Received: 7 March 2020 | Accepted: 16 April 2021

DOI: 10.1111/gcbb.12844

RESEARCH REVIEW

GCB-BIOENERGY Open Access BIOPRODUCTS FOR A SUSTAINABLE BIOECONOMY WILEY

Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy

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This manuscript is co-authored by employees (Keith L. Kline and Patrick Lamers) of the Alliance for Sustainable Energy, LLC, the manager and operator of the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308 and UT-Battelle, LLC, the manager and operator of Oak Ridge National Laboratory (ORNL) under contract DE-AC05-00OR22725 with US DOE. By accepting the article for publication, the publisher acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this manuscript, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

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Funding information
US Department Energy Bioenergy Technologies Office, Grant/Award Number: EE0007088, DEAC36-08GO28308 and DE-AC05-00OR22725; Koneen Säätiö; IEA Bioenergy Technology Collaboration Programme

Abstract

The scientific literature contains contrasting findings about the climate effects of forest bioenergy, partly due to the wide diversity of bioenergy systems and associated contexts, but also due to differences in assessment methods. The climate effects of bioenergy must be accurately assessed to inform policy-making, but the complexity of bioenergy systems and associated land, industry and energy systems raises challenges for assessment. We examine misconceptions about climate effects of forest bioenergy and discuss important considerations in assessing these effects and devising measures to incentivize sustainable bioenergy as a component of climate policy. The temporal and spatial system boundary and the reference (counterfactual) scenarios are key methodology choices that strongly influence results. Focussing on carbon balances of individual forest stands and comparing emissions at the point of combustion neglect system-level interactions that influence the climate effects of forest bioenergy. We highlight the need for a systems approach, in assessing options and developing policy for forest bioenergy that: (1) considers the whole life cycle of bioenergy systems, including effects of the associated forest management and harvesting on landscape carbon balances; (2) identifies how forest bioenergy can best be deployed to support energy system transformation required to achieve climate goals; and (3) incentivizes those forest bioenergy systems that augment the mitigation value of the forest sector as a whole. Emphasis on short-term emissions reduction targets can lead to decisions that make medium- to long-term climate goals more difficult to achieve. The most important climate change mitigation measure is the transformation of energy, industry and transport systems so that fossil carbon remains underground. Narrow perspectives obscure the significant role that bioenergy can play by displacing fossil fuels now, and supporting energy system transition. Greater transparency and consistency is needed in greenhouse gas reporting and accounting related to bioenergy.

KEYWORDS

energy system transition, forest carbon stock, forest management, greenhouse gas accounting, landscape scale, reference system

1 | INTRODUCTION

Many countries have included support for bioenergy in their energy and climate policies, as a component of national strategies to curb greenhouse gas (GHG) emissions. However, the scientific literature shows wide variation in quantitative assessments as well as perspectives concerning the climate change mitigation effects of bioenergy, including when derived from forest biomass. Many studies have found that forest bioenergy can contribute to climate change mitigation, especially in the medium to long term (e.g. Creutzig et al., 2015; Dwivedi et al., 2019; Favero et al., 2017, 2020; Gustavsson et al., 2017, 2021; Kilpeläinen et al., 2016; Kraxner et al., 2003; Lundmark et al., 2014; Marland & Schlamadinger, 1997; Nabuurs et al., 2017; Smyth et al., 2014; Vance, 2018). Other studies contest the climate benefits of forest bioenergy, especially in the short term (e.g. Booth, 2018; Brack, 2017; Hudiburg et al., 2011; Norton et al., 2019; Pingoud et al., 2016; Schlesinger, 2018; Soimakallio, 2014; Sterman et al., 2018). Specific areas of concern include 'carbon neutrality' assumptions, climate impacts of the growing international biomass pellet trade, timing of mitigation benefits and the treatment of bioenergy in the United Nations Framework Convention on Climate Change (UNFCCC) rules for compiling national GHG inventories (Mather-Gratton et al., 2021). Diverging conclusions can arise from studies that consider different research questions and that use different methodologies and scope, yielding diverging results.

In this paper, we examine debated aspects related to climate impacts of forest bioenergy, in applications including heat production, electricity generation and transport. We identify factors that are relevant to understanding the climate effects of forest bioenergy, and misconceptions that can lead to conclusions that exaggerate or underestimate the effects. We discuss aspects that pertain to analysing the climate effects of forest bioenergy systems (Sections 2–11) and approaches used in GHG inventory reporting and accounting for forest bioenergy (Section 12). Our objective is to reduce confusion arising from publication of diverging studies on forest bioenergy, to inform policy development, business decisions and the public debate on bioenergy.

2 | BIOENERGY IN ENERGY SYSTEM TRANSITIONS

Global energy supply currently depends heavily on fossil fuels, with coal, oil and natural gas providing 84.3% of global primary energy use in 2019 (BP, 2020). The use of fossil fuels is projected to increase in absolute amount, despite an expected increase in the share of renewable energy sources (IEA, 2019). The most important climate change mitigation measure is the transformation of energy, industry and transport systems so that fossil carbon remains underground (IPCC, 2014, 2018; Johnsson et al., 2019; Peters et al., 2020; Tong et al., 2019). This will require a combination of measures and technologies, likely to include energy efficiency and conservation; carbon capture and storage (CCS); replacing fossil fuels with biomass-based fuels, hydrogen and e-fuels from renewable electricity; as well as non-thermal technologies such as hydro, wind and solar power supporting, inter alia, electrification of the transport sector (IPCC, 2018).

Biomass-based electricity can provide balancing power needed to maintain power stability and quality as the contribution from solar and wind power increases (Arasto et al., 2017; Lenzen et al., 2016; Li et al., 2020), complementing other balancing options such as battery storage, reservoir hydropower, grid extensions and demand-side management (Göransson & Johnsson, 2018).

Beyond its value as a dispatchable resource for electricity generation, biomass is an important option for renewable heating in buildings and industrial processes. In 2019, bioenergy contributed almost 90% of renewable industrial heat consumption and two-thirds of the total modern renewable heating and cooling in buildings and industrial processes (IEA, 2020; IRENA/IEA/REN21, 2020). It is one of the options available to reduce emissions from heavy industries such as iron and steel production (Mandova et al., 2018, 2019) and cement production (IEA, 2018). Furthermore, carbon-based transportation fuels will remain important in the coming decades, as electrification of the transport sector will take time (IEA-AMF/IEA Bioenergy, 2020). Biofuels can contribute to reducing fossil fuel use and associated GHG emissions while there remain vehicles that use carbon-based fuels. In the longer term, biofuels will likely be used in sectors where the substitution of carbon-based fuels is difficult, such as long-distance aviation and marine transportation. As discussed in the following sections, the impact on atmospheric GHG concentrations will depend on how biomass use for bioenergy influences the land carbon stock over time.

In the Intergovernmental Panel on Climate Change (IPCC) Special Report on limiting warming to 1.5°C (SR1.5), the contribution of bioenergy to mitigation pathways is substantial, increasing to a median value of 27.3% of global energy supply in 2050 across the full range of 1.5°C pathways analysed (Rogelj et al., 2018). Various bioenergy options contribute to these mitigation pathways, including substantial use of biomass for heat and liquid fuel applications (Fuss et al., 2018). Biomass use for energy may also be combined with carbon capture and storage (BECCS) to provide carbon dioxide removal (CDR) from the atmosphere. Reaching global net zero, or net negative, GHG emissions will require CDR, to offset residual emissions in 'hard-to-abate' sectors. The SR1.5 found that most scenarios that achieve climate stabilization at 1.5 or 2°C warming require substantial deployment of CDR technologies, including BECCS (IPCC, 2018; Roe et al., 2019).

