FROM SCIENCE TO POLICY 3

Forest biomass, carbon neutrality and climate change mitigation

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SUMMARY

The Paris Agreement and the EU Climate and Energy Framework set ambitious but necessary targets. Reducing greenhouse gas (GHG) emissions by phasing out the technologies and infrastructures that cause fossil carbon emissions is one of today's most important challenges. In the EU, bioenergy is currently the largest renewable energy source used. Most Member States have in absolute terms increased the use of forest biomass for energy to reach their 2020 renewable energy targets.

In recent years, the issue of 'carbon neutrality' has been debated with regard to the bioenergy products that are produced from forest biomass. There is no clear consensus among scientists on the issue and their messages may even appear contradictory to decision-makers and citizens. Divergence arises because scientists address the issue from different points of view, which can all be valid. It is important to find agreement on some basic principles, to inform policy makers. Guidance is also needed on how the results should be interpreted.

This report provides insights into the current scientific debate on forest biomass, carbon neutrality and climate change mitigation. It draws on the science literature to give a balanced and policy-relevant synthesis, from both an EU and global perspective.

Forest carbon neutrality is an ambiguous concept and its debate distracts from the broader and much more important question: how European forests and the associated industries can contribute to climate change mitigation while serving many other functions. Rather than debating the carbon neutrality of bioenergy, we should be concerned with the net climate change effects of bioenergy, assessed in the specific context where bioenergy policies are developed and bioenergy is produced.

Forest bioenergy is not a single entity, but includes a large variety of sources and qualities, conversion technologies, end products and markets. Forest bioenergy systems are often components in value chains or production processes that also produce material products, such as sawnwood, pulp, paper and chemicals. Consequently, the technological and economic efficiencies as well as the climate mitigation value will vary.

The science literature provides different views, depending on the context of the analysis and policy objectives. These have a strong influence on the formulation of research questions, as well as the methods and assumptions about critical parameters that are then applied, which in turn have a strong impact on the results and conclusions. For example, studies that analyse carbon flows at individual forest stand level are very restricted, and therefore not very useful for informing policy making. Instead, wider forest landscape level studies and energy system and integrated assessment models should be used.

Bioenergy can play an important role in climate change mitigation and there is a high risk of failing to meet long-term climate targets without bioenergy. The promotion of forest bioenergy needs to reflect the variety of ways that forests and forest-related sectors contribute to climate change mitigation. There can be trade-offs between carbon sequestration, storage, and biomass production. There can also be trade-offs between short- and long-term climate objectives. But a strong focus on short-term GHG targets may result in decisions that make longer-term objectives more difficult to meet.

Policy implications

- Assessing GHG balances and the climate effects of forest bioenergy is essential for informed policy development and implementation. The topic can be approached from different points of view, and methodological decisions and parameter assumptions have a strong influence on the outcome. Results must be interpreted with this in mind. **Involving policymakers and stakeholders in defining policy-relevant research questions (e.g., in defining objectives, scope and selecting reference scenarios) increases the likelihood that results are relevant, interpreted correctly, and useful in the policy development process.**

- Forest bioenergy systems can be effective means for displacing fossil fuels. Supply chain energy use is typically low and the associated GHG emissions are of minor importance for the total GHG balance of bioenergy production. **To realise high GHG savings, it is critical that policies and regulations create a situation where the promotion of bioenergy and other non-fossil energy options leads to fossil fuel displacement rather than competition among non-fossil options.** The impact that bioenergy production has on decreasing investments in technologies and infrastructure that rely on fossil fuels is also important, since this has implications for future emissions.

- How will incentives (policies) for bioenergy affect the state of forests and the forest sector's contribution to climate change mitigation? The answer varies. Changes in forest management that take place due to bioenergy demand depend on factors such as forest product markets, forest type, forest ownership and the character and product portfolio of the associated forest industry. How the forest carbon stock and biomass output are affected by these changes in turn depends on the characteristics of the forest ecosystem. **Consequently, policymakers need to consider policies in the context of the regional forest and energy sector. One-size-fits-all policies are unlikely to be optimal.**

- The impact of bioenergy implementation on net GHG emission savings is context- and feedstock-specific due to the fact that many important factors vary across regions and time. **A generic categorisation system which specifies only some forest biomass types as eligible bioenergy feedstocks may prevent the effective management of forest resources to economically meet multiple objectives, including climate change mitigation. There is a risk that bureaucracy and costly administration discourage actors from investing in bioenergy.**

- Cascading use, which makes sense as a general rule, should not be a straightjacket. Applying a cascading principle that promotes the use of forest biomass for wood products ahead of energy may not always deliver the greatest climate or economic benefits. **It is important that cascading is applied with flexibility, and considering what is optimal for the specific regional circumstances (feedstock, industry and energy system setting).**

- **Knowledge and experiences of management practices from European regions where biomass utilization has been a long-lasting practice should be shared and discussed. This would help to facilitate the development of locally adopted management guidelines in other regions.** Best practices, as well as failures, provide important insights. However, forest area, biome, ownership, income and employment generation, and the objectives and culture related to forests differ significantly between Member States, and even between regions. Regionally tailored guidelines are also needed.

- **The use of forest biomass for energy is likely to make economic and environmental sense if accompanied by a package of measures to promote best practices in forest management for climate change mitigation.** These should consider the diversity of forest types and management systems across Europe, ensure biodiversity safeguards, and aim to balance all forest functions. With the right incentives, the EU forest sector can make an important contribution to climate change mitigation while also serving other objectives.

1. Purpose and background: a timely debate

World leaders finalized a historic global agreement to combat climate change in Paris in December 2015. They agreed on the need for global greenhouse gas (GHG) emissions to peak as soon as possible; to achieve GHG neutrality in the second half of this century; and to hold global warming well below 2°C relative to pre-industrial levels.

As part of this global effort, EU Member States adopted the Climate and Energy Framework in 2014, which sets three key targets for the year 2030:

- at least 40% cuts in GHG emissions (from 1990 levels)
- at least 27% share for renewable energy
- at least 27% improvement in energy efficiency.

To implement these targets, the EU is currently in the process of updating its climate and energy policies. These should be decided late 2016/early 2017, and implemented from 2021 onwards.

According to the Intergovernmental Panel on Climate Change (IPCC), scenarios with a likely chance of keeping warming below 2°C involve substantial cuts in anthropogenic (man-made) GHG emissions, via large-scale global changes in energy systems and potentially land use. The IPCC notes that bioenergy can play a critical role in mitigation but entails challenges. Issues to consider include the sustainability of land use practices and the efficiency of bioenergy systems.

The climate impact of bioenergy is of critical importance in the EU since bioenergy is currently the largest renewable energy source used. Although its relative share is slowly declining, woody biomass was still contributing 44% to overall renewable energy production in 2014.

Most EU Member States have in absolute terms increased the use of woody biomass for energy to reach their 2020 renewable energy targets. Further intensification of forest resource utilization is discussed in several countries, driven also by the recent EU Bioeconomy Strategy. The bioenergy used in the EU is mainly produced within the region, but some liquid and solid biofuels are imported (for example pellets are imported mainly from North America).

A key issue in the debate about the climate impacts of bioenergy is the question of 'carbon neutrality': bioenergy systems can influence the cycling of biogenic carbon between the biosphere and atmosphere, but studies sometimes disregard this when estimating GHG balances. In other words they assume that bioenergy systems can be considered neutral in regard to the biosphere-atmosphere CO_2 flows.

In recent years, this issue has also been debated with regard to bioenergy products that are produced from forest biomass (forest bioenergy). There is no clear consensus among scientists on the issue and their messages may even appear contradictory to decision-makers and citizens. Some scientists, for example, signal that the use of forest biomass for energy enhances global warming, while others maintain that forest bioenergy can play a key role in climate change mitigation.

The confusion is heightened by the fact that both sides can be said to be correct. The divergence arises because scientists address the issue from different points of view, which can all be valid. Different points of view concerning policy objectives, for example, motivate different methodology approaches, which result in different outcomes.

In addition, forest bioenergy is often an integral part of the forest management, forestry and energy-industry system. Bioenergy is therefore not readily separated from other activities in the forest sector, and any change in biomass usage affects not only environmental sustainability but also leads to economic and social effects.

It is important to find agreement on some basic principles for the relevant context in which the issue should be addressed, to inform policy makers. Guidance is also needed on how the results should be interpreted.

This report provides insights into the current scientific debate on forest biomass, carbon neutrality and climate change mitigation. Its objective is to provide a balanced and policy-relevant synthesis on the issue, taking into account EU and global perspectives. Other societal objectives and interests are briefly touched upon but the focus is on climate change mitigation.

2. Bioenergy systems – an overview

In industrialized countries, forest biomass for bioenergy is typically obtained from a forest managed for multiple purposes, including the production of pulp and saw logs, and provision of other ecosystem services. Bioenergy feedstocks mainly consist of by-products from sawnwood and pulp and paper production, and small diameter trees and residues from silvicultural treatments (e.g., thinning, fire prevention, salvage logging) and final felling. A large fraction of this biomass is used to supply energy within the forest industry. For example, sawmill residues are used for drying sawnwood, and pulp mills use black liquor – a byproduct from the pulping process – as an energy source. Energy coproducts (electricity and fuels) from the forest industry are also used in other sectors.

