



Areas of concern and disagreement in the climate effects of bioenergy from forests

Weier Liu^{1,2,3} , Miaohan Tang⁴

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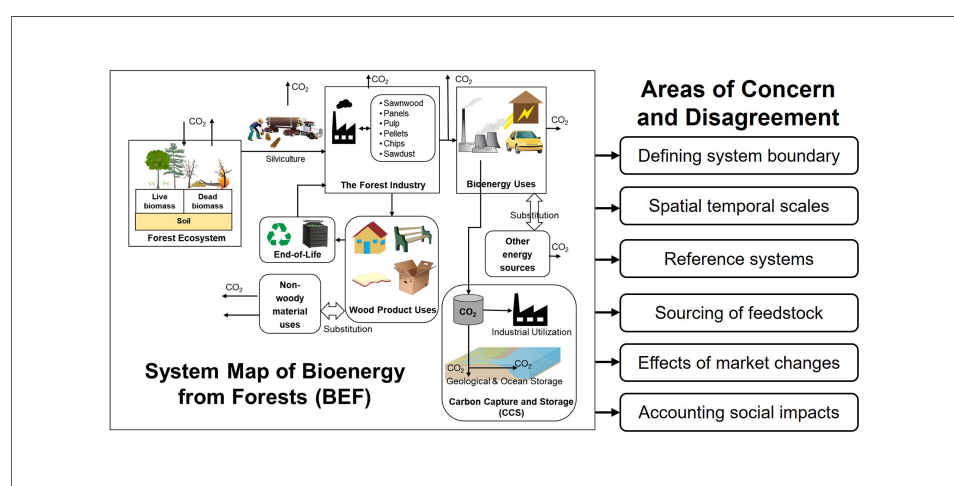
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Abstract

Bioenergy from forests (BEF) is widely promoted as a significant contributor to the global renewable energy transition and a primary pathway of achieving climate goals. However, the climate effects of BEF remain deeply contested due to the complexity of the BEF system that requires a multitude of methodological choices and assumptions to contextualize. The resulting divergent conclusions across studies generated scientific disagreement and policy concerns. This review provides a holistic synthesis of the environmental, economic, and social contexts shaping the climate effects of BEF. We first conducted a bibliometric analysis of BEF-related articles to map research trends and dominant paradigms, resulting in four major research clusters spanning forestry systems, bioenergy production, bioeconomy interactions, and emerging climate solutions. Building on this overview, we identifies six key areas of concern and disagreement that critically influence BEF climate assessments: system boundaries, spatial and temporal scales, reference systems, feedstock sourcing, effects of market changes, and social impacts. We provide methodological recommendations for the six aspects. For each area, we articulate contrasting perspectives, underlying assumptions, and empirical evidence, highlighting how methodological choices can lead to fundamentally different conclusions regarding BEF's climate performance. We provide methodological recommendations to improve



¹Xianghu Laboratory, Hangzhou 311231, Zhejiang, China.

²The Forest School at the Yale School of the Environment, Yale University, New Haven, CT 06511, USA.

³Yale Center for Natural Carbon Capture, Yale University, New Haven, CT 06511, USA.

⁴School of Public Administration, Zhejiang University of Finance & Economics, Hangzhou 310018, Zhejiang, China.

Correspondence to: Dr. Miaohan Tang, School of Public Administration, Zhejiang University of Finance & Economics, Hangzhou 310018, Zhejiang, China. E-mail: miaohan.tang@zufe.edu.cn

comparability, transparency, and policy relevance of BEF assessments. By clarifying sources of disagreement and framing BEF within a broader sustainability context, this work aims to reduce confusion and support more informed, evidence-based decision-making on the future role of BEF in climate mitigation strategies.

INTRODUCTION

Bioenergy from forests (BEF) is widely considered a renewable energy^[1,2] but deeply contested for its net climate effects^[3-5]. Through forest harvesting and thinning operations, tree trunks, branches, tops, and other forest residues comprise forest biomass streams for energy production. BEF uses wood biomass directly as energy sources or as feedstock for further processing into other energy products like pellets or biofuels. Globally, carbon accumulation through forest growth, including regrowth of harvested forests, is greater than carbon loss through disturbances and deforestation. Forests are therefore estimated to be a net carbon sink of -7.6 Gt CO₂e per year^[6]. Therefore, under the assumption that across large spatial scales and for longer time horizons, forests accumulate carbon through photosynthesis at a faster rate than they lose carbon through the BEF supply chain, the production and consumption of BEF are considered net carbon neutral^[7-10].

