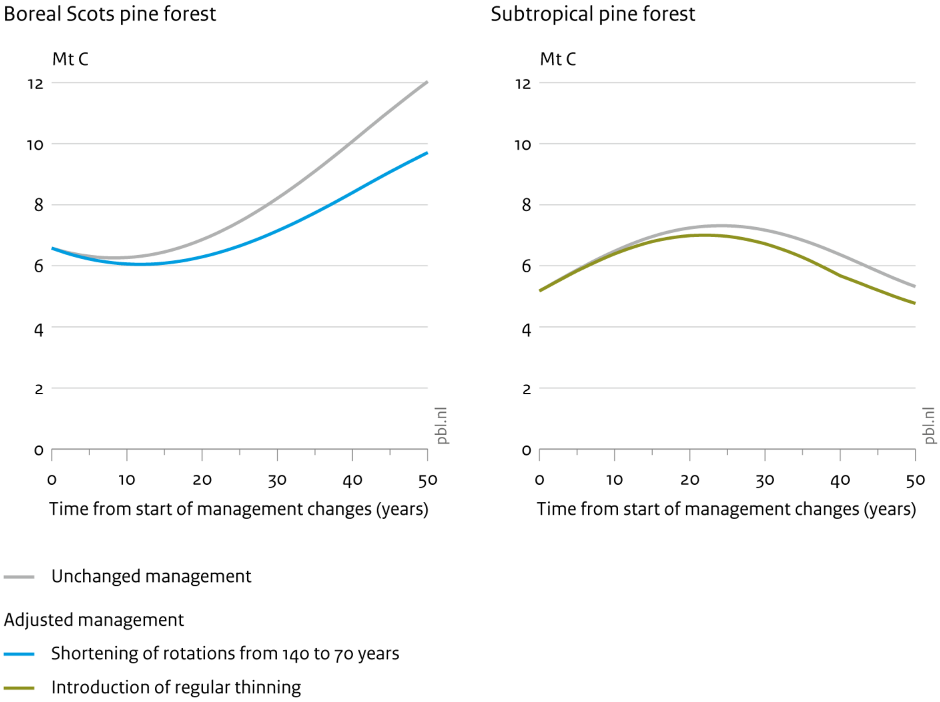
Hence, when considering real forests and forest management practices, it may be very difficult to determine the impacts of changes to forest management on the development of carbon stocks over time, by simply directly monitoring carbon stock changes. Indeed, attempting to do so is often likely to lead to false conclusions and misunderstandings. This is particularly important when considering what measures may be appropriate for evaluating the effects of forest management practices on carbon stocks, as discussed in Section 2.2 and Chapter 5. This point is highlighted by considering Figure A2.13, which shows the development of carbon stocks in the two example forests with uneven age distributions considered above, during the first 50 years following the start of adjustments to forest management to supply extra stemwood biomass.

In the case of the boreal coniferous forest example (blue line, left-hand graph), carbon stocks decline slightly over the first 10 to 12 years, but then increase continuously over the rest of the period, even though forest management has been changed to supply extra wood. In the case of the subtropical pine forest example (green line, right-hand graph), carbon stocks increase continuously over the first 22 years.

However, it should be apparent from the discussion so far that it would be wrong to conclude from these observations that increasing the rate of wood supply is not causing a carbon debt (so that the woody biomass supplied could be regarded as carbon neutral or better). If forest management is not adjusted (the counterfactual scenario), the increases in carbon stocks would be greater than observed for the situation in which wood supply is increased (grey lines in Figure A2.13).

Figure A2.13

Impact of adjusted management on carbon stocks in boreal and subtropical forests with uneven stand age distributions



Source: Forest Research UK

Another way of considering the impact of changed forest management over this period is to calculate the quantity of carbon sequestered per ton of stemwood supplied under each scenario, as shown in Table A2.6. The suggested ratio can be calculated in two ways:

1. The simpler ratio is calculated by dividing the carbon stock change in the forest (in living tree) over the specified period by the total stemwood supplied during the period.
2. The alternative calculation essentially allows additionally for the carbon retained in the supplied wood, assuming that none of this carbon is lost during the specified period (such as as a result of manufacturing process, or being burnt as fuel etc.).

Regardless of how the ratio is calculated, it is clear from Table A2.6 that the ratio is smaller as a result of supplying extra stemwood from the forest through adjustments to forest management practices, even though the carbon stocks are increasing during the periods considered.

The logic of the analysis presented above extends to situations where carbon stocks in forests are declining rather than increasing, as is the case for the subtropical pine forest in the period between 22 years and 50 years from the start of adjustments to forest management (green line in Figure A2.14, right-hand graph). Carbon stocks decline during this period, regardless of whether forest management practices are adjusted to supply extra stemwood or continued without changes to existing management practices. However, as with the earlier positive trend in carbon stocks, the pattern during this period is principally a reflection of the age distribution of stands forming the forest.

Table A2.6
Relationship between stemwood biomass supply and carbon stock changes in two example forests showing effects of increasing stemwood biomass supply

Forest system	Period (years)	Stemwood biomass supply during period (Modt)	Carbon stock change during period (MtC)	Carbon sequestered per unit of stemwood biomass supplied (tC/odt)	
				Not allowing for carbon in harvested wood	Allowing for carbon in harvested wood
Boreal, no increase	50	0.429	5.46	12.7	13.2
Boreal, increased supply	50	0.626	3.13	5.0	5.5
Subtropical, no increase	22	0.482	2.00	4.1	4.6
Subtropical, increased supply	22	0.533	1.68	3.2	3.7

A2.6 Key insights arising from this illustration

The possibility of a 'carbon debt' being associated with bioenergy produced from forests is not an artefact of modelling – it is an undeniable, physical fact that such an outcome can occur in certain circumstances, just as it is physically possible for using forest bioenergy to involve zero net CO_2 emissions. Both outcomes are possible, depending on the amount of bioenergy produced from the forests and how the forests are managed to produce the bioenergy. As discussed in Section 3.5, there can also be situations where managing forests to produce bioenergy and other wood products can result in net negative CO_2 emissions (or net carbon sequestration). In fact, it should be noted that scenarios in which producing biomass from forests result in a carbon debt or net negative CO_2 emissions are more likely than the often rather theoretical scenario in which the carbon flows between forests, wood products and the atmosphere are in perfect balance.

Simple monitoring of forest carbon stocks is useful as one indicator of sustainable management, but this is insufficient for determining whether woody biomass harvested and extracted from forests involves (or avoids) a carbon debt. A more elaborate analysis is required for this purpose, which involves comparing the actual carbon stocks observed in forests against 'benchmark estimates' of carbon stocks, for a counterfactual scenario in which the woody biomass is not harvested and extracted.

In practice, it can be highly challenging to define a clear and generally accepted counterfactual scenario for the management of forests, and then estimate how carbon stocks would develop under this scenario. This is one major cause of divergent results reported in scientific studies of the impacts of woody biomass harvesting on forest carbon stocks and sequestration, as discussed further in Chapter 4. Ideally, a relatively simple approach is needed for practical implementation, and some possible approaches are explored in Chapter 5.

Whilst the example calculations in this appendix are simplistic, it should be apparent that the magnitude and duration of any carbon impacts associated with forest management and biomass production are inextricably linked to the quite numerous parameters and assumptions that underly the calculations. If these parameters and assumptions are varied, then the direction, magnitude and duration of any carbon impacts will also vary, potentially considerably. This is one of the key reasons why widely varying estimates of the CO_2 emissions of forest bioenergy systems can be reported by different scientific studies, and why the conclusions of studies of bioenergy can disagree.

This emphasises the importance of presenting assumptions, calculations and parameters as transparently as possible, including clearly and thoroughly defining the scenario under which bioenergy or wood-based products in general are produced from forests, and its counterfactual scenario, where this is relevant.

Appendix 3. Carbon stock dynamics: Carbon gain

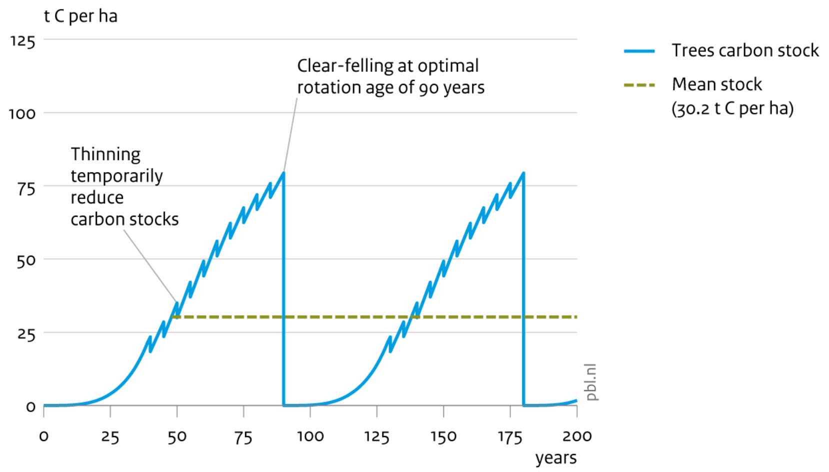
This appendix provides information in support of the results presented as part of the example in Section 3.5 of this report. The illustrations below are based on theoretical examples of forests formed of stands of Scots pine trees, with a mean stem volume growth rate of 4 and 6 m^3/ha/yr when stands are managed on an optimum rotation. This tree species and growth rates can be encountered in Northern Europe, in countries such as Sweden, Finland and the Baltic States. Scots pine is also commonly found in other parts of Europe, where growth rates can be faster.

The Scots pine forest stands are assumed to be managed with the regular thinning of trees during the rotation, with a final harvest by clear-felling at the optimum rotation age for stemwood production. Thinning can help to ensure that good quality stemwood is produced at the end of the rotation. It is assumed that defective or damaged stem sections, branches and roots of harvested trees are left to decay in the forest.

It is possible to calculate the mean carbon stock in trees over a rotation for this kind of Scots pine stand, in the same way as for the Sitka spruce stands considered in examples in Appendix 2. In Figures A3.1 and A3.2, the stands of trees are assumed to be created at time zero, managed with thinning, and clear-felled on an optimum rotation for stemwood rotation volume production, with immediate restocking and regrowth after clear-felling. Only carbon stocks in growing trees are shown in the figure, to keep the discussion simple.