The finding from the global integrated assessment modelling studies included in the SR1.5 report, that bioenergy commonly has important roles in 1.5 or 2°C pathways, is not unanimously supported by studies that apply a more restricted temporal and spatial scope and use other methodological approaches than integrated assessment modelling to quantify GHG balances and climate effects. One explanation is that different methodologies capture different aspects of mitigation and systems transition. For example, indirect effects and substitution are not relevant in integrated assessment modelling, yet they are important considerations in life cycle assessment (LCA). Conversely, LCA and carbon accounting frameworks do not capture aspects such as inertia in energy/transport/industry infrastructure, and economic competition among mitigation options.

3 | 'CARBON NEUTRALITY' OF BIOENERGY

Bioenergy is often characterized as being 'carbon neutral' based on the observation that the biogenic carbon released when biomass is combusted was previously sequestered as the plants grew, and will be sequestered again during regrowth. However, 'carbon neutrality' is an ambiguous term that is used differently in different contexts (Berndes et al., 2016). Forest biomass is sometimes said to be carbon neutral if derived from a forest system in which carbon stocks are stable or increasing. However, forest bioenergy should not be *assumed* to be carbon neutral by default. As described in methodology developed over 20 years ago for the evaluation of climate effects of bioenergy (Schlamadinger et al., 1997), both biogenic carbon flows and GHG emissions associated with the life cycle of the bioenergy system need to be considered (Section 9), and GHG emissions associated with the bioenergy system need to be compared with GHG emissions in a realistic reference situation (counterfactual scenario) where energy sources other than bioenergy are used (Section 8).

Furthermore, climate effects of forest bioenergy also depend on how bioenergy incentives influence forest management, which in turn depends on biophysical conditions and forest characteristics, prevailing forest management practices, the character and product portfolio of the associated forest industry, alternative land use options and land owners' expectations of forest product markets (Abt et al., 2012; Buchholz et al., 2019; Eggers et al., 2014; Johnston & van Cooten, 2016; Levers et al., 2014; Nepal et al., 2019; Nielsen et al., 2020; Sedjo & Tian, 2012; Tærø et al., 2017; Trømborg & Solberg, 2010). Studies that include economic factors and consider the diversity and dynamic characteristics of forests and the wood products sector reveal that the effects of forest bioenergy incentives on the development of forest carbon stocks can be positive or negative, depending on the situation and management response (Baker et al., 2019; Cintas, Berndes, Hansson, et al., 2017; Costanza et al., 2017; Daigneault et al., 2012; Dale et al., 2017; Duden et al., 2017; Dwivedi et al., 2019; Gustavsson et al., 2017; Hudiburg et al., 2011; Kallio et al., 2013; Khanna et al., 2017; Kim et al., 2018; Law et al., 2018; Nabuurs, Delacote, et al., 2017; Pingoud et al., 2016; see also Section 6). Thus, the possible trade-off between storing carbon in the forest and harvesting the forest for wood products needs to be considered, along with other objectives, when strategies for climate change mitigation are developed (Berndes et al., 2018; Kurz et al., 2016). The concept of climate-smart forestry is an example of a strategy recognizing this. It seeks to integrate climate objectives across the value chain from forest to wood products and energy, with the aims to (i) sustainably increase forest productivity; (ii) reduce GHG emissions and remove carbon from the atmosphere; and (iii) support adaptation and build resilience to climate change (Nabuurs, Delacote, et al., 2017; Nabuurs et al., 2019).

The treatment of bioenergy in UNFCCC reporting is sometimes described as 'assuming carbon neutrality' because CO_2 emissions from bioenergy are reported as zero in the energy sector. This may appear to be an inaccurate simplification; however, this approach is necessary to avoid double counting, because all carbon emissions associated with forest harvest are already counted in the 'Land use, land-use change and forestry' sector (see Section 12).

4 | PAYBACK TIME AND CLIMATE TARGETS

If forest management is adapted to provide biomass for energy in addition to other forest products, this influences the magnitude and timing of carbon sequestration and emissions in the forest, which in turn influences the scale and timing of the climate effect (Cowie et al., 2013). Concepts such as 'carbon debt' and 'payback time' have been raised in the context of land use change emissions associated with expansion of energy crops (Fargione et al., 2008; Gibbs et al., 2008), and also in relation to forest bioenergy, where the magnitude and timing of forest carbon sequestration and emissions is the concern. Wide variation in published estimates of payback time for forest bioenergy systems reflects both inherent differences between these systems and different methodology choices (Bentsen, 2017; Buchholz et al., 2016; Cintas et al., 2016; Hanssen et al., 2017; Lamers & Junginger, 2013; Ter-Mikaelian et al., 2015; Ter-Mikaelian, Colombo, Lovekin, et al., 2015). Critical methodology decisions include the definition of spatial and temporal system boundaries (see Sections 7 and 11) and reference (counterfactual) scenarios (see Section 8).

Some authors (e.g. Booth, 2018; Brack, 2017; Norton et al., 2019) propose that forest bioenergy should only receive support under renewable energy policies if it delivers net reduction in atmospheric CO_2 within about a decade, due to the urgent need to reduce GHG emissions. However, besides the subjectivity of payback time analysis raised above, applying a 10-year payback time as a criterion for identifying suitable mitigation options is inconsistent with the long-term temperature goal of the Paris Agreement, which requires that a balance between emission and removals is reached in the second half of this century (Tanaka et al., 2019). Furthermore, it reflects a view on the relationship between net emissions, global warming and climate stabilization that contrasts with the scenarios presented in the SR1.5: The report shows many alternative trajectories towards stabilization temperatures of 1.5 and 2°C warming that reach net zero at different times and require different amounts of CDR (IPCC, 2018). The IPCC report did not determine that individual mitigation measures must meet specific payback times, but rather that a portfolio of mitigation measures is required that together limits the total cumulative global anthropogenic emissions of CO_2. Furthermore, applying a payback time criterion when evaluating forest bioenergy, and determining the contribution of bioenergy to meeting the Paris Agreement temperature goal, is complicated by the fact that bioenergy systems operate within the biogenic carbon cycle (see Section 3), which implies a fundamentally different influence on atmospheric CO_2 concentrations over time compared to fossil fuel emissions (Cherubini et al., 2014).

The IPCC emphasizes the need for transformation of all sectors of society to achieve the 'well below 2°C' goal of the Paris Agreement (IPCC, 2018). This will entail technology and infrastructure development to generate a portfolio of emissions reduction and CDR strategies. Such investments may include, for example, scaling-up battery manufacturing to support electrification of car fleets, building rail infrastructure and district heating networks and changing the management and harvesting of forests and other lands to provide biomass for biobased products. The mobilization of mitigation options such as these can initially increase net GHG emissions while providing products and services with low, neutral or net negative emissions in the longer term (Cuenot & Hernández, 2016; Hausfather, 2019). The contribution of specific options to mitigation will depend on technology readiness level, costs, resource availability and inertia of existing technologies and systems. Options assessed as having low net GHG emissions per unit energy provided may be restricted by immature development, high cost or dependence on new infrastructure. Other options, including bioenergy, have greater near-term mitigation potential due to being compatible with existing infrastructure and cost competitive in many applications.