Because many consider BEF as a renewable energy source, it has been at the forefront of the global sustainable energy transition and widely included in projections of how to meet international carbon neutrality goals. Currently, modern bioenergy (excluding traditional use of biomass such as wood, charcoal and dung) accounts for 55% of global renewable energy supply and over 6% of global energy supply^[11]. In Europe, forestry accounts for more than 60% of all EU domestic biomass supply for energy purposes^[12]. One-third of the global population uses of BEF in the form of fuelwood and wood charcoal to support domestic energy provisioning^[13], consuming 2,525.7 million m³ of wood biomass globally in 2019 according to latest estimations^[14]. Processing wood into pellets for bioenergy is rapidly growing in global popularity. Between 2012 and 2022, global pellet production more than doubled from less than 20 million tons to over 40 million tons, while the total amount of pellets export globally tripled from around 10 million tons to 30 million tons^[15]. By 2050, BEF is projected to represent up to 18% of the world's primary energy consumption^[16].

There are longstanding and unresolved concerns and disagreements about the climate effects of BEF, leading to science and policy debates and public confusion that made the production and utilization of BEF controversial. Conversion of wood biomass to energy involves a complex system consisting of interacting ecological, technological, economic, and social processes^[17]. Analysis of the BEF system requires a series of methodological choices and model assumptions on the context of the system and its underlying processes. These choices and assumptions resulted in conflicting outcomes in terms of the potential of future BEF market expansion and the climate effects, pointing to different directions where BEF has net positive or negative impact on global sustainability^[3,10,18-20].

There is a vast amount of literature discussing climate effects of bioenergy, which some existing studies tried to synthesize to alleviate discrepancies. For example, a meta-analysis by Buchholz *et al.* (2016)^[21] identified in BEF greenhouse gas (GHG) emission accounting studies that the inclusion of wildfire dynamics was the most influential assumption. Martin-Gamboa *et al.* (2020)^[22] reviewed life cycle assessment (LCA) of biomass pellets and identified key methodological choices related with multifunctionality and allocation. Cowie *et al.* (2021)^[18] stressed that temporal and spatial system boundaries and reference (counterfactual) scenarios are key methodological choices that strongly influence results. Here, we try to build upon current synthesis on BEF's climate effects and provide a more holistic view of the BEF system context across the environmental,

economic and social pillars.

In this review, we aim to provide a holistic view for the environmental, economic and social contexts of the BEF system and the implications of the system contexts on BEF's climate effects. We performed a bibliometric analysis to depict the current state and development patterns of BEF-related research. We summarize from the current state of research six major areas of concern and disagreement related to the BEF system context. Our work complements existing efforts to reconcile the ongoing debate by articulating opposing perspectives and evidence on each of the six key areas. Our goal is to reduce confusion arose from the diverging studies on the climate effects of BEF, thus building a common ground for future discussions around policy and industrial developments of BEF.

CURRENT STATE OF BEF RESEARCH

We performed a bibliometric analysis to give a comprehensive overview of the current state and development patterns of research related to BEF and its climate effects. We selected the Web of Science Core Collection database with records dated from 2006 to 2025 for a complete coverage of the most recent and influential literature. We used the search term “forest” OR “forestry” OR “wood” OR “woody” AND “bioenergy” AND “climate change”. The search resulted in 2,379 articles after removal of duplication. We used VOSviewer v1.6.20 to perform keyword co-occurrence analysis^[23] (original input and output files uploaded in [Supplementary Material](#)).