2.1 Supply chain emissions and GHG savings

A typical supply chain for forest biomass consists of a harvester that cuts and delimbs the trees, and a forwarder (purpose-built forest tractor) that transports stems or other biomass to the roadside. From here it is transported with trucks and possibly reloaded to other modes such as sea and rail for longer distances. If chipping of the wood is done prior to transport a diesel chipper is used. If chipping is done at large terminals or at the energy plant an electric chipper may be used.

The fossil fuel used for harvesting, chipping and truck transport typically corresponds to less than 5% of the energy content in the supplied biomass.

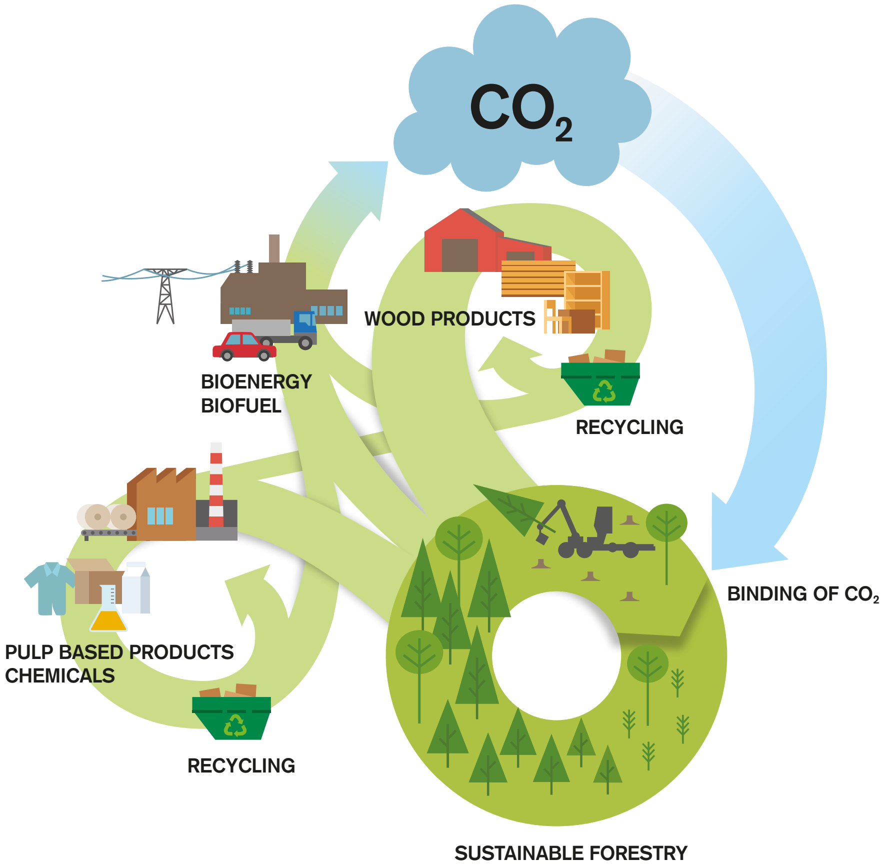

Figure 1. When forest biomass is used to produce pulp, paper and other wood products, bioenergy is produced simultaneously. Biomass from forestry operations and byproducts from wood processing are used to make electricity, heat and fuels. This bioenergy is used to meet internal process energy needs in the forest industry and is also used outside the forest industry. Figure: Sveaskog.

Consequently, the supply chain emissions correspond to a small fraction of the biogenic carbon flows associated with the forest operations.

There are examples with relatively higher fossil GHG emissions, such as when coal is used as a process fuel when wet feedstocks are used to produce pellets. But fossil fuel use is not an intrinsic characteristic of the system. Other process fuels can be used, such as biomass itself, though this reduces the output of bioenergy products per unit biomass used.

Another issue is dry matter losses due to biomass degradation during storage, which can reach 1% per month of storage, i.e., significant enough to influence the CO_2 emissions per unit of wood chips delivered to the energy plant. On the other hand, if logging residues would have been left in the forest to decay the dry matter loss would be similar or higher.

Studies show that:

- Supply chain emissions are of minor importance when forest biomass is used in surrounding areas, where average transport distance is typically less than 100 km.
- With efficient handling and shipping, biomass transported over long distances can deliver high GHG emissions reduction.
- Supply chain emissions are not particularly affected by biomass source per se, i.e., whether roundwood or other forest biomass sources are used.
- Biomass conversion efficiency and the GHG displacement efficiency – the emissions avoided per unit of bioenergy used – become increasingly important as the supply chain emissions increase.

2.2 Impacts of albedo, ozone precursors, aerosols and black carbon

Bioenergy systems can also affect climate change through emissions of short-lived climate forcers (non-GHG factors behind climate warming or cooling). These include aerosols (sulphur dioxide, black carbon) and ozone precursors (nitrogen monoxide, carbon monoxide and non-methane volatile organic compounds). These can have positive or negative influences on global warming.

For example, black carbon is emitted through incomplete combustion of biomass. It is a short-lived but powerful climate forcing agent: it absorbs radiation, influences cloud formation, and reduces albedo (the fraction of solar energy that is reflected by the earth) when deposited on snow and ice. The effect is site-dependent and there is high uncertainty over the net impact. Organic carbon particles released through biomass combustion scatter radiation, and have a cooling effect that offsets the global warming caused by black carbon.

Changes in land management and/or land use may also have an impact on global and local climate through surface albedo change, as well as through modifications in evapotranspiration, surface roughness, etc. Ice and snow have very high albedo, reflecting over 60% of radiation, whereas forests, especially snow-free coniferous forests, have a much lower albedo (c. 10% reflectance). Modifying vegetation to produce biomass for energy may increase or decrease albedo, depending on the forest management and location.

In high latitudes, where snowfall is common, increased harvest intensity in evergreen forests can increase albedo, counteracting warming in situations where forest carbon losses increase the level of atmospheric CO_2. Removal of forest slash may increase albedo, although the effect appears to be small.

Conversion of an agricultural field (cropland or pasture) to an evergreen species to establish a bioenergy crop may reduce albedo, partly negating the benefits of carbon sequestration in soils and biomass and displacement of fossil fuels. In lower latitudes that do not experience widespread snowfall, changes in vegetation management have a smaller impact on albedo. However, the replacement of grassland with evergreen plantations can reduce albedo in savanna regions characterised by dry periods where grasses die off.

Because albedo impacts are highly sensitive to location, land use change, vegetation species and management it is necessary to consider the features of individual projects to assess the scale and direction of albedo impact.

The results of the interactions between all these forcers is still not fully understood. While non-GHG climate forcers may sometimes mitigate the overall climate impact of bioenergy, there are other environmental impacts associated with both land use changes and air pollutants, e.g., secondary particulate matter formation, acidification and photochemical ozone formation. Advanced bioenergy plants employ effective technologies to control black carbon emissions.

2.3 Carbon neutrality: balancing carbon emissions and sequestration

Studies that estimate the GHG emissions and savings associated with bioenergy systems have often focused on supply chain emissions and have adopted the assumption that the bioenergy systems under study do not have any impact on the carbon that is stored in the biosphere. This "**carbon neutrality**" of bioenergy is claimed on the basis that the bioenergy system is integrated in the carbon cycle (Figure 2) and that carbon sequestration and emissions balance over a full growth-to-harvest cycle.

While the reasoning behind the carbon neutrality claim is valid on a conceptual level, it is well-established that bioenergy systems – like all other systems that rely on the use of biomass – can influence the cycling of carbon between the biosphere and the atmosphere. This is recognised in the United Nations Framework Convention on Climate Change (UNFCCC) reporting: biogenic carbon emissions associated with bioenergy are not included in the reporting of energy sector emissions, not because bioenergy is assumed to be carbon neutral but simply as a matter of reporting procedure. Countries report their emissions from energy use and from land use, land use change and forestry (LULUCF) separately. Because biogenic carbon emissions are included in the LULUCF reporting, they are not included in the energy sector as this would lead to double-counting.

Scientists have reported that bioenergy systems can have **positive, neutral or negative effects on biospheric carbon stocks**, depending on the characteristics of the bioenergy system, soil and climate factors, and the vegetation cover and land-use history in the locations where the bioenergy systems are established. Much attention has been placed on the risks that bioenergy expansion would cause losses in biospheric carbon stocks which would seriously impact the climate change mitigation benefit of bioenergy. The prominent example put forward is when dense forests are converted to croplands to provide biofuel feedstock.

When biomass from existing managed forests is used for bioenergy, the critical question is how this biomass use influences the **balance and timing** of carbon sequestration and emissions in the forest, and hence, the timing and the overall magnitude of net GHG emission savings. The fossil fuel (GHG) displacement efficiency – how much fossil fuels or GHG emissions are displaced by a given unit of bioenergy – is another critical factor.