Figure A3.1

Tree carbon stocks in a Scots pine stand managed on a clear-fell rotation of 90 years, growth rate 4 m^3 per ha per year

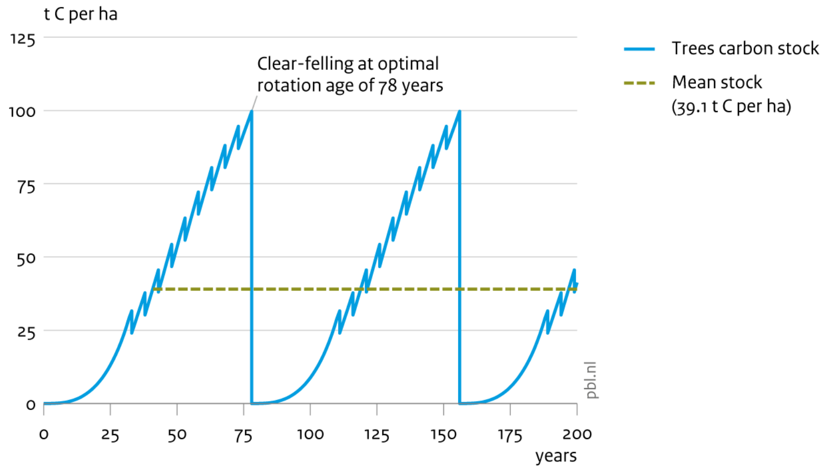


Source: Forest Research UK

Figure A3.1 shows the development of carbon stocks in a notional one hectare stand of Scots pine trees with a mean stem volume growth rate of 4 m^3/ha/yr when stands are managed on an optimum rotation of 90 years. The carbon stocks in trees accumulate from the time of planting up to the end of each rotation. The regular thinning of the stand during the rotation temporarily reduces the carbon stocks, but these increase again as the remaining standing trees continue to grow, taking advantage of the extra growing space left by the trees that have been removed. After clear-felling, the carbon stocks accumulate again following replanting with the result that, over repeated rotations, carbon stocks in living trees ‘cycle’ between zero and almost 80 tC/ha every 90 years. For comparison, Figure A3.2 shows the development of carbon stocks in a stand of Scots pine trees with a faster mean stem volume growth rate of 6 m^3/ha/yr when stands are managed on a shorter optimum rotation of 78 years. The general pattern of development of carbon stocks in the stand is similar to that for the stand with the slower growth rate (Figure A3.1), but the mean carbon stock in trees is slightly higher.

Figure A3.2

Tree carbon stocks in a Scots pine stand managed on a clear-fell rotation of 78 years, growth rate 6 m^3 per ha per year



Source: Forest Research UK

Now suppose that forestry practitioners respond to increased interest in using biomass (for non-energy products and bioenergy) by taking actions to improve the productivity of Scots pine stands, as outlined in Section 3.5. These actions might happen as a result of increased economic incentives to supply biomass, or possibly in response to policy measures to support an increase in biomass supply from forests. Suppose the additional forest management practices have the effect of increasing the stemwood growth rate of the Scots pine stands from 4 to 6 m^3/ha/yr over an optimum rotation. Because the growth rate is enhanced, the optimum rotation age is also shortened, to 78 years instead of 90 years.

The mean carbon stocks in the faster growing Scots pine stands can be calculated to be 39.1 tC/ha (see Figure A3.2). Hence, the changes in forest management practices result in an increase in mean carbon stocks, or net carbon sequestration, of almost 9 tC/ha. This equates to a removal of CO_2 from the atmosphere of 32.5 tCO_2/ha. Suppose that the additional management practices are introduced over 90 years (the original rotation applied to the Scots pine stands). If the change in mean carbon stocks happen over this 'transition period', this gives a mean rate of carbon sequestration of 0.11 tC/yr (0.4 tCO_2/ha/yr). These results are summarised in Table A3.1.

Table A3.1
Carbon stocks and stemwood biomass production in example stands of Scots pine managed with growth rates of 4 and 6 m^3/ha/yr, with rotations of 90 years and 78 years, respectively.

Measurement	Growth rate 4 m^3/ha/yr	Growth rate 6 m^3/ha/yr	Change 4 to 6 m^3/ha/yr	Change (%)
Total carbon stock in living trees (tC/ha)	30.2/110.7[a]	39.1/143.3[a]	+8.9/32.5[a]	+29%
Annualised carbon stock change (carbon sequestration, tC/ha/yr / tCO_2/ha/yr)	-	-	+0.11/0.4[a,b]	-
Total annual stemwood volume production (m^3/ha/yr)	3.6[c]	5.4[c]	+1.8	+50%
Total annual stemwood biomass production (odt/ha/yr)	1.51[d]	2.27[d]	+0.76	
Total annual stemwood carbon production (tC/ha/yr)	0.76[e]	1.13[e]	+0.38	
Annual stemwood carbon production used for bioenergy (tC/ha/yr)	0.21[f]	0.32[f]	+0.11	
Annual stemwood biomass production used for bioenergy (odt/ha/yr)	0.42[f]	0.64[f]	+0.21	
Annual stemwood biomass production used for bioenergy (GJ/ha/yr)	7.6[g]	11.4[g]	+3.8	
Annual stemwood biomass production used for paper and related (tC/ha/yr)	0.11[f]	0.17[f]	+0.06	
Annual stemwood biomass production used for other wood products (tC/ha/yr)	0.43[f]	0.65[f]	+0.22	

[a] CO_2 estimates calculate by multiplying carbon estimates by 44/12 (the ratio of the molecular masses of CO_2 and carbon).

[b] Calculated by dividing the total carbon stock change by the original rotation of 90 years (implicitly it is assumed that the forest undergoes the transition from being managed on longer rotations to shorter rotations over a period of 90 years).

[c] Extracted stemwood calculated from the maximum stemwood production assumed (4 or 6 m^3/ha/yr) multiplied by 0.9 to allow for conversion of standing stemwood in the forest into extracted products.

[d] Extracted stemwood biomass in odt/ha/ha calculated by multiplying extracted stem volume by a value for the nominal specific gravity of Scots pine stemwood (0.42 odt/m^3, Lavers and Moore, 1983).

[e] Extracted stemwood carbon in tC/ha/ha calculated by multiplying extracted stem biomass by a value for the carbon content of oven-dry wood (0.5 tC/odt, Matthews, 1993).

[f] Calculated by first allocating total stemwood production to raw wood products of sawlogs, small roundwood and bark using a stemwood assortment model (Matthews & Mackie, 2006) then allocating fractions of these raw products to bioenergy, paper and related products and other products according to fixed proportions. The net result is an allocation of 28% of harvested stemwood to bioenergy, with 15% allocated to paper and related products and the remainder (57%) allocated to other products

[g] Calculated by multiplying the annual stemwood biomass production in units of kodt by an estimate of the net calorific value of wood (MJ/odkg). The net calorific value of an energy source is sometimes also referred to as the lower heating value. Net calorific value represents the quantity of heat produced by the complete combustion of a given amount of a substance, allowing for any moisture content. The estimate referred to here (18 MJ/odkg). This is an estimate for woody biomass with a relatively low moisture content, expressed per unit of oven-dry biomass.

The change in forest management also increases the supply of biomass from the Scots pine forests, for use as bioenergy and for non-energy products, as also shown in Table A3.1. The extra biomass does not become available immediately but will start to be produced as the faster-growing trees that replace the slower-growing trees reach the phase of growth suitable for thinning and, eventually, final harvesting.

If the management of the forest is not changed, then the quantities of extra bioenergy and non-energy products shown in Table A3.1 do not become available (and therefore are not supplied).

If it is assumed that there is still a requirement for the extra energy and other products, then it is necessary to supply these from other sources. Suppose that the consequence is that the extra energy is supplied by burning a mixture of natural gas and coal instead of supplying the extra bioenergy, and that non-wood materials are used in place of the extra non-energy wood products.
An amount of energy supplied by consuming a roughly 50:50 mixture of natural gas and coal will result in greenhouse gas emissions of about 75 gCO_2eq per megajoule of energy, or 0.075 tCO_2eq per gigajoule (tCO_2eq/GJ). For the calculations presented here, it is assumed that not supplying the extra paper and related products has no impact on greenhouse gas emissions. This assumption has been made for simplicity. More elaborate approaches include assuming that:

- The paper is supplied using wood from a different area of forest (which may have widely varying impacts on the carbon balance, depending on the details of the scenario).
- Electronic systems such as notepads are used instead of paper.
- Petroleum-based products of some sort are used in place of paper.

For the other non-energy products, it is assumed here that the magnitude of greenhouse gas emissions avoided when these products displace non-wood products is 1.2 tCeq emissions avoided by not consuming a non-wood product, for every tC of carbon contained in the wood making up a product (1.2 tC/tC; see discussion in Section 3.4). This equates to 4.4 tCO_2eq emissions avoided by not consuming a non-wood product, for every tC of carbon in the wood products. These assumptions can be used to calculate the greenhouse gas emissions avoided by producing the extra bioenergy and non-energy wood products, as shown in Table A3.2. The annual greenhouse gas emissions by using the bioenergy are 0.29 $tCO_2eq/ha/yr$, whilst the emissions avoided by using the non-energy products are 0.95 $tCO_2eq/ha/yr$. Hence, the supply of the extra bioenergy and non-energy products avoids a total of 1.23 $tCO_2eq/ha/yr$.

Table A3.2
greenhouse gas emissions avoided by increasing the supply of biomass for this example of improved management of a Scots pine forest

Wood product type	Additional supply and units	Emissions factor and units	Avoided emissions ($tCO_2eq/ha/yr$)
Bioenergy	3.8 GJ/ha/yr	0.075 tCO_2/GJ	0.29
Paper and related products	0.06 tC/ha/yr	0	0
Other non-energy products[a]	0.22 tC/ha/yr	1.2 tCeq/tC[b]	0.95
All products			1.23

[a] Such as panels and structural timber.
[b] Equals to 4.4 tCO_2eq/tC.

The complete carbon balance for this example of improving forest management to supply more biomass for use in a range of products can be calculated by combining the results for carbon sequestration in Table A3.1 with the results for avoided greenhouse gas emissions in Table A3.2. Allowance also needs to be made for contributions to the carbon balance made by carbon stock changes in deadwood, litter and soil and carbon retained in wood products. These calculations are described in Section 3.5.

