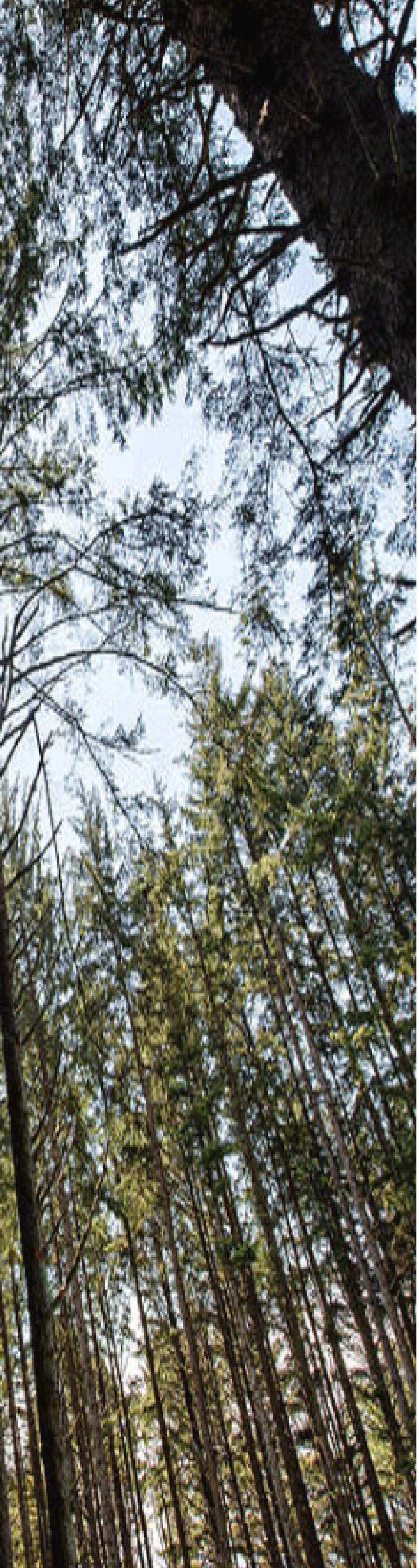

Bioenergy From Forests

Background Paper

Prepared for TFD's Bioenergy
from Forests Scoping Dialogue

February 2024

Yale SCHOOL OF THE ENVIRONMENT
The Forest School

The Forests Dialogue

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About This Paper

This report provides an overview of the current state of knowledge about forest-based bioenergy. This overview could serve as a scientific ‘common ground’ for future discussions. Forest bioenergy production is a complex system that includes transdisciplinary subjects such as the conservation and restoration of forest ecosystems, transition towards renewable energy and materials, and environmental justice issues related to indigenous or other underrepresented communities connected to forest landscapes. The combination of uncertainties within each of the scientific disciplines and mismatches between disciplines has created disagreements among scientists and practitioners as well as confusion in the public. In this overview, we first provide an interdisciplinary-systematic summary of the basic scientific knowledge related to forest bioenergy production and utilization. We then introduce the major areas of disagreement that are actively under debate within and between scientific disciplines before ending with a summary of four focus group discussions held between April and August of 2023. We focus on the breadth of information to provide a wide foundation that we think will contribute to more constructive and just dialogues.

About The Forests Dialogue

The Forests Dialogue (TFD) is an organization that designs and implements multi-stakeholder dialogues aimed at fostering social learning, building trust, and supporting processes for collaborative and adaptive land management across sectors. TFD believes that structured dialogue is fundamental to breaking deadlocks and creating meaningful change in the forest sector. Housed within The Forest School at the Yale School of the Environment, TFD’s secretariat is directed by a group of steering committee members representing globally significant forest stakeholders. TFD implements its mission through initiatives. Initiatives address a global forest issue identified by TFD’s Steering Committee members through a series of dialogues. TFD’s process includes mixing international and national perspectives, engaging the private sector in all dialogues, combining field discussions with structured meeting facilitation, and giving participants the mandate to determine outputs and outcomes. Dialogues often occur in countries where the issue is or has historically caused conflict and seek to deliver impact in-country and inform global discourse through grounded examples. Country level dialogue topics and case studies are driven by local priorities, as determined by in-country host organizations and vetted by TFD.

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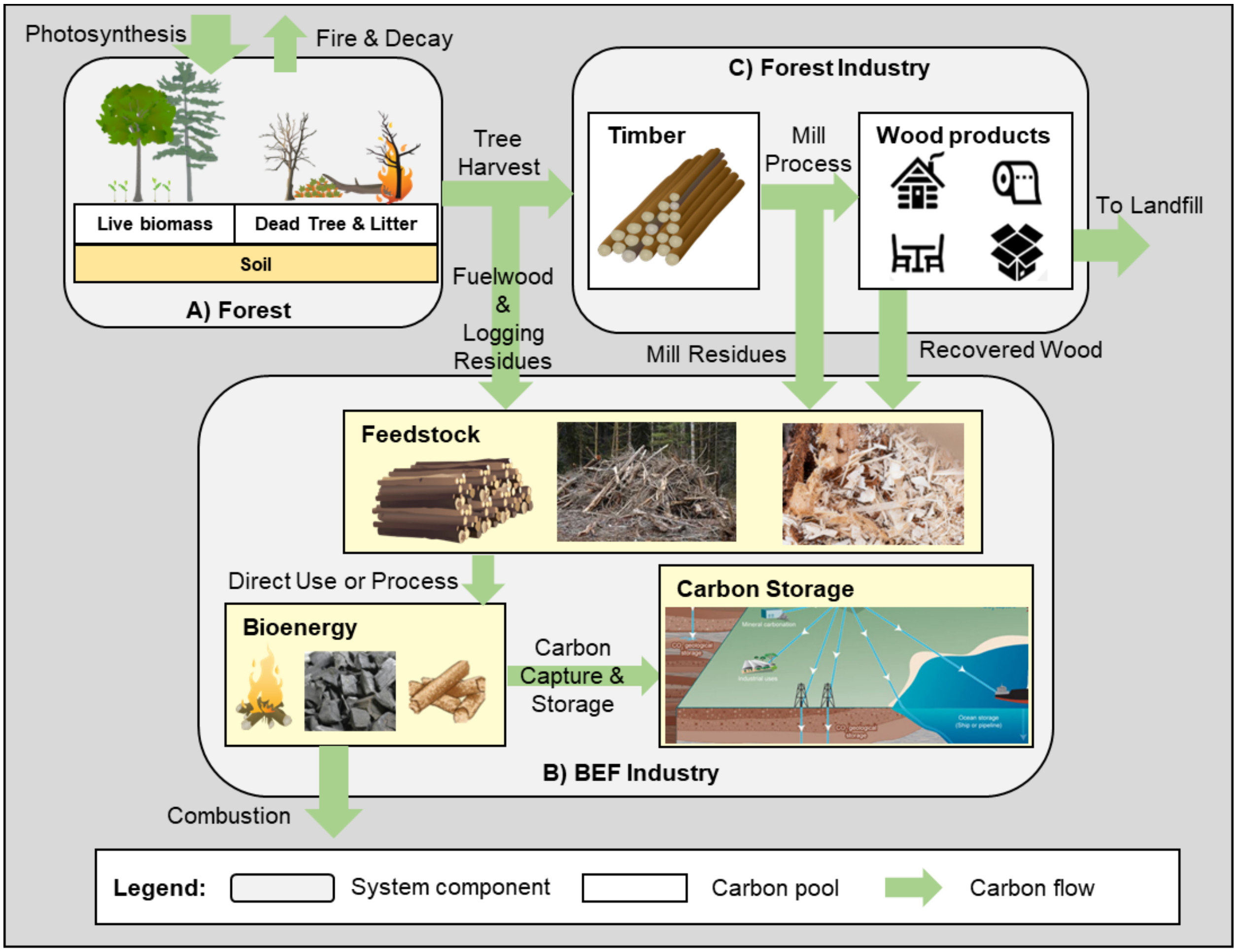
This report provides an overview of the current state of knowledge about bioenergy from forests (BEF). In this document, BEF describes energy generated from the combustion of woody biomass and biofuels derived from woody biomass. BEF is a complex system that includes multiple scientific disciplines such as forest ecology, global change, land use management, renewable energy transition, environmental justice and equity, etc. Production and utilization of BEF is controversial in part because of the importance of forest ecosystems and their irreplaceable ecosystem services. Concerns and disagreements arose around BEF because each of the scientific disciplines treat forests differently using various methods and assumptions, leading to science and policy debates and public confusions. Additional concern and disagreement relate to the potential impact of BEF production and utilization on forests, climate, and communities.

In this overview, we provide a broad summary of the basic ecological, engineering, and environmental science knowledge related to BEF. We then introduce the major areas of concern and disagreement that are actively under debate. We end with a summary of four focus group discussions held between April and August of 2023. We synthesize peer-reviewed scientific articles and grey literature from the globe to provide a breadth of information and a wide foundation for future discussions. We aim to use the overview as a scientific common ground that we think will contribute to more constructive and just dialogues.

1. Overview of the Life Cycle of Bioenergy From Forests

In the first part of this overview, we follow a life-cycle approach to provide a complete picture of the BEF system. Figure 1 illustrates the BEF life cycle from feedstock to the production processes to the final products and end-of-life. Forests provide wood biomass as the feedstock of forest bioenergy while delivering other ecosystem services. The forestry sector harvests woody biomass using various forest management techniques and transports biomass to mills and factories that create a diversity of wood products and bioenergy products. Each step of the life cycle from feedstock to the end-of-life of products has environmental impacts, such as greenhouse gas emissions and water and air pollution, and effects on social and economic systems. In the following subsections, we overview the critical components and processes in the forest bioenergy life cycle according to Figure 1.



* Photo and icon credits: Giuntoli et al. 2022; University of Maryland Center for Environmental Science; U.S. Forest Service, 2017. How much logging residue is left behind?; IPCC, 2005. Special report on carbon capture and storage.

Figure 1. Framework of the BEF system (adopted from Giuntoli et al. 2022). The forest bioenergy system consists of three major system components including A) forest ecosystems (**Sections 1.1, 1.2**), B) the BEF industry (**Section 1.3**), and C) the forest industry. The squares and arrows illustrate a simplified carbon flow among major carbon pools in the BEF system.

1.1 Forests carbon cycling and bioenergy feedstock

The world's forests currently hold a total of 861 Pg C in four major carbon pools including live biomass (42%), deadwood (8%), litter (5%), and soil (to 1-m depth, 44%) (Pan et al. 2011). Trees and other forest vegetation sequester carbon through photosynthesis that captures atmospheric carbon dioxide (CO_2) and transforms it into organic carbon molecules using solar energy. The accumulated carbon is allocated and stored in live plant biomass like tree trunks, branches, leaves, and roots. A portion of the carbon in live biomass accumulates in dead wood and litter pools as standing dead trees, dead roots, fallen branches and leaves through natural mortality of the trees or due to disturbances such as fire, drought, and storm. Decomposition of the dead materials as well as the burning of forest fires provide organic materials to the soil carbon pool and emit CO_2 back to the atmosphere. Globally, the accumulation of carbon through forest (re)growth is greater than loss of forest carbon through disturbances and deforestation. Thus, forests are estimated to be a net carbon sink of -7.6 Gt CO_2-e per year (Harris et al. 2021).

BEF uses woody biomass as raw material (i.e., feedstock) (**Figure 1 A**). Through harvesting and thinning operations, live tree biomass is removed as logs, branches, and forest residues (including unmerchantable and small-diameter trees, tops, and limbs, produced during thinning and timber harvest operations, Bergman et al. 2018). Some of this biomass may be used directly as energy sources or further processed into other energy products (see **Section 1.3**). The carbon contained in forest biomass is 'biogenic carbon'—carbon that cycles between the atmosphere and forest carbon pools. Under the assumption that forests accumulate carbon through photosynthesis at a faster rate than they lose carbon through harvest removal, combustion, and decomposition, forest bioenergy can be considered a renewable energy.

Global changes have profound impacts on forest ecosystems, and therefore on the future supply of BEF. Global changes in land uses (e.g., deforestation), long-term environmental drivers (e.g., CO_2, temperature, precipitation), and increased frequency and severity of natural disturbances (e.g., drought, wind, wildfire, pest, and disease) influence forest tree growth, mortality, and regeneration at an increasing pace (Anderegg et al. 2022; McDowell et al. 2020). Twenty-seven percent of global forest loss between 2001 and 2015 can be attributed to deforestation through permanent land use change for commodity production, and 23% through wildfire (Curtis et al. 2018). In the Western U.S., the profound climate drivers are projected to further increase forest-fire area by mid-21st century.