As we explore in section 3, the diverging standpoints on bioenergy can be explained to a significant degree by the fact that scientists address these critical factors from different points of view. The conclusions vary because the systems under study differ, as do the methodology approaches and assumptions about critical parameters.

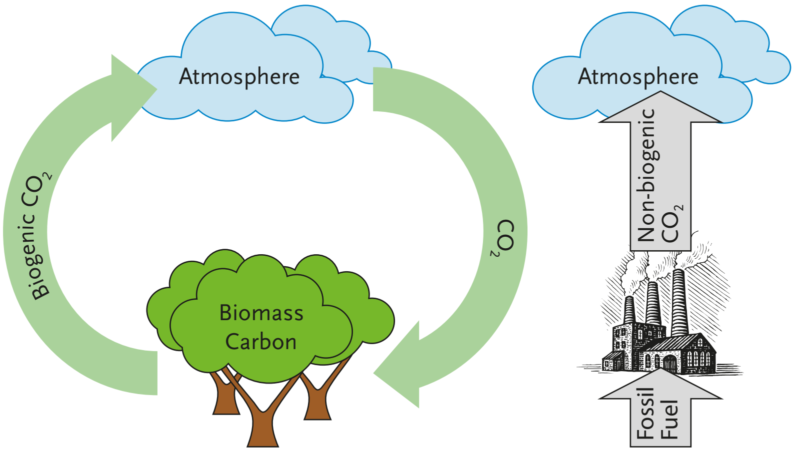

Figure 2. Illustration of the important distinction between bioenergy (cyclic carbon flow) and fossil-based energy (linear carbon flow). The IPCC distinguishes between ***the slow domain*** of the carbon cycle, where turnover times exceed 10,000 years, and ***the fast domain*** (the atmosphere, ocean, vegetation and soil), where vegetation and soil carbon have turnover times of 1–100 and 10–500 years, respectively. Fossil fuel use transfers carbon from the slow domain to the fast domain, while bioenergy systems operate within the fast domain. Figure: National Council for Air and Stream Improvement.

3. Evaluating carbon balances and climate change impacts

In this section, we present an overview of the approaches used to assess the climate change mitigation benefits of bioenergy systems. Different analytical approaches and impact metrics give different insights – **it is important to understand the appropriate context for the chosen methods in order to draw the correct conclusions and policy implications.**

Forest carbon balances are assessed differently due to the different objectives of studies. For instance, the objective might be to determine the impact of specific forest operations (e.g., thinning, fertilization, harvest) on forest carbon stocks and GHG emissions; or determine the carbon footprint of a bioenergy product; or investigate how different forest management alternatives contribute to GHG savings over varying timescales.

The IPCC concludes that cumulative emissions of CO_2 largely determine global warming by the late 21st century and beyond. The exact timing of CO_2 emissions is much less important than how much carbon is emitted in total in the long run. This means we should focus on how biomass harvest for energy influences forest carbon stocks over the longer term, since this in turn influences cumulative net CO_2 emissions. The influence of bioenergy expansion on investments into technologies and infrastructure that rely on fossil fuels is also critical, since this has strong implications for future GHG emissions. A long-term view is also needed to align assessments with timescales suitable for forest ecosystems and forest management planning.

Short-term GHG emissions reduction targets have been adopted to drive progress towards the cuts necessary to meet the global temperature target. Short-term GHG targets can also be due to concerns over ocean acidification, and a desire to slow the rate of warming, which has important consequences for the capacity of ecosystems to adapt to climate change, and avoid transgressing possible climate tipping points. It is important to clarify how forest bioenergy and forest management in general can serve both these short-term and long-term objectives.

Major methodological choices which can have large influence on outcomes include:

- **definition of a counterfactual no-bioenergy (reference) scenario**: how do forest markets, forest management, and forest carbon stocks evolve in the absence of bioenergy demand and production? Which energy alternatives are used instead of bioenergy?
- **spatial system boundary**: are carbon balances assessed at the forest stand level or at the forest landscape (system) level?
- **temporal system boundary**: what is the time period of assessment and how does it compare with the forest rotation period? When is the accounting begun in relation to the first harvest for bioenergy?
- **scope**: are economic and social aspects included and are market-mediated effects considered? Is the bioenergy system assessed in isolation or does the study examine how forest management as a whole responds to bioenergy incentives and how this in turn affects the state of the forests and forest product outputs? Does the study investigate the role of bioenergy within the integrated energy-land use-natural carbon cycle?

3.1 Reference scenarios

The range of reference (counterfactual) scenarios in the literature represents the differences in the scope and objectives of studies, and the context of the bioenergy system being evaluated. It can also reflect aspects such as access to data and models, and the principles associated with the chosen assessment method.

Studies that quantify GHG balances for bioenergy systems either focus on absolute GHG emissions and carbon sequestration, or consider net GHG balances by comparing a bioenergy scenario with a reference scenario where the assessed bioenergy system is absent. This reference scenario must include a specification of a reference forest system and a reference energy system. For the latter, a straightforward and transparent approach is to specify the GHG displacement efficiency based on the characteristics of the chosen reference energy system. The parameter can be held constant, or set to change over time to reflect the fact that the reference energy system may change over time.

Studies that assess the emissions reduction due to a specific bioenergy product often consider forest bioenergy as a marginal activity. Additional harvest for bioenergy is compared with a "business as usual" (BAU) situation with forest management producing the same mix of forest products, besides the bioenergy product. For example, a bioenergy scenario where residues from forest felling are harvested for bioenergy may be compared with a reference scenario where these residues are left to decompose on the ground.

Studies that also model economic and market reactions include economic equilibrium modelling where the reference is represented by a state in equilibrium. The GHG and other impacts associated with the bioenergy system are investigated by applying a bioenergy demand shock to this market equilibrium state. The impacts are quantified by comparing the old and new state of market equilibrium.

Studies that use integrated systems modelling also commonly include reference scenarios. Rather than providing a basis for calculating net effects, these reference scenarios are usually presented and analysed together with several alternative scenarios that may include more or less bioenergy supply.

The definition of the reference scenario has a strong influence on the outcome of assessments. It is essential that reference scenarios are explicitly presented and justified.

The boxes in this section describing the context for bioenergy in Canada and the south-east US are illustrative of the importance of good knowledge and data when bioenergy and reference scenarios are developed. The south-east US example illustrates the possible effects of bioenergy demand in a region where decisions by private land owners shape much of the landscape, and hence the development of forest carbon stocks over time. The Canadian example shows the dominating influence of natural disturbances on the forest carbon stock, which has been unrelated to levels of wood extraction in the country.

Will increasing demand for forest biomass for bioenergy in Europe cause a carbon stock loss in Canada?

Contrary to other more densely populated regions, there is little competitive use for most forest lands in Canada. Deforestation rates remain very low (less than 0.02% in 2012), and the demand for wood products has no influence on land use change. Carbon stock changes through time are therefore mostly related to changes in the carbon density of forests over the full landscape.

Disturbances, both natural (fire and insect) and man-made (forest management) can affect forest carbon density. Disturbances induce direct losses of carbon from forest ecosystems in several ways: combustion in wildfire, exports in harvested wood products, and by causing the death of trees which then enter a stage of decomposition.

Apart from these direct effects, disturbances have long-lasting effects on the carbon cycle as they drive the age-class distribution of forest stands within a region:

- recently disturbed sites are a net source of CO_2 to the atmosphere
- juvenile stands are a strong sink
- old stands, while often more carbon dense, oscillate between being small carbon sinks or carbon neutral.

An increase in the level of disturbance (harvest or natural) lowers the regional average age of stands and induces short-term decreases and long-term increases of net carbon sequestration rates. The overall impact of harvested wood product (HWP) extraction on ecosystem carbon cycling is complex, but it is only one part of the larger overall carbon flux changes through time (Figure 3).