[Figure 1](#) illustrates four clusters of research keywords that tend to co-occur in literature. We interpreted the co-occurring keywords in each of the clusters and summarized four major topic areas of current BEF studies. The green cluster focuses on the forest and forestry system, with keywords related to tree species (e.g., poplar, eucalyptus) and biogeochemical processes (e.g., soil organic carbon/SOC, evapotranspiration). The blue cluster focuses on the bioenergy industry system, with keywords related to biomass processing technologies (e.g., pyrolysis, gasification) and bioenergy types (e.g., biogas, bioethanol). The red cluster broadly addresses the bioeconomy, with more general keywords that are sustainability-related (e.g., mitigation, renewable energy, biogenic carbon, carbon neutral). The yellow cluster is relatively small that covers emerging topics of climate solutions such as CDR (carbon dioxide removal), BECCS (bioenergy with carbon capture and storage) and afforestation/reforestation.

The keyword clusters represent the current research paradigms of BEF, with the co-occurring keywords reflecting the different methodological choices made. Results of research from each cluster should be interpreted only in the context of the related methodological choices. Here, we synthesize from current research keywords six key areas of concern and disagreement related to the climate effects of BEF.

DEFINING SYSTEM BOUNDARY

System boundary is a key methodological choice that strongly influences the climate effects of BEF systems and the comparability of results. The BEF system context consists of processes and flows that describe inputs and outputs of the biosphere (i.e., interactions with the natural environment, such as consumption of natural resources and emissions to soil, water, or air) and technosphere (i.e., inputs and outputs of technological systems, such as energy and material consumption)^[24]. Each BEF system analysis needs to draw a distinctive boundary between the technical system and the environment, between the significant and insignificant processes, and between the technological system under study and other technological systems^[25]. The complex system map of the BEF system provides a multitude of plausible methodological choices in defining system boundaries, from including or excluding components of the forest ecosystem (e.g. soil carbon) to processes of the bioeconomy (e.g. product substitution) [[Figure 2A-D](#)]. Many keywords emphasized by

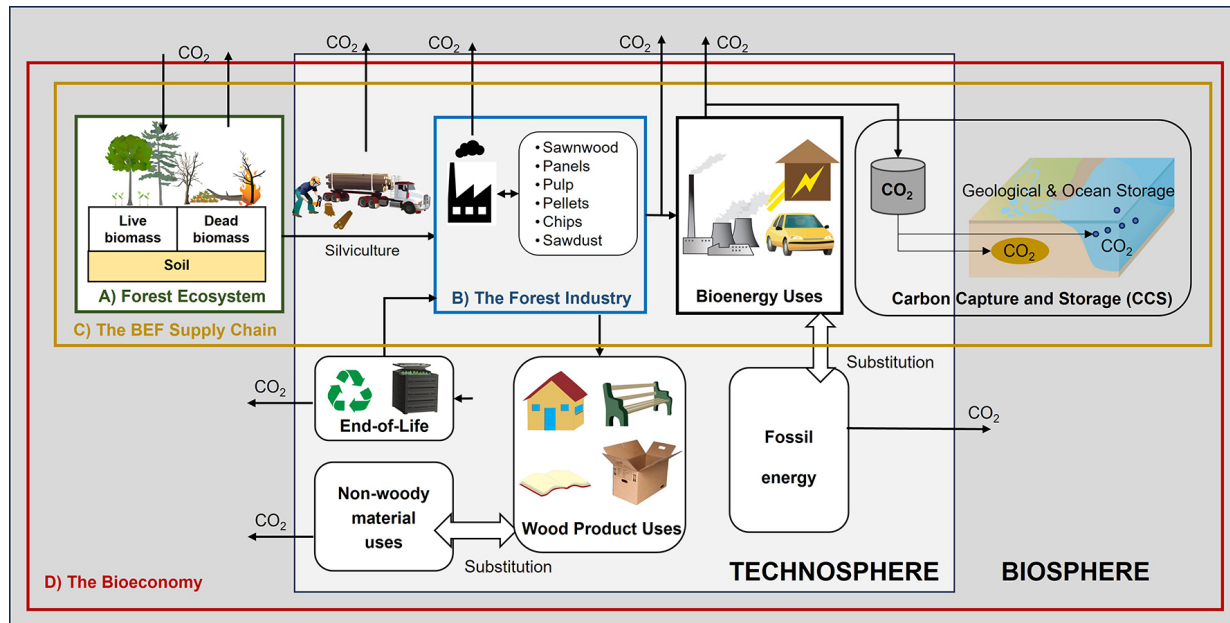


Figure 2. Schematic framework of the BEF system context that includes biosphere and technosphere processes and flows (The concept of the figure is referenced from Giuntoli et al.^[177] and Cowie et al.^[183]). Rectangles of different colors represent choices of system boundaries. Icons are sourced from Integration and Application Network^[26].