Appendix 4. Analysis of selected studies

This appendix gives details of an assessment of a selection of published studies, the main findings of which have been presented in Section 4.5 of Chapter 4 of this report. The assessment illustrates the kinds of issues that can arise when trying to review and interpret evidence from scientific studies of the CO_2 emissions resulting from forest management and biomass use, for bioenergy or non-energy purposes.

The 16 selected papers are assessed in Tables A4.1 to A4.15, according to a set of factors described in Table 4.9 in Section 4.5. The assessments also give details of the location of the forest systems considered, and a brief description of the types of scenario for forest management and/or biomass use covered in each study. Possible issues related to how each study represents 'forest management and effects on carbon stock changes' (see Table A4.7) are assessed further in Table A4.16.

Table A4.1
Assessment of study of Aguilar et al. (2022)

Full reference	Aguilar, F.X., Sudekum, H., McGarvey, R., Knapp, B., Domke, G. and Brandeis, C. (2022) Impacts of the US southeast wood pellet industry on local forest carbon stocks. Scientific Reports, 12:19449, https://doi.org/10.1038/s41598-022-23870-x
Location	Southeastern USA
Scenarios	One scenario involving wood pellet production from forests in the region.
Spatial scale	Real landscape
Static/dynamic forest area	Unclear, possibly dynamic but unclear from description of methods.
Temporal scale	Short, 2000 to 2019
Forest management and effects on carbon stock changes	Forest carbon stocks directly measured in US national forest inventory plots were subjected to a complicated statistical analysis, which involved stratifying the inventory plots into two groups: those falling within the catchment of wood pellet mills, and those outside catchment areas. Plots were also matched to form pairs for comparison, involving consideration of a number of factors (e.g. type of forest, evidence of damage, stand structural complexity). The analysis permitted changes in carbon stocks in forests inside and outside catchment areas to be compared (although this point is not stated clearly in the paper).
Counterfactual forest management	Not specified directly, but represented by the sample plots outside catchment areas of wood pellet mills.
Bioenergy feedstocks	Not represented, out of scope of the study
Wood product substitution	Not represented, out of scope of the study
Metric	Carbon stock change between 2000 to 2019, but interpreted as part of complex statistical analysis
Outcome	Positive for total carbon stocks (for live trees, deadwood, and soil) slightly negative for soil.

Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The statistical analysis of national forest inventory data avoids reliance on modelling and assumptions involved. However, the statistical analysis methods in this study are very complicated and the description is opaque. It is, therefore, difficult to assess the validity of the methods and their results. The conclusion is drawn in the paper that the presence of wood pellet mills is having a net positive impact on forest carbon stocks within the catchment areas where they operate. However, statistically significant correlation does not necessarily imply causality. A possible alternative interpretation could conclude that the locations selected for pellet mills are being selected in regions where forest carbon stocks and productivity are already more vigorous. The conclusions appear to depend critically on the robustness of the plot pairing methodology. It may also be noted that carbon stocks in catchment areas were found to be statistically higher concurrently with, and five years after, the operation of pellet mills, but no longer significantly higher after ten years.

Table A4.2
Assessment of study of Bernier and Paré (2013)

Full reference	Bernier, P. and Paré, D. (2013) Using ecosystem CO_2 measurements to estimate the timing and magnitude of greenhouse gas mitigation potential of forest bioenergy. *GCB Bioenergy*, **5**, 67-72. https://doi.org/10.1111/j.1757-1707.2012.01197.x
Location	Canada
Scenarios	One scenario involving clear-felling stands to use stemwood as bioenergy.
Spatial scale	Effectively theoretical landscape scale (stands of different ages combined to form chronosequences).
Static/dynamic forest area	Static, only considers carbon balance of research study areas where flux measurements have been collected.
Temporal scale	Long, 120 years from time of harvest (assuming clear-felling)
Forest management and effects on carbon stock changes	Estimated as carbon 'net increment' of unmanaged forests minus 'harvest emissions', estimated as smokestack emissions. This approach may not fully represent effects of forest management on forest carbon stock dynamics.
Counterfactual forest management	No harvesting, which in this special case may represent what happens if there is no demand for bioenergy. Assumes that CO_2 flux (sequestration) observed at age 120 years continues indefinitely.
Bioenergy feedstocks	All stemwood used for bioenergy (wood pellets), which in this special case may represent actual use.
Wood product substitution	Included: fuel oil (for small-scale heat)
Metric	Annual net change in emissions and carbon payback time
Outcome	Negative
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change' but this is a special case in which 'no harvesting' is a realistic assumption for a counterfactual scenario, and all stemwood is used as the bioenergy feedstock.

Table A4.3
Assessment of study of Chen et al. (2018)

Full reference	Chen, J., Ter-Mikaelian, M.T., Yang, H. and Colombo, S.J. (2018) Assessing the greenhouse gas effects of harvested wood products manufactured from managed forests in Canada. *Forestry*, **91**, 193-205, https://doi.org/10.1093/forestry/cpx056
Location	Ontario
Scenarios	Increased harvesting in four case study forest management units managed for timber production, with five scenarios for utilisation of harvested wood: 1. Prioritise structural timber. 2. Prioritise plywood and oriented strand board. 3. Prioritise other wood based panels e.g. chipboard. 4. Prioritise pulp and paper. 5. Continue current pattern of utilisation of harvested wood for different products.
Spatial scale	Real landscape
Static/dynamic forest area	Static, only considers carbon balance of existing forest areas in forest management units.
Temporal scale	Long, 100 years from time of increased wood supply
Forest management and effects on carbon stock changes	Forest model applied to forest inventory data for the 4 case study forest management units. Forest harvesting consists of clear-felling with no thinning during the rotation. The 'increased harvesting' scenario involved increased clear-felling in available forest areas, within the limits of sustainable yield (see Box 3.1). Wood products retain carbon according to IPCC modelling methods, with a bespoke long half-life for construction timber and additional modelling of HWP disposed to landfill.
Counterfactual forest management	Forest harvesting continues at existing levels (without increase). For wood products, continue current pattern of utilisation of harvested wood for different products.
Bioenergy feedstocks	Industrial residues
Wood product substitution	Included: zero, 2.43 tCeq/tC (average), 0.68 (low) and 4.18 (high) as sensitivity test. The average value is high relative to most recently published estimates. Bioenergy substitutes for fossil fuels with an emissions displacement factor of 0.55 tCeq/tC. Capture and burning methane from landfill for energy substitutes for fossil fuels with an emissions displacement factor of 0.93 tCeq/tC.
Metric	Net change in annual CO_2 emissions over 100 years from start of increase in harvesting. Also carbon payback time.
Outcome	Variable, sensitive to how harvested wood is used for different products and assumed wood product emissions displacement factor. Best positive results obtained for use of wood in structural products.
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The modelling of forest carbon stock changes and wood utilisation is sophisticated. The forest management practices assumed to be involved in scenarios are relatively simple but reflect reality on the study region. The study demonstrates how outcomes depend on how harvested wood is used for different products and the opportunities to achieve high wood product substitution benefits.

Table A4.4
Assessment of study of Cintas et al. (2016)

Full reference	Cintas, O., Berndes, G., Cowie, A. L., Egnell, G., Holmström, H., and Ågren, G. I. (2016). The climate effect of increased forest bioenergy use in Sweden: evaluation at different spatial and temporal scales. *Wiley Interdisciplinary Reviews: Energy and Environment*, **5**, 351–369. https://doi.org/10.1002/wene.178
Location	Sweden (sub-regions)
Scenarios	One scenario in which bioenergy supply is increased.
Spatial scale	Theoretical stand, theoretical landscape and examples of real forest landscapes (real forest landscapes mainly considered for this review)
Static/dynamic forest area	Static, only considers carbon balance of existing forest areas in studied sub-regions.
Temporal scale	Long, for real forest landscapes, up to 100 years from start of increased supply of bioenergy
Forest management and effects on carbon stock changes	Forest model applied to forest inventory data for 3 sub-regions in Southern Sweden. Additional bioenergy supply is met through changes in thinnings and rotations applied to stands. Improved stand regeneration practice in some cases. Carbon retained in wood products estimated using gamma decay functions. Very small proportion of wood products assumed to be disposed of in landfill. Large majority assumed to go to incineration.
Counterfactual forest management	Existing management continues without responding to requirement to supply more bioenergy.
Bioenergy feedstocks	Forest harvest residues. Bioenergy derived from industrial residues and from post-consumer waste not counted towards bioenergy supply in the modelled scenarios.
Wood product substitution	Included: about 2.5 tCeq/tC assumed for wood products, which is high relative to most recently published estimates. Bioenergy substitutes for coal and/or natural gas in power/heat/CHP generation with improved efficiency in some cases. The assumed emissions displacement factor (1.27 tCeq/tC) is quite high relative to most published estimates.
Metric	Change in carbon stocks over time compared to year when bioenergy supply is increased. Also, cumulative net emissions allowing for substitution effects reported each year from the time when bioenergy supply is increased.
Outcome	Variable for forest carbon stocks. Positive for cumulative net emissions (allowing for wood product and bioenergy substitution effects)
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The modelling of forest carbon stock changes and wood utilisation is sophisticated. The forest management practices assumed to be involved in scenarios is also sophisticated. The study demonstrates how outcomes depend on local circumstances within a region, opportunities for and choice of forest management interventions, and potential for wood product and bioenergy substitution.

Table A4.5
Assessment of study of Duden et al. (2023)

Full reference	Duden, A.S., Verweij, P.A., Faaij, A.P.C. Abt, R.C. Junginger, M. and van der Hilst, F. (2023) Spatially-explicit assessment of carbon stocks in the landscape in the southern US under different scenarios of industrial wood pellet demand. *Journal of Environmental Management*, **342**, 118148, https://doi.org/10.1016/j.jenvman.2023.118148
Location	Southern USA
Scenarios	Four scenarios: 1. Low demand for bioenergy, high demand for wood products (counter-factual scenario). 2. High demand for bioenergy, low demand for wood products. 3. High demand for bioenergy, high demand for wood products. 4. Low demand for bioenergy, low demand for wood products.
Spatial scale	Real landscape
Static/dynamic forest area	Dynamic, afforestation and deforestation rates determined by demand for wood.
Temporal scale	Short, 2010 to 2030
Forest management and effects on carbon stock changes	Forest model applied to US forest inventory data, but carbon stocks assumed not to change in existing forests, only in cases of land use change (afforestation or deforestation) and changes in the composition of existing forest areas (e.g. replacing broadleaves with pine plantations). Carbon retained in wood products not considered.
Counterfactual forest management	Land use change for a scenario with 'low' demand for bioenergy and 'high' demand for wood products.
Bioenergy feedstocks	Wood products and bioenergy not represented explicitly
Wood product substitution	Not represented
Metric	Change in total forest carbon stock in study region between 2010 to 2030
Outcome	Positive
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change', but the assessment is only partial, because it only considers responses in terms of changes in afforestation and deforestation rates.