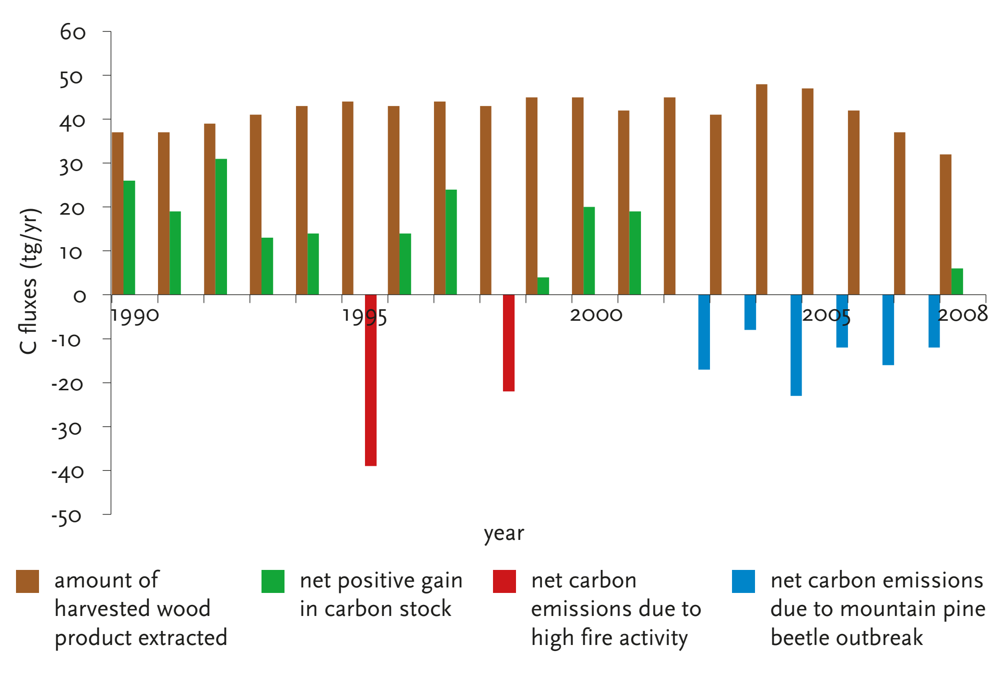

Figure 3. Carbon fluxes in Canadian managed forest (1990–2008). Despite the occurrence of unusually large natural disturbance events, the forest ecosystem remained a net carbon sink during this period while producing a substantial share of the world's harvested wood product that contributed to climate change mitigation. Figure: Stinson et al. 2011.

Significant industrial pellet production started in 2000, but the highest yearly production rate has still been less than 3% of harvested wood product. Because of their lower market value, the feedstocks dedicated to bioenergy are generally the ones that are not used for traditional forest products. The use of these residual feedstocks generally delivers short-term atmospheric benefits. The use of salvage wood as a bioenergy feedstock could also become an important climate change mitigation activity. A greater threat to the large carbon stocks of the boreal ecosystem is human-caused climate change.

3.2 Assessment scales in time and space

The appropriate spatial and temporal scales for assessment are key when assessing forest carbon balances.

In countries where "final felling" dominates forest harvesting, one spatial scale considered in assessments is the *forest stand*, i.e., the typical scale for final felling operations. Such studies often focus on assessing the carbon balance associated with distinct operations, such as salvage harvest and residue collection for bioenergy at final felling. They also consider changes in forest management practices, such as when thinning intensity increases and some volume of biomass is extracted for energy, in addition to the wood that is extracted for the production of sawnwood, paper and other forest products. The bioenergy system is often evaluated in isolation, i.e., it is not considered whether the forest management and output of other forest products is affected by the presence of the bioenergy system.

Studies may consider forest carbon balances over one or several rotation periods for the stand, i.e., longer than a 100-year time horizon. If the policy objective is short-term emission reductions, studies may evaluate bioenergy options by calculating carbon balances for a shorter time than a forest rotation.

One drawback of stand-level assessments is that they prescribe a strict sequence of events (site preparation, planting or natural regeneration, thinning and other silvicultural operations, final felling) that in reality occur simultaneously across the forest landscape. **The assessment outcome can therefore vary drastically depending on how the temporal carbon balance accounting window is defined.**

If the carbon accounting is started at the time of the first biomass extraction and use for bioenergy, i.e., commencing with a pulse emission followed by a phase of sequestration, there will be – by design – often an initial net GHG emission. This initial net GHG emission is commonly referred to as a "carbon debt" and it follows that net emissions savings are delayed until this debt has been repaid. The exception occurs when the bioenergy system displaces more GHG emissions than those associated with the bioenergy system itself.

If the purpose is to investigate the effects of introducing biomass extraction for energy as a new component in the management of an existing forest, it might be appropriate to start the accounting at the time of the first biomass extraction for bioenergy. However, if the purpose is to investigate the climate effects of incentivizing bioenergy, the definition of the time period for accounting is less clear. Land owners and other actors in the forest sector can respond to bioenergy incentives in many different ways, and forest management might be adapted to anticipated bioenergy demand in advance of the first biomass extraction and its use for bioenergy. Due to this, it might be considered appropriate to start the carbon balance accounting clock earlier, e.g., at the time of a change in forest management.

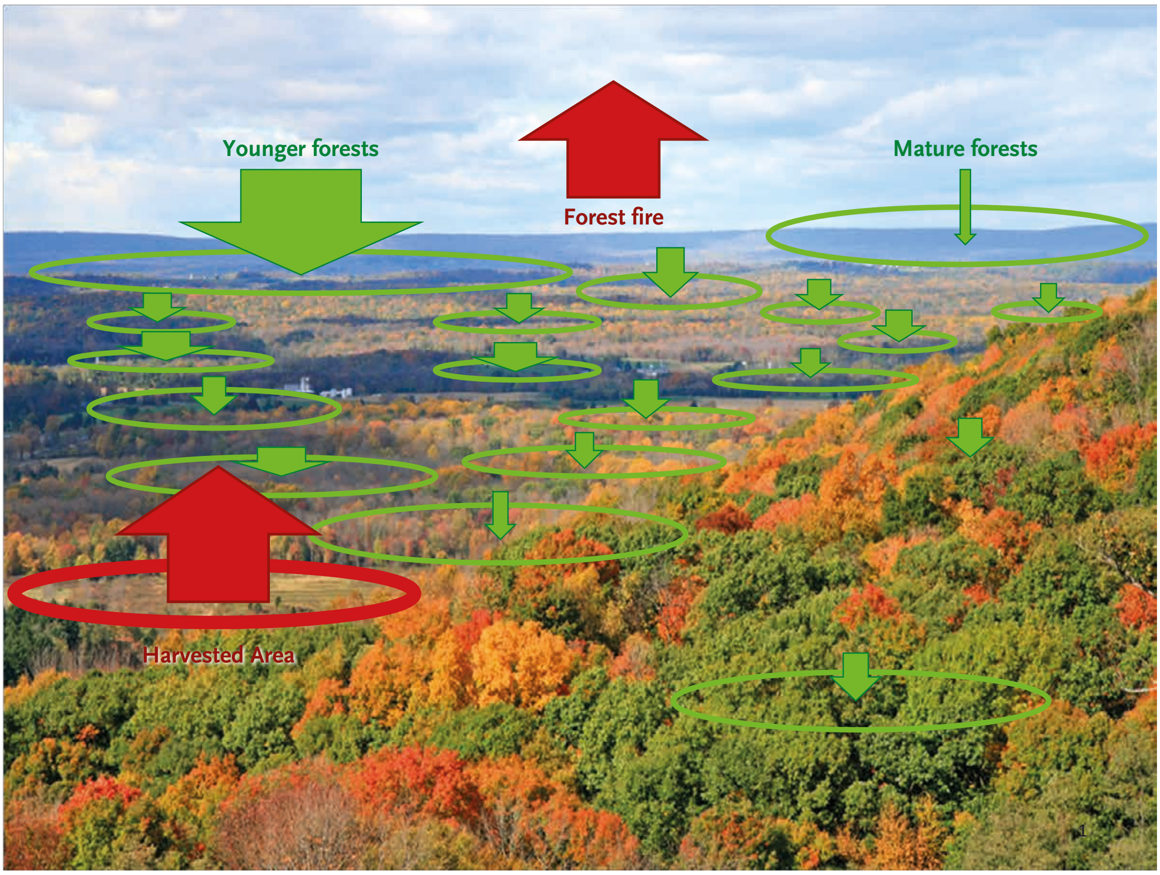

Figure 4. Forest management is planned and coordinated across a mosaic of forest stands to supply a continuous flow of biomass for multiple forest products. The carbon balance switches abruptly from sequestration to emissions when there are fires or stands are harvested (red arrows). But carbon losses in some stands are counteracted by carbon gains in other stands (green arrows, varying size to illustrate variation in sequestration rate), so that across the whole landscape the forest carbon stock fluctuates around a trend line that can be increasing, decreasing or roughly stable. The carbon balance at the landscape level is affected by many factors and taken together, these may have a positive, negative, or neutral influence on the development of forest carbon balances. Figure: National Council for Air and Stream Improvement.

As the outcome of stand-level assessments is very sensitive to these types of methodological decisions, this may at least partly explain strongly divergent views on the climate effects of forest bioenergy. Statements such as: "*it can take many decades until a regrowing forest has captured the carbon that was released when trees were harvested and burned for energy*" and "*theories on carbon debt and payback time of biomass are not credible, because they are based on the unrealistic assumption that trees are burned before they have grown*" implicitly reflect positions on the proper time period for accounting, which are left undeclared in the debate.

Studies intending to inform policy development need to consider how bioenergy incentives can affect the state of forests and the forest sector's contribution to climate change mitigation through carbon sequestration, carbon storage and fossil fuel displacement, and how this in turn affects the GHG impacts of bioenergy implementation over time.

Landscape-scale assessment can provide a more complete representation of the dynamics of forest systems, as it can integrate the effects of all changes in forest management and harvesting that take place in response to – experienced or anticipated – bioenergy demand. It can therefore help to clarify how total forest carbon stocks are affected by specific changes in forest management.