Under these global change pressures, current tree species and forest ecosystems may be able to 1) adapt to the new climate condition and persist, 2) shift to and colonize new locations, or 3) become extinct due to failed regeneration and migration (Liang et al. 2023 and references therein). For BEF, these different responses of forests to global change may lead to possible future scenarios of 1) continued BEF supply, 2) altered BEF supply rates due to changes in tree type and/or productivity, or 3) failed BEF supply due to losses of forest cover (e.g., shifts toward treeless vegetation projected in the subtropic Americas, Anadón, Sala, and Maestre 2014), respectively. Therefore, future development of BEF needs to acknowledge the projected future conditions of global forests (see **Sections 2.3, 2.4**).

1.2 The multiple uses of forests

There is no consensus on how to 'best' manage and use forests. Humans rely on forests for a wide range of products, functions, and services that often cannot be achieved simultaneously.

The disagreements on management strategies and conflicts on management objectives affect the supply and demand of BEF. Humans manage and use forests to meet the following goals:

- *Producing Food and Raw Material:* Forests produce a wide range of products for a variety of industry sectors. Wood is the dominant product from forests. Wood is harvested and processed as roundwood, sawnlog, veneer log, wood panels, pulpwood, etc. for building, construction, and paper industry (FAO 2020). Woody biomass is used and processed for BEF as fuelwood, charcoal, wood pellets, etc. (see **Section 1.3**). Non-timber forest products, including seeds, flowers, fruits, leaves, roots, bark, latex, resins and other non-wood plant parts, are also harvested by human populations over thousands of years (Ticktin 2004). For example, forests produce a large variety of nutrient-rich food including fruits, nuts, and vegetables, and can enhance human access to dairy and meat by providing livestock fodder (Ickowitz et al. 2022).

- *Mitigating Climate Change:* Supply of biomass for bioenergy is only one dimension of forests' role in combating global climate change. Forests are direct carbon capture and storage facilities that remove carbon through photosynthesis and store carbon in tree biomass (Pett-Ridge et al. 2023). Conserving and restoring the world's forests could mitigate 226 Gt of carbon dioxide if human activities are minimized (Mo et al. 2023). Forests also influence local and regional climate through direct biogeophysical factors such as albedo (the reflection of solar radiation back to the atmosphere), moisture exchange (evapotranspiration), and aerosols (solid particles or liquid droplets emitted by trees) (Bright et al. 2015).

- *Protecting Air, Water, Soil, and Biodiversity:* Trees trap airborne particulate matter and thus improve air quality and human health (Krieger 2001). Forested watersheds capture and store water, thus contributing to the quantity of water available and the seasonal flow of water. Forests also help purify water by stabilizing soils, reduce erosion and sedimentation, and filtering contaminants (Krieger 2001). Forests are global biodiversity hotspots, providing habitat for 80% of amphibian species, 75% of bird species and 68% of mammal species, and tropical forests contain about 60% of all vascular plant species (FAO 2022).

- *Recreation, Tourism, and Cultural Values:* Scenic beauty and recreational amenities associated with forests make them popular a variety of activities such as hunting, fishing, hiking, birdwatching, etc. (Krieger 2001) Forests also hold strong cultural values such as being a historical or family heritage, or serve as spiritual and cultural symbols for specific ethnic and racial communities (Kreye et al. 2017).

- *Supporting Global Economies*: The FAO estimates that the forest sector creates 33 million jobs and contributes more than USD 1.52 trillion to world gross domestic product. Forest ecosystem services value for recreation, wildlife habitat, water supply and quality, etc. are estimated at USD 7.5 trillion. Over 95% of the global rural population lives in or near forest landscapes and relies on forests for a major portion of their income (FAO 2022).

1.3 Bioenergy products and use cases

There are many different kinds of BEF products that have different life cycle attributes from production, processing, and utilization (**Figure 1 B, C**). Here, we divide BEF products into four major categories (Giuntoli et al. 2022; Shabani, Akhtari, and Sowlati 2013): primary bioenergy, secondary bioenergy, tertiary post-consumer bioenergy, and processed bioenergy (**Table 1**).

Table 1. BEF product classification.

Classification	Forest Bioenergy	Forest Resources and Production Processes
Primary Bioenergy	Slash	Residual harvested from final felling and thinning
	Stumps	Uprooted from the final felling
	Discarded wood	Discarded trunks unsuitable for industry, like rotten or sprinted stems, or species
	Firewood	Collected from logs, branches, or wood pieces sourced from various trees and woody vegetation found in the forest
	Roundwood	Wood in its natural state as felled, with or without bark. It may be round, split, roughly squared or in other forms. Can be used for firewood production.
	Pulpwood	Timber primarily used for making wood pulp in paper production. Can be used for bioenergy production.
Secondary Bioenergy	Bark	Directly from the trunks and branches of trees
	Sawdust	A by-product during various wood processing activities

	Chips	A by-product during various wood processing activities
	Black liquor	A by-product of the pulp-making process
	Tall oil	A by-product of the pulp-making process. Some fractions of tall oil can be processed into biofuels or used as additives in biodiesel production
Tertiary Post-consumer Bioenergy	Recovered wood	Include construction and demolition debris, discarded wood from furniture, packaging, pallets, and other wood-containing products that have reached the end of their life cycle
Processed Bioenergy	Pellets	Pelletization (compression and densification) of forest residuals, chips, sawdust, bark, or others
	Wood charcoal	Pyrolysis or destructive distillation (in the presence of limited oxygen) of wood
	Biochar	Pyrolysis (in the absence of oxygen) of chips, sawdust, leaves, bark, or forest residuals
	Bio-oil	Pyrolysis of chips, sawdust, forest residues, or other woody materials
	Ethanol	Biochemical conversion or gasification of logging residues, forest thinning, branches, and others
	Syngas	Gasification or pyrolysis of wood chips, sawdust, or others

Primary, secondary, and tertiary post-consumer BEF products are forest biomass that could either be directly used by combustion or indirectly used as feedstock for processed bioenergy sources. ***Primary bioenergy sources*** are residual biomass derived from logging activities including harvesting and thinning residues, discarded wood, and firewood (including stemwood and other wood components) used in fireplaces. ***Secondary bioenergy sources*** come from timber mills or other wood processing facilities that are waste from the forest industry and processes for the production of other wood products. ***Tertiary post-consumer bioenergy sources*** are wood waste generated after its initial use in products or applications. Combustion is the direct bioenergy use method where tree biomass burns in the open air, and the photosynthetically stored chemical energy of the biomass is converted into heat (Yu et al.

2021). Combustion has long been the dominant use case of BEF. 95–97% of the global bioenergy production is based on the direct combustion of biomass (Fouilland, Grace, and Ellis 2010). Co-firing of forest biomass and coal has also been used to generate energy.

Production and utilization of ***processed bioenergy sources*** involves specific processing or treatment techniques and various use cases. The primary processing and treatments currently used are pelletization, pyrolysis, biochemical conversion and thermochemical conversion:

- *Pelletization* produces wood pellets that are mainly used for combustion, or co-fired with coal, to produce electricity or generate heat.
- *Pyrolysis* is a thermochemical valorization technique for producing a variety of solid, liquid, and gaseous products from forest biomass via different pyrolysis conditions (Aghbashlo et al. 2019). Slow pyrolysis produces solid products such as wood charcoal and biochar, while fast pyrolysis results in the production of bio-oil. Wood charcoal is a traditional fuel for cooking and industrial processes; biochar is designed for soil improvement and environmental applications, contributing to sustainable land management; bio-oil has potential applications as a precursor for transportation fuels, as well as in the production of chemicals, resins, or as an additive for improving the properties of other fuels.
- *Biochemical or thermochemical conversion (e.g., gasification)* are two primary methods used to process lignocellulosic feedstocks (i.e., plant dry matter, or biomass) into bioethanol (Soltanian et al. 2020). The biochemical conversion starts with pretreatment to separate hemicellulose and lignin from cellulose and is followed by hydrolysis of cellulose to obtain fermentable sugars. Finally, sugars are fermented into ethanol. Gasification is the partial oxidation of biomass into synthesis gas (syngas) at elevated temperatures (Gao et al. 2023). During gasification of the lignocellulosic biomass at high pressure and in the absence of inert gases, lignocellulosic biomass is converted into syngas, which will then be converted into bioethanol (Laesecke, Ellis, and Kirchen 2017). Syngas is a mixture of carbon monoxide (CO), hydrogen (H2), and other trace gases. Syngas can be used as a fuel for vehicles and fuel cells, as well as to create other chemicals, including synthetic natural gas, methanol, and petroleum (Rauch, Hrbek, and Hofbauer 2014).

Bioenergy with carbon capture and storage (BECCS) is the combination of bioenergy and carbon capture and storage (CCS) technologies for climate mitigation. In the context of BEF, BECCS mainly refer to the process of capturing CO_2 emissions from the combustion of biomass energy and storing it in geological formations (Gough and Upham 2011). Post-combustion CCS is also the most studied form of CCS due to its relative ease to retrofit in existing power plants and other industries. Notable examples of capture methods include absorption, adsorption, chemical looping combustion, selective membrane separation, hydrate-based separation, cryogenic distillation, and enzyme-based capture (Babin, Vaneeckhaute, and Iliuta 2021). To date, however, there is currently no commercial application of BECCS technologies at scale.

1.4 Life-cycle environmental impacts

Life-cycle assessment modeling is a standard tool that can compute potential environmental impacts throughout the life cycle of a product, such as wood biomass feedstocks (**Section 1.1**) or BEF production and utilization (**Section 1.3**). It has the advantage of being specific for the accounting at each production stage of a product for the comparison of different products. These characteristics make life-cycle assessment a widely used method for exploring the environmental impacts linked to BEF and comparing BEF with fossil energy (Hosseinzadeh-Bandbafha, Aghbashlo, and Tabatabaei 2021). A life-cycle assessment consists of four phases (Finnveden et al. 2009):

1) **Goal and Scope Definition.** This phase includes the reasons for carrying out the study, the intended application, and the intended audience. It determines the functional unit of the accounting—the quantitative unit of the product or product system to determine the focus of the accounting, such as in 1 MJ energy unit or 1 t carbon unit. It is also the place where key model assumptions such as the system boundaries (**Sections 2.2**) and counterfactual scenarios (baseline scenarios that project the situations to be compared with the BEF scenario being assessed, **Section 2.3**) of the study are described.
2) **Life-Cycle Inventory Analysis.** This phase details the inputs (resources) and outputs (emissions) from the product over its life cycle.
3) **Life-Cycle Impact Assessment.** This phase aims at understanding and evaluating the magnitude and significance of the potential environmental impacts of the studied system.
4) **Interpretation.** This phase seeks to interpret the results from the previous phases and evaluate them in relation to the goal and scope in order to reach conclusions and recommendations.

A life-cycle environmental impact assessment of BEF production involves estimating the various environmental impacts on climate change, land-use change, biodiversity, water use, acidification, ecotoxicity throughout all stages of the BEF production and utilization processes. These stages include 1) forest cultivation and harvest, 2) biomass processing and treatment, 3) transportation, 4) energy generation, and 5) post-combustion CCS.