FAO Yearbook of Forest Products^[31]. We subsequently classified the BEF product terms into primary, secondary, tertiary post-consumer, and processed bioenergy^[17,30]. Physiochemical properties of the wood biomass feedstock^[32] and the treatment techniques^[33] determine the energy intensity of BEF production and energy efficiency of the final product^[34]. Wood pellets produced from steam exploded shavings have 4 times higher global warming potential (GWP) than untreated mixed sawdust^[35]. Different pyrolysis pretreatment pathways for biogas co-production lead to GWPs that widely range from 135 to 206 kg CO₂-eq per kg main product^[36]. Technical pathways included in a BEF system boundary would therefore lead to diverging climate effects.

(3) Supply chain. At the BEF supply chain level [Figure 2C], inclusion and exclusion of key processes strongly determine BEF's total climate effects. For example, shipment contributes to 31% of the total carbon footprint of wood pellets exported from the US to the UK^[37]; inclusion of carbon capture and storage (CCS) after BEF combustion, termed bioenergy with carbon capture and storage (BECCS)^[38], could achieve negative-emissions in specific BEF cases^[39].

(4) Substitution. At the bioeconomy level [Figure 2D], consumption of BEF products provides energy that would otherwise be provided by the combustion of fossil fuels, therefore avoiding fossil emission. Substitution or displacement factors measure this climate benefit, which widely ranges from -0.08 to up to 2.5 t C/t C according to existing literature^[40], meaning that the use of BEF could induce extra GHG emissions or avoid emissions of up to 2.5 t C from fossil fuels.

Depending on the scientific discipline and the research objective, analysis of BEF systems may choose system boundaries at the forest ecosystem, the forestry industry, the BEF supply chain, and the bioeconomy levels. The varying climate effects resulted should therefore only be compared at the same system level to avoid misinterpretation. Different technosphere options such as the biomass processing techniques and incorporation of CCS should be evaluated using tools such as the Global Sensitivity Analysis (GSA)^[24,41], to provide ranges of potential outcomes rather than single-point estimates.

Table 1. Product classification of bioenergy from forests

Classification	Bioenergy from forests	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 sprouted 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
	Bark	Directly from the trunks and branches of trees
Secondary Bioenergy	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	Including construction and demolition debris, discarded wood from furniture, packaging, pallets, and other wood-containing products that have reached the end of their life cycle
	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
Processed Bioenergy	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

SPATIAL AND TEMPORAL SCALES

The temporal dynamics of forest ecological and management processes and spatial heterogeneity of forest ecosystem properties are major sources of uncertainty in the climate effects of BEF. Choosing a specific time point or period on the curve of forest carbon stock leads to different results of forest standing carbon values and net carbon balances [Figure 3]. From a temporal perspective, the term “carbon debt” is a hotspot of current BEF research [Figure 1]. It describes the pulse of carbon emissions following harvesting and burning of forest biomass produces, while the time required for new trees to gradually remove atmospheric CO₂ and store carbon in trees and soils is termed “payback time”^[4]. From a spatial perspective, current research adopts multiple choices of scales from plantation to countries (e.g., China, Brazil) and regions (e.g., EU) [Figure 1]. Under these different spatial scales, the harvest-regrow cycle and the associated carbon debt-payback time are diluted over larger scales, because forest management and BEF production generally follow a management plan that involves multiple stands and operates in rotation^[18,42] [Figure 3]. Carbon storage per unit area therefore shows milder fluctuations due to the mixture of forest stands at different stages (age classes) in the forest parcel or landscape.