For example, stand-level assessments show that carbon stored in logging residues is emitted earlier to the atmosphere when these are used for energy instead of being left to decay in the forest. In such studies, the assessment outcome is simply determined by the decay time of residues in the forest, and the GHG displacement efficiency of bioenergy use. Assuming the same GHG displacement efficiency, slash tends to score better than stumps in the same location, because stumps decay slower, and each type of residues scores worse in boreal biomes than in temperate and tropical biomes where it decays faster. Landscape-level assessments provide another perspective. They show that the gradual implementation of residue collection at logging sites will have a relatively small influence on the development of the carbon stock in the forest as a whole, which is affected by many other factors that can change in response to bioenergy incentives.

A forest landscape can simply be represented by a series of time-shifted stands. Such theoretical landscapes can be used to illustrate how forest carbon stocks are affected by specific changes in forest management, such as an altered average rotation period or the establishment of new practices such as stump harvesting at final felling.

3.3 Integrated modelling of forest systems and associated markets

Forest management is linked to the economic incentives and market expectations of forest owners for different forest products. Bioenergy is typically only one of the many forest products that are supplied to markets. Although in many European countries sawnwood currently generates the major income for forest owners, an anticipated increase in demand for bioenergy can incentivize investments in measures to increase forest production and biomass output. For example, forest owners may implement measures to protect their forests against disturbances, replanting and tending the forest and introducing more productive tree species and provenances.

In contrast to studies that use theoretical landscapes, an integrated modelling approach that captures economic and biophysical dynamics and interactions can be used to study how forest management will vary depending on the characteristics of demand, forest structure, climate, forest industry profile, forest owners' views about emerging bioenergy markets, and the outlook for other forest product markets. Such studies can reveal how adjustments across affected systems (including the forest, product uses, markets and processing technologies) combine into a positive, negative, or neutral influence on the development of forest carbon stocks and GHG emissions.

One fundamental finding is that **the effects of bioenergy on atmospheric carbon are more variable than suggested by studies which exclude economic factors and fail to consider the diversity and dynamic characteristics of forests and the forest sector.**

As an illustration of the variation of outcomes, incentivizing wood-based energy markets could potentially increase the price of small-diameter logs used for pulp, board, round timber and other products. In some regions this might encourage forest owners to opt for shorter rotation ages, and the pulp and paper industry could face increased raw material competition. In other regions, forest management aimed at an economically optimal output of forest products might instead result in longer average rotation periods, reduced sawnwood output, and increased pulpwood and forest fuel output due to increased thinning frequency. The effects on forest carbon storage can vary from positive to negative depending on the character of the forests and conditions for its management.

Insights from integrated modelling approaches give strong reason to object against generalizing statements about the climate effects of forest bioenergy.

Evidence suggests that incentives to promote forest bioenergy can result in decreases as well as increases in forest carbon stocks in the landscape. The longer-term climate benefit of different forest management scenarios depends on the structure of the forest and associated industry and markets. (See also the boxes in this section describing the situation in Canada and the south-east US).

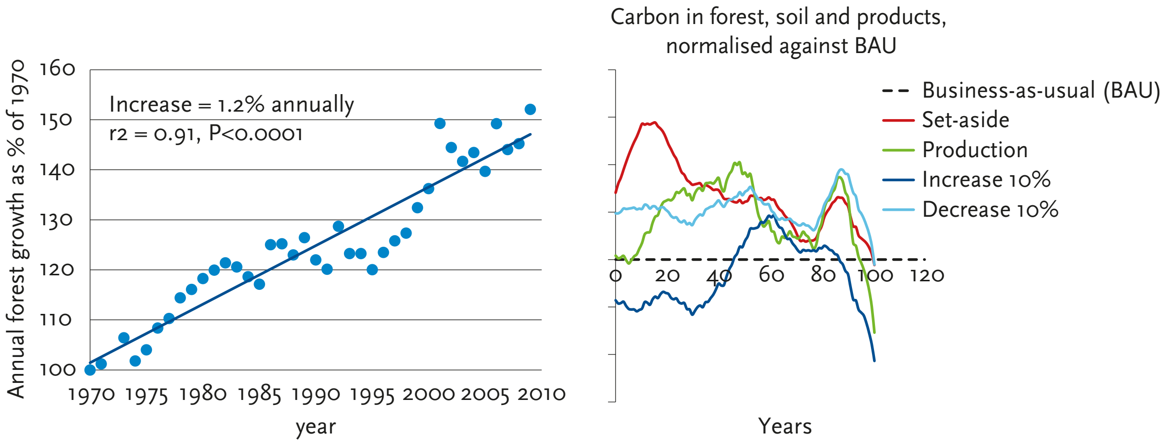

Figure 5. Forest bioenergy use in Sweden has increased drastically since 1970, mainly due to the need to displace fossil fuels in forest industry and in heat-and-power production. As shown in the left-hand diagram, this increase in bioenergy use has not impacted forest growth. The right-hand diagram shows how carbon in forests (soil and trees) and forest products (including domestic use and export) changes under different management scenarios extending 100 years into the future, compared to a business-as-usual situation. The outcome is strongly determined by the current structure of the forest and associated forest industry and markets. Short-term carbon gains or losses need not mean long-term climate benefit or dis-benefits. Figure adapted from Gustavsson et al, 2017.

Forestry and pellet production in the south-east US

Pellets are exported from the south-east US to a number of EU Member States, especially to the Netherlands and the UK. Consequently, if we want to analyse the possible "carbon leakages" of forest biomass consumption in the EU, it is important also to assess the forestry in this region.

Pellet demand in context

The forest economy in south-east US forests is a highly productive, privately owned market-driven bioeconomy, with 87% under private ownership and 95% privately harvested. It produces most US timber, and more than any other country.

The region's forests cover over 60% of the land area and are predominately hardwood or mixed pine-hardwood forest with approximately 20% in intensively managed pine plantations and 15% in natural pine. Forestland is intermingled with agricultural land and intensively managed forests compete with marginal agriculture. These fast-growing forest lands are price responsive, such that increased demand for wood can lead to long-term increases in forest carbon relative to a low demand baseline. This is due to both higher growth rates of managed stands and increases in timberland area due to higher returns. Over the past 40 years the loss of timberland to urbanization has been offset by gains from agriculture. Partly this is because trees are the default land cover in the region, so abandoned or unmanaged land quickly reverts to forest. Active conversion occurs in regions of concentrated wood demand where plantations compete with marginal agriculture.

Wood pellet exports from the region have grown over the past decade from an insignificant amount to 3.2 million metric tons in 2015. Most are sent to the EU to produce heat and power. In 2013, wood requirements to produce pellets corresponded to less than 3% of all forest harvest removals and 7% of non-sawnwood removals. Increased exports in 2014 and 2015 suggest that wood requirements could have reached a level corresponding to 10% of non-sawnwood removals in those years.

Approximately 80% of pellet feedstock is pine, primarily coming from thinnings in plantation. The rest is hardwood-based, concentrated in North Carolina and Virginia. Since hardwood forests over 50 years old are the most common forest type in the region, hardwood pellet feedstocks often consist of trees unsuitable (due to species, grade, or size) for sawnwood uses and harvest residuals. Harvests of this forest type fuel the debate about potential effects on south-east US forests – particularly impacts on old-growth and bottomland forests (a riparian ecosystem in the US that typically has distinct ecological zones at different elevations and flood frequencies), with consequences for biodiversity and GHG emissions.

Designated old-growth forests are under some form of protection where logging is prohibited but active management can be necessary to retain old-growth characteristics. The major threats to bottomland forests are conversion to developed uses, changes in flooding patterns, sea-level rise, and invasive species. The material used for the production of wood pellets from bottomland forests is similar to that used by pulp mills, and harvesting must occur according to practices set out in the Clean Water Act.

The biodiversity effects of wood pellet production are not straightforward: some species may benefit and others may decline. Increased thinning for pellet productions enhances forest habitat for some birds, and changes in standing dead wood can induce declines in other species. The south-east US has a long history of forest usage, and the existing biodiversity and ecosystem services reflect that history.

The production of wood pellets for export provides an income stream to US forest landowners and provides jobs in often low-income rural communities. This market is a small part of overall demand and a smaller part of forest income, since pellets utilize low-value feedstocks. But an increase in pellet demand may contribute to: forest type conversion from natural forests to plantations; intensification of management and harvesting; increased pressure on forests of high biodiversity value; and competitive displacement and price impacts in forest product markets. Yet, the forest management responses to increased demand for pellets and other forest products have to be carried out within the existing mix of state and federal regulations, best management practices, and forest and fibre-sourcing certification programmes that seek to protect forest health.

Future prospects

The status of the forest is monitored continuously by the US Forest Service Forest Inventory and Analysis (FIA) group. To date, the levels of harvest, the conversion of lands and the management of private forests has not been shown to differ from conditions in the south-east US over the last decade. There were higher levels of harvest and conversion before the housing crisis than since pellet production increased.