- ***Forest Cultivation and Harvest***: Tree harvest directly affects forest carbon cycling by removing biomass carbon out of forest ecosystems. Intensive forest cultivation and harvest—with intensive fertilizer use, energy consumption, and mechanical operation—also has higher risks of increased soil erosion, water pollution, and reduction of biodiversity in forested landscapes (see **Section 2.4.1**). Harvest operations have direct greenhouse gas emissions at different levels depending on the harvesting technique applied (e.g., chainsaw-based or feller buncher-based, Abbas and Handler 2018). When loggers disturb soils through the use of heavy logging equipment and removal of vegetation, soil erosion is likely until new vegetation establishes in the forest. Exposed soils can erode into nearby waterways and increase sedimentation or change the paths of forest streams. The use of fertilizers, pesticides, and herbicides in forest plantations can also reduce water quality if these chemicals run off into water bodies. BEF production may alter the structure of forest habitats and affect biodiversity. For instance, the removal of downed woody debris or a standing dead tree can negatively affect wildlife that depend on these structures as habitat. On the other hand, Tarr et al. (2017) pointed out that landscape-scale impacts on wildlife habitat vary among species. For example, removal of hardwood ingrowth in longleaf pine forests increases the survival of the endangered red-cockaded woodpecker (*Picoides borealis*) (D. M. Richardson and Smith 1992).
- ***Biomass Processing and Treatment***: Biomass processing includes grinding, chipping, and drying wood, which is energy-intensive, requires high water use, and emits greenhouse gasses. For instance, producing wood briquettes from forest residues accounts for about 82% of greenhouse gas emissions across all life cycle stages. The energy consumption for processing forest biomass can vary widely based on factors such as the type of biomass (such as logs versus sawmill residues) and the processing technologies (such as the scale of the power plants) (Guest et al. 2011; Puettmann et al. 2020).
- ***Transportation:*** Transportation, including transportation of wood from the forest to mills and facilities and the transportation of BEF products from facilities to end-users, can be a significant contributor to the life-cycle greenhouse gas emissions of BEF (Beagle and Belmont 2019). The total transportation emissions relate to the distance traveled, the type of transportation vehicle, and the efficiency of the transportation vehicle. For example, in different regions of the United States, emissions from biomass transportation contributed between 5.9 g CO_2e/kWh to 21.3 g CO_2e/kWh (Xu et al. 2021). The transatlantic shipment of pellets from the Southern United States to the United Kingdom accounted for 28.1% of the life-cycle greenhouse gas emissions of the bioelectricity generation (Dwivedi et al. 2016). Smaller and less efficient BEF power

plants could have smaller life-cycle greenhouse gas emission when the transportation distance is shorter (Sunde, Brekke, and Solberg 2011; Cleary and Caspersen 2015).

- ***Energy Generation***: The energy generation stage involves the transformation of BEF into electricity, heat, or fuels, mainly through combustion. The environmental impacts of bioenergy combustion include greenhouse gas emissions, particulate matter emissions, photochemical ozone formation, water acidification, and water eutrophication (da Costa et al. 2018). Xu et al. (2021) found that greenhouse gas emissions from the bioelectricity generation stage contributed to more than 50% (about 20.0 g CO_2e/kWh) of life-cycle emissions of bioelectricity in 12 U.S. states. Improvement of energy bioenergy system design and advancements in bioenergy technologies have improved energy conversion efficiencies and reduced emissions. In developing countries, the transition from traditional, low-grade heating and cooking to more modern bioenergy applications is likely to significantly improve energy efficiency, reduce biomass demand, and mitigate negative environmental impacts (Jink van Dam 2017; Lindgren 2020). More efficient bioenergy systems—such as combined heat and power facilities instead of heat-or-power-only facilities—can also increase the rates of biomass conversion in existing modern applications (Guest et al. 2011).

- ***BECCS***: The BECCS technology adds three key components to the post-combustion process of BEF: CO_2 capture from power plants, transportation of CO_2 to storage sites, and long-term underground CO_2 storage (Gough and Upham 2011). Directly capture and store CO_2 from BEF power plants has the potential to reduce greenhouse gas emissions by inducing “negative emissions” (Babin, Vaneeckhaute, and Iliuta 2021). Besides the above-mentioned BEF-related processes, The capture, transportation, and storage of CO_2 also has land, water, and energy consumption and associated environmental impacts, which are the main challenges facing large-scale implementation of BECCS (Babin, Vaneeckhaute, and Iliuta 2021). Depending on the conditions of its deployment, BECCS can be climate beneficial but also can be detrimental due to its lifecycle emissions (Fajardy et al. 2018). Large uncertainties remain and there is yet any commercial-scale deployment.

1.5 Current state of bioenergy from forests globally

Today, use of all four forms of BEF continues to grow globally. According to the latest statistics from the World Bioenergy Association, bioenergy currently accounts for 9% of the renewable electricity produced, 96% of the renewable heat produced, and 90% of renewable energy used in the transportation sector globally (World Bioenergy Association 2023). Globally, bioenergy is the largest source of renewable energy today, accounting for 55% of global renewable energy supply and over 6% of global energy supply (IEA 2023). Forest-based biomass plays a significant role in the global bioenergy supply. Solid biomass sources, including wood chips, wood pellets, and traditional biomass sources, comprise 86% of the biomass supply (World Bioenergy Association 2023). **Figure 2-4** illustrates the production, import, and export data for three major BEF types per continent in the last decade (FAO 2023).

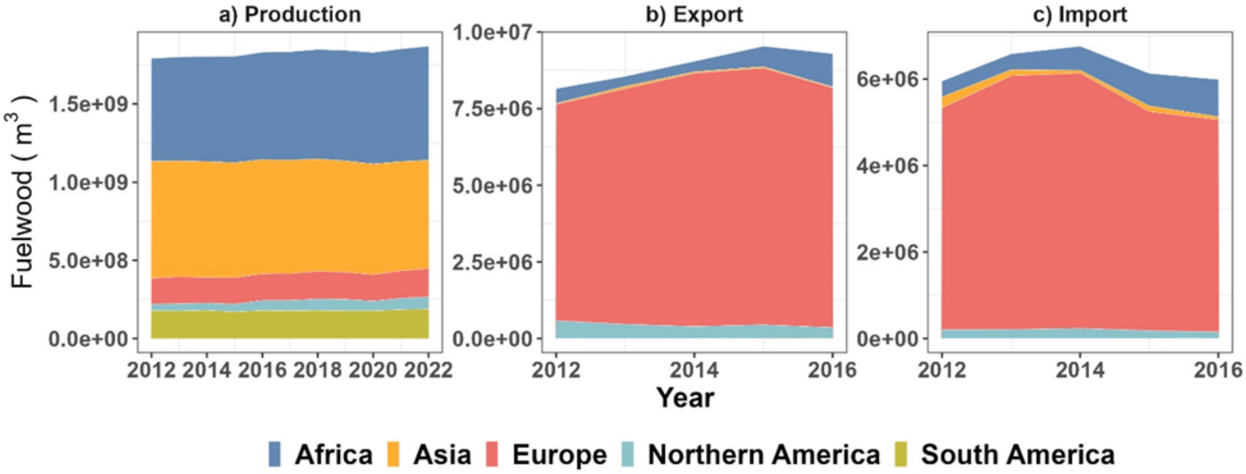


Figure 2. Global market of fuelwood per region for the past 10 years (FAO 2023).

Fuelwood, an unprocessed primary bioenergy source, constitutes the largest consumption of BEF (Figure 2). In 2022, 1.9 billion m^3 of firewood was produced globally, Africa and Asia accounted for most of the production with shares of 37% each, followed by the Americas at 18% (World Bioenergy Association 2023). More than 81% of the African population–accounting for 653 million people–rely on biomass for their energy demands for cooking and heating. The figure is over 90% for some sub-Saharan lower-income countries such as the Central African Republic, Burundi, and Rwanda (Nyika et al. 2020). Similarly, rural populations in Asian developing countries such as China (Yang et al. 2020), India (Bošković et al. 2023), and Bangladesh (Rahman et al. 2024) also rely on fuelwood for cooking and heating due to its accessibility.

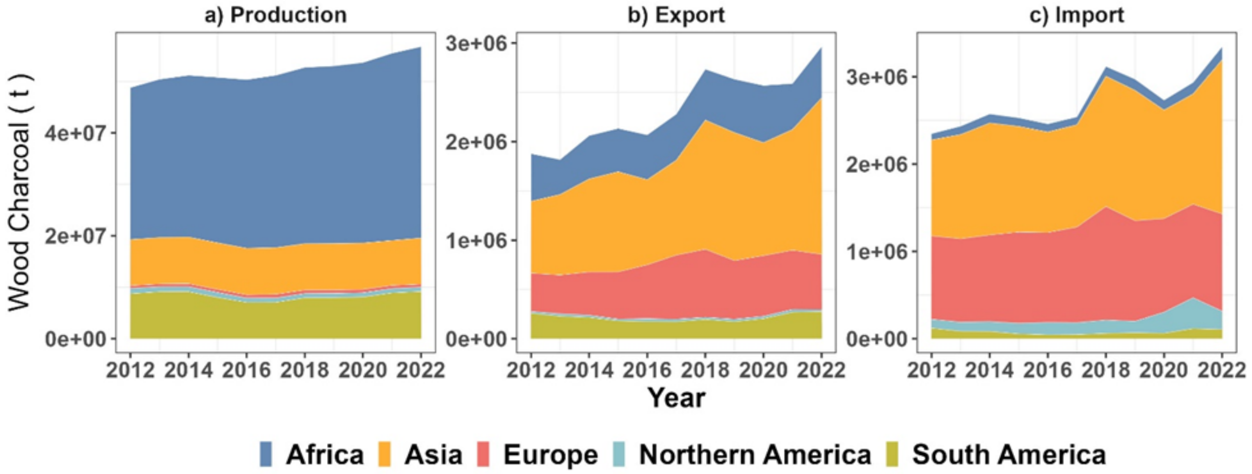


Figure 3. Global market of wood charcoal per region for the past 10 years (FAO 2023).

Wood charcoal, a processed bioenergy source, is another important BEF product in developing countries (Figure 3). Together with fuelwood, these two BEF types form the energy base of the world’s poor (FAO 2010). Of all the wood used as fuel worldwide, about 17% is converted to charcoal (Jinke van Dam 2017). In 2022, global wood charcoal production amounted to 55 million tons with Africa producing 70% of charcoal (World Bioenergy Association 2023). Charcoal consumption in Africa increased rapidly in the past decades, primarily due to migration to urban and peri-urban areas, because charcoal is easier and cheaper to transport and trade to urban populations than fuelwood (FAO 2010). It has also become a significant output of forest bioeconomy and an essential livelihood support system (Nyarko et al. 2021). South America also has large charcoal production, with Brazil leading global productivity at 6.5 million tons per year (FAO 2023), mainly characterized by *eucalyptus* plantations for charcoal use in the steel industry.

Fuelwood and charcoal are mostly used with traditional technologies such as traditional open cookstoves. This traditional use of biomass is likely unsustainable for growing populations and has low energy efficiency and high air pollution. Yet one-third of the global population (about 2.6 billion people) rely on traditional bioenergy for household cooking, causing air pollution that is responsible for 1.63–3.12 million premature deaths per year (FAO 2022). Therefore, the focus of sustainable BEF in the Global South naturally centers around the transition towards modern bioenergy sources and the promotion of more efficient energy technologies, such as improved cook stoves (Lindgren 2020) and more efficient charcoal production (Jinke van Dam 2017).

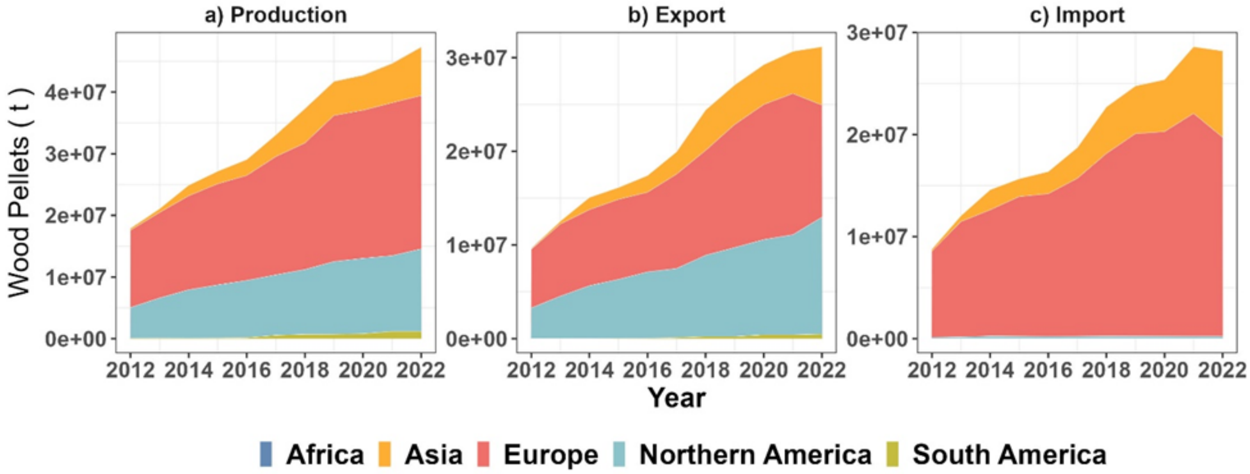


Figure 4. Global market of wood pellets per region for the past 10 years (FAO 2023).