Such temporal dynamics and spatial heterogeneity caused discrepancies in the estimated carbon debts and payback times. Studies estimated BEF payback times that ranges from less than one year to up to 1,000 years^[4,43]. When looking at fine scales and short terms, harvest typically removes a large portion of the carbon within the system, causing large carbon debts. Some thus argue that this initial carbon debt from BEF

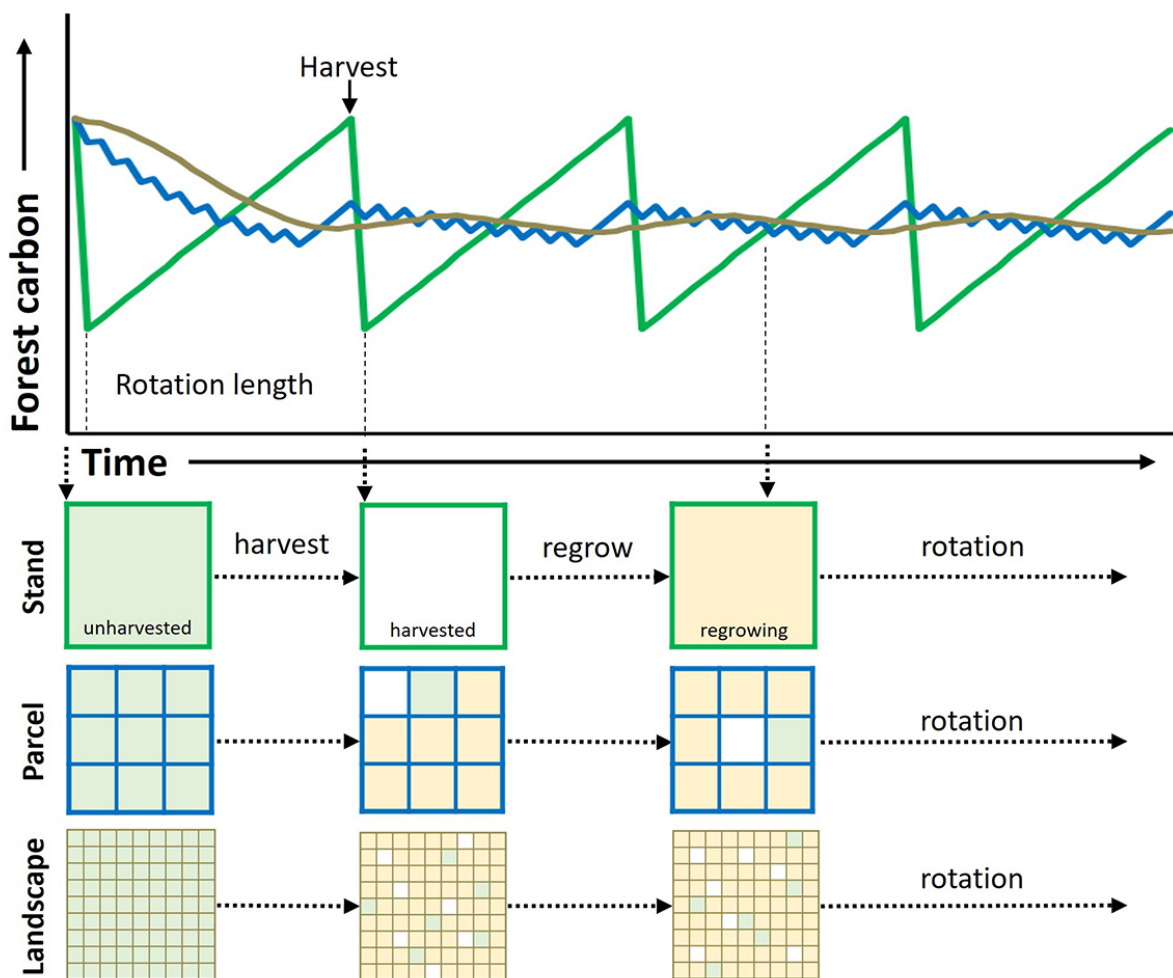


Figure 3. Illustration of forest carbon dynamics under different spatial and temporal scales (The concept of the figure is referenced from Janowiak et al.^[42]). Fluctuations of forest carbon per unit area in the line graph depict carbon debt and its payback time at different forest scales. The gridded plots illustrate the harvest rotation of forest stand, parcel and landscape that leads to different behaviors of the dynamics of area-averaged carbon storage.

sourcing, production and combustion poses a risk of crossing a climate tipping point that could lead to irreversible harm^[44,45]. Meanwhile, studies at regional level show higher emission reductions compared to forest plot level^[46]. At larger time horizons (> 60 years), emissions from BEF also have lower GWP than fossil energy, with values between 0 to 1 CO₂-equivalent depending on harvest rotation length^[47,48]. Overall, many large-scale and long-term estimations show that BEF's carbon debt payback time is less than 100 years, indicating emission reduction scenarios that fit within the time horizons of nations' climate targets^[49-51].