There is evidence that US forest landowners respond to both timber prices (keeping more land in forest when prices are higher) and urban and agricultural land prices (converting land to other uses). The influence of pellet production on timber prices has not yet been shown to be outside the range of normal market influences.

Projections of pellet impacts show that housing market recovery is the dominant driver of future forest conditions. The impact of pellets as a forest management driver is higher with low housing demand, but **pellet demand consistent with current trends leads to small increases in total forest carbon with a slightly higher proportion in planted stands over the next 20 years**.

3.4 Integrated modelling of bioenergy in global climate scenarios

Energy system (ES) modelling and integrated assessment (IA) modelling frameworks cover all major energy sectors, and for IA models also the agriculture, forestry, and climate and ocean carbon pools. They integrate questions about energy infrastructure turnover, energy substitutions and counterfactuals, and are suited to examining the evolution of the modelled systems in a holistic and consistent fashion.

The IA models analyse the spatial and temporal trade-offs among land-use and land cover changes, deforestation and reforestation, investments in fossil, renewable, and other technologies. Any solutions from the models must be understood in the context of the emissions trade-offs made in the models. For example, the slower adoption of low-carbon technologies in one sector or time period often implies more rapid reductions elsewhere in the system.

ES/IA modelling studies show the relative cost-effectiveness of bioenergy options in different sectors in the context of climate targets, other policy objectives, and alternative energy options. They can reveal competitive and also synergistic interaction with other energy technologies. They can also provide insights into the long-term benefits of investments in R&D and technological change, and the influence of bioenergy incentives on investments in industry, energy and transport systems with implications for future GHG emissions commitments. As shown in Figure 6, the last decade has seen a significant rise in global investments in renewable energy sources (RES). However, so far these investments have not brought about the rate of decline in fossil energy use which is judged to be needed for reaching ambitious climate targets. Besides the immediate GHG savings associated with their use, bioenergy and other mitigation options need to be evaluated for their contribution to phasing out technologies and infrastructure that rely on fossil fuels, so that fossil carbon is left in the ground permanently.

Conclusions from ES/IA modelling studies may appear counter-intuitive and difficult to reconcile with simple stand/landscape-level assessments. The dominant bioenergy options in scenarios that meet stringent climate targets may not be the ones that are assessed as having the highest GHG reduction capacity per unit of biomass.

For example, assessments of GHG balances may indicate that using bioenergy to displace fossil fuels in heat and electricity generation provides a larger GHG emissions reduction per unit of biomass (or land) than displacing petrol or diesel used in transport. But ES/IA modelling shows that the

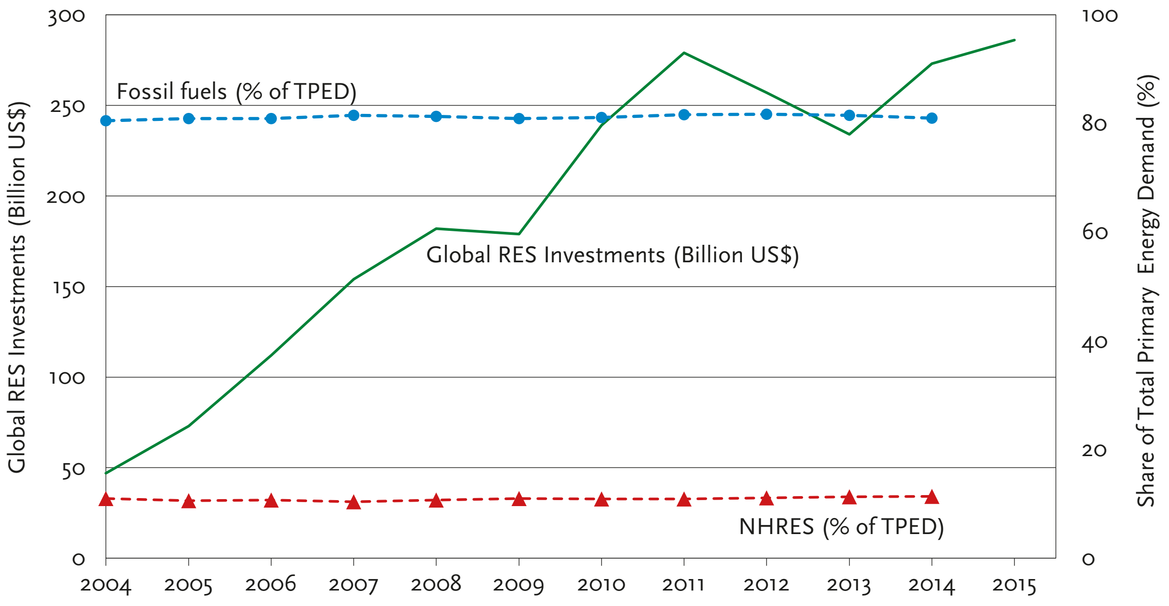

Figure 6. Global investments in renewable energy sources (RES). TPED: total primary energy demand. NHRES: non-hydro RES. Figure: Filip Johnsson, Jan Kjaerstad and Johan Rootzén, Chalmers University of Technology, Sweden.

attractiveness of different bioenergy options depends on – among other things – the availability and cost of other carbon-free options than biofuels in the transport sector, and how the carbon emission reduction targets are implemented. To take another example, bioenergy options that cause relatively higher upfront emissions (due to biospheric carbon losses) may be among the preferred ones in scenarios that meet stringent climate targets.

The consensus view expressed in the IPCC is that there is no agreed vision about where biomass could be cost-effectively deployed within the energy system, due in large part to uncertainties about technological developments and costs over time. But it has been consistently shown that bioenergy contributes significantly to the energy supply in most scenarios that meet ambitious climate targets (this result is also summarised by the IPCC 5th Assessment Report).

The ES/IA modelling results indicate a high risk of failing to meet long-term climate targets without bioenergy. The results show that, with existing technologies, it would be very difficult to meet the temperature target set out in the Paris Agreement, unless bioenergy contributes a significant share of energy needs.

3.5 Impact metrics and policy targets

The most commonly applied metric to quantify climate effects is Global Warming Potential (GWP), which is used to calculate results in "CO_2 equivalents" (see below).

Emissions metrics

A metric is a measure used to quantify or assess a variable of interest. The usual metric for quantifying the climate effects of different GHGs, applied in greenhouse gas accounting such as for reporting to the UNFCCC, is **Global Warming Potential** (GWP).

GWP expresses the integrated radiative forcing (warming impact) of a greenhouse gas relative to that of CO_2, over a fixed period, usually 100 years (GWP100). Using the relevant GWP for each different greenhouse gas, the aggregated value is then expressed as "CO_2-equivalents" (CO_2-e).

Global Temperature change Potential (GTP) has been proposed as an alternative metric. The IPCC's Fifth Assessment Report (2014) provides GTP as well as GWP values for the greenhouse gases, with time horizons of 20 and 100 years. GTP is more closely related than GWP to the ultimate impacts of climate change: specifically, it refers to the impact on temperature reached at a defined future date. GTP_{100} emphasises the greenhouse gases with longer-term effects, reducing the contribution for gases with short atmospheric lifetimes such as methane.

To inform policy development, it is recommended that both GWP and GTP are applied, to gain a full understanding of the likely range of outcomes.

Recently several new metrics have been proposed that incorporate additional climate change effects that are relevant to bioenergy, including methods to:

- incorporate the effects of timing of emissions
- equate albedo effects (see section 2.2) with CO_2 emissions
- quantify the marginal impact on forest carbon stock due to marginal changes in forest management
- integrate several aspects of temperature effects (absolute temperature reached, relative change and rate of change).

These metrics have been devised for application in life cycle analysis (LCA) studies. They are 'characterisation factors', which are multiplied by the emissions and removals quantified in the life cycle inventory to calculate climate change impact. None of these more nuanced metrics is currently applied under any carbon offset or renewable energy scheme.

The net GHG emissions of a bioenergy product may be expressed as CO_2 equivalent per energy unit (MJ, per kWh) or per unit of "service" provided by the bioenergy product (e.g., heat generated or km driven). It is also relevant to consider the emissions saved per hectare of forest or per unit weight of biomass, or per euro spent. Different factors may define the extent to which land management and biomass-derived fuels can contribute to climate change mitigation, making the following indicators relevant in different contexts:

- The *displacement factor* describes the reduction in GHG emissions from the displaced energy system per unit of biomass used (e.g., tonne of CO_2-e avoided per tonne of carbon contained in the biomass that generated the reduction). This indicator does not discourage fossil inputs in the bioenergy chain if these inputs increase the displacement efficiency. It does not consider costs.
- The *relative GHG savings* describes the percentage emissions reduction with respect to the fossil alternative for a specific biomass use. GHG savings favour biomass options with low supply chain GHG emissions. However, this indicator alone cannot distinguish between different biomass uses, such as transport fuel, heat, electricity or combined heat and power, to determine which use reduces emissions more. It ignores the amount of biomass, land or money required, and it can be distorted as each use can have different reference systems.
- The indicator *GHG savings per ha (or m^2 or km^2)* of land favours high biomass yield and conversion efficiency but ignores costs. Intensified land use that increases the associated GHG emissions (e.g., due to higher fertilizer input) can still improve the indicator value if the biomass yield increases sufficiently.
- The indicator *GHG savings per euro spent* input tends to favour the lowest cost, commercially available bioenergy options. Prioritisation based on monetary indicators can lock in current technologies and delay (or preclude) future, more cost-effective or GHG reduction-efficient bioenergy options because their near-term costs are higher.