Wood pellets, a form of processed bioenergy, are produced internationally (Figure 4). Wood pellet production has increased significantly over the past decade, following the maturation of pelletization technology in the 1980s and 1990s (FAO 2010). In 2022, wood pellet production was estimated at 46.4 million tons, Europe accounted for most of the production with a share of 55% followed by America at 31% (World Bioenergy Association 2023; FAO 2023). According to Bioenergy Europe's pellets report, world pellet production is steadily increasing, with the global production in 2021 approximately 6.8% higher than in 2020 (Bioenergy Europe 2022). Seven out of the ten top producers in the world are from Europe, led by Germany and Latvia. The surge of wood pellet markets in Europe was driven by the European countries' need to reach their national renewable energy goals under the European Renewable Energy Directive (European Commission 2018). Processed wood bioenergy is also increasingly recognized as a tool for coping with the ongoing energy crisis in Europe (Stojilovska et al. 2023).

The increased EU demand for wood pellets also, apart from increased EU production, resulted in increased imports, with main sources from Russia, Canada, and, particularly, the US (Jonsson and Rinaldi 2017; Aguilar et al. 2020). The US has been the leader of global wood pellet production (Bioenergy Europe 2022). The production has primarily been exported, amounting to 8.9 million out of the 9.5 million tons produced (FAO 2023), with the main recipients being the UK, Japan, and the Netherlands.

Asia also observed an increased consumption of wood pellets by about 33% between 2020 and 2021. It is likely that the increase in production shown by Figure 4 is valid, but the trend cannot be validated due to difficulties in obtaining data, especially in China where the market is supposedly large but comprises mainly small producers without sufficient statistics. The

Chinese market appears to be exclusively local with nearly no imports or exports, having little to no impact on the global market.

2. Areas of Concern and Disagreement

Bioenergy has been at the forefront of the global energy transition and meeting carbon neutrality goals. The European Union raised its renewable energy target to 42.5% of the total energy supply by 2030 in the recent update of the Renewable Energy Direct, and bioenergy is mentioned extensively to achieve this goal (European Commission 2023). According to Faaij (2022), global potential of annual biomass energy supply was found to range between 100 EJ and over 500 EJ per year in 2050, compared to a total global primary energy use of about 570 EJ today, and the current bioenergy supply at 360 EJ per year (World Bioenergy Association 2023). Specifically for BEF, Smeets and Faaij (2007) projected that the global theoretical potential of BEF supply will reach 71 EJ per year by 2050. Lauri et al. (2014) projected that woody biomass is possible to satisfy up to 18% of the world's primary energy consumption in 2050. However, some argued that many of these projections and aspirational goals could be difficult or impossible to achieve due to non-realistic model assumptions that lack considerations of various ecological, economic, and environmental justice constraints (Searle and Malins 2015).

Discussion about BEF is challenging because the systems are complex (**Figure 1**). Scientific discussions of BEF have continued for more than three decades, yet are still hindered by large uncertainties (see **Section I**). IPCC acknowledges the controversies and variances around BEF by stating “In the case of bioenergy from managed forests, the magnitude and timing of the net mitigation benefits is controversial as it varies with differences due to local climate conditions, forest management practice, fossil fuel displacement efficiency and methodological approaches” (IPCC 2019b). Context—such as the differences stated by the IPCC—is a critical determinant of appropriate assumptions and varies greatly around the world. Attempts to generalize context-specific analysis is in an early stage (Dale et al. 2013). This section summarizes and structures the main areas of concern and disagreement from the different context applied in different analysis. The context of a sustainability assessment for BEF includes the purpose or perspective of the assessment (**Section 2.1**); temporal and spatial extent considered (**Section 2.2**); baseline or counterfactual scenarios (**Section 2.3**); the particular bioenergy feedstock, forest management, and distribution system, and location (**Section 2.4**); and variability in environmental, social, economic, and policy conditions and stakeholder values (**Sections 2.5, 2.6**) (Efroymson et al. 2013; Dwivedi et al. 2019). However, the different aspects of context are connected and cannot be discussed independently. Therefore, we refer to other aspects of the context where applicable in the discussions of each section for individual topics.

2.1 Accounting climate effects of bioenergy from forests

BEF is often referred to as a renewable and carbon neutral energy source based on the assumption that the biogenic carbon emissions from burning biomass is sequestered again through forest regrowth (see **Section 1.1**). Therefore, the overall climate effect of using BEF would be beneficial compared to the use of fossil fuels. These assumptions around the accounting of climate effects for BEF have been evaluated by numerous studies using various methods including life-cycle assessment. Many areas of disagreement emerged because of differences in methods and assumptions of accounting.

2.1.1 Greenhouse gas accounting for bioenergy from forests

Greenhouse gas emissions from biomass used for energy are not currently accounted for in the energy sector in contrast to all other fuels (Pulles, Gillenwater, and Radunsky 2022). The United Nations Framework Convention on Climate Change (UNFCCC) require its parties to report national greenhouse gas inventories following the 2006 IPCC (Intergovernmental Panel on Climate Change) Guidelines (IPCC 2006; 2019a). The current guideline attribute emissions from biomass used for energy to the Land-Use and Land-Use-Change and Forestry (LULUCF) sector rather than the Energy sector (IPCC 2006; 2019a). This accounting approach assumes that the combustion of biomass and the accumulation of carbon in terrestrial biogenic carbon pools—including forests and agricultural lands—through photosynthesis happen in the same country. Bioenergy is therefore considered carbon neutral by default, as emissions are masked under the LULUCF emissions, which encompass estimated mass changes of terrestrial carbon pools over a calendar year.

The increasing production, consumption, and international trade of bioenergy are, however, not tracked in this accounting framework (**Figure 5**). Pulles, Gillenwater, and Radunsky (2022) therefore raised the concern that current IPCC guidelines are incapable of reporting the emissions from biomass harvested in one country and burned in another, and cannot report emissions from bioenergy comparable to other combusted fuels in the Energy sector. Under the current accounting framework, the increasing wood pellet trade also risks creating an emissions burden for exporting countries (McKechnie, Colombo, and MacLean 2014). This effect of shifted forest harvest activity outside the accounting boundary—or displacement of sourcing activity to other jurisdiction—is termed leakage (Buchholz et al. 2016; Murphy and McDonnell 2017). Funk et al. (2022) further argued that growth in global wood pellet trade—such as trade between Europe and U.S. Southeast—could lead to increases in unaccounted emissions from the harvest of biomass feedstocks and accelerate the growth in bioenergy production beyond what is optimal for the climate or for forest health. Improvement of the accounting framework requires detailed accounting methods for bioenergy production, consumption, and trade. Current methods for bioenergy emissions accounting, however, need further standardization given the wide range of results from the various contexts applied.

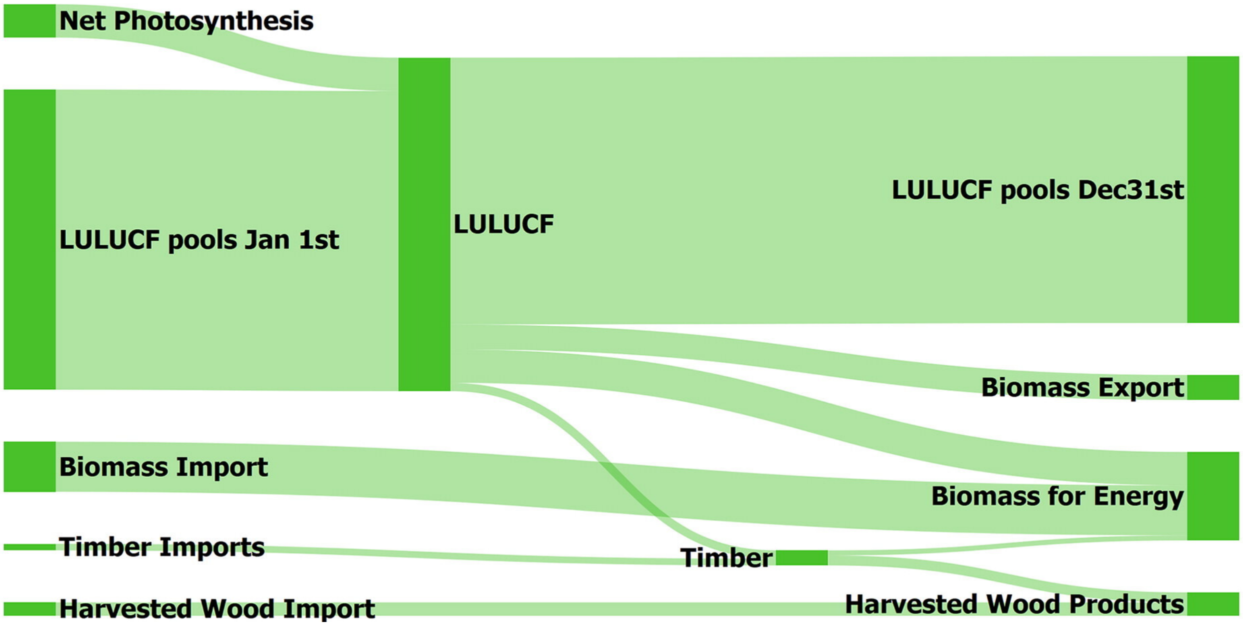


Figure 5. Carbon mass flow related to LULUCF with import and export (retrieved from Pulles, Gillenwater, and Radunsky 2022). Dark green bars are the carbon pools, and light green areas illustrates the carbon flows over the accounted time period. Current national inventory accounting only documents net changes in the LULUCF sector. Imported carbon from biomass, timber, harvested wood imports, and emissions associated with biomass for energy uses are not accounted for.

2.1.2 Life cycle assessment for bioenergy from forests

While life-cycle assessment is a great tool for evaluating the environmental impact of BEF and comparing it with fossil energy (**Section 1.4**), the results can be variable depending on the specific model assumptions adopted in the assessment (W. Liu et al. 2018; Zanchi, Pena, and Bird 2012). Much of the ongoing debates can be attributed to uncertainties and different assumptions applied in the four phases of life-cycle assessment: 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment, and 4) Interpretation (**Section 1.4**):

Phases 2) Inventory Analysis and 3) Impact Assessment require state-of-the-art scientific knowledge on the process-based understanding of the product life cycle and the best available data including parameters and indicators. Uncertainties in these two phases are mainly from data that are erroneous, incomplete, approximated, or variable (Finnveden et al. 2009). For example, the emission factors of timber transportation from logging sites to sawmills differ among ways of transportation and locations; estimations of sawmill efficiencies also have large variability among wood product types and locations. Such uncertainties affect the precision of the climate effect accounting for BEF.

Phases 1) Goal and Scope Definition and 4) Interpretation define the model structure, assumptions, and model implications. Model differences in these two phases are mainly from the different choices made by researchers, which are often shaped by the specific policy and decision-making objectives behind the analysis. The definition of sustainability of BEF rather than precision issues of the climate effect accounting is more likely to emerge from these two phases. For example, one assumption relates to whether BEF is renewable or carbon neutral and whether the production and utilization of BEF could bring net positive or negative climate effects. Flexibility in these choices allows for testing multiple future scenarios but also leads to misconceptions and confusions in the use of scientific knowledge for policy negotiation (Cowie et al. 2021). In the following sections, we focus on the variety of choices available in life-cycle assessment for BEF to identify main areas of disagreement. For example, the choices of system boundary (**Section 2.2**) and counterfactual (**Section 2.3**) in the Goal and Scope Definition phase, and the choices considered for assessing implications of BEF development on land, economy, and society (**Sections 2.4, 2.5**) in the Interpretation phase.

2.2 System boundary

2.2.1 Options of system boundary

Inclusion or exclusion of certain components of the BEF life cycle has profound impact on the results of life-cycle assessment. Cowie et al. (2021) illustrated the primary system boundaries applied in studies for BEF (**Figure 6**). System boundaries of many BEF life-cycle assessments only consider the stack emissions from the bioenergy facilities (**Figure 6**, *Option 1*) or the carbon impacts within the harvested forest stand (**Figure 6**, *Option 2*). The narrow spatial system boundaries of *Option 1* neglect carbon emissions related to the sourcing of bioenergy or additional climate effects of changes in albedo or evapotranspiration resulting from changes to forest structure (See **Section 1.1**). The narrow spatial system boundaries of *Option 2* neglect the carbon emissions from the processing of the harvested biomass and the utilization of the final bioenergy product. A more inclusive system boundary includes the complete supply chain of BEF (*Option 3*). *Option 3* also provide the possibility of including CCS components for a BECCS system boundary. This option therefore accounts for both emissions–from the forest, the bioenergy facilities and the CCS processes–and negative emissions of long-term carbon storage. However, *Option 3* overlooks market interactions between bioenergy and other forest products, or the leakage of carbon emissions to other jurisdictions. The most inclusive LCA system boundary covers the whole bioeconomy (*Option 4*) and thus provides the most holistic assessment of the climate effects of BEF. It is argued that full-life cycle assessment with a whole-system perspective should be applied for the evaluation of climate benefits for BEF (*Option 4*) (Cowie et al. 2021). However, some authors argue the importance of acknowledging the significant environmental impacts from a smaller system boundary, such as the carbon losses from forest harvesting (*Option 2*) (Peng et al. 2023; Sterman et al. 2022).