Table A4.6
Assessment of study of Forster et al. (2021)

Full reference	Forster, E.J., Healey, J.R., Dymond, C. and Styles, D. (2021) Commercial afforestation can deliver effective climate change mitigation under multiple decarbonisation pathways. *Nature Communications*, **12**, 3831, https://doi.org/10.1038/s41467-021-24084-x
Location	UK
Scenarios	Two scenarios for woodland creation: 1. Natural broadleaves 2. Managed fast-growing conifers.
Spatial scale	Theoretical stand and theoretical landscape (30 year planting programme)
Static/dynamic forest area	Dynamic, but woodland creation only (the study is limited to considering afforestation scenarios).
Temporal scale	Long, 100 years from start of planting (2020)
Forest management and effects on carbon stock changes	Forest model applied, but only two tree species, each with a single growth rate and one or two management regimes considered. Wood products retain carbon according to IPCC modelling methods. Some wood products assumed to be disposed of in landfill, based on available statistics, retaining carbon according to IPCC default modelling methods.
Counterfactual forest management	No afforestation, representation of previous land use limited to considering loss of carbon stock from previous grassland. There is also a comparison with a scenario involving afforestation with a woodland with no harvesting

	but this represents an alternative woodland creation option, not the counterfactual scenario.
Bioenergy feedstocks	Allocation of wood feedstocks to end uses based on a combination of modelling and statistics (essentially byproducts of the wood industry).
Wood product substitution	Included: wood products substitute for a combination of concrete, steel and plastics, or do not substitute, depending on scenario. Bioenergy substitutes for coal and/or natural gas, hydrogen later in some scenarios. Emissions displacement factors are not used directly, but implied values are high relative to most recently published estimates.
Metric	Cumulative emissions (saved) over 100 years
Outcome	Positive
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The scope is narrow, in that only afforestation scenarios are considered and the specific cases (relatively unusually fast growing conifers and 'natural' broadleaves) are very specific to certain locations in the UK. Land afforested is assumed to be 'spare' (the assumed counterfactual land use), hence no indirect land use change occurs. Inclusion of CCS in some scenarios leads to very positive outcomes.

Table A4.7
Assessment of study of Funk et al. (2022)

Full reference	Funk, J.M., Forsell, N., Gunn, J.S. and Burns, D.N. (2022) Assessing the potential for unaccounted emissions from bioenergy and the implications for forests: The United States and global. *GCB Bioenergy*, **14**, 322-345, https://doi.org/10.1111/gcbb.12912
Location	USA/Global
Scenarios	Several scenarios involving different levels of bioenergy consumption under different IPCC Shared Socioeconomic Pathways, compared to 2005-2010 baseline.
Spatial scale	Real landscape
Static/dynamic forest area	Static, does not allow for changes in afforestation or deforestation rates when considering different scenarios.
Temporal scale	Medium, from 2010 to 2050
Forest management and effects on carbon stock changes	Estimated as carbon 'net increment' minus 'harvest emissions'. Carbon net increment is incorrectly termed 'forest sequestration' in the paper. Net carbon increment is assumed to remain constant over time. The rate is slightly different depending on the disturbance levels assumed in scenarios. Harvest emissions are related to emissions reported for the baseline period, assuming a linear relationship between these emissions and the harvest rate.
Counterfactual forest management	Comparison to baseline rates of increment and emissions in 2005-2010 or 2012.
Bioenergy feedstocks	Not represented
Wood product substitution	Not represented
Metric	Results for annual emissions reported for the years 2030 and 2050
Outcome	Negative
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change', but the modelling of forest carbon stock changes and emissions from bioenergy use are simplistic (assumption of static forest area, no representation of forest management practices involved in different scenarios or potential effects). Effectively, the study assumes that increased biomass consumption simply leads to increased harvesting.

Table A4.8
Assessment of study of Holtsmark (2015)

Full reference	Holtsmark, B. (2015) Quantifying the global warming potential of CO_2 emissions from wood fuels. *GCB Bioenergy*, **7**, 195-206, https://doi.org/10.1111/gcbb.12110
Location	Not explicitly stated, Nordic region
Scenarios	One scenario involving harvesting a forest stand for bioenergy.
Spatial scale	Theoretical stand
Static/dynamic forest area	Static, only considers carbon balance of existing theoretical stand.
Temporal scale	Long, 200 years from time of harvesting
Forest management and effects on carbon stock changes	Forest model applied, but only one tree species with one assumed growth rate and forest management practice (clear-felling at age 100 years with no thinning). Carbon retained in wood products not represented (all harvested wood assumed to be used for bioenergy).
Counterfactual forest management	Assumed to involve no harvest and trees continuing to grow undisturbed.
Bioenergy feedstocks	Stemwood and either none or 25% of forest harvest residues.
Wood product substitution	Not represented
Metric	GWP_{bio} (see Section 4.4.7 of Chapter 4)
Outcome	Negative
Overall assessment	The study is effectively addressing a research question of the type 'Natural Alternative' but presents the results as though they are the emissions from current and potential future levels of bioenergy use. The use of GWP_{bio} as the metric makes results harder to understand.

Table A4.9
Assessment of study of Kilpeläinen et al. (2011)

Full reference	Kilpeläinen, A., Alam, A., Strandman, H. and Kellomäki, S. (2011) Life cycle assessment tool for estimating net CO_2 exchange of forest production. GCB *Bioenergy*, **3**, 461-471. https://doi.org/10.1111/j.1757-1707.2011.01101.x
Location	Finland (northern and southern)
Scenarios	Four scenarios consisting of combinations of: • Two scenarios for forest management and biomass use, 'Traditional timber production regime' or 'integrated timber and bioenergy production regime'. • Excluding or allowing for future climate change (effects of forest productivity).
Spatial scale	Theoretical stand
Static/dynamic forest area	Static
Temporal scale	80 years (one forest rotation)
Forest management and effects on carbon stock changes	Sophisticated forest model applied, but one tree species and growth rate (varying with climate change) considered, and one forest management practice per scenario. Wood products retain carbon according to bespoke modelling.
Counterfactual forest management	Not represented (zero baseline).
Bioenergy feedstocks	Tree biomass harvested in an early 'energy wood thinning' not included in 'traditional timber production regime' scenario, and forest harvest residues extracted during final felling
Wood product substitution	Not represented

Metric	For wood products, kilograms CO_2 emitted per cubic metre of supplied saw-logs and pulpwood For bioenergy, kilograms CO_2 emitted per megawatt-hour of supplied energy in unprocessed biomass
Outcome	Positive, including relatively low emissions factors for bioenergy, but 'integrated timber and bioenergy production regime' gives lower benefits than 'traditional timber production regime'
Overall assessment	Essentially this is an attributional LCA study of fossil fuels emissions from a wood production and supply chain, but allowing for carbon stock changes in forests. This study is effectively addressing a research question of the type 'Here and Now'. For this reason, results are presented for overall net sequestration/emissions for the system. This obscures the outcome that results for the 'with bioenergy' scenarios are 'worse' than for the 'without bioenergy' scenarios.

Table A4.10
Assessment of study of Magelli et al. (2009)

Full reference	Magelli, F., Boucher, K., Bi, H.T., Melin, S. and Bonoli, A. (2009) An environmental impact assessment of exported wood pellets from Canada to Europe. *Biomass and Bioenergy*, **33**, 434-441, https://doi.org/10.1016/j.biombioe.2008.08.016
Location	British Columbia
Scenarios	One scenario involving supply of wood pellets to Sweden.
Spatial scale	Not represented
Static/dynamic forest area	Not represented
Temporal scale	Short/current, roughly 2003 to 2008
Forest management and effects on carbon stock changes	Not represented, only fossil fuel emissions in forest operations and the wood pellet supply chain are considered, not including conversion to final energy use. Emissions from burning wood is explicitly assumed to be zero.
Counterfactual forest management	Not represented (see above).
Bioenergy feedstocks	Industrial (sawmill) residues
Wood product substitution	Not represented
Metric	Kilograms CO_2 emitted per gigajoule of supplied energy in wood pellets
Outcome	Positive
Overall assessment	Essentially this is an attributional LCA study of fossil fuels emissions from a wood pellet supply chain. This study is effectively addressing a research question of the type 'Here and Now' but the assessment is only partial because it makes the simplistic assumption that biomass supplied from forests is carbon neutral, so that there is no consideration of forest carbon stock changes occurring directly as result of the wood pellet production. This assumption may be justified on the grounds that the biomass feedstock considered is a specific case of wood shavings and sawdust generated as a 'waste' byproduct of sawmilling.