The choice of metric should be governed by the objective of the study, but is partly a subjective choice.

4. Forest bioenergy sustainability: more than climate impact

The latest State of Europe's Forests reports in 2011 and 2015 showed that forests in Europe are expanding in area, with wood increments exceeding harvests, and a subsequent increase in carbon stocks. Enhanced protection measures also led to positive trends in particular sustainable forest management indicators, such as the average amount of standing dead wood, which is important for biodiversity.

The main question analysed in this section is the sustainability impacts of intensifying biomass extraction to provide biomass for energy on soils, water and biodiversity. There are two main options:

- logging residues that are left to decay in the forest in stem-only harvests can instead be extracted
- small diameter trees from forest tending operations such as early thinnings can be used, reducing natural mortality compared to unmanaged stands.

The results reviewed in this section mostly come from experiments where baseline management practices were compared with intensive biomass extraction, such as whole-tree harvest. It should be noted that real management practice differs from the often extreme conditions in field experiments. Impacts of resource use intensification vary greatly across forest types, site conditions, and the feedstock extracted (slash, stumps, roundwood). The policy context and/or management strategy also matters, as intensive forest production on a limited area may allow the setting aside of larger areas, whereas moderately intense forest production with a smaller proportion of set-aside land would result in different local and regional impacts.

4.1 Impacts on soils and forest productivity

Negative impacts of logging residue harvest on soil nutrient pools and forest productivity have been documented, but they are mostly restricted to poor forest soil conditions and intensive harvest rates. On an extensive network of research sites covering the continental US, stem-only and whole-tree harvesting produced similar effects on biomass and nutrition. Long-term trials have also revealed that early-stage impacts could be temporary and that, by the end of the rotation, they could become small or negligible.

- Reviews have concluded that there are no consistent, unequivocal and universal effects of more intense biomass harvest on sites.
- Effects are site-specific, particularly for final felling, where wood production of the subsequent stand, apart from nutrient supply, also depends on other factors determining the regeneration success.

The effect of more intense biomass harvest in thinnings tends to induce growth reductions in the residual stands more often.

- Avoidance of nutrient-poor sites, monitoring changes and adopting practices like fertilization and strengthened regeneration efforts is likely to prevent detrimental effects.
- In energy wood thinnings, delimbing trees at the harvest site is advisable to mitigate the nutrient export from twigs and needles.

4.2 Impacts on water

Forest bioenergy systems are judged compatible with maintaining high-quality water supplies in forested catchments, as long as best management practices that are designed for environment and resource protection and include nutrient management principles are followed. Erosion and short-term water impacts can occur, but normal management operations appear not to cause long-term adverse impacts.

- Careful planning of forest operations when biomass harvest for bioenergy takes place near open waters is the key to maintaining water quality, as it is for any forest operation.

Nitrates and phosphates are the main nutrients driving eutrophication of surface waters. The removal of those two nutrients from a forest site increases substantially when logging residues are harvested. Increased biomass harvest therefore has the potential to alleviate nutrient leaching to surrounding waters. Fertilization to counteract growth reductions works in the opposite direction.

- A synthesis conclusion is that intense biomass harvest has limited effect on eutrophication.

Forest operations can cause the transport of bioavailable methyl mercury to surface waters, but there is no consistent evidence suggesting that intensified biomass harvest will increase that risk. Wood ash recycling is sometimes suggested as a measure to mitigate the reduced soil pH recovery following more intense biomass harvest and to mitigate growth reductions on peat soils.

4.3 Impacts on biodiversity

The lack of dead and decaying wood in managed forests is a key factor behind the decline of many forest species. Biomass removal for energy may decrease the amounts and diversity of dead or decaying wood that saproxylic species are dependent on for food and habitat. Logging residue harvesting can also affect non-saproxylic species through physical changes such as soil compaction and disturbance due to increased machine traffic, and chemical changes in soil and water properties.

Many site-level studies show a population decrease (or rather a lower population increase following harvest) for species which use logging residues as a food source and/or breeding habitat. Longer-term effects in the soil food web with population declines in predatory species have also been reported. This primarily includes common species, often disproportionally favoured in managed forest landscapes.

- Although viable populations are key for biodiversity, decreases in population sizes for common forest species do not provide strong evidence for high risks involved in logging residue harvest.
- What happens with rare species in the forest landscape, disfavoured by previous forest management, is more critical. A recent review concluded that clearcutting is the main cause of decline for such species and that logging residue harvest has small additional effects.

Studies have also shown that ground-dwelling openland species could be favoured by logging residue removal. That could add to biodiversity in a forested landscape, but probably not in an open landscape with patches of forests. Studies suggest that the quality of dead wood is more important for biodiversity than the quantity, with coarse wood like stemwood and stumps being more valuable than slash. The negative impacts of bioenergy extraction on dead wood-dependent species are thus larger with stump extraction, compared to extracting slash only. Concentrating the extraction to part of the landscape has a positive effect on rare and short-dispersing species. For less common tree species in the landscape, slash could also add to biodiversity and it is recommended to maintain appropriate amounts on site.

4.4 Impacts on landscape structure and disturbance risks

In certain regions biomass removal can also have positive impacts on habitat preservation and biodiversity, e.g. in traditional agroforestry landscapes or where the diversity values for species of concern depend on maintaining open land. Activities intending to control invasive species can also benefit from access to a bioenergy market.

A recent review of fuel-treatment studies from forests in the western US suggests that thinning plus burning reduced fire severity and tree mortality following wildfires.

- A biomass market would offer revenue for such biomass and could substantially reduce fire-induced carbon emissions. This could be a promising fire management tool in dry forests in southern Europe.

5. The role of bioenergy in climate change mitigation: a synthesis

Rather than debating the *carbon neutrality* of bioenergy, we should be concerned with the net climate change effects of bioenergy, assessed in the specific context where bioenergy policies are developed and bioenergy is produced. For forest bioenergy, this often means that studies should analyse bioenergy systems as components in value chains or production processes that also produce material products, such as sawnwood, pulp, paper and chemicals.

The science literature provides different views and conclusions on the climate impacts of forest bioenergy. This divergence appears to arise from different points of view on the context of the analysis and policy objectives. These have a strong influence on the formulation of research questions, as well as the methods and assumptions about critical parameters that are then applied in analyses, which in turn have a strong impact on the results.

- Studies analysing carbon flows in individual forest stands can provide useful information within the limited boundaries of the studies, e.g., allowing benchmarking of different pathways on a common scale. However, the definition of the time period for carbon balance accounting (i.e., when to start the clock) has a strong impact on the outcome. The studies can even be misleading as a model for the forest sector and its overall impact on climate. Their limited scope reduces their usefulness for informing policy making.
- The definition of reference scenarios (counterfactual) has a strong influence on the outcome of assessments. These scenarios should be clearly defined and justified in relation to the objectives of the study. It is essential that the results are carefully explained and interpreted correctly.

Information and knowledge from many scientific disciplines, applying a range of different methodologies, is needed to inform policy making for forest bioenergy. In particular, important results and insights can be gained from studies that use energy system (ES)/integrated assessment (IA) modelling, and from model-based assessments at larger landscape scales that use location-specific biophysical and socio-economic data, and consider management responses and market effects in parallel sectors. These modelling studies should employ several alternative scenarios for critical factors, including policy options and energy technologies.

Some findings are intuitive and have implications for policy:

- The efficiency of biomass conversion and the GHG displacement associated with the use of bioenergy and other forest products are very influential on the assessed mitigation value of forest bioenergy, regardless of feedstock.
- The mitigation value grows over time as the quantity of displaced GHG emissions accumulates. In this sense, bioenergy is more favourable when long time horizons are applied, although uncertainty also grows with longer time horizons.

It has been consistently shown with ES/IA models (summarised in the IPCC 5th Assessment Report) that bioenergy contributes significantly to the energy supply in most scenarios that meet ambitious climate targets. The results indicate that there is a high risk of failing to meet the long-term climate target without bioenergy.

Bioenergy feedstocks

The IPCC did not find any convergence between ES/IA modelling studies regarding the most cost-effective bioenergy deployment within the energy system, but lignocellulosic feedstocks dominate. Some conclusions can be drawn from other types of studies about feedstocks from forests:

- The bioenergy based on byproducts from forest industry processes (sawdust, bark, black liquor, etc.) is typically found to contribute positively to climate change mitigation also in the short-term.
- Tops and branches and biomass from some silviculture operations such as fire prevention and salvage logging are often found to support short-term mitigation.