Within each component of the BEF system (**Figure 1, Figure 6**), choices of whether to include individual ecological or technical processes are also impactful. For example, greenhouse gas emissions from changes in the soil organic carbon pool could account for up to 66% of life-cycle greenhouse gas emissions of biofuel from forest residue (Lan et al. 2024), which would reduce the climate benefit of BEF uses expected. However, incorporating more processes, such as the soil carbon dynamic, into the life-cycle assessment brings large uncertainties due to the contrasting evidence from empirical studies (Jandl et al. 2007). The effects of biomass removal on soil carbon storage could range from trivial (~3% reduction) to profound (up to 30% reduction), depending on soil depth, harvest intensity, timing of measurement, and forest conditions (Ameray et al. 2021). BECCS may contribute to higher net carbon sequestration and storage in the projections of BEF utilization scenarios (Tokimatsu, Yasuoka, and Nishio 2017). Other processes that are hard to include in a life-cycle climate-effect accounting include the emissions of non-CO_2 greenhouse gasses, such as nitrous oxide from soil (H. Zhang et al. 2022) and bioenergy combustion (Ter-Mikaelian, Colombo, and Chen 2015).

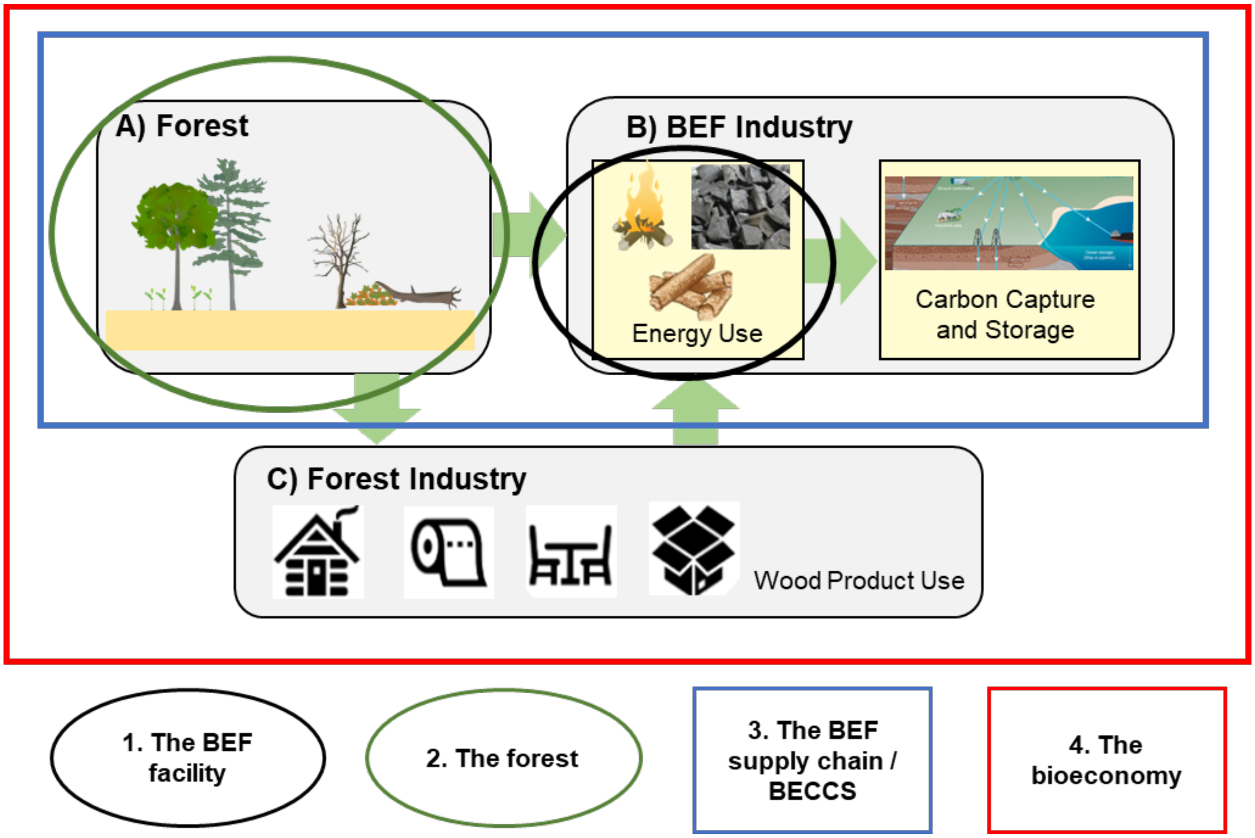


Figure 6. Four primary options (1-4) of system boundaries that have been applied in life-cycle assessment models of BEF. Adopted from Cowie et al. (2021). System components are the same as in the BEF framework in **Figure 1.**

2.2.2 Temporal scales and carbon debt

The choice of temporal scale matters in the accounting of BEF climate effect because forest carbon pools are part of a dynamic system. As shown in **Figure 7**, choosing a specific time point or period on the forest carbon storage curve leads to different results of forest standing carbon values and net carbon balances. Harvesting and burning forest biomass produces immediate CO_2 emissions. As the forest regrows, the new trees gradually remove atmospheric CO_2 and store carbon in trees and soils. As a result of this temporal change in emissions and removals, climate models project initial CO_2 emissions from bioenergy have global warming effects followed by cooling effects as the forests regrow. The rate at which the climate warming effect decreases depends on the time required for forest regrow. Thus, the temperature impact of forest harvesting when viewed at a larger time horizon (> 60 years) is expected to have a lower contribution on the global temperature rises than fossil fuels (Cherubini et al. 2014). Therefore, BEF achieves climate benefits in the long-term and when considering fossil fuel substitution. However, continuous debates center around the timing of the initial biogenic carbon emission from bioenergy uses - termed “carbon debt” - and the time required for forest regrowth - termed “payback time” (Bentsen 2017).

Many studies evaluate the timing issue of the climate effects of BEF using this concept of carbon debt payback time (Bentsen 2017). Some authors argue that carbon debt is not an issue because short payback times are usually less than the 100-year time horizon normally used in nations’ climate targets (Jonker, Junginger, and Faaij 2014; Favero et al. 2023; Nabuurs, Arets, and Schelhaas 2017). Others argue that the initial emissions from bioenergy are contrary to the Paris Agreement’s short-term temperature target of ‘reaching global peaking of greenhouse gas emissions as soon as possible’, and that these emissions further the risk of crossing a climate tipping point that could lead to irreversible harm (Norton et al. 2022; Sterman et al. 2022). These diverging conclusions are results of a lack of consensus on assumptions. The payback time of a harvesting carbon debt can range from less than a year to up to 1000 years depending on the model and assumptions made (Bentsen 2017). The concept of carbon debt payback time needs to be interpreted with considerations of other issues including the choice of system boundary (see Section 2.2.1), spatial scale (see **Section 2.2.3**), and counterfactual (see **Section 2.3**).

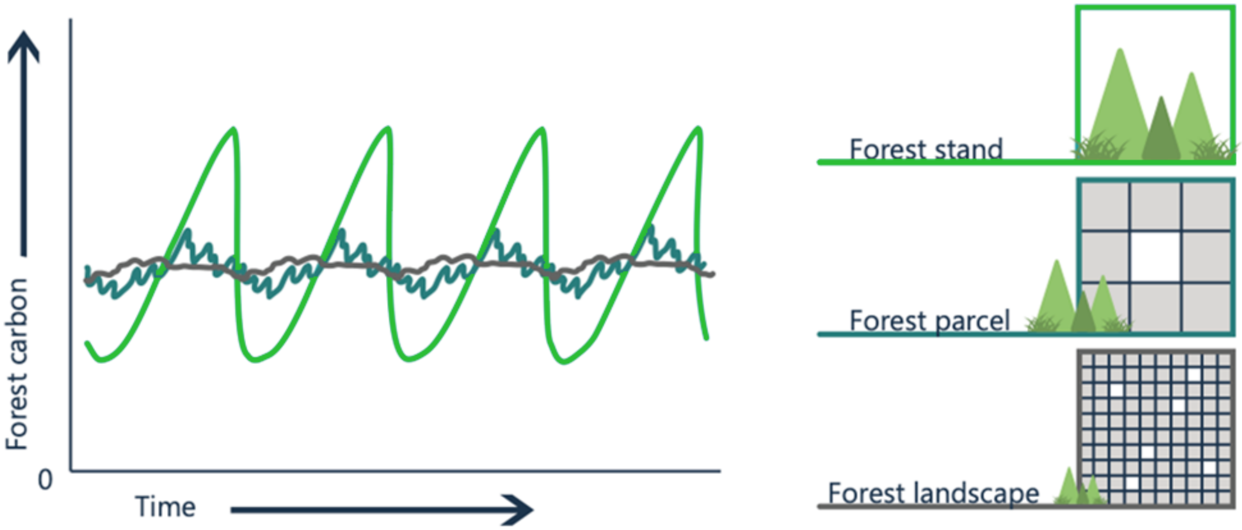


Figure 7. The influence of spatial and temporal scales on forest carbon storage. Retrieved from Janowiak et al. (2017).

2.2.3 Spatial scales

Another factor that influences the climate effect of BEF is the spatial scale of the life-cycle assessment models. Spatial extents can range from fine-scale assessments of the carbon impacts on an individual forest stand to broad-scale assessments of carbon impacts across forested landscape, region, or globe. Stand-level assessments can capture the carbon consequences of forest management activities like planting, thinning, or specific silvicultural operations. The results provide detailed information about forest vegetation and carbon dynamics, but the interpretation is sensitive to the temporal scales assumed (see **Section 2.2.2**). For example, Cherubini et al. (2011) analyzed the climate effect of BEF using the spatial unit of a single biomass rotation. The authors found that one biogenic CO_2 molecule has a global warming potential between 0 and 1 fossil CO_2-equivalent. In addition, local biotic, abiotic, and climatic conditions also play an essential role in assessing the climate effects of BEF, particularly when considering potential trade-offs with other ecosystem functions such as biodiversity (Giuntoli et al. 2022; St-Laurent et al. 2022). In practice, forest managers can mitigate such effects by avoiding areas of high conservation value (HCV) (HCV Network 2024). Furthermore, sustainable management strategies can simultaneously achieve multiple conservation, climate mitigation, and development goals (see **Section 2.4.1**) (Sunderland and Rowland 2019; Dale, Efroymson, and Kline 2011). Therefore, comparisons of small-scale results for BEF climate effects should consider the site-specific context.

Some authors thus argue that stand-level assessments could give inconsistent and misleading results because forest management and wood production for bioenergy generally involve multiple stands (Cowie et al. 2021). When looking at fine spatial scales and short timeframes, harvest typically removes a large portion of the carbon within the system. However, across larger spatial scales and time periods, reduction in forest carbon stocks from harvest are diluted (**Figure 7**) (Janowiak et al. 2017). For example, Galik and Abt (2012) evaluated six assessment scales when projecting the net greenhouse gas balance of woody biomass co-firing in Virginia. The authors found substantially higher greenhouse gas emission reduction from state-level assessments compared to results at forest-plot levels because the large-scale assessment resulted in higher biomass production and less forest carbon loss. Landscape-level analysis, however, may result in longer payback time than stand-level analysis. In a meta-analysis by Buchholz et al. (2016), the authors found shorter payback time in stand-level studies because only one year of fossil fuel emission associated with the management operations need to be offset, compared to multiple years of fossil fuel emissions from the landscape scale.

In practice, most forest statisticians recommend using a consistent forest management unit (FMU), which refers forests being managed according to a set of common objectives and using a long-term forest management plan (Colfer 1995). A forest management unit may cover several hundred hectares or fractions of that. Therefore, large-scale integrated assessments are important for the accounting of BEF's greenhouse gas emission impacts, with sufficient account of different context of sectorial, geographical, and temporal scales (Giuntoli et al. 2022; Cowie et al. 2021).