Strategy development needs to recognize the complementarity of many mitigation options, and balance trade-offs between short- and long-term emissions reduction objectives. Critically, strategies based on assessments of individual technologies in isolation from their broader context, and that apply a strong focus on emissions reduction in the short term, can make long-term climate goals more difficult to achieve (e.g. Berndes at al., 2018; Smyth et al., 2014). Mitigation options available in the near term need to be evaluated beyond the direct effect on GHG emissions, considering also their influence on systems transition and implementation of other mitigation options (see Section 2).

Risks related to climate tipping points are sometimes raised in relation to the timing of GHG savings: crossing thresholds, for example, associated with forest dieback or thaw of permafrost, could lead to large, irreversible changes in the global climate system (e.g. Grimm et al., 2013). A recent study found a low probability of crossing a tipping point in the global climate system if warming does not exceed 2°C (Fischer et al., 2018). Also, critical threshold values and irreversibility of specific tipping points are uncertain (Collins et al., 2013), and the universal application of critical threshold values is questioned in relation to ecosystem function (Hillebrand et al., 2020). Nevertheless, uncertainties and risks associated with climate tipping points are additional considerations in evaluations of different trajectories towards temperature stabilization. Rather than connecting the timing of GHG savings to specific but uncertain climate tipping points, evaluation of bioenergy options is preferably based on a holistic assessment that considers how bioenergy can contribute to resilience and adaptation to changes in climate along with other environmental stressors.

5 | EMISSIONS OF BIOGENIC VERSUS FOSSIL CARBON

Some scientific papers state that burning biomass for energy produces higher emissions of CO_2 per kWh of electricity at the smoke-stack compared with burning coal due to lower energy density of wood and/or less efficient conversion to electricity (e.g. Brack, 2017; Norton et al., 2019; Searchinger et al., 2018; Sterman et al., 2018; Walker et al., 2013), leading to the assertion that 'biomass is worse for the climate than coal' (Johnston & van Kooten, 2015; McClure, 2014; PFPI, 2011; RSBP, 2012; Tsanova, 2018; Yassa, 2017). However, this interpretation neglects several significant factors.

First, stack emissions will not necessarily increase when there is a shift to biomass fuels. The CO_2 emission factor (g CO_2 per GJ of fuel) is solely dependent on the chemical composition of the fuel. Wood and coal have similar CO_2 emission factors, as the ratio of heating values between the two fuels is similar to the ratio of carbon content (ECN, undated; Edwards et al., 2014; US EPA, 2018; van Loo & Koppejan, 2008). Where biomass is co-fired with coal in large power plants, the conversion efficiency may decrease a few percent, although there is usually no significant efficiency penalty when the co-firing ratio is below 10% (van Loo & Koppejan, 2008). Conversion efficiencies depend on fuel properties including moisture content and grindability in addition to heating value (Mun et al., 2016; Shi et al., 2019; Zuwała & Lasek, 2017). For low rank coal, biomass co-firing (especially torrefied biomass) can increase the boiler efficiency and net power plant efficiency (Liu et al., 2019; Thrän et al., 2016).

Smaller biomass-fired plants can have lower electric conversion efficiency than large coal-fired plants, but as they are typically combined heat and power plants, they also displace heat production from other sources, that could otherwise have generated fossil fuel emissions (e.g. Madsen & Bentsen, 2018). Large dedicated biomass units (converted from coal) can operate with roughly the same level of thermal efficiency as delivered historically from coal (Koss, 2019). For example, stack emissions from the Drax power station in the United Kingdom have been independently estimated at 2% higher for biomass than coal (SIG, 2017).

Second, and much more important, comparing GHG emissions from biomass and fossil fuels at the point of combustion ignores the fundamental difference between fossil fuels and biomass fuels. Burning fossil fuels releases carbon that has been locked up in the ground for millions of years. Fossil fuel emissions transfer carbon from the lithosphere to the biosphere–atmosphere system, causing temperature increases that are irreversible on timescales relevant for humans (Archer et al., 2009; Solomon et al., 2009; Ter-Mikaelian, Colombo, & Chen, 2015). In contrast, bioenergy operates within the biosphere–atmosphere system, and burning biomass emits carbon that is part of the continuous exchange of carbon between the biosphere and the atmosphere (Smith et al., 2016). Therefore, the effect on the atmospheric CO_2 concentration of switching from fossil fuels to biomass cannot be determined by comparing CO_2 emissions at the point of combustion (Nabuurs, Arets, et al., 2017; Schlamadinger et al., 1997). To do so essentially equates biomass harvest with deforestation to establish another land use, such as agriculture or urban infrastructure, causing permanent transfer of carbon from land to atmosphere.

6 | SOURCING BIOMASS FOR BIOENERGY, AND EFFECTS ON FOREST MANAGEMENT AND FOREST CARBON BALANCE

The source of forest biomass is a key determinant of climate change effects of bioenergy (Matthews et al., 2018). Concerns have been raised that bioenergy demand could lead to widespread harvest of forests solely for bioenergy, causing large GHG emissions and forgone carbon sequestration (Brack, 2017; Norton et al., 2019; Searchinger et al., 2018). However, long-rotation forests are generally not harvested for bioenergy products alone: Biomass for bioenergy is usually a by-product of sawlog and pulpwood production for material applications (Dale et al., 2017; Ghaffariyan et al., 2017; Spinelli et al., 2019; Figure 1). Logs that meet quality requirements are used to produce high-value products such as sawnwood and engineered wood products such as cross laminated timber, which can substitute for more carbon-intensive building materials such as concrete, steel and aluminium