The study results differ from each other the most concerning the GHG balance and mitigation value of using slowly decaying residues and roundwood as a feedstock for bioenergy.

- Studies that do not consider dynamic factors (e.g., forest management responses to bioenergy demand) may find that the use of small diameter trees and slowly decaying residues (e.g., stumps) does not contribute to net GHG savings in the short- or even medium-term (several decades). The use of larger diameter roundwood for bioenergy is sometimes found to not even deliver net GHG savings on multi-decade to century timescales.

- Studies that include parallel sectors and employ biophysical-economic modelling for larger landscapes report mixed results. Results are more favourable if the increased forest biomass demand also triggers investments that increase forest area and productivity, which in turn result in carbon gains on the landscape level.
- Certain parameter assumptions have a large influence on the outcome, for example, the GHG displacement efficiency.

Forest bioenergy is not a single entity, but includes a large variety of sources and qualities, conversion technologies, end products and markets. Consequently, its technological and economic efficiencies as well as climate mitigation value will vary.

Forest bioenergy should be considered as one of several products in a value chain or production process that also includes material products, such as sawnwood, pulp, paper and chemicals. The forest product portfolio may include bioenergy products that, according to some studies, do not provide near/medium-term GHG savings. But it is not certain that excluding these feedstocks from bioenergy markets will result in a new product portfolio with a higher contribution to climate change mitigation in the short and longer-term.

Regarding the need to balance short-term GHG targets with strategies that pursue long-term temperature stabilization goals, we caution that a strong focus on short-term GHG targets may result in decisions that make the longer-term objectives more difficult to meet. For example, a decision to prioritize carbon sequestration and storage in forests managed for wood production may help in meeting near-term GHG targets. However, this could mean an end-point where forests store more carbon but have a lower capacity for producing bioenergy and other forest products. The lack of viable alternatives and strategies towards long-term emissions targets implies a prolonged lock-in and continuous investments in fossil technologies. Events such as storms, insect infestations and fires can cause forest damage and losses of some of the carbon that was sequestered into forests as compensation for GHG emissions, which can further hamper the fulfillment of longer-term objectives.

Scientific gaps

There are aspects which science needs to address:

- Most current studies focus on greenhouse gases, despite the fact that the effect of other climate forcers can be significant. The effects of all climate forcers influenced by vegetation cover and forest management should ideally be included.
- The coupling of energy systems and land use, in particular the terrestrial carbon sink (dominated by forests remaining forest), can be further improved. For example, when developing a new generation of global climate scenarios, a better reflection of the effects of forest management should be a priority, especially for scenarios with a high share of bioenergy in the energy mix.
- The effects of climate change on forest growth and soil carbon are uncertain. Climate change is associated with risks, such as fires, storms, diseases and insect outbreaks that could greatly affect the carbon stock in the forest. Capacity for risk management and salvage logging following events such as storm fellings depends on whether forests are managed for wood production. These aspects need to be further addressed in future studies since they have strong implications for the attractiveness of different forest management strategies.

6. Policy implications

Forest carbon neutrality is an ambiguous concept and its debate distracts from the broader and much more important question: how European forests and the associated industries can contribute to climate change mitigation while serving many other functions. The Paris Agreement and EU climate policy set targets that have generally been acknowledged to be very ambitious, but necessary. Reducing GHG emissions by phasing out the technologies and infrastructures that cause fossil carbon emissions is one of today's most important challenges. Simultaneously meeting this and the other objectives of the EU Energy Union requires a focus on the energy system as a whole, to ensure correct conditions for the necessary large-scale energy transition.

Policies and actions put in place to drive changes have to be realistic and possible to implement, otherwise they will not enable us to reach the climate targets. It is increasingly acknowledged that climate policy, and policy-relevant research, cannot be developed in "sectoral silos" any more, but have to seek synergies with other societal goals.

Policies should recognise the important roles that European forests and forest industries play in the EU GHG balance: they sequester and store carbon and displace fossil fuels and other products that would otherwise cause GHG emissions. **A holistic perspective is needed to develop concepts and frameworks for a portfolio of societal objectives**, including climate mitigation and environmental protection, bioeconomy, energy security, public health, rural policy, and forest-based recreation.

There will always be trade-offs between different objectives, but the more synergies are found with climate mitigation policies and other forest sector objectives, the more likely it is that ambitious climate policies can be implemented and forest sector actors follow them in practice.

- Assessing GHG balances and the climate effects of forest bioenergy is essential for informed policy development and implementation. The topic can be approached from different points of view, and methodological decisions and parameter assumptions have a strong influence on the outcome. Results must be interpreted with this in mind. **Involving policymakers and stakeholders in defining policy-relevant research questions (e.g., in defining objectives, scope and selecting reference scenarios) increases the likelihood that results are relevant, interpreted correctly, and useful in the policy development process.**

- Forest bioenergy systems can be effective means for displacing fossil fuels. Supply chain energy use is typically low and the associated GHG emissions are of minor importance for the total GHG balance of bioenergy production. **To realise high GHG savings, it is critical that policies and regulations create a situation where the promotion of bioenergy and other non-fossil energy options leads to fossil fuel displacement rather than competition among non-fossil options.** The impact that bioenergy production has on decreasing investments in technologies and infrastructure that rely on fossil fuels is also important, since this has implications for future emissions.

- How will incentives (policies) for bioenergy affect the state of forests and the forest sector's contribution to climate change mitigation through carbon sequestration, carbon storage and displacement of fossil fuels and other products that would otherwise cause GHG emissions? The answer varies. Changes in forest management that take place due to bioenergy demand depend on factors such as forest product markets, forest type, forest ownership and the character and product portfolio of the associated forest industry. How the forest carbon stock and biomass output are affected by these changes in turn depends on the characteristics of the forest ecosystem. **Consequently, policymakers need to consider policies in the context of the regional forest and energy sector. One-size-fits-all policies are unlikely to be optimal.**

- The impact of bioenergy implementation on net GHG emission savings is context- and feedstock-specific due to the fact that many important factors vary across regions and time. **A generic categorisation system which specifies only some forest biomass types as eligible bioenergy feedstocks may prevent the effective management of forest resources to economically meet multiple objectives, including climate change mitigation. There is a risk that bureaucracy and costly administration discourage actors from investing in bioenergy.**

- Cascading use, which makes sense as a general rule, should not be a straightjacket. Applying a cascading principle that promotes the use of forest biomass for wood products ahead of energy may not always deliver the greatest climate or economic benefits. **It is important that cascading is applied with flexibility, and considering what is optimal for the specific regional circumstances (feedstock, industry and energy system setting).**

- **Knowledge and experiences of management practices from European regions where biomass utilization has been a long-lasting practice should be shared and discussed. This would help to facilitate the development of locally adopted management guidelines in other regions.** Best practices, as well as failures, provide important insights. However, forest area, biome, ownership, income and employment generation, and the objectives and culture related to forests differ significantly between Member States, and even between regions. Regionally tailored guidelines are also needed.

- **The use of forest biomass for energy is likely to make economic and environmental sense if accompanied by a package of measures to promote best practices in forest management for climate change mitigation.** These should consider the diversity of forest types and management systems across Europe, ensure biodiversity safeguards, and aim to balance all forest functions. With the right incentives, the EU forest sector can make an important contribution to climate change mitigation while also serving other objectives.

Glossary

Bioenergy feedstocks: biomass utilized for bioenergy

Biogenic carbon: carbon derived from biomass.

Carbon sequestration: the addition of carbon to a carbon pool e.g, a forest.

Carbon stock: the mass of carbon in a carbon pool.

Carbon pool: a component of the climate system, other than the atmosphere, which has the capacity to store, accumulate or release carbon e.g., oceans, soils and forests.

Eutrophication: enrichment of water body with nutrients, such as through runoff water containing fertilizer, and which may cause impacts such as algal blooming.

GHG displacement efficiency: in the context of this report, GHG displacement efficiency reflects the amount of GHG emissions avoided per unit of bioenergy or biomass used. It can also be expressed in terms of e.g., hectare of forest used or euro spent.

Salvage wood: wood extracted following forest disturbances from e.g., fire, wind, pests and diseases.

Saproxylic species: organism dependent on dead and decaying wood.

Sink: any process, activity or mechanism that removes a greenhouse gas, an aerosol, or a precursor to a greenhouse gas from the atmosphere.

Slash: biomass debris generated during logging operations e.g., branches, tops and small-diameter trees.

Source: any process, activity or mechanism that releases a greenhouse gas, an aerosol or a precursor to a greenhouse gas into the atmosphere.

Wood increments: increase in stem volume over a specified period.

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We are living in a time of accelerated changes and unprecedented global challenges: energy security, natural resource scarcity, biodiversity loss, fossil-resource dependence and climate change. Yet the challenges also demand new solutions and offer new opportunities. The cross-cutting nature of forests and the forest-based sector provides a strong basis to address these interconnected societal challenges, while supporting the development of a European bioeconomy.

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