2.3 Counterfactuals (baselines)

To determine the climate effects of scaling up BEF in the future, it is necessary to compare with a counterfactual scenario that represents an anticipated future system without BEF against the BEF system of interest. This model system could either assume a future that is like the present (business-as-usual) or a projected diversion from the present (Cowie et al. 2021; Finnveden et al. 2009). Here we focus on the energy system (**Section 2.3.1**) and land use and management system (**Section 2.3.2**) in the counterfactual scenarios. However, counterfactual scenarios are also subject to the context of the analysis. Consistent and transparent counterfactual scenarios require identification of the current forest condition and major influences on it, documentation of underlying assumptions and associated uncertainties, identifying the most likely alternative fates of woody feedstocks that would be used for bioenergy, and estimating the effects of no demand for BEF on future forest conditions (E. S. Parish et al. 2017). There are other aspects of counterfactuals related to energy system and land use that are elaborated more in other sections, such as forest management strategies (**Section 2.4**) and economic conditions (**Section 2.5**).

2.3.1 Counterfactual energy system and substitution effect

A large portion of studies estimated the climate effects of BEF based on the counterfactual energy system assuming that the continued use of fossil fuels will be the business-as-usual scenario. Within the analysis with fossil energy as counterfactuals, the results are also influenced by the specific energy source compared, such as coal, oil, or natural gas, and the type and source of BEF applied (see **Sections 1.3, 2.4**). Other plausible counterfactual energy systems involve renewable energy sources such as solar and wind energy. These studies find climate benefits of BEF based on substitution effects and used displacement factors to describe the emission reduction for a wood-based product or fuel, which is used in place of a non-wood alternative (Howard et al. 2021; Leturcq 2020; Myllyviita et al. 2021). According to a literature review by Myllyviita et al. (2021), the most commonly used displacement factor for energy substitution was 0.8 t carbon/t carbon, meaning that the use of bioenergy with 1 ton carbon content could avoid emissions from fossil energy use equivalent to 0.8 t carbon. However, the use of bioenergy does not guarantee displacement of fossil fuel. Assumptions on amount of fossil fuel displaced by BEF uses alters the estimated climate effect of BEF (Brown et al. 2024). Studies have found lower or even negative displacement factors, implying that BEF did not replace fossil energy or even increased fossil energy use. For example, Smyth et al. (2014) found negative displacement effects when forests are clear-cut for domestic bioenergy supply in Canada. The scope of the analysis (**Section 2.2**), source of the biomass (**Section 2.4**), type of bioenergy products (**Section 1.3**), combustion technology, and the energy being substituted all have strong influence on the outcome of displacement factors (Petersen Raymer 2006).

It is impossible to specifically determine the counterfactual energy system displaced by BEF because of the multitude of energy sources and technologies including fossil and renewable sources that can be used for generation of electricity and heat for power grids and heat networks (Cowie et al. 2021). One particular energy source that is intensively discussed with bioenergy is natural gas. Natural gas has been considered as a 'bridge fuel' or 'transition fuel' in the global clean-energy transition due to its lower greenhouse gas intensity compared to other fossil energy sources (UNEP 2023). The displacement of natural gas therefore provides less emission avoidance than coal or oil-based energy. Choosing natural gas as the counterfactual energy scenario can influence the projected BEF system due to the issues of 'carbon lock-in', i.e., the inertia of carbon emissions due to mutually reinforcing physical, economic, and social constraints (Seto et al. 2016) on either natural gas or bioenergy. Infrastructures for both natural gas and BEF will remain for a long period of time if established (Reid, Ali, and Field 2020). Model results showed that raw material prices and infrastructure costs could encourage more use of natural gas instead of investments in bioenergy by 2050 (Jåstad et al. 2021). Some countries such as the United States have already observed such trends with faster growth of natural gas infrastructure than bioenergy (Reid, Ali, and Field 2020).

Comparisons between BEF and other renewable energy sources—such as wind and solar—are scarce. Renewable energy sources other than BEF have constraints of wind and solar resources to meet energy demands consistently, limitations of energy transmission, storage, and high geophysical variances (Tong et al. 2021). Solar and wind energy systems thus provide much less capacity than traditional fossil energy sources like coal and natural gas. Therefore, BEF is not often compared with solar and wind energy as counterfactuals but considered as a complement to fill in the gaps of the fluctuating solar and wind energy supply (Thrän et al. 2015). Some authors argue, however, that as fossil fuel use declines and renewable energy production increases, wood will compare less favorably as an energy substitution (Brown et al. 2024; Picciano et al. 2022). This transition to renewables can reduce net carbon benefits of BEF uses, because the energy mix of the counterfactual energy system becomes less carbon intensive, meaning that there is less fossil fuel that could be displaced, therefore lower displacement factors. It is therefore important to situate BEF within the broader portfolio of climate mitigation actions to understand the trade-offs and synergies and avoid undermining other climate strategies.

2.3.2 Counterfactual land use

The counterfactual land use systems are the most likely land use and land management scenarios in the absence of bioenergy production. There are a wide range of possible scenarios in absence of BEF production. Demand of BEF may alter the management strategy on working forests in terms of harvest intensity (see **Section 2.4.1**). Without management for the production of BEF, an existing forest may persist without human disturbances (Peng et al. 2023) or deforest and convert into buildup areas (Costanza et al. 2017). Demand of BEF may also incentivize afforestation and reforestation on lands that are currently unforested (Gelfand et al. 2013). Each of the counterfactual scenarios provides different results for the climate effect of BEF. The lack of consensus on the appropriate land reference systems has contributed to misunderstanding and disagreements about the climate effects of bioenergy (Koponen et al. 2018).

When unharvested forests are evaluated as the counterfactual scenario, the climate effects of BEF production are associated with the impact of the added tree harvest activities, which links back to the discussions around carbon debts (See **Section 2.2.2**). For example, Peng et al. (2023) assessed the climate effects of global wood supply of long-lived, short-lived, and bioenergy wood products. The authors made the assumption on the counterfactual scenario that the forests not harvested would otherwise grow without harvest activity. The authors therefore estimated an annual carbon cost of 3.5-4.2 Gigaton CO_2-equivalent between 2010 and 2050. Based on this result, some argued that forests should be managed without harvest because tree harvest has net negative climate effects (Moomaw and Law 2023).

When deforestation or non-forest land uses are assumed as the counterfactual land use, climate effects of BEF are beneficial because of the avoided forest losses or the additional forest carbon storage. The counterfactual of forest conversion may be especially likely for many private forests if there is no motivation for keeping the forest for production purposes. Costanza et al. (2017) projected lower urbanization rates, thus less loss of forest cover and forest carbon storage, due to bioenergy production. Afforestation or forest plantations for BEF production with the counterfactual of unforested land also has a large body of literature. For example, many authors discussed the potential climate benefits of bioenergy production on marginal lands, defined as lands that are unproductive or unsuitable for crop production due to poor soil properties, low quality groundwater, drought, undesired topology, and unfavorable climatic conditions. Conventional food crop production on these lands is likely to be unprofitable (Gelfand et al. 2013; Mehmood et al. 2017).

The counterfactuals of land use systems need regional-specific considerations. The above-mentioned systems of unharvested forests, unforested lands, and forest conversion are broad assumptions that cannot be applied on a global context. In New England, Duveneck and Thompson (2019) found increasing impact of harvest on private-corporate forests and pressure of development on non-corporate private forests, pointing to counterfactual land use systems of intensively managed forests and forest conversion, respectively. In the Western U.S., increasing risk of high-severity short-interval fire that removes areas of mature trees is likely to drive more conversion to non-forest (Coop et al. 2020; Parks et al. 2019), implying a counterfactual system with high risks of disturbance.

2.4 Sourcing forest biomass for bioenergy

2.4.1 Intensive versus sustainable forest management

The source of forest biomass for bioenergy is an important factor that determines both the climate effects and the realistic potential of BEF supply. Some have concerns that increased demand for biomass for bioenergy will drive unsustainable forest management practices, for example sourcing from forests that carry higher carbon debt or need longer payback time (Buchholz, Gunn, and Saah 2017) (see **Section 2.5.2** about forest biomass demand). There are two diverging strategies regarding how to manage forests to supply bioenergy sources sustainably. One is to manage forests intensively and increase biomass production for large-scale energy transition towards bioenergy. The other is to manage forests with improving forest health and resilience as the sustainability goal, while producing tree biomass for bioenergy as a co-benefit.

Intensive tree harvest. Intensive forest management focuses on the regeneration of young forest through planting and clearcuts of plantation forests in short rotations (European Environment Agency 2015). Some authors stated that this intensive forestry model has increased the carbon storage in the forest ecosystems while simultaneously providing a large stream of wood raw materials and, therefore, substituting fossil-based materials at a large regional scale (Kauppi et al. 2022; Lundmark et al. 2014).

However, many authors criticized the destructive consequences of forest clearing. Several contexts are at stake here—the spatial temporal scales of the intensively managed forest (**Section 2.2**), the counterfactual forest system compared to the intensive plantation (**Section 2.3**), and the specifics of the forest management practices. For example, intensive forest management leads to substantial losses of intact forests of large and continuous areas that are a key entity supporting ecological legacies, biodiversity and ecosystem services, resilience, and adaptive capacity (Svensson et al. 2020; 2019). Intensive harvest leads to soil organic carbon losses in all layers of forest soils (Achat, Fortin, et al. 2015), and the associated soil nutrient loss could, in turn, have negative effect on the subsequent forest growth (Achat, Deleuze, et al. 2015). In addition, most intensively managed forests are single-species plantations (Liu, Kuchma, and Krutovsky 2018). These monocultural plantations are important for providing timber, but harbor less biodiversity and are potentially more susceptible to disturbances than natural or diverse planted forests (Gibson et al. 2011; Hua et al. 2022). Many authors therefore call for promoting increased resilience and ecosystem service provision of functionally diverse and species diverse planted forests compared to monospecific ones (Messier et al. 2022). These confounding factors will hamper the ability of the world's managed forests–native and planted–to supply the biomass sources demanded. Yet these risks and uncertainties are not sufficiently reflected in the latest projections of future bioenergy sources globally (Lauri et al. 2014; Searle and Malins 2015).

Logging residue extraction. Another way to intensify the extraction of forest tree biomass but without increasing harvest volume is to utilize logging residues from forestry operations. A large proportion of the tree biomass (tops, foliage, branches, stumps, and small and unmerchantable trees) is left on the logging site in conventional stemwood harvest. Some of this material is left onsite to decay but much of it is burned onsite with the carbon going directly to the atmosphere with no benefit to humans. The recovery of these logging residues could provide 17-20% additional biomass to the timber and pulp harvest (Egnell and Björheden 2013). Some authors term such biomass sources as "surplus biomass" (Agar et al. 2020). This biomass is also categorized as low- or minimal-value products whose potential utilization has been discussed as a sustainable bioeconomy pathway (Max Nielsen-Pincus and Cassandra Moseley 2009; Dong et al. 2022; Field et al. 2023; Barrette et al. 2015; J Barrette et al. 2017).

Evaluations of the environmental impacts of logging residue extraction showed mixed results (Ranius et al. 2018). Hoefnagels, Junginger, and Faaij (2014) estimated in the Southeastern United States the potential production of 4.1 Tg wood pellets using harvest residues at costs competitive to conventional pellets production. However, Lundmark (2006) pointed out that it becomes more profitable to use roundwood for bioenergy after using a certain amount of logging residue. Also, the removal of forest residue is expected to have negative effects on long-term soil carbon storage (Lan et al. 2024) and a large proportion of forest biodiversity that rely on dead wood structures for their habitat, such as beetles, fungi, lichens, and understory vegetation (Ranius et al. 2018). In some specific cases, however, some authors showed insignificant impacts of tree harvest on biodiversity. In Sweden, for instance, Dahlberg et al. (2011) estimates that removing 70% of fine wood debris on 50% of the clearcut sites of Norway spruce has minor contribution to regional biodiversity losses.

Sustainable forest management. The other forest management strategy that focuses on the health and resilience of forests is often termed as improved forest management or sustainable forest management (Gan and Cashore 2013; Kaaraka et al. 2021). This management strategy involves silvicultural practices that integrate multiple goals including biomass production, plus carbon sequestration, wildlife habitat, and forest health and resilience. The management practices include mixed-forest planting, extended rotations for plantations, stand improvement, fuel management, partial harvesting for enhanced natural regeneration and uneven-aged forests, and avoiding logging damages to remaining trees, etc. (Kaarakka et al. 2021). These practices may lead to improved forest resilience of various forest types to multiple disturbances such as insects and fire (Churchill et al. 2013; DeRose and Long 2014). When forest disturbances are included in the counterfactual system, proactive management of forests could not only promote resilience and forest recovery, but also provide additional climate benefits by utilizing the wood biomass that would otherwise be lost due to the disturbances (see Chapter 2 in Jennifer Pett-Ridge et al. 2023).