Table A4.11
Assessment of study of Peng et al. (2023)

Full reference	Peng, L., Searchinger, T.D., Zionts, J. and Waite, R. (2023) The carbon costs of global wood harvests. *Nature*, 620, 110-115 https://doi.org/10.1038/s41586-023-06187-1
Location	Globe
Scenarios	One scenario for total wood production over time, seven scenarios for forest management to meet the projected supply: 1. Supply prioritised from existing plantation forests, then from middle-aged managed regenerated forests. 2. Supply prioritised from existing plantation forests, then from middle-aged managed regenerated forests which are converted to more productive tree plantations. 3. As Scenario 1 except that older regenerated forests are harvested as well as middle-aged regenerated forests. 4. As Scenario 1 but also tree plantations created on agricultural land in tropical regions. 5. As Scenario 1 but also productivity of existing plantation forests is increased. 6. As Scenario 1 but with more efficient wood harvesting/extraction from managed regenerating forests, reducing the area harvested. 7. Reduced wood fuel demand/consumption (less harvesting).
Spatial scale	Real landscape (forest areas in 30 countries selected to represent global forests)
Static/dynamic forest area	Static, does not allow for changes in afforestation or deforestation rates when considering different scenarios.
Temporal scale	Medium, 2010 to 2050
Forest management and effects on carbon stock changes	Simplistic forest model applied to forest inventory data (FAO), limited representation of forest types, growth rates and management. Wood products retain carbon according to IPCC modelling methods. However, the precise methods used to represent wood products are unclear from the paper. Assumes that all wood products are disposed of in landfill and decay, with some release of methane.
Counterfactual forest management	Assumed to involve no harvest, with trees continuing to grow undisturbed. This also applies to historical management, at least back to 2010.
Bioenergy feedstocks	Consistent with historical use/proportions of wood feedstocks for bioenergy with other feedstocks providing wood products (essentially byproducts of the wood industry).
Wood product substitution	Included: 1.2 tCeq/tC assumed for wood products, 0.175 tCeq/tC assumed for traditional wood fuel use, substitution value for industrial bioenergy use not specified (not included?). Emissions displacement factor for bioenergy is low relative to most published estimates.
Metric	‘Average annual CO_2 costs’, calculated as the sum of annual net emissions over 40 years (2010 to 2050), discounted at 4% rate.
Outcome	Negative
Overall assessment	The study is effectively addressing a research question of the type ‘Natural Alternative’ or possibly more arguably ‘Human Footprint’ but presents the results as though they are the emissions from current and potential future levels of bioenergy use. The use of a metric more commonly referred to in economics studies complicates interpretation of results.

Table A4.12
Assessment of study of Schlamadinger and Marland (1996)

Full reference	Schlamadinger, B. and Marland, G. (1996) Full fuel cycle carbon balances of bioenergy and forestry options. *Energy Conversion and Management*, **37**, 813-818. https://doi.org/10.1016/0196-8904(95)00261-8
Location	Unspecified, hypothetical
Scenarios	Two scenarios: 1. Harvesting in an existing forest stand for wood products and bioenergy. 2. Planting of short rotation forestry on surplus agricultural land.
Spatial scale	Theoretical stand
Static/dynamic forest area	Static for existing forest scenario, dynamic for short rotation forestry scenario.
Temporal scale	Long, 100 years from start of harvesting or planting
Forest management and effects on carbon stock changes	Forest model applied, but one hypothetical tree species, growth rate, and forest management practice per scenario. Sensitivity is analysed with respect to assumed growth rate, clear-fell rotation age, initial carbon stocks, share of post-consumer waste wood used for bioenergy, efficiency of biomass use, mean lifetime of wood products, and emissions displacement factor. Wood products retain carbon according to bespoke modelling.
Counterfactual forest management	For forest harvesting scenario, forest is not harvested; for short rotation forestry scenario, land remains under agricultural use.
Bioenergy feedstocks	A fraction of the harvested biomass (specific wood products are not represented) and post-consumer wood waste.
Wood product substitution	Included: 0.5 tCeq/tC assumed for wood products and 0.6 tCeq/tC assumed for bioenergy as default case. The value for wood products is low relative to most recently published estimates.
Metric	Cumulative change in carbon stocks and emissions over 100 years
Outcome	Variable, dependent of scenario and other factors (such as growth rate)
Overall assessment	The study is effectively addressing research questions of the type 'Natural Alternative' and 'Pathways to Change', depending on the scenario, but in the former case the results are presented as though the latter type of question is being addressed. The study thoroughly demonstrates how outcomes for CO_2 emissions from using biomass supplied from forests depends on the type of forest involved, including initial carbon stocks, growth rates, how biomass is utilised, and potential for displacing non-wood products and fossil fuels.

Table A4.13
Assessment of study of Smyth et al. (2020)

Full reference	Smyth, C.E., Xu, Z., Lemprière, T.C. and Kurz, W.A. (2020) Climate change mitigation in British Columbia's forest sector: greenhouse gas reductions, costs, and environmental impacts. *Carbon Balance and Management*, 15:21, https://doi.org/10.1186/s13021-020-00155-2
Location	British Columbia
Scenarios	Six scenarios: 1. Harvest less (reduced annual harvest area). 2. Restricted harvest (reduced harvesting of old stands). 3. Higher recovery (higher biomass extraction from harvested areas). 4. Residues for bioenergy (forest harvest residues). 5. Higher recovery and residues for bioenergy. 6. Longer-lived wood products (shift of wood use from short-lived to long-lived applications).
Spatial scale	Real landscape
Static/dynamic forest area	Static, does not allow for changes in afforestation or deforestation rates when considering different scenarios.

Temporal scale	Medium, 2020 to 2070
Forest management and effects on carbon stock changes	Forest model applied to forest inventory data for British Columbia (spatially explicit). Forest management practices represented include shortened or lengthened rotations (implicitly), conservation of forest areas, more or less extraction of forest harvest residues, depending on scenario. Forest management practices influence the frequency and intensity of natural disturbances. Wood products retain carbon and are disposed of according to bespoke modelling methods.
Counterfactual forest management	Continuation of business as usual forest management practices, natural disturbances, and wood use.
Bioenergy feedstocks	Industrial residues, forest harvest residues, post-consumer waste.
Wood product substitution	Included: zero (no substitution benefit), 0.45, 0.54, 2.1 or 2.2 tCeq/tC, depending on wood products type and end use. Bioenergy substitutes for a range of fossil fuels with an implied emissions displacement factor of typically 0.4 to 0.5 tCeq/tC.
Metric	Cumulative emissions increase or reduction between 2020 to 2070
Outcome	Variable, depending on scenario, location within region, and assumed substitution benefits
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The modelling of forest carbon stock changes and wood utilisation is sophisticated. The forest management practices assumed to be involved in scenarios are relatively simple but reflect reality on the study region. The study demonstrates how outcomes depend on local circumstances within a region, choice of forest management interventions, and potential for wood product and bioenergy substitution.

Table 4.14
Assessment of study of Stephenson and Mackay (2014)

Full reference	Stephenson, A.L. and MacKay, D.J.C. (2014) *Life Cycle Impacts of Biomass Electricity in 2020: Scenarios for Assessing the Greenhouse Gas Impacts and Energy Input Requirements of Using North American Woody Biomass for Electricity Generation in the UK*. Report for DECC to accompany BEAC (Biomass Emissions And Counterfactual) model URN 14D/243. Department of Energy and Climate Change: London, https://www.gov.uk/government/publications/life-cycle-impacts-of-biomass-electricity-in-2020
Location	North America
Scenarios	Many scenarios (29 plus some sub-cases) involving wood pellets supply to Europe for electricity generation.
Spatial scale	Theoretical stand
Static/dynamic forest area	Most scenarios implicitly assume a static forest landscape, a few consider afforestation or tree species replacement.
Temporal scale	Three timescales considered ('Short', 'Medium' and 'Long'): up to 20 years, 40 years, and 100 years from start of harvesting biomass
Forest management and effects on carbon stock changes	Forest model applied, usually only one tree species, growth rate, and management practice assumed per scenario. Forest management interventions assumed to involve shortening clear-fell rotations, introducing faster growing tree species to increase production managed on a short rotation. Wood products retain carbon according to bespoke modelling methods. Some scenarios involve use of wood for products being displaced by use for bioenergy.
Counterfactual forest management	Dependent on scenario, based on assumptions: burn industrial residues as waste (no energy recovery), leave forest harvest residues and salvaged dead trees in the forest or burn at roadside, no changes to clear-fell rotations in existing forests, no improvements to tree growth rates, land remains abandoned (afforestation scenarios).

Bioenergy feedstocks	Forest harvest residues sometimes including tree stumps, industrial residues, salvaged dead trees, stemwood, pulpwood.
Wood product substitution	Not represented: explicitly excluded as considered not relevant to scenarios.
Metric	Main metric referred to is kilograms of equivalent CO_2 per megawatt-hour of delivered energy.
Outcome	Very variable, depending on scenario
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change', but the modelling of forest carbon stock changes is relatively simple (stand scale and one management intervention). Management practices and counterfactuals are based on assumption and are sometimes hypothetical. However, the study amply demonstrates how results and outcomes depend on forest management practices, counterfactuals, and biomass feedstocks involved in supplying bioenergy.

Table A4.15
Assessment of study of Tian et al. (2018)

Full reference	Tian, X., Sohngen, B., Baker, J., Ohrel, S. and Fawcett, A.A. (2018) Will U.S. forests continue to be a carbon sink? *Land Economics*, **94**, 97-113, https://doi.org/10.3368/le.94.1.97
Location	USA
Scenarios	Five scenarios involving assumptions about evolution of forest area and planned forest management: 1. No change to (planned) management of existing forests, but forest area can change in response to demand for wood products and bioenergy. 2. No expansion or loss of forest area, but (planned) forest management practices can change in response to demand for wood products and bioenergy. 3. No expansion or loss of forest area and no change to (planned) management of existing forests in response to demand for wood products and bioenergy. 4. All management of forest areas is stopped. 5. Forest area and (planned) forest management can change in response to demand for wood products and bioenergy; demand for timber is increased compared to other scenarios. Each scenario is considered in the presence and absence of climate change impacts on forest growth rates.
Spatial scale	Real landscape
Static/dynamic forest area	Static or dynamic depending on scenario (sensitivity to this assumption explicitly investigated).
Temporal scale	Long, 2020-2120
Forest management and effects on carbon stock changes	Forest model applied to forest inventory data for USA, with land use change and forest management linked to (global) timber demand through an economic model. Forest management practices not clearly specified but appears to include tree planting or regeneration, fertilisation, thinning, and clear-felling. Carbon retained in wood products is not represented (the study is concerned with carbon sequestration in forests).
Counterfactual management	Forest management practices evolve according to baseline projection of timber demand and timber prices.
Bioenergy feedstocks	Not represented: study is concerned with timber demand.
Wood product substitution	Not represented
Metric	Annual carbon sequestration between 2020-2120; above ground carbon in 2050 and 2100
Outcome	Positive if dynamic forest area and changing management practices are represented, variable otherwise: • Carbon sequestration is diminished in scenarios where the forest area is static and forest management practices do not respond to trends in timber demand.