It is therefore crucial to weigh and synthesize BEF's climate effects at different spatial and temporal scales to understand the implications of BEF development. Key scale-related elements in an LCA for BEF include spatial scales of the studies forest landscape and the BEF supply chain, and temporal scales of the forestry operations (e.g., rotation length^[52]) and the climate targets of interest. Dynamic^[53,54] and spatially explicit^[55] LCA approaches could address the discrepancies by providing more consistent and higher-resolution climate effects.

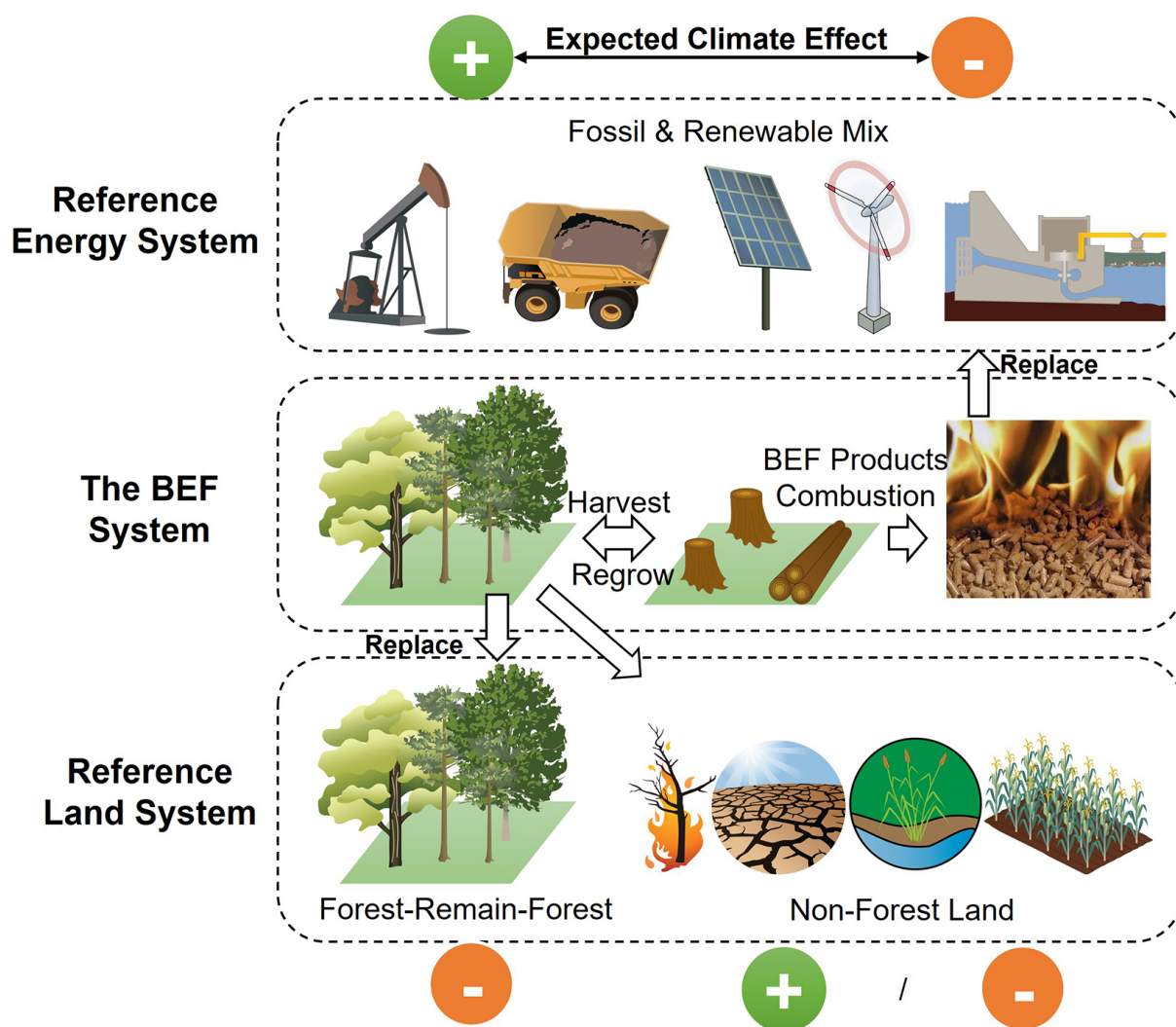


Figure 4. Possible reference energy and land use systems replaced by the BEF system and their influence on the resulting climate effects. Icons are sourced from Integration and Application Network^[26].

REFERENCE SYSTEM

Climate effects of BEF are relative to a reference system (or baseline, counterfactual) that represents the situation in absence of the BEF system of concern. The system contexts often considered are either related to the products replaced by BEF^[40] or to the land use changed for BEF production^[56] [Figure 4]. Assumption on the reference system is a driving factor for the direction of the climate effects of a BEF system.

Climate effects of BEF are highly sensitive to the reference energy system or the energy system replaced. "Substitution" therefore becomes a key node on the keyword map of current BEF research [Figure 1]. However, the multitude of energy sources and technologies involved in the electricity and heat generation processes makes the energy mix highly variable^[18,57]. For example, Leturcq^[58] compared displacement factors of wood fuels displacing anthracite, heating oil and natural gas at different point-in-time in the energy consumption processes, and found results ranged from net negative impact of -0.95 t C/t C to an emission reduction of 0.88 t C/t C. The share of renewable energy in the counterfactual energy structure also plays a vital role. In current studies, 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 due to

constraints in energy generation, transmission and storage^[59,60]. Some authors argue, however, that as fossil fuel use declines and renewable energy production increases, wood will compare less favorably as an energy substitution^[61,62].

The reference land system or the land use replaced by BEF production also has multiple plausible choices that would largely determine the overall climate effect of a BEF system. Assuming existing forests that would persist without human disturbances, the introduction of BEF production induces large carbon footprints^[63] that was estimated to cause annual carbon costs of 3.5–4.2 Giga-ton CO₂-equivalent between 2010 and 2050^[64]. On the