Overall, the IPCC summarizes the benefits of improved sustainable forest management including maintaining and enhancing forest carbon stock, increasing wood quality, continuously producing wood, partially preventing and counteracting the impacts of disturbances, as well as increasing benefits for climate change adaptation, biodiversity conservation, microclimatic regulation, soil erosion protection, and water and flood regulation with reduced lateral carbon fluxes (IPCC 2019b). These benefits of improved sustainable forest management in terms of forest management technique can be translated into the sustainability of BEF sourcing in terms of lower carbon debt, shorter payback time, and, overall, more positive climate effects. Notably, improved sustainable forest management does not prioritize woody biomass production but focuses on enhancing overall health and resilience of the forests. Therefore, possible trade-offs between BEF sourcing and improved sustainable forest management need to be accounted in the projections of future BEF development.

Regional difference. Forest management is regionally specific. Proper management treatment is determined by the regional forest type and the site-specific forest condition. The exact management practice applied then determines the type and amount of tree biomass extracted. For example, fertilization and planting density in intensive rotational plantations affects the feedstock production in Southeastern U.S. (Zhang et al. 2023). Improved and sustainable forest management for forest health and resilience may require ground fuel control in dry Western U.S. forests but partial harvest treatments in the northeast (Jennifer Pett-Ridge et al. 2023). Feedstocks produced in different cases therefore involves different amount of forest residue, pulpwood, or roundwood. In addition, the impact of forest harvest management on other forest functions also has regional or site disparities, such as the variable responses of forest fauna biodiversity depending on the taxonomic group assessed (Jones et al. 2022); and the different impact of forest management on soil carbon depending on forest type and condition (Mayer et al. 2020). These regional differences are an important context that may influence the sustainability of BEF sourcing.

Policy. There is currently a lack of regulation globally to explicitly require bioenergy sources to be sustainable (Norton et al. 2019). There are guidelines and certificates available for sustainability in the U.S. market, such as the Sustainable Forestry Initiative's certified Fiber Sourcing Standard (SFI 2022), which expects responsible procurement of all fiber and is audited by an independent third party. This standard requires feedstocks to come from forests where logging is supervised by professionals trained in wildlife habitat conservation, water quality protection, and other Best Management Practices (BMPs) (National Association of State Foresters 2015). It has been documented that loggers who received training are likely to implement BMPs during harvesting operations on nonindustrial private forests (Davis and Clatterbuck 2003). However, there are no regulations that require producers to obtain these certificates to be able to enter the international trade. It is currently not clear how consistently the guidelines are applied spatially and temporally (Titus et al. 2021).

2.4.2 Domestic source versus global trade

The recent boost of the global market for BEF has driven growing international trade of bioenergy sources, especially wood pellet trades between the United States and Europe (see **Section 1.5**). The increase of international bioenergy trade was viewed as necessary by some, as domestic sources are often already exploited, and there are gaps to fill between regional supply and demand (Bauen et al. 2009; Matzenberger et al. 2015).

Many authors discovered overall climate benefits of BEF trade. For wood pellet production in the southeastern U.S. and Europe, Parish et al. (2018) found mutually environmental and socioeconomic benefits with the potential to provide benefits in both sides despite some negative effects on the coal industry. Klein et al. (2013) identified the positive effects of this trade on the Sustainable Development Goals (SDGs) including affordable and clean energy (SDG 7), decent work and economic growth (SDG 8), industry innovation and infrastructure (SDG 9), responsible consumption and production (SDG 12), and life on land (SDG 15). Wang et al. (2015) estimated that using the wood pellets exported by the United States to produce electricity in Europe could provide 74% to 85% greenhouse gas savings compared to coal-based electricity generation, accounting the direct emissions associated with the production, transportation, and conversion of the biomass to pellets, and the accompanying indirect market and land use effects in the southern United States. A separate assessment by Dwivedi et al. (2014) showed similar benefits for the United States export of wood pellets to the United Kingdom, amounting to around 50% to 68% savings in greenhouse gas emissions, where production and shipment of wood pellets contributes to 48% and 31% of the emissions, respectively. Other in situ data for the southeastern U.S. production of bioenergy also document that this system results in carbon neutrality with some tradeoff between carbon pools (Aguilar et al. 2022; Dale et al. 2017).

Meanwhile, some argue that the negative environmental impact of global trade undermines this benefit. Searchinger et al. (2018) argued that scaling up Europe’s bioenergy supply would require expanding harvests in forests all over the world, which would lead to negative effects on the climate and biodiversity. For example, a report from the Southern Environmental Law Center stated that the deciduous forest clearing rate in Virginia and North Carolina between

2016 to 2018 is 1.5 time higher than the rate before initiation of wood pellet mills between 2009 to 2012 (Williams 2021). A different source by NCASI, however, found slightly declined harvest rates and continued surplus of growth compared to harvest in the entire southeastern U.S., despite a doubling in wood pellet production between 2009-2017 (Munro et al. 2022). These two sources used different data, modeling approach, and considered different forest types and regions. It is therefore important to further specify the regional differences when accounting for this leakage issue of the U.S. – Europe wood pellet trade.

Some other authors stressed the trend of leakage more broadly regarding greenhouse gas emissions. For instance, Kanemoto et al. (2014) found that the embedded emissions in global trades, especially the non-CO2 emissions such as SOx and NOx, were not sufficiently accounted for in national and sectoral carbon budgets. They raised the concern that leakage may undermine national emissions reductions targets (see **Section 2.2.1**). However, large-scale quantification of the relationship between BEF and deforestation is difficult due to limited data availability (Gao et al. 2011).

The issues of greenhouse gas accounting and leakage for domestic and international sourcing are essentially reflections of the context at a supply-chain scale. For example, the ability of the system boundary (**Section 2.2**) to capture potential CO_2 leakage, the counterfactual energy sources to be substituted (**Section 2.3**), and the ways in which biomass is extracted (**Section 2.4.1**). To mitigate the potential negative environmental impacts of international trade, some authors argued for better regulation of the imported sources of BEF. For instance, Norton et al. (2019) called for the change of the current United Nations Framework Convention on Climate Change's accounting rules. Currently, these rules allow imported biomass to be treated as zero emissions at the point of combustion, ignoring the risks of unsustainably extracted biomass and embedded emissions of international trades. Some authors argued that the use of domestic biomass sources could avoid some of the negative environmental impacts of global trades and improve domestic energy security. Mandley et al. (2020) showed that there is a significant untapped domestic potential for Europe to meet the projected demand.

2.5 Effects of market changes

Despite the growing need for BEF at global scale, local market development has various barriers such as market creation, infrastructure development, community engagement, inconsistent policy support, etc. (Mayfield et al. 2007; Galik et al. 2021). For example, wood pellet prices can be uncompetitive due to high costs of feedstock (including sustainable forest management) and pellet plant operation (Visser, Hoefnagels, and Junginger 2020). Reduced employment with an aging workforce over the past two decades (He et al. 2021) and lack of training (Vaughan, Edgeley, and Han 2022) in the U.S. logging industry also pose challenges to the expansion of local BEF industry. Nonetheless, many studies projected further growth of the BEF industry and global trade and raised various concerns regarding the consequences of the subsequent market changes.

2.5.1 Land-use conflicts

Land is a finite resource demanded for the production of food, animal feed, fiber, and various biobased materials including bioenergy. The increasing demand of biomass for the production of bioenergy is generating land-use conflicts, and some claim it is causing land-use change (Dauber et al. 2012). Global analysis by Kraxner et al. (2013) indicated that with rising population and projected consumption levels, there will not be enough land to simultaneously conserve natural areas completely, halt forest loss, and switch to 100% renewable energy. Land-use changes related to bioenergy from forests can be direct, where land use is changed to bioenergy feedstock production itself. Indirect land-use change is the change in land use outside of the bioenergy production area induced by the changes of bioenergy feedstock supply and demand. For example, when the conversion of land use or diversion of crop use leads to the displaced crops to be produced elsewhere or to require more land areas to meet the demand (Wicke et al. 2012). These processes are associated with many environmental and ethical problems. Deforestation or other land-use changes will increase greenhouse gas emissions and offset the potential climate effects of bioenergy utilization (Peng et al. 2023; Abt, Abt, and Galik 2012). When bioenergy competes with food production, it raises the risk of harming food security, especially of poor populations (Gamborg et al. 2012). The competition between bioenergy and other renewable energy technology also raises the need to consider tradeoffs in benefits (Galik et al. 2021), such as solar farm development versus bioenergy production (Calvert and Mabee 2015).

However, land use conflicts can be reconciled, and multiple demands can be integrated to improve resource management (Kline et al. 2017). Researchers have proposed solutions in different directions, to either integrate or segregate the food and biomass production systems. For example, agroforestry has been promoted for its coproduction of food and biomass and multiple ecosystem services, including carbon sequestration, biodiversity conservation, soil improvement, and air and water quality (Jose 2009; Sharma et al. 2016). Calvert and Mabee (2015) identified possibilities of meeting regional electricity demand with sufficient biomass resources and having rooftop solar PV as backup to cope with peak demands. In a parallel approach, bioenergy production could be dedicated on ‘surplus’ lands where minimal or no land competition would be developed (Dauber et al. 2012). Surplus lands are 1) land currently not in use for the production of food, animal feed, fiber or other renewable resources due to poor soil fertility or abiotic stress, and 2) land currently no longer needed for food and feed production because of the intensification and rationalization of production, resulting in yield increases and thus a reduced requirement for land (Dauber et al. 2012). For example, the potential of bioenergy production on marginal land has been discussed and assessed by numerous studies (Gelfand et al. 2013; Mehmood et al. 2017) (see **Section 2.3.2**). Kline et al. (2017) summarized six priorities for fostering appropriate synergies between bioenergy and food security including clarity of communication; recognition of the potential of synergy; investments to build capacity and infrastructure; incentivization for local production; and stakeholder engagement.

2.5.2 Competing demand for wood biomass

Increases in population size and affluence have driven the rise of demand for forest-based biomass, mainly in the construction and packaging sectors where demands are expected to triple and double by 2030, respectively, compared to 2018 levels (FAO 2022). How does the forest sector supply biomass production sufficiently to meet this increasing biomass demand in conjunction with the development of bioenergy becomes a critical question.

Some authors are concerned that the increasing demand for BEF may exceed the potential increase in sustainable supply of wood biomass (Börjesson, Hansson, and Berndes 2017). A possible consequence is the increase of harvest level (Buchholz, Gunn, and Saah 2017), which greatly affects the climate effects of BEF due to the increase of harvest rates, the decrease of forest carbon stocks, increase of greenhouse gas emissions, and changes of surface albedo and aerosols (Peng et al. 2023; Abt, Abt, and Galik 2012; Kalliokoski et al. 2020). In a broader sense, some estimate that we have exceeded the limit to the human appropriation of biosphere's net primary production as a planetary boundary (K. Richardson et al. 2023), and crossing the tipping point can lead to irreversible cascading effects including forest dieback and other societal crises (Pörtner et al. 2023). Increased harvest is, however, not always the case, as Jåstad et al. (2021) estimated only a 1.6% increase in harvest after tripling the amount of heat generated by bioenergy. Meanwhile, many authors showed that biomass demand growth can drive forest resource investment and management, which can improve global forest management, promote forest health and resilience, therefore provide benefits on carbon, climate, biodiversity, and multiple ecosystem services (Kim et al. 2018; Favero et al. 2023; Kraxner et al. 2013; Cantegril et al. 2019).

Some also are concerned that increasing and competing wood biomass demand will lead to market disruption of the forest sector. For instance, Buongiorno, Raunikar, and Zhu (2011) projected that doubling the growth rate of global bioenergy demand would cause the price of industrial roundwood to rise by nearly 30% in 2030, and subsequently lead to up to 15% higher prices for sawnwood, panels, and paper. Nepal et al. (2019) projected that increased consumption of wood for energy in the United State in 2050 will lead to the diversion of about 37 million m^3 of pulpwood away from pulpwood-using traditional products (e.g., panels and paper), reducing production and net exports of paper and paperboard by up to 3 million tonnes. Brandeis and Abt (2019) already found increased roundwood use for pellet production in Southern U.S. between 2011 and 2015.