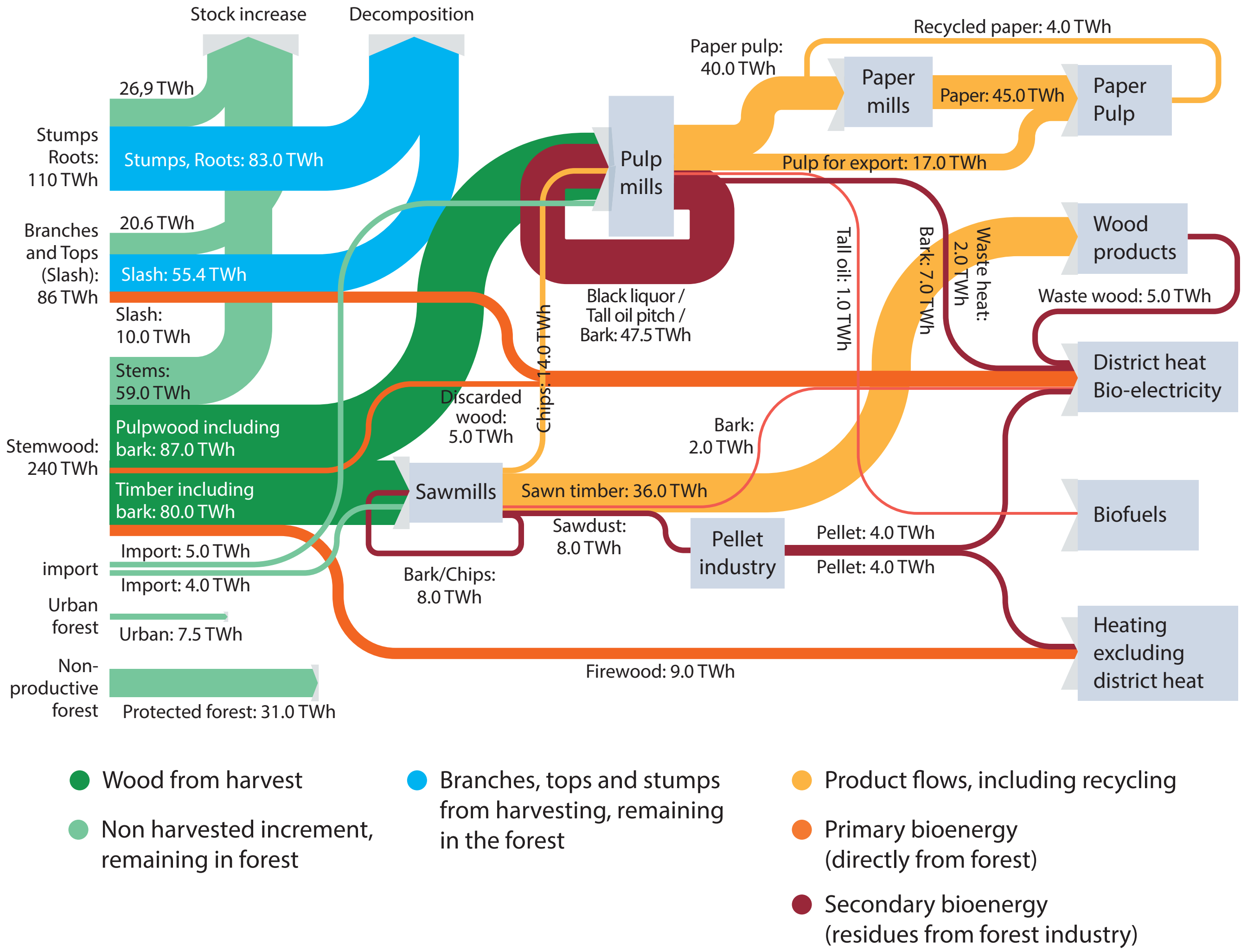

FIGURE 1 Biomass and energy flows from Swedish forest
Source: IRENA, 2019

(Leskinen et al., 2018). Residues from forestry operations (tops, branches, irregular and damaged stem sections, thinnings) and wood processing residues (e.g. sawdust, bark, black liquor) are used for bioenergy (Kittler et al., 2020), including to provide process heat in the forest industry (Hassan et al., 2019). These biomass sources have high likelihood of reducing net GHG emissions when substituting fossil fuels (Hanssen et al., 2017; Matthews et al., 2018), and their use for bioenergy enhances the climate change mitigation value of forests managed for wood production (Cintas, Berndes, Hansson, et al., 2017; Gustavsson et al., 2015, 2021; Schulze et al., 2020; Ximenes et al., 2012). Part of the forest biomass used for bioenergy comprises roundwood (also referred to as stemwood), such as small stems from forest thinning. For example, roundwood was estimated to contribute around 20% of the feedstock used for densified wood pellets in the United States in 2018 (US EIA, 2019).

The capacity of the world's managed forests to sustainably supply biomass is limited, both in terms of rate of increase and absolute potential, and lower than the future biomass demand in many scenarios that achieve climate stabilization at 1.5 or 2°C warming. The GHG consequences of increasing the biomass supply depend on how this is done, as there can be synergies and trade-offs between forest growth rate, forest carbon stocks and production of biomass and other wood products (e.g. Wang et al., 2015). The critical question is how the net GHG emissions change when the forest sector devises management approaches that enable biomass production for energy in conjunction with supply of sawlogs and pulpwood. One option is to use more residues from forestry operations and wood processing (Egnell & Björheden, 2013). Another option could involve increase in the harvest of roundwood, which could diminish the mitigation value if forest carbon stocks and forest sink strength are decreased, such as due to a rapid increase in roundwood harvest rates (Agostini et al., 2014; Kallio et al., 2013; Olesen et al., 2015; Pingoud et al., 2018).

Expectation of increasing biomass demand could stimulate establishment of new forests to secure future wood production, which would provide additional carbon storage, and motivate management changes in existing forests to enhance growth (e.g. improved site preparation, faster growing tree species, fertilization), which could improve the climate outcomes from forests managed for biomass and other products (Favero et al., 2020; Galik & Abt, 2012; Kauppi et al., 2020; Laganière et al., 2017). For example, in Sweden, which was widely deforested in the 1800s, forest expansion together with intensive forest management has doubled the standing volume of forests over the last 100 years, at the same time as annual harvest has increased (Figure 2). This outcome was supported by forest policy that ensures harvest does not exceed growth, and forests are regenerated after harvest (Eriksson et al., 2018). A similar trend of increased forest carbon stock with simultaneous increase in harvest has occurred in Denmark (Nord-Larsen et al., 2020), Finland (Luke, 2017) and in the southeast United States (Aguilar et al., 2020).

The existence of a bioenergy market can improve the financial viability of forest thinning (Cintas et al., 2016), which stimulates production of high-quality timber with the aforementioned climate benefits from product substitution. In addition, extracting (otherwise unutilized) lower quality biomass (e.g. resulting from pest and disease impacts or overstocking) can reduce the frequency and severity of wildfires and associated loss of forest

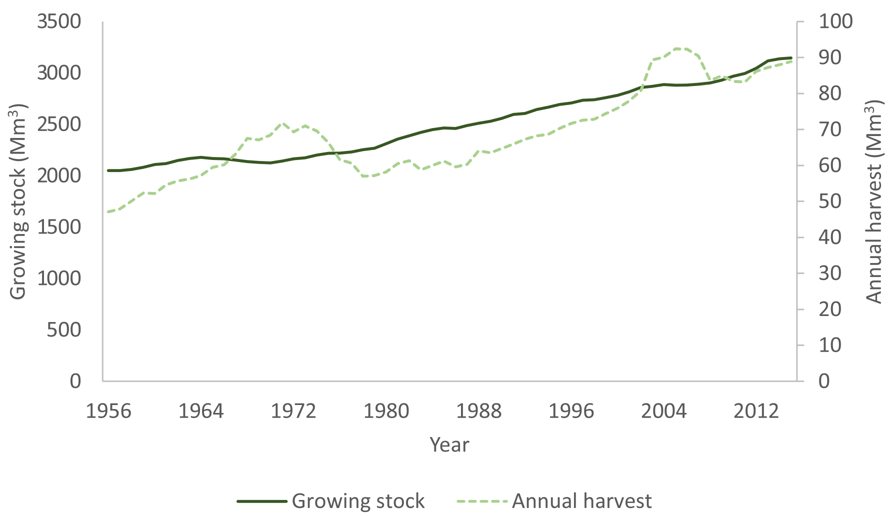

FIGURE 2 Forest stock and annual harvest in Sweden. Growing stock and annual harvest on managed forest land in Sweden 1955–2015 (5-year moving average). Excl. national parks, nature reserves and nature protection areas. The peaks in harvest levels coincide with major storm damage in 1969, 2005 and 2007, followed by bark beetle damage and consequently salvage logging

Source: Swedish National Forest Inventory, Swedish Forest Agency Swedish University of Agricultural Sciences carbon and release of non-CO_2 GHGs, further enhancing the climate benefit (Agee & Skinner, 2005; Evans & Finkral, 2009; Mansuy et al., 2018; Regos et al., 2016; Sun et al., 2018; Verkerk et al., 2018). On the other hand, the mitigation value of forest bioenergy could be diminished if policies supporting bioenergy reduce timber availability for material applications (Favero et al., 2020), thereby reducing the wood products pool and increasing use of GHG-intensive materials; if excessive removal of residues reduces forest productivity (Achat et al., 2015; Helmisaari et al., 2011); or if reforestation displaces food production and results in deforestation elsewhere to provide new cropland.