	• Carbon sequestration is also diminished under a no management scenario (no investment in replanting and regeneration, diminishing rate of carbon uptake in older forests). • Higher demand for timber results in changes to forest management practices that improve forest regrowth and in some cases clear-felling rotations are extended to increase productivity.
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The modelling of forest carbon stock changes and the influence of forest management is sophisticated.The forest management practices involved in the scenarios are not fully described. Results are highly dependent on assumed behavioural responses to increased timber demand and higher prices. This is acknowledged in the study.

Table A4.16
Assessment of study of Zanchi et al. (2012)

Full reference	Zanchi, G., Pena, N. and Bird, N. (2012) Is woody bioenergy carbon neutral? A comparative assessment of emissions from consumption of woody bioenergy and fossil fuel. *GCB Bioenergy*, **4**, 761-772 https://doi.org/ 10.1111/j.1757-1707.2011.01149.x
Location	Austrian Alps as theoretical example
Scenarios	Six scenarios: • Two involving increased harvesting (clear-felling) in existing forest. • One involving increased biomass extraction in existing forest (forest harvest residues). • Three involving afforestation to supply more biomass than previously, for use as bioenergy.
Spatial scale	Theoretical landscape
Static/dynamic forest area	Static for existing forest scenarios, dynamic for afforestation scenarios.
Temporal scale	Long, 400 years from start of increased bioenergy supply
Forest management and effects on carbon stock changes	Forest model applied, but one hypothetical tree species, growth rate, and forest management practice per scenario. The forest consists of 90 hectares, partly unmanaged and partly managed on a 90 year rotation, see similar example for managed forests in Section A2.4 of Appendix 2) Management practices involve: increasing the area clear-felled (including some of the unmanaged area), extraction of forest harvest residues, planting forests on surplus agricultural land, and replacing forests with tree plantations managed on short rotations for bioenergy supply. Carbon in wood products not represented because all scenarios involve additional bioenergy supply only.
Counterfactual forest management	For clear-felling scenarios, the area clear-felled remains unchanged; for extraction of forest harvest residues, these remain to decay in the forest; for tree planting scenarios, land remains under the pre-existing land use.
Bioenergy feedstocks	Depends on scenario, either all extra harvested biomass, or forest harvest residues.
Wood product substitution	Included: bioenergy substitutes for coal, oil, or natural gas.
Metric	'Carbon neutrality factor' (see Section 4.4.7). Also net change in annual emissions over 400 years from start of increase in bioenergy supply
Outcome	Variable, depending on scenario and other factors (such as assumed emissions displacement factor)
Overall assessment	The study is effectively addressing a research question of the type 'Pathways to Change'. The study demonstrates how outcomes for CO_2 emissions from using biomass supplied from forests depends on the type of forests involved and potential for displacing non-wood products and fossil fuels. However, the systems studied are simplistic and hypothetical.

Table A4.17
Summary assessment of forest management and effects on carbon stock changes

Aguilar et al. (2022)	Issues: Based on complicated and opaque statistical analysis. Statistically significant correlation does not imply causality and several contrasting interpretations of the results are possible.
Bernier and Paré (2013)	Issue: Carbon stock changes estimated as carbon 'net increment' in unharvested stands minus 'harvest emissions' but this approach might not capture the response of forest carbon dynamics to forest management.
Chen et al. (2018)	No issues: The modelling is sophisticated. Forest management practices assumed to be involved are relatively simple but reflect reality on the study region.
Cintas et al. (2016)	No issues: Modelling and representation of forest management practices is sophisticated.
Duden et al. (2023)	Major issue: Carbon stocks assumed not to change in existing forests, only in cases of land use change (afforestation or deforestation). Issue: Carbon retained in wood products not considered.
Forster et al. (2021)	Issues: Limited representation of tree species, growth rates and management practices. The scope is narrow (afforestation scenarios considered only). Inclusion of CCS in some scenarios leads to very positive outcomes, but allowance for CCS is not included in the majority of studies published to date. CCS only contributes negative emissions if the emissions from bioenergy are already low without applying CCS. Inclusion of CCS therefore makes the results harder to interpret when trying to determine whether bioenergy is carbon neutral or otherwise, before application of CCS.
Funk et al. (2022)	Major issue: Estimated as carbon 'net increment' minus 'harvest emissions', and net carbon increment is assumed to remain constant over time. Issues: Harvest emissions are related to emissions reported for the baseline period, assuming a linear relationship between these emissions and the harvest rate. Effectively, the study assumes that increased biomass consumption simply leads to increased harvesting.
Holtsmark (2015)	Issue: Limited representation of tree species, growth rates and management practices. Carbon retained in wood products not represented (all harvested wood assumed to be used for bioenergy).
Magelli et al. (2009)	Major issue: Forest carbon stock changes and forest management effects not represented; emissions from burning wood is explicitly assumed to be zero.
Peng et al. (2023)	Issues: Simplistic forest model applied to forest inventory data (FAO), limited representation of forest types, growth rates and management. Assumes that all wood products are disposed of in landfill and decay, with some release of methane.
Schlamadinger and Marland (1996)	Issue: Limited representation of tree species, growth rates and management practices.
Smyth et al. (2020)	No issues: The modelling is sophisticated. Forest management practices assumed to be involved are relatively simple but reflect reality on the study region.
Stephenson and Mackay (2014)	Issue: Usually only one tree species, growth rate, and management practice assumed per scenario.
Tian et al. (2018)	Issues: The forest management practices involved in the scenarios are not fully described. Results are highly dependent on assumed behavioural responses to increased timber demand and higher prices. Carbon retained in wood products is not represented (the study is concerned with carbon sequestration in forests).
Zanchi et al. (2012)	Issues: One hypothetical tree species, growth rate, and forest management practice per scenario. The systems studied are simplistic and hypothetical. Carbon in wood products not represented because all scenarios involve additional bioenergy supply only.

Appendix 5. Calculation of estimated changes in forest carbon stocks and rates of biomass supply resulting from changes in forest management

This appendix illustrates the calculation of the projected effects on forest carbon stocks and woody biomass supply rates from a planned change to the management of a forest unit. Estimates of this kind are referred to in the discussion in Section 5.4 of the main report. In particular, Tables 5.3 and 5.5 give estimates for several examples of forest units (labelled A to K), where forest management is changed in distinct ways, either to enhance tree carbon stocks or to increase biomass supply, or for both objectives. Illustrations are given in Sections A5.2 and A5.3, respectively for the examples of forest units in 'Class F' and 'Class G' in Figure 5.3 and Tables 5.3 to 5.5 in the main report. Brief descriptions of the main methods and assumptions underlying the calculation of all the estimates in these tables are given in Section A5.4.

Most of the examples of changed forest management are concerned with potential impacts on carbon stocks in living trees in forest units, and/or on the rate of stemwood biomass supply from these forests. An exception is the example of forests in 'Class J', which involve the increased extraction of forest harvesting residues, for which the biomass produced is likely to be suitable only as a feedstock for bioenergy or possibly making biochemicals or bioplastics. Stemwood supply is unchanged in this example.

A5.1 General description of method

For a given forest class, the method first involves:

- Characterizing the existing state of the forest class (e.g. tree species and growth rate) and its existing management.
- Characterizing the planned interventions in the forest class (e.g. changes to management and possibly other aspects such as introducing new tree species).
- Estimating the long-term mean carbon stocks per hectare and the long-term mean annual woody biomass production per hectare in the forest class under the existing state and management, and under the planned changed management.
- Calculating the impact on forest carbon stocks and woody biomass production of changes to management as the difference between the two estimates of per-hectare carbon stocks and woody biomass production per hectare, respectively, as calculated above.

The basis of these calculations and the relevance of estimates of long-term mean carbon stocks and woody biomass production rates in this context has been discussed in detail in Appendices 2 and 3, where several examples are also given.

Having calculated the estimate of the projected change in mean forest carbon stocks and woody biomass production, these estimates may be adjusted by a probability, to allow for risks or uncertainties as to whether the projected changes may not be realised in practice. The results are multiplied by the area of the forests being considered, to give a total change in forest carbon stocks and a total change in woody biomass production in the forest class.

A5.2 Example 1: Forests in 'Class F'

Forest system: initial state and management

This example is based on a situation potentially relevant in the context of forestry practices in the UK. The example forest class consists of stands of Scots pine trees with a growth rate of 8 m^3/ha/yr. The stands are thinned regularly with a final harvest by felling on a rotation of 74 years, followed by immediate restocking of the forest stands.

Forest system: planned change to management

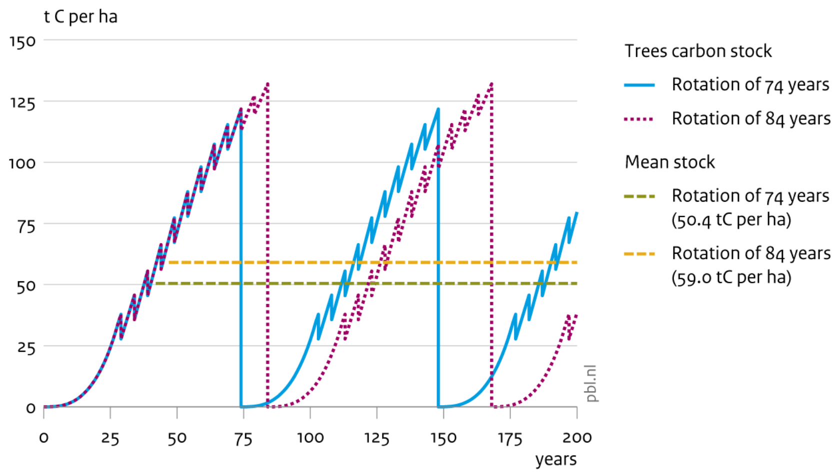
The planned intervention in the forest class is to extend the felling rotations applied to the forest stands by 10 years, i.e. from 74 to 84 years. In all other respects, the composition and management of the forest class is consistent with the pre-existing situation. The possibility of extending rotations in managed forests as a relatively simple and potentially practical measure for enhancing carbon stocks in managed forests has long been understood. However, changing rotations in forest can also affect the potential for supplying woody biomass, as already discussed in Section A2.3 in Appendix 2. Lundmark et al. (2018) have assessed the likely impacts of implementing such a measure in forests in the Nordic region.