other hand, assuming non-forest lands as reference systems leads to mixed effects. For example, converting peatland to forests does not lead to climate benefit but impede peat carbon storage^[65]. Meanwhile, wood production on marginal lands is considered climate beneficial, where counterfactual land management would not involve productive uses due to poor soil properties, low quality groundwater, drought, undesired topology, and unfavorable climatic conditions^[66–68].

It is therefore important to evaluate the BEF system in the context of a broader portfolio of climate mitigation actions including energy transition and sustainable land use and management. Energy system contexts (e.g., energy structure, policy directions and technology development) and land use system contexts (e.g., forest ownership type and management plan) are essential in determining the climate effects of BEF. Prospective LCA approaches stand better chances in accounting for such contexts by evaluating the BEF system under projected future states^[69]. Combination with analytical tools such as the Integrated Assessment Models (IAM)^[70] is already represented in the current research [Figure 1]. Such methodological advances would allow better understanding of the trade-offs and synergies among actions and avoid BEF from undermining other climate strategies.

SOURCING OF FEEDSTOCK

Sourcing of BEF feedstock involves forest management, harvesting, processing, transportation and many other processes that determine the climate effect of BEF products. Feedstock is an important topic in current BEF research [Figure 1]. Table 2 gives a comprehensive summary of BEF feedstock sourcing strategies including intensive forest management^[71,72], sustainable forest management^[73–75], residue mobilization^[76–79], domestic sourcing^[80,81], and international sourcing^[82,83]. Assumptions can be broken down into the questions of how and where the feedstock is acquired. The ‘how’ question reflects pathways of the harvesting and processing of wood biomass. For example, despite the high productivity, intensive management strategy is widely criticized for the destructive consequences of forest clearing^[84–87]. Sustainable forest management, on the other hand, is argued to be able to provide climate benefits by improving forest resilience while utilizing the wood biomass that would otherwise be lost due to the disturbances and allowing faster forest recovery^[88]. Mobilizing logging residue could intensify BEF feedstock extraction without extra tree harvest, and was estimated to be able to provide 17%–20% additional biomass to the timber and pulp harvest^[52]. Sourcing scenarios therefore largely determine the carbon intensity and the cost-efficiency of the BEF system.