In some situations, such as high latitudes where forest productivity is very low, greater abatement may result from retaining and enhancing forest carbon stocks than harvesting forests for wood products including bioenergy, especially if the GHG savings from bioenergy use are small (Marland & Schlamadinger, 1997; Schlamadinger & Marland, 1996a). The choice to manage for in-forest carbon sequestration alone or for wood products should also consider a broader range of impacts beyond climate, to identify and manage trade-offs and synergies such as between carbon sequestration and biodiversity (Kline & Dale, 2020).

The argument has been made that bioenergy contributes to climate change mitigation only if obtained from 'additional' biomass, defined as biomass grown in excess of that which would have grown anyway or residues that would otherwise decompose, precluding biomass obtained from existing forests if there is a decline in forest carbon stock (Haberl et al., 2012; Schlesinger, 2018; Searchinger et al., 2009). However, using forest biomass for bioenergy will give a climate benefit if the stock reduction is smaller than the net GHG savings from displacement of fossil fuels. The biomass produced cumulatively across subsequent rotations can far exceed the biomass produced in the no-bioenergy scenario, thus constituting 'additional biomass', delivering cumulative net GHG savings that exceed the GHG cost of forest carbon stock reduction (Cowie et al., 2013). This is particularly the case where active management maintains high forest growth (i.e. a strong carbon sink), allowing sustained harvesting.

7 | STAND VERSUS LANDSCAPE SCALE ASSESSMENT

Some studies of forest bioenergy consider carbon dynamics at the individual stand level (e.g. Cherubini et al., 2011; Holtsmark, 2015; Pingoud et al., 2012; Schlamadinger & Marland, 1996b; Walker et al., 2013). Stand-level assessments represent the forest system as a strict sequence of events (e.g. site preparation, planting or natural regeneration, thinning and other silvicultural operations, final felling). Results are strongly influenced by the starting point: commencing the assessment at harvest shows upfront emissions, followed by a CO_2 removal phase, giving a delay before forest bioenergy contributes to net reductions in atmospheric CO_2, particularly in long-rotation forests. This delay has been interpreted as diminishing the climate benefit of forest bioenergy (e.g. Holtsmark, 2013; Norton et al., 2019; Sandbag, 2019). In contrast, commencing at the time of replanting shows the opposite trend: a period of CO_2 removal during forest growth, followed by a pulse emission returning the CO_2 to the atmosphere. Thus, stand-level assessments give inconsistent results and can be misleading as a basis to assess climate impacts of forest systems (Berndes et al., 2013; Cintas, Berndes, Cowie, et al., 2017; Peñaloza et al., 2019). Furthermore, when considering only the stand level, it is difficult to identify whether the forest is sustainably managed or subject to unsustainable practices that cause declining productive capacity and decreasing carbon stocks.

Note that we are referring to even-aged stands, harvested by clear-cutting at the rotation age. This management approach differs from selective logging, also known as continuous cover forestry. The temporal carbon stock fluctuations at stand level are less extreme under selective logging, but the same considerations apply when assessing the climate effects of forest bioenergy.

The alternative to stand level is landscape-scale assessment, that considers the total area of managed forests. Stand- and landscape-level assessments respond to different questions. Stand-level assessment provides detailed information about plant community dynamics, growth patterns and interactions between carbon pools in the forest. But the stand-level perspective overlooks that forests managed for wood production generally comprise a series of stands of different ages, harvested at different times to produce a continuous supply of wood products. Across the whole forest landscape, that is, at the scale that forests are generally managed, temporal fluctuations observed at stand level are evened out and the forest carbon stock fluctuates around a trend line that can be increasing or decreasing, or roughly stable, depending on the age class distribution and weather patterns (Cowie et al., 2013). Landscape-level assessment provides a more complete representation of the dynamics of forest systems, as it can integrate the effects of all changes in forest management and harvesting taking place in response to—experienced or anticipated—bioenergy demand, and it also incorporates the effects of landscape-scale processes such as fire (Cintas et al., 2016; Cowie et al., 2013; Dwivedi et al., 2019; Koponen et al., 2018; Peñaloza et al., 2019).

In undertaking a landscape-level assessment, a constant spatial boundary should be applied, rather than an expanding boundary in which stands are added sequentially, in order to accurately reflect how the management changes affect the carbon stock in the whole landscape over time

(Cintas, Berndes, Cowie, et al., 2017). A forest landscape can be modelled as a series of identical time-shifted stands, for example, an ideal forest with uniform age distribution, with the same number of stands as the number of years in the rotation period. Alternatively, if data are available, models can also be used to represent real forest landscapes, which usually have unequal distributions of age classes and stands of different sizes (e.g. Cintas, Berndes, Cowie, et al., 2017).

A forested area often also includes areas that are unharvested, for example, to comply with conservation regulations or best practices. If the management, size and conditions of these areas are identical in the 'with bioenergy' and 'without bioenergy' scenarios, then they can be excluded when estimating effects of forest management on climate change mitigation. However, there could be differences, for example, if forests actively managed for bioenergy are less prone to wildfire and disease, which can otherwise spread into and damage neighbouring forest reserves (Kline et al., 2021).

In a forest managed such that annual carbon losses due to harvest plus other disturbances and natural turnover equal the annual growth in the forest, there is no change in forest carbon stock when considered at landscape level (Jonker et al., 2014). If incentives for bioenergy lead to an increase in the fraction of annual growth extracted, then landscape-scale forest carbon stocks can decline, or can increase at a slower rate than the no-bioenergy scenario, until a new equilibrium is reached between harvest and growth (Heinonen et al., 2017; Kallio et al., 2013; Soimakallio et al., 2016). Any reduction in forest carbon stock in the new equilibrium relative to the no-bioenergy scenario reduces the climate benefit of bioenergy. Forest management that enhances forest growth (See Section 6) could moderate negative impacts on forest carbon stock under the bioenergy scenario (Cowie et al., 2013; Favero et al., 2020; Gustavsson et al., 2017; Jonker et al., 2018; Khanna et al., 2017; Sathre et al., 2010; Sedjo & Tian, 2012).

To conclude, impacts of bioenergy policy should be assessed at the landscape scale because it is the change in forest carbon stocks at this scale, due to change in management to provide bioenergy along with other forest products, that determines the climate impact. Understanding of stand-level dynamics is critical to forest management and is useful to inform assessments at the landscape scale. Studies of real forest landscapes show that the net GHG effects of bioenergy incentives are more variable than suggested by studies that do not consider economic factors and varying conditions in the forest and wood products sector.