Estimation of per-hectare carbon stocks and stock change

The development of carbon stocks in living tree biomass (foliage, branches, stem and coarse and fine roots) in an individual stand of trees in this forest class is shown in Figure A5.1, for the case of pre-existing forest management (solid lines) and changed management (dashed lines).

Figure A5.1

Tree carbon stocks in a Scots pine stand managed on a clear-fell rotation of 74 or 84 years, growth rate 8 m^3 per ha per year



Source: Forest Research UK

The development of tree carbon stocks has been simulated using the CARBINE forest sector carbon accounting model developed by Forest Research (Matthews et al., 2009; Matthews, 1994, 1996;

Thompson & Matthews, 1989). CARBINE is one example of several forest carbon accounting models developed around the world, some of which are available to download[29]. Carbon stocks in deadwood, litter, soil and wood products are not included in the estimates in Figure A5.1. In principle, these could also be included but, in the case of these examples, this would not substantively change the outcome of the assessment being made in this context (specifically, this would not shift results from positive to negative carbon stock changes or vice versa).

Under the initial management with a rotation of 74 years, tree carbon stocks develop according to a cycle as the trees grow and are felled, between 0 and 122 tC/ha. Under the changed management (84 year rotation), tree carbon stocks develop over a longer cycle between 0 and 132 tC/ha. In both cases, there are regular short-term reductions in carbon stocks during the tree growth cycle, associated with thinning activities.

As explained elsewhere in this report (see in particular Appendices 2 and 3), long-term mean carbon stocks are an appropriate metric to refer to when estimating forest carbon stocks and stock changes at the landscape scale. For the example in Figure A5.1, the effect on forest carbon stocks of extending rotations in these forest stands is 59.0 – 50.4 = 8.6 tC/ha.

Risk adjustment

Potential changes in carbon stock estimated to occur in response to planned changes in forest management may not be realised in practice. In the case considered here, there may be practical or operational constraints that prevent rotations from being adjusted in all of the stands comprising the area of the forest class. This could be allowed for by assuming an estimate of the probability with which the changed management (and the associated change in carbon stocks) is achieved in practice, when the proposed plan for management is implemented. If it is assumed that rotations can be extended as planned in 90% of the forest area, the forest carbon stock change that remains is 0.9 × 8.6 = 7.7 tC/ha.

Whilst calculations for national greenhouse gas emissions inventories aim to neither overestimate nor underestimate emissions or 'removals' (carbon sequestration), it may be appropriate to be cautious about the potential for carbon sequestration through forest management activities, especially where significant risks or uncertainties are involved. Hence, adjustments of the kind illustrated above may be important particularly in the case of positive estimates of carbon stock changes. Assessing risks and deriving probabilities as applied here involves an element of subjective judgement but formal approaches and checks could be developed to provide a systematic basis for their estimation.

The final per-hectare estimate of the carbon stock change expected to occur as a result of implementing the change in management in the forest class is multiplied by the total area of forests in the class F, to obtain an estimate of the total carbon stock change. The areas given in Figure 5.3 and

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[29] See for example the CBM-CFS3 model at https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/carbon-accounting/carbon-budget-model/13107 and the CO2FIX model at https://www.wur.nl/en/product/carbon-balance-model-co2fix-downloaded-by-over-5000-people-worldwide.htm.

Table 5.3 in Section 5.4 are in arbitrary units; if it is assumed that the units are thousands of hectares, then the projected total carbon stock change is 7.7× 50 = 385 ktC.

Estimation of per-hectare annual woody biomass supply

Table A5.1 shows the schedule of stemwood volume supply per hectare over a rotation for the managed Scots pine stands considered in this example. The table shows the stemwood supply from thinning, which starts when the stand is age 19 years and is repeated every 5 years subsequently, up to the harvest at the final felling at the rotation age.

Table A5.1
Volume of stemwood and sawlog supply from example Scots pine stands

Stand age (years)	Volume supply (m^3/ha) Total stemwood[1] Rotation age 74 years	Total stemwood[1] Rotation age 84 years	Sawlog[2] Rotation age 74 years	Sawlog[2] Rotation age 84 years
29	28	28	0	0
34	28	28	0	0
39	28	28	0	0
44	28	28	0	0
49	28	28	0	0
54	28	28	2	2
59	28	28	6	6
64	28	28	10	10
69	28	28	14	14
74	339	25	298	18
79	-	22	-	21
84	-	368	-	341
Total[2]	591	666	329	410
Annualised	8.0	7.9	4.4	4.9
Extracted[3]	7.2	7.1	4.0	4.4
odt/ha/yr[4]	3.02	3.00	1.65	1.85
Change	-0.02 (-0.8%)		0.17 (+10%)	

[1] See definition of stemwood in Box 5.3 in Section 5.3 in the main report.

[2] Sawlog volume is defined here as stem volume with a diameter of at least 18 cm over bark. The remainder of the stemwood is usually referred to as 'small roundwood'. Usually both sawlogs and small roundwood are extracted and used for a range of products, with lower quality wood and offcuts from finished products sometimes being used for bioenergy. The quantities of small roundwood supplied are not shown in the table but can be calculated as the difference between the total stemwood supply and the sawlog supply.

[2] Sum of standing stem volumes harvested as thinnings and in the final felling; volume is over bark for standing trees.

[3] Reduction of standing stem volume and sawlog volume by 10% to allow for efficiency of conversion of standing trees to felled products, including allowing for defective stemwood (Forest Research, 2022).

[4] Sawlog and stemwood supply in odt/ha/yr is calculated by multiplying extracted stem volumes by an assumed wood density for Scots pine of 0.42 odt/m^3 (Lavers and Moore, 1983). Note that this calculation is slightly simplified because the values in the table are for trees measured over bark, and strictly the quoted wood density does not apply for the bark component.

The schedule and volumes of thinnings follow the recommended prescription for management of Scots pine stands in the UK with the growth rate in this example. These, and the final felling volumes, are given in standard forest yield models applicable to forest stands growing in the UK (Matthews, Henshall, et al., 2016; Matthews, Jenkins, et al., 2016). A version of these yield models forms a component of the CARBINE model, so that CARBINE calculates consistent results for stemwood supply. This also applies for estimates of sawlog volume supply from thinnings and fellings, as shown in Table A5.1, which are also given by the standard yield models. For the example in Table A5.1, the long-term annual reduction in stemwood biomass supply from the Scots pine stands when the rotation is extended by 10 years is -0.02 odt/ha/yr, or less than 1%. Multiplying by the area of forests in Class F (50 kha), results in a change in woody biomass supply of -1.0 kodt/yr.

Change in sawlog supply

The methods described in Section 5.4 of the main report only consider effects of changed forest management on woody biomass supply expressed as total stemwood biomass supply (with the exception of a case involving extraction of forest harvest residues). However, the analysis of effects on biomass supply could be more detailed, for example, considering effects on sawlog biomass supply as well as total stemwood supply, as included in the example in Table A5.1. The long-term annual sawlog biomass supply from the Scots pine stands increases from 1.68 to 1.85 odt/ha/yr (+10%) when the rotation is extended by 10 years.

Following similar calculations to those described above for woody stemwood biomass supply, the estimate of the change in sawlog biomass supply for this forest class is 7.5 kodt/yr. It is interesting to note that, for the example forest class considered here, the changed management results in an increase in forest carbon stocks at the expense of a small reduction in annual woody biomass supply, but also results in an increase in potential sawlog supply, which is usually of higher value to the forest grower.

Allowing for timescale of changes

The methods described here and in Section 5.4 of the main report do not allow for the time taken for stock changes to occur in forests. However, the methods could be elaborated to allow for that. In the case of the example here, the driver of long-term carbon stock changes is the adjustment of the rotation age, from 74 years to 84 years. It is not practical to extend all the rotations of the stands forming the forest area all at once, because this would result in a pause in all harvesting for a period of 10 years (the difference between the two rotations). Hence, the extension of rotations needs to be phased in gradually. Furthermore, if a stand of trees in this class is quite young at the time when changes are implemented (e.g. 10 years), the effect of extending the rotation in this stand will not become apparent until decades later (when the initial rotation age is reached). Based on these observations, it may be speculated that carbon stocks in the forests are likely to be enhanced over a period roughly equal to the rotation ages involved. If the longer rotation is selected, this gives a transition period of 84 years. In practice, introducing changes in all the affected forest units may take longer than this, so a realistic estimate of the transition period is 90 to 100 years (i.e. a mean rate of carbon stock change between 3.85 and 4.27 ktC/yr).

At the end of the transition, there are no further changes to the long-term total carbon stocks in the forests, and the rate of carbon sequestration in the forests is therefore zero, indicating that any biomass supplied from the forests from this point onwards is ‘carbon neutral’ (see Section 3.1 in the main report and Appendix 2). Changes in woody biomass supply are likely to occur over a similar timescale to carbon stock changes.

A5.3 Example 2: Forests in ‘Class G’

Forest system: initial state and management

This example is again based on a situation potentially relevant in the context of forestry practices in the UK. As in the previous example, the forest area consists of stands of Scots pine trees with a growth rate of 8 m³/ha/yr. The stands are thinned regularly with a final harvest by felling on a rotation of 74 years, followed by immediate restocking of the forest stands.

Forest system: planned change to management

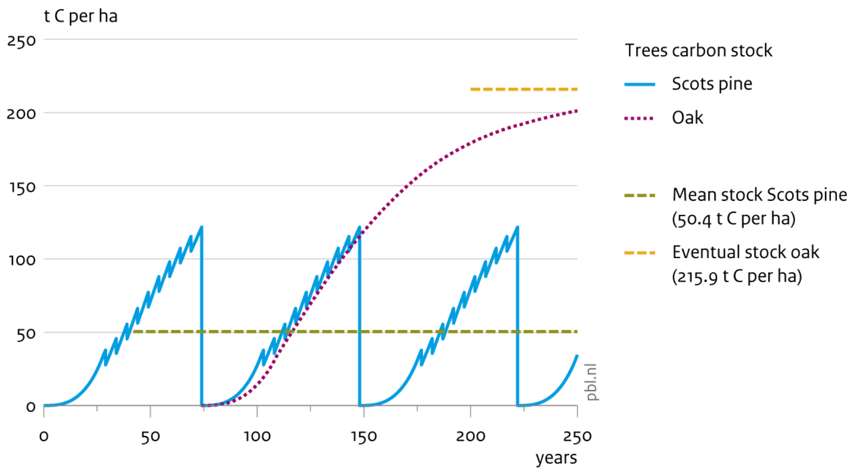
The planned intervention in the forest area is to replace the existing Scots pine stands managed for supply with slower growing but more enduring oak trees managed so as to minimise harvesting and natural disturbances, with the aim of accumulating significant carbon stocks in the forest. The stands of oak trees have a growth rate of 4 m³/ha/yr. The oak is introduced into the forest at the time when individual stands of Scots pine are clear-felled.