However, most of the BEF demand can be met with logging and mill residues that will also increase following increased harvest and wood production. A survey in the U.S. South showed that 70% of mills already uses woody residues for energy purposes (Pokharel, Grala, and Grebner 2017). By the end of the century, some predict residues can supply between 20% and 100% of the demand, depending on the scenario (Favero et al. 2023). The economic model from Nepal et al. (2019) also projected that logging and mill residues met 99.9% of their baseline BEF demand in 2050, although the increased demand in the high-energy scenario has to be met with pulpwood. The U.S. Department of Energy Billion Ton Report projected that logging residue can provide over 20 million dry tons BEF feedstock at the price of USD 40 in their baseline scenario in 2040 (Langholtz, Stokes, and Eaton 2016). An extra 95 million dry tons biomass can be supplied by whole-tree biomass but with double the price at USD 80. These research showed that increasing capacity of logging and mill residue utilization is an prerequisite of achieving the projected higher BEF demand. Notably, economic models evaluating market changes also incorporate different context. Interpretation of different results also need to consider the differences in assumptions and methods discussed in previous sections (**Sections 2.1-2.4**).

2.6 Environmental Justice and Equity

2.6.1 Defining environmental justice for bioenergy from forests

The definition of environmental justice involves the four pillars of the theories of justice (Schlosberg 2007; Levenda, Behrsin, and Disano 2021): 1) *distributive justice*, the equitable distribution of environmental risks and benefits; 2) *procedural or participatory justice*, the way in which individuals and groups are included in decision-making activities and processes; 3) *recognition*, the inclusion and valuing of divergent perspectives rooted in social, cultural, ethnic, racial and gender differences; and 4) *capability*, the ability for people to live healthy, safe, dignified lives.

The U.S. EPA defines environmental justice as the just treatment and meaningful involvement of all people, regardless of income, race, color, national origin, Tribal affiliation, or disability, in agency decision-making and other Federal activities that affect human health and the environment so that so that people are: fully protected from disproportionate and adverse human health and environmental effects (including risks) and hazards; have equitable access to a healthy, sustainable, and resilient environment in which to live, play, work, learn, grow, worship, and engage in cultural and subsistence practices (US EPA 2024).

The demographic groups related to the definition of environmental justice are often termed as *environmental justice communities*. These communities include local communities, indigenous and tribal communities, communities of color, low-income communities, women, ethnic minorities, rural communities, small-scale farmers, unemployed people, foreign-born residents, lower class, and other disadvantaged or marginalized groups (Mohai, Pellow, and Roberts 2009; Levenda, Behrsin, and Disano 2021).

Currently, the primary focus of environmental justice studies for bioenergy are *distributive and procedural* concerns of unequal distribution of environmental burdens and benefits, and *procedural or participatory justice* issues of lacking upstream engagement (Shrader-Frechette and Preisser 2013; Levenda, Behrsin, and Disano 2021).

2.6.2 Distribution of environmental burdens and benefits

Bioenergy projects are often disproportionately sited near environmental justice communities and impose more ecological and environmental burdens on these communities (Shrader-Frechette and Preisser 2013). In the United States, The National Association for the Advancement of Colored People (NAACP) reported that African Americans who reside near energy production facilities including biomass power plants are more likely to suffer negative health impacts than any other group of Americans (NAACP 2013). Koester and Davis (2018) estimated that wood pellet production facilities in the southeastern United States are 50% more likely to be located in environmental justice communities. In the global south where domestic energy consumption relies on primary bioenergy sources (**see Section 1.5**), there is also a gender issue that imposes more health risks to women, for their traditional role in the collection and use of fuelwood (Wickramasinghe 2003; Das, Pradhan, and Nonhebel 2019).

Air pollution and the associated human health issues following increases in BEF production and consumption raised strong environmental justice and equity concerns. Buonocore et al. (2021) identified the primary driver of health impacts of air pollution in the U.S. has shifted from coal combustion in 2008 to a mixture of energy types—largely gas and biomass—indicating growing public health burdens from biomass combustion. Similarly, Picciano et al. (2022) simulated possible consequences of subsidizing woody biomass co-firing power plant in the Eastern U.S., and found negative impacts on air quality compared to positive outcomes from other decarbonization pathways such as nuclear, wind, and solar. Air pollution burdens are not equally distributed. Rogalsky et al. (2014) estimated that between 5 and 6 million low-income people in the United States are likely exposed to household air pollution from burning solid fuels including wood and coal. Tran, Juno, and Arunachalam (2023) estimated that 2.3 million people live within 2 km of a biomass facility and could be subject to adverse health impacts from their emissions, with disparities for racial and ethnic minority groups.

Meanwhile, it is unclear whether the environmental justice communities at risk also receive benefits from bioenergy projects (Buck 2019), and the economic profits of bioenergy production (like any production) may not be distributed equally (White, 2016). Co-benefits are often mentioned when discussing the distributive justice benefits from bioenergy. For example, Zurba and Bullock (2020) highlighted the ability of new bioenergy infrastructures to support wellbeing in areas beyond the sectoral need of energy for Canadian indigenous people, such as short- and/or long-term economic gains, employment, and infrastructures for transportation, education, etc. A guide for sustainable bioenergy in the global south by the Center for International Forestry Research (CIFOR) also summarized the benefits of BEF development for local communities such as new employment, income generation, and sustainable forest management (Brady and Sharma 2023).

2.6.3 Upstream engagement and participatory decision making

The *procedural or participatory justice* issues mainly concern the lack of upstream engagement and meaningful participation in decision-making (Levenda, Behrsin, and Disano 2021). For example, White (2016) found that traditional landowners not directly involved in the bioenergy market expansion may suffer greater restrictions on traditional land-use rights. Some authors argued that *procedural justice* is essential in establishing the *social license to operate*, which describes the perceptions of local stakeholders that a project, a company, or an industry that operates in a given area or region is socially acceptable or legitimate (Buck 2019; Dowd, Rodriguez, and Jeanneret 2015). Surveys in the Southern United States showed that private landowners' attitude and perception towards bioenergy strongly affect their willingness and intention to produce wood biomass for bioenergy (Hodges et al. 2019; Leitch et al. 2013). The major barriers or the primary ways of enhancing future bioenergy production are identified as future market values, as well as technical and financial support. Mittlefehldt and Tedford (2014) described the local decision-making process for community-scale bioenergy systems in Vermont, where local residents were able to oppose the construction of a biomass heating system for air quality concerns. The authors therefore argued that when people who will be affected by decisions about energy technologies are involved in the planning process, more equitable outcomes are likely to result. However, O'Beirne et al. (2020) argued that there is likely to be a fundamental clash between the needs and interests of the public at different scales. It is therefore necessary to find the scale at which socio-legal governance is required and consider different levels of participation and engagement.

2.6.4 Integrated environmental and socioeconomic assessment

One way to support environmental justice and equity in BEF is the integration of socio-economic and environmental values for more nuanced policy rationales (Holmgren, D’Amato, and Giurca 2020). Indicators for the evaluation of socioeconomic performance of BEF are readily available: Dale et al. (2013) identified six categories of socioeconomic indicators including social well-being (e.g., employment, income, health), energy security (e.g., energy price), trade (e.g., trade volume), profitability (e.g., net present value), resource conservation (e.g., depletion of fossil energy), and social acceptability (e.g., public opinion, transparency). More integrated assessments (e.g., Cambero and Sowlati 2016) are needed to identify environmental justice and equity issues in BEF projects and facilitate more socially and environmentally sustainable BEF options.

3. Focus Group Participant Perspectives

Between April and August of 2023, four focus groups were organized under The Forests Dialogue's Bioenergy from Forests Initiative. Each distinct focus group represented one stakeholder group (Forest Owners and Managers, Civil Society Organizations, Research and Academia, or the Wood Pellet and Energy Sectors), and provided firsthand insights into the complexities surrounding the future of BEF in the United States. The three-part structure of each focus group included sharing perspectives on key objectives, concerns, and opportunities related to BEF, group discussions on the conditions for a successful and sustainable bioenergy sector, and learning about The Forests Dialogue (TFD) and exploring the potential for a BEF dialogue process. The nuanced discussions within these groups unveiled three key conversation topics: The sourcing of biomass and the social and ecological conditions around its production, BEF in the context of the wider markets of forest products & energy, and BEF and the delivery of climate benefits.

3.1 Dimensions of Perspectives

Dimension I: The Sourcing of Biomass and the Social and Ecological Conditions Around its Production

Participants often discussed the complexities of biomass sourcing, emphasizing the social and ecological conditions surrounding its production. Participants mostly expressed agreement that biomass can be a product or byproduct of managing forests for various values, economic and non-economic. Forest Owners and Managers, in particular, stressed the importance of managing forests for climate resilience, including promoting practices such as the removal of low-grade wood, and the role of providing economic markets to incentivize these practices. The need for fire prevention in the Western US was brought up, with some noting that managing forests to prevent catastrophic wildfires has become an environmental justice issue due to the associated health impacts of air pollution. Lastly, participants often highlighted and discussed the need for transparent sourcing, certification, and sustainability guidelines to ensure the sustainability of biomass supply.

Dimension 2: BEF in the Context of the Wider Markets of Forest Products & Energy

The second dimension of conversations focused on BEF within the broader context of forest products and energy markets. Some participants emphasized the importance of recognizing biomass production as an integral part of an integrated forest product supply chain. These participants underscored the "cascading use" principle, advocating for the prioritized utilization of raw material for long-lived and efficient forest products before resorting to biomass at the end of its life cycle. Some participants highlighted opportunities for biomass in energy production, especially in areas with a biomass surplus due to the closure of pulp and paper mills. Divergent views were present on issues such as certification, sustainability guidelines, and sourcing standards. Some participants emphasized the importance of stringent criteria to ensure sustainability, while others raised concerns about potential environmental and social impacts, calling for a careful balance between economic considerations and sustainable forest management practices.

Dimension 3: Delivery of Climate Benefits

Participants expressed a strong desire to understand BEF's role in climate change resilience and mitigation pathways. Discussions highlighted BEF's potential in net-zero emissions pathways, particularly utilizing bioenergy with carbon capture and storage (BECCS). However, concerns were raised around the assumption of the carbon neutrality of these practices, with some participants emphasizing the need for nuanced greenhouse gas accounting. Some participants recognized the short and medium-term importance of BEF for climate benefits but stressed the eventual need for phasing it out as cleaner energy sources become more available. Varied perspectives emerged on the geographical and temporal nuances of climate benefits, emphasizing the importance of considering local usage versus export scenarios and the associated impacts on climate and ecology.

3.2 Various Stakeholder Entry Points

Consistently, conversations highlighted the diverse entry points of stakeholders around BEF-related topics. Geographic differences, particularly between the Western and Southeastern United States, contributed to distinct perspectives. While topics surrounding Western forests were weighted towards their fire-prone conditions, topics around Southeastern forests focused on the demand for bioenergy and the impacts on disenfranchised communities. Northeast forest topics focused on the importance of using local biomass for energy production and home heating, considering recent changes in the forest products market.

Participant entry points also varied in their emphasis on climate change mitigation as the primary motivation to engage in BEF. Some participants' primary focus on bioenergy from forests was for its potential role in achieving net zero climate emissions. These actors tended to be interested in identifying areas of agreement for when and where bioenergy from forests has a positive climate impact in order to catalyze collaborative actions or make policy recommendations. While other participants were interested in understanding the climate impacts of BEF they did not list this as their primary motivation. Some participants cautioned others to not focus on climate change mitigation in isolation from other equity, environmental, and social considerations and impacts.

3.3 Areas for Further Discussion, Dialogue and Conclusions

In addition to conversations around the three key topics, focus groups identified critical areas for further discussion as well as recommendations for dialogue:

Areas for Further Discussion:

- How to understand the sustainability of biomass for BEF: traceability & different interpretation of sustainability
- The meaning of community risks and benefits
- Suggestions and cautions for regulatory and market mechanisms for BEF
- Appropriate scale for BEF as a nature-based solution to climate change

Recommendations for Dialogue:

- Do not presume or rely on technical expertise (inclusive to non-research participants)
- Use specific framing around appropriate uses for biomass, energy sources, and carbon-capture technology
- Hear from critics of BEF
- Engage communities and learning about environmental justice concerns directly
- Be aware of debates and confusion over terminology
- Learn from diverse BEF contexts
- Avoid using the dialogue as a venue to resolve highly technical academic debates

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