8 | REFERENCE SYSTEM (COUNTERFACTUAL)

To determine the climate effects of forest bioenergy, it is necessary to compare the bioenergy scenario with a reference 'no-bioenergy' scenario (Gustavsson et al., 2000; Schlamadinger et al., 1997) that delivers the same services to society. The reference land use is a critical methodological decision (Dwivedi et al., 2019; Johnson & Tschudi, 2012; Koponen et al., 2018). Some studies assess unharvested forest as one (and sometimes the only) reference scenario (e.g. Haus et al., 2014; Holtsmark, 2015; Lamers et al., 2014; Mitchell et al., 2012; Pingoud et al., 2012; Soimakallio et al., 2016) and attribute extra GHG emissions to the bioenergy system based on forgone sequestration in comparison with natural regeneration. Others use a historical baseline reference point, without considering the dynamic nature of carbon stocks under a no-bioenergy scenario (see Buchholz et al., 2016). However, to accurately quantify the consequences of forest bioenergy, the reference land use should represent the land carbon stock trajectory under the most likely land use(s) in the absence of bioenergy (Koponen et al., 2018; Lamers & Junginger, 2013; Parish et al., 2017). For biomass obtained as a co-product from forests managed for timber production, the relevant reference is commonly management for timber only, with thinning and harvest residues decomposing (or burned) on-site (Hanssen et al., 2017). In some situations, the most likely reference land use could involve land use change. For example, markets for wood products can be an important incentive for private landowners to retain land as managed forest rather than converting to other uses (Hodges et al., 2019); the reference scenario in this situation may involve: regeneration of natural forest, possibly subject to higher incidence of wildfire; replacement of forest stands with agriculture; or urbanization, each with different impacts on the land carbon stock (Parish et al., 2017; Wear & Greis, 2013). Assuming the forest would remain unharvested in the no-bioenergy scenario is not a realistic reference in situations where landholders use the land to generate income, unless landholders can obtain equivalent income from payments for carbon sequestration or other ecosystem services (Srinivasan, 2015). In cases where a no-harvest scenario is a valid reference case, there are challenges in quantifying future carbon stocks: carbon sequestration rate in unharvested forests, especially in the longer term, is uncertain in many cases due to a paucity of relevant data (e.g. Derderian et al., 2016) and uncertain effects of climate change. Furthermore, accumulated carbon is vulnerable to future loss through disturbances such as storm, drought, fire or pest outbreaks. Where more than one alternative is plausible, it is informative to analyse several alternative reference land-use scenarios (Koponen et al., 2018).

The reference system also needs to describe the wood products flow in the absence of bioenergy, as bioenergy incentives may influence the quantity and assortment of wood products available (see Section 6), and could divert biomass from non-energy uses such as pulp or composite products (Cowie & Gardner, 2007; Wang et al., 2015). The alternative fate of biomass residues and waste in the reference case could involve decomposition, incineration or landfilling, each with different emissions implications.

The reference no-bioenergy scenario should also identify the reference energy system assumed to be displaced by bioenergy, which is commonly based on fossil fuels (see Section 2). Displacing natural gas gives less benefit due to its lower GHG intensity compared with coal, and oil typically lies between them. A multitude of energy sources and technologies including fossil and renewable sources can be used for generation of electricity and heat for power grids and heat networks, varying geographically and over time, which can make it difficult to determine the energy source displaced by bioenergy (Bentsen, 2017; Soimakallio et al., 2011). Uncertainty in the rate of uptake and rate of technological improvements of other renewables makes it hard to characterize the appropriate reference energy system in the medium and long term. It is likely, however, that fossil fuels will continue to be used, and displaced on the margin, for a considerable time (IEA, 2019).

9 | SUPPLY CHAIN EMISSIONS

It is commonly perceived that bioenergy supply chain emissions are substantial, particularly when biomass is transported internationally, and could negate the climate benefits of fossil fuel substitution. However, fossil energy use along domestic forest biomass supply chains, from harvest, processing and transport, is generally small compared to the energy content of the bioenergy product and, with efficient handling and shipping, even when traded internationally (Batidzirai et al., 2014; Dwivedi et al., 2014; Ehrig & Behrendt, 2013; Gustavsson et al., 2011; Hamelinck et al., 2005; Jonker et al., 2014; Mauro et al., 2018; Miedema et al., 2017; Porsö et al., 2018; Uslu et al., 2008). The European Commission's Joint Research Centre determined that shipping pellets between North America and Europe increases supply chain emissions by 3–6 g CO_2/MJ, from around 3–15 g CO_2/MJ for wood chips or pellets dried using bioenergy and transported 500 km by truck (Giuntoli et al., 2017). For context, the EU average emission factors for hard coal are 96 and 16 g CO_2/MJ for combustion and supply respectively (Giuntoli et al., 2017). This underscores the importance of assessing actual supply chains. For example, the international pellet supply chain between the southeast United States and Europe has been intentionally designed to minimize trucking and associated handling costs, with pellet mills and large end users such as power plants located near rail lines, waterways and ports, thereby minimizing transport emissions and increasing net climate benefits (Dwivedi et al., 2014; Favero et al., 2020; Kline et al., 2021).

10 | NON-CO_2 CLIMATE FORCERS

The climate effects of forest-based bioenergy can be augmented or diminished by associated changes in biophysical properties of land, such as surface albedo, emissions of biogenic volatile organic compounds, surface roughness, evapotranspiration and sensible heat fluxes that directly or indirectly affect climate (e.g. Anderson et al., 2011; Bonan, 2008; Favero et al., 2018; Lutz & Howarth, 2015; Luyssaert et al., 2018). These effects are complex and highly dependent on location, tree species and management practice, and have implications for global as well as regional and local climate (e.g. Arora & Montenegro, 2011; Jia et al., 2019). Inclusion of non-CO_2 climate forcers can significantly influence assessments of forest bioenergy, particularly in areas with seasonal snow cover (e.g. Arvesen et al., 2018), although the warming and cooling effects of non-CO_2 forcers can also counteract each other (e.g. Kalliokoski et al., 2020). These factors need further study to understand their climate effects and develop agreed methodology for their quantification.

11 | SIGNIFICANCE OF THE SYSTEM BOUNDARY

Studies evaluating climate effects of forest-based bioenergy have produced divergent results due to inherent differences between bioenergy systems and different analytical approaches and assumptions (Cherubini et al., 2009). As discussed above, the choice of spatial system boundary and temporal scope is critical (Cherubini et al., 2009; Gustavsson et al., 2000; Marland, 2010; Schlamadinger et al., 1997) and should be coherent with the question studied (Koponen et al., 2018). Figure 3 illustrates alternative system boundaries that have been applied in studies of forest-based bioenergy. Focus on stack emissions (Option 1) neglects the key differences between fossil and biogenic carbon (see Section 3). Focus on the forest only (Option 2) captures the effects of biomass harvest on forest carbon stocks (see Section 6) but omits the climate benefits of displacing fossil fuels. Option 3, the biomass supply chain, overlooks the interactions between biomass and other forest products (Section 6). Option 4 covers the whole bioeconomy, that is, the forest, the biomass supply chain and all bio-based products from managed forests, and thus provides a more complete assessment of the climate effects of forest bioenergy.