Estimation of per-hectare carbon stocks and stock change

The development of carbon stocks in living tree biomass (foliage, branches, stem and coarse and fine roots) in an individual stand of trees in this forest class is shown in Figure A5.2, for the case of pre-existing forest management (solid lines) and changed management (dashed lines).

Figure A5.2

Tree carbon stocks in a Scots pine stand managed on a clear-fell rotation of 74 years, showing effect of replacing with unmanaged oak stand after first rotation



Source: Forest Research UK

The development of tree carbon stocks has again been simulated using the CARBINE model. As before, carbon stocks in deadwood, litter, soil and wood products are not allowed for in the estimates. Under the initial management with a rotation of 74 years, tree carbon stocks develop with a mean carbon stock of 50.4 tC/ha. Under the changed management, a clear-felled Scots pine stand is replaced with oak trees, which are managed minimally, notably without any thinning or harvesting of trees (to meet ecological or amenity objectives). It is also assumed that the stand of oak trees is not disturbed by fires, storms or pest and disease outbreaks. Consequently, the oak stand continues to grow and accumulate carbon stocks over many decades. Eventually, the rate of carbon capture by the oak trees is balanced by losses from respiration and mortality, so that the carbon stock in the stand of trees approaches a maximum value of 216 tC/ha. Thus, the estimated carbon stock increase is almost 166 tC/ha.

Risk adjustment, total carbon stock change and woody biomass supply

As discussed earlier for Example 1, potential changes in carbon stock estimated to occur in response to planned changes in forest management may not be realised in practice. In the case considered here, in reality the oak stands are likely to require some management, even if just to remediate damage, e.g. from storms, or otherwise to meet amenity/ecological objectives. These factors could result in the full carbon stock changes only being partially achieved. Here, it is assumed that 70% of the potential carbon stock change is realised in practice, resulting in an adjusted carbon stock increase 116 tC/ha. If the final per-hectare estimate of the carbon stock change is multiplied by the total area of forests in class G (2 kha), this results in 232 ktC. The calculation of the long-term annual stemwood biomass supply from the initial managed Scots pine stands has been described earlier for Example 1, and is 3.02 odt/ha/yr. Consequently, the total decrease in woody biomass supply for forest class G (2 kha) is -6.0 kodt/yr.

As discussed earlier, the 'risk' in the case of forest class 'G' relates to the expected accumulation of carbon stocks not being fully achieved, because of natural disturbances of the unmanaged stands, or as a result of some 'light touch' management for amenity purposes, for example, some limited thinning of trees for access. Related to this, if, in practice, some trees are felled, these could potentially supply wood products and bioenergy in small amounts, in which case, woody biomass supply would not be reduced to zero as assumed above. However, a conservative assumption is made here, that any trees felled to remediate disturbances or for amenity objectives are left to decay in the forest.

Allowing for timescale of changes

Obviously, it is not practical to fell the Scots pine stands all at once, because this would result in a spike in woody biomass supply. There are also very likely to be operational constraints on managing a programme to restock the Scots pine stands with oak trees. Consequently, the restocking is likely to take place over a period of at least 200 years, resulting in a mean rate of carbon stock change of 1.16 ktC/yr. At the end of the transition, there are no further changes to the long-term total carbon stocks in the forests, and the rate of carbon sequestration in the forests is therefore zero. For this example class of forests, changes in woody biomass supply will occur more quickly than changes in carbon stocks, with all supply of biomass from the forests ceasing when the last remaining stands of Scots pine are felled, perhaps after several decades.

A5.4 Main methods and assumptions made in deriving estimates for forest classes A to K

As explained in Section 5.4 of the main report, and in Section A5.1 above, estimates of forest carbon stocks in living trees and rates of biomass supply were derived from results produced using the CARBINE forest carbon accounting model. It is apparent from the examples above that the calculations involve specifying certain parameters defining the 'initial state' of a forest class:

- Tree species.
- Tree stand growth rate.
- Existing management of the stands (e.g. none, thinning, felling, continuous cover).
- Clear-felling rotation age (where relevant).

The planned changes to the 'state' of the forest are then specified, in terms of changes to the above parameters. These parameters can be used as inputs to the CARBINE model, to derive results that can be used to estimate carbon stocks and rates of biomass supply. Table A5.2 gives the parameters defining the initial and changed states for each forest class ('A' to 'K') included in the illustration in Section 5.4.

Table A5.2
Parameters defining initial and changed states of forest classes A to K

Forest class	State	Tree species	Growth rate (m³/ha/yr)	Management	Rotation (years)
A	Initial	Grass with assumed 2.5 tC/ha in living biomass			
	Changed (component 1, 20% of area)	Oak	4	No harvesting	-
	Changed (component 2, 80% of area)	Norway spruce	10	Thin and fell	73
B	Initial	Sitka spruce	12	Thin and fell	54
	Changed	No change from above			
C	Initial	Sitka spruce	14	Thin and fell	52
	Changed	Sitka spruce	24	Thin and fell	43
D	Initial	Norway spruce	14	Thin and fell	64
	Changed	Douglas fir	18	Thin and fell	48
E	Initial	Unspecified monoculture forest, destroyed by disturbance			
	Changed (component 2, 33.3% of area)	Same as tree species in initial monoculture forest, still destroyed by disturbance			
	Changed (component 2, 33.3% of area)	Douglas fir	10	Thin and fell	60
	Changed (component 3, 33.3% of area)	Western red cedar	12	Thin and fell	63
F	Initial	Scots pine	8	Thin and fell	74
	Changed	Scots pine	8	Thin and fell	84
G	Initial	Scots pine	8	Thin and fell	74
	Changed	Oak	4	No harvesting	-
H	Initial	Sitka spruce	16	Clear-fell but no thinning	51
	Changed	Sitka spruce	16	Thin and fell	51
I	Initial	Sitka spruce	16	Thin and fell	61
	Changed	Sitka spruce	16	Thin and fell	51
J	Initial	Sitka spruce	14	Thin and fell	52
	Changed	As initial state, but with 30% of forest harvest residues extracted for use as bioenergy			
K	Initial	Sitka spruce	12	Thin and fell	54
	Changed	Conversion to grass with assumed 2.5 tC/ha in living biomass			

All the scenarios are relevant for forests growing in the UK, mainly involving those forests already under management for wood supply. It should be apparent that most of the scenarios involve relatively simple changes to one parameter or at most two parameters, e.g. an improved growth rate, the introduction of thinning where previously this practice did not occur, or an adjustment to the rotation age. However, two of the cases ('A' and 'J') are more complex and warrant further explanation.

Forest class 'A' represents the creation of new forest areas (i.e. afforestation). These forests are assumed to be created on what was formerly (grazed) grassland. The living biomass of the grass is assumed to amount to a carbon stock of 2.5 tC/ha. It is assumed that 20% of the area of the new forests consists of broadleaf trees, managed mainly for amenity value with minimal tree felling, and 80% of the area is formed of coniferous trees managed mainly to supply stemwood for the wood processing and biomass industries. (However, in reality, both the broadleaf and coniferous forest areas would be managed for multiple objectives.) The parameters selected are intended to represent the typical characteristics of broadleaf and coniferous forests growing in current conditions in the UK.

Forest class 'E' is intended to represent a scenario in which action is taken now, to ensure that in the future forests formed of single tree species (monocultures) are less susceptible to complete destruction by a pest or disease outbreak. This is achieved by introducing equal proportions of two other tree species alongside the existing species. The modelling aims to represent the consequences of a future pest of disease outbreak on carbon stocks in living trees. Under the initial state, the trees forming the monoculture forest are all killed and carbon stocks are reduced to zero. Under the changed state, the two other tree species in the forest are not susceptible to the pest or disease, hence, the carbon stocks in these trees are retained after the outbreak. This is intended to be a simplistic but reasonable way of representing such a scenario. Similar approaches be applied for representing management to mitigate other types of natural disturbance. An example might involve preemptive thinning and/or felling of small areas of forest stands to create fire breaks, so that a proportion of the maximum possible carbon stock in the forest is conserved by avoiding a severe fire outbreak, instead of being completely lost in a fire.

One of the forest classes, 'J', does not involve any change to the management of the trees in the forests. In this case, some of the forest harvest residues (stem offcuts and branchwood) accumulated during the harvesting of stemwood are extracted and used for bioenergy, whereas previously these residues would be left to decay in the forest. For this scenario, it was assumed that 30% of the biomass in residues would be extracted, with the remaining 70% left behind to decompose in the forest as before. This was assumed to result in a 30% reduction in carbon stocks in deadwood and litter in the forests. Removing just 30% of forest harvest residues may appear to be a relatively small percentage. The reason for this is that the quantities of deadwood in forests following harvesting derived from CARBINE model results include tree stumps and root systems. These components of deadwood biomass, which represent quite a significant proportion of the total, were assumed to be left in the forest, with most of the branchwood and stem offcuts being extracted. The total amount of residues extracted following stemwood harvesting was expressed as an annual rate, by dividing the estimated total by the rotation period assumed for the forests. The calculation methods were similar to those illustrated in Section A5.2 for stemwood and sawlog supply.

A5.5 Concluding observations

It is important to stress that the methods described in Chapter 5 and in this appendix would require further development and testing before they could be put into practice. The technical details would require further research and development, for example, to produce generally accepted default values for estimating carbon stock changes. The methods described here have concentrated on representing tree carbon stocks and stock changes, but consideration is needed of including other carbon pools, notably forest deadwood, litter and soil. The possibility of developing 'Tier 3' methods, as defined in IPCC Guidance (see Box 3.1.1 in IPCC, 2003) could also be explored.
Administrative frameworks would also be required to support the application of these methods. In this context, it may be noted that the methods could potentially work within a range of possible policy frameworks, from regulation to carbon trading systems.