In order to quantify the net climate effect of forest bioenergy, assessments should take a whole systems perspective. While this increases the complexity and uncertainty of the assessments, it provides a sound basis for robust decision-making. Biomass for bioenergy should be considered as one component of the bioeconomy (Option 4, Figure 3). Studies should therefore assess the effects of increasing biomass

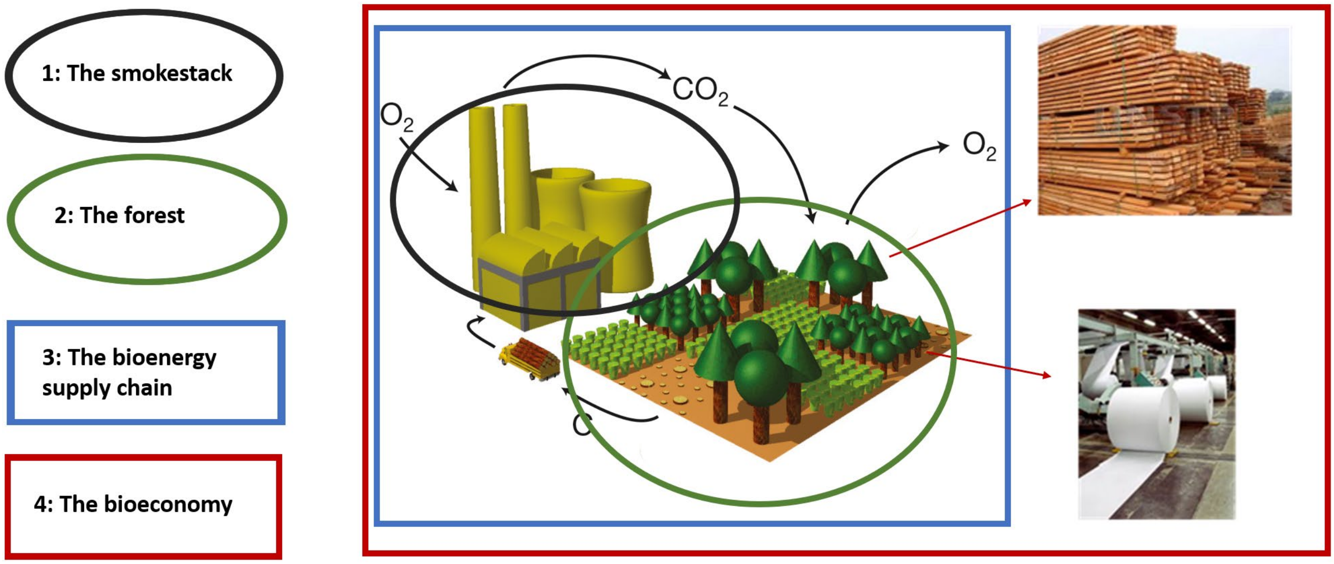

FIGURE 3 Alternative system boundaries that have been applied in studies assessing climate effects of forest-based bioenergy. Option 1 (black) considers only the stack emissions; Option 2 (green) considers only the forest carbon stock; Option 3 (blue) considers the bioenergy supply chain; Option 4 (red) covers the whole bioeconomy, including wood products in addition to biomass

demand for bioenergy on carbon stocks of the whole forest, and also include the broader indirect impacts on emissions (potentially positive or negative) due to policy- and market-driven influences on land use, use of wood products and GHG-intensive construction materials, and fossil fuel use, outside the bioenergy supply chain. The bioenergy system should be compared with a realistic counterfactual(s) that includes the reference land use and energy systems (Cherubini et al., 2009; Koponen et al., 2018; Schlamadinger et al., 1997). This approach is consistent with consequential LCA (Brandão et al., 2017). The temporal boundary should recognize: forest carbon dynamics, for example, modelling over several rotations; the trajectory for energy system transition; and short- and long-term climate objectives. Matthews et al. (2018) suggest criteria that could be used to identify woody biomass with greater climate benefits when assessed from a full life cycle, whole system perspective.

12 | REPORTING AND ACCOUNTING FOR BIOENERGY

The discussion above focusses on methodologies and results of studies assessing the climate effects of increased demand for forest bioenergy, considering GHG emissions and removals across the life cycle of bioenergy systems including the forest and co-product impacts, and comparison with a no-bioenergy counterfactual. Another context in which GHG emissions and removals associated with bioenergy are relevant is country-level reporting and accounting under the UNFCCC, and this is another aspect debated in the literature. In the UNFCCC context, the terms ‘reporting’ and ‘accounting’ have specific meaning: *Reporting* refers to the national inventories of annual GHG emissions and removals that parties submit to the UNFCCC, whereas *accounting* pertains to comparing GHG emissions with commitments, initially under the Kyoto Protocol (2008–2020; Cowie et al., 2006), and now the Paris Agreement.

The UNFCCC reporting requirements specify that CO_2 emissions associated with biomass combustion are counted in the land use sector, that is, where the harvest takes place; they are therefore reported as zero in the energy sector to avoid double-counting (Goodwin et al., 2019). This reporting approach is accurate, has no gaps and does not assume that bioenergy is carbon neutral (Haberl at al., 2012; Marland, 2010), although it has sometimes been described as such (e.g. Norton et al., 2019; Searchinger et al., 2009). Decisions on the approach to reporting and accounting for bioenergy and other wood products were informed by consideration of impacts on incentives for forest harvest and trade in wood products, practicality of calculation and data availability (Cowie et al., 2006; Höhne et al., 2007; Houghton et al., 1997 Vol 3; Lim et al., 1999; Penman et al., 2003; Sato & Nojiri, 2019; Schlamadinger et al., 2007). As explained by Rüter et al. (2019), emissions associated with wood products including bioenergy may be reported by the producing or consuming country, and may be based on carbon stock change in the forest or in the wood products pool, depending on the approach chosen by each party for reporting of harvested wood products (HWP). While the UNFCCC reporting approach is theoretically sound, incomplete coverage of the Kyoto Protocol created a gap in *accounting*: if an Annex I party (i.e. country with a Kyoto Protocol commitment) imported forest biomass from a country with no Kyoto Protocol commitment, any associated stock change in the forest of the exporting country was not accounted. The issue of incomplete coverage for accounting could potentially have been overcome under the Paris Agreement, as all parties now have targets (their nationally determined contributions, NDCs) against which they are required to account. However, the disparity in sectors and emission sources covered in countries' NDCs, and inconsistency in the HWP accounting approach applied, perpetuates risks of double-counting or omissions (Rüter et al., 2019; Sato & Nojiri, 2019). Within a country, the forest accounting approach used in the second commitment period of the Kyoto Protocol (2013–2020) allowed a policy-driven increase in harvest, such as resulting from an increase in bioenergy, to be included in a country's 'forest management reference level', and therefore not counted as a debit in the land sector (Grassi et al., 2018). Grassi et al. (2018) proposed an accounting approach using continuation of historical forest management as the reference to avoid the loophole of unverified counterfactuals, which has been adopted by the EU under Regulation 2018/841 of the EU Climate and Energy Framework (Camia et al., 2021). Several authors (Brack, 2017; Hudiburg et al., 2019; Norton et al., 2019) propose changing the UNFCCC accounting rules by which biomass is treated as having zero emissions at the point of combustion. However, accounting for CO_2 emissions from bioenergy within the energy sector would require revision of the established GHG accounting framework to adjust the land sector values to remove the component related to biomass used for energy, to avoid double-counting of emissions, which would be very difficult to achieve, as explained by Camia et al. (2021). It would create a disincentive for countries to utilize biomass to displace fossil fuels, adversely affecting all types of bioenergy systems irrespective of their potential to provide climate benefits (Pingoud et al., 2010). Rather than changing the accounting convention solely for bioenergy, a flux-based 'atmospheric flow approach' (Rüter et al., 2019) could potentially be applied to all wood products. However, if carbon fluxes from all wood products were to be reported at the time and place of emission, emissions due to forest harvest for export would not be reported by the country where the harvest takes place, thereby removing incentives for maintaining forest carbon stocks and potentially leading to deforestation because the country where the harvest takes place would report no emissions. Furthermore, reporting only at the time and place of emission would create a disincentive for use and trade in all sustainable wood products, including use for construction and bioenergy (Apps et al., 1997; Cowie et al., 2006; UNFCCC, 2003).

We suggest that improvements are required to achieve greater transparency in GHG reporting and accounting related to bioenergy, so that the connections between forest carbon stock change and use of biomass for energy are not overlooked (Cowie et al., 2017; Kurz et al., 2018; Searchinger et al., 2018). But rather than counting bioenergy emissions at the point of combustion, which would inhibit the beneficial use of wood products and forest bioenergy for climate change mitigation, we suggest that rules should ensure that all parties include the land sector comprehensively and transparently in reporting and accounting with respect to their emissions reduction commitments, and apply consistent approaches to ensure that omissions and double-counting are avoided (Sato & Nojiri, 2019; Schlamadinger et al., 2007). Transparency and measures to prevent double-counting and perverse incentives are also important considerations in formulation of domestic policies to support national targets for climate action, to avoid bioenergy incentives causing 'leakage', inadvertently stimulating loss of forest carbon stock domestically or abroad (Fingerman et al., 2019; Searchinger et al., 2018), or indirectly increasing fossil fuel emissions (Cowie & Gardner, 2007).

Furthermore, it is not the purpose of national-level reporting and accounting of GHG emissions to ensure sound decision-making and practices by actors operating 'on the ground'. Rather, effective sustainability governance is also required, to provide appropriate incentives and boundaries for actors in the land use and energy sectors, that also takes into consideration issues beyond climate.

13 | CONCLUSION

Rapid transformation of all sectors of society is needed to phase out the use of fossil fuels that adds carbon dioxide to the atmosphere causing global warming that is irreversible on timescales relevant for humans. The use of sustainable forest biomass for energy (heat, electricity or transport fuels) can effectively reduce fossil fuel use in the short term, and can contribute to phasing out use of fossil fuels in technologies and infrastructure that rely on carbon-based fuels, reducing future emissions. Furthermore, when combined with CCS, forest bioenergy can deliver CDR, likely to be required to meet the Paris Agreement's long-term temperature goal.

Misleading conclusions on the climate effects of forest bioenergy can be produced by studies that focus on emissions at the point of combustion, or consider only carbon balances of individual forest stands, or emphasize short-term mitigation contributions over long-term benefits, or disregard system-level interactions that influence the climate effects of forest bioenergy. Payback time calculations are influenced by subjective methodology choices and do not reflect the contribution of bioenergy within a portfolio of mitigation measures, so it is neither possible nor appropriate to declare a generic value for the maximum acceptable payback time for specific forest bioenergy options.

To answer the key question 'what are the climate implications of policies that promote bioenergy?' assessment should be made at the landscape level, and use a full life cycle approach that includes supply chain emissions, changes in land carbon stocks and other variables influenced by the policies studied. Effects on land cover, land management and the wood products and energy sectors need to be considered, including indirect impacts at international level. The bioenergy system should be compared with reference scenarios (counterfactuals) that describe the most likely alternative land use(s) and energy sources that would be displaced by the bioenergy system, and the probable alternative fates for the biomass being utilized. A no-harvest counterfactual is not realistic in most current circumstances, but markets that pay for carbon sequestration and other ecosystem services could change incentives for harvest in future.

Holistic assessments show that forests managed according to sustainable forest management principles and practices (around one billion hectares globally, of which over 420 million hectares are certified; UNECE FAO, 2019) can contribute to climate change mitigation by providing bioenergy and other forest products that replace GHG-intensive materials and fossil fuels, and by storing carbon in the forest and in long-lived forest products. Assessments also show that the impact of bioenergy implementation on net GHG emission savings depends on both feedstock and context, as many important factors vary across regions and time. Demand for forest bioenergy can influence land use and forest management decisions, and the wood products sector, and these effects can augment or diminish the mitigation value.

The issue of timing of mitigation benefits needs to be considered within a holistic assessment that includes land carbon dynamics and energy system transition. As for other mitigation options, the perceived attractiveness of specific forest bioenergy options is influenced by the priority given to near-term versus longer term climate objectives. It is important to consider how forest bioenergy and forest management more broadly can serve both short-term and long-term objectives.

With respect to the treatment of bioenergy in UNFCCC reporting and accounting, we disagree with proposals to count emissions at the point of combustion, which could have adverse climate impacts. We recommend that complete and transparent reporting and accounting be applied consistently across the whole land sector, to ensure recognition of the interactions between terrestrial carbon stocks and biomass use for energy and other purposes, and to incentivize land use and management systems that deliver climate benefits.

Effective sustainability governance is required to ensure that forest biomass used for energy makes a positive contribution to mitigating climate change, and to broader environmental and socioeconomic objectives. The sustainability governance being developed and implemented for bioenergy through the Global Bioenergy Partnership (GBEP, 2020) and the revised EU Renewable Energy Directive ('REDII'; European Commission, 2018) applies measures to ensure climate benefits, and includes, inter alia, safeguards for food security and areas of high conservation value, for example. Consistent application of sustainability governance measures globally and across the whole land sector would support achievement of the Sustainable Development Goals.

ACKNOWLEDGEMENTS

This paper is an output of the IEA Bioenergy Technology Collaboration Programme Task 45 'Climate and Sustainability Effects of Bioenergy within the broader Bioeconomy'. We thank Gregg Marland for constructive suggestions. Sampo Soimakallio's contribution to this paper is funded by Kone Foundation. Keith Kline's (ORNL) and Patrick Lamers' (NREL) contributions were sponsored by the U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO). Keith Kline's research is supported by DOE BETO under award number EE0007088 to ORNL. ORNL is managed by the UT-Battelle, LLC, for DOE under contract DE-AC05-00OR22725. NREL is managed by the Alliance for Sustainable Energy, LLC, for DOE under contract DEAC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

DATA AVAILABILITY STATEMENT

There is no data available, as no new data were produced in this study.

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How to cite this article: Cowie AL, Berndes G, Bentsen NS, et al. Applying a science-based systems perspective to dispel misconceptions about climate effects of forest bioenergy. *GCB Bioenergy*. 2021;13:1210–1231. https://doi.org/10.1111/gcbb.12844