The “where” question reflects the carbon intensity of the BEF supply chain as well as the regional differences of forest management. 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^[15]. Many studies concluded overall climate benefits of BEF international trades with estimated net carbon neutrality^[89,90] or carbon savings^[37,91]. However, some argue that embedded emissions of international trades, especially the non-CO₂ GHGs and air pollutants such as SO_x and NO_x, are not sufficiently accounted for^[92]. In addition, there are concerns that Europe’s international sourcing for BEF would lead to expanded forest clearing worldwide and cause climate and biodiversity deterioration^[93], yet empirical evidence is insufficient at large scales^[94].

Table 2. Comparison of different feedstock sourcing strategies for BEF supply

Feedstock sourcing strategies	Sourcing processes involved	Examples	Climate effects	Side effects	References
Intensive forest management	Harvesting	Plantation, clearcut, 'Swedish forestry model'	High direct emissions, high productivity/fossil substitution	Negative impacts on native habitats and biodiversity	[71,72]
Sustainable forest management		Partial/selective logging, uneven-aged forest management, stand improvement	Relatively low direct emissions, low productivity/fossil substitution	Improvement of forest health and resilience	[73-75]
Residue mobilization	Harvesting and processing	Logging and mill residue utilization, wood product recycling	Relatively low productivity/fossil substitution, potential impact on soil carbon sequestration	Potential impacts on the forest floor ecosystem functions and biodiversity	[76-79]
Domestic sourcing	Harvesting, processing and transportation	Afforestation/reforestation, intensification	Potentially higher emissions through intensification and/or lower emissions through improved forest management	Market impacts on domestic forestry industry and land sector	[80,81]
International trade		EU wood pellet imports from the US	Embedded emissions of international transportation, regionally different carbon intensity of forest management	Inequality of climate and health risks to the exporting regions	[82,83]

Despite that how and where the feedstock is sourced would lead to substantial differences in the climate effect of BEF, the current United Nations Framework Convention on Climate Change (UNFCCC) accounting rules treat all imported biomass as zero emissions at the point of combustion^[95]. It is necessary to account for the effects of different forest management strategies on spatial temporal dynamics of the forest carbon cycle. Meanwhile, BEF scenarios should sufficiently evaluate the availability of domestic and international feedstock^[81] as well as risks of leakage^[96] to ensure a holistic view of BEF's climate effects.

EFFECTS OF MARKET CHANGES

Growing demand for BEF at global scale induces market changes in multiple industries including energy, forestry and agriculture [Figure 5]. Evaluation of market-driven effects should adopt consequential LCA as the approach expands the product system to include activities expected to change as a consequence of a change in demand^[97,98]. However, definition of market-mediated scenarios is difficult in practice and becomes the main source of uncertainty^[99]. On the one hand, BEF market expansion creates conflicts in wood biomass uses. Competition between BEF and the booming traditional wood sectors, such as packaging and construction^[13], may cause significant disruptions of the forestry sector. Global projections indicated that increasing demand for BEF would cause nearly 30% price increase for industrial roundwood and 15% for sawnwood, panels and paper by 2030^[100], which could hinder the substitution of fossil-based products. Meanwhile, it is not clear whether the ever-growing wood biomass demand would lead to production exceeding the sustainable supply capacity^[101,102], or stimulate more investment that facilitates sustainable management strategies^[103-106] and the mobilization of residue biomass.

On the other hand, expanding demand for wood biomass requires larger forest area. Such higher demand may incentivize afforestation and reforestation on lands that are currently unforested^[66], leading to net climate benefits. For example, Costanza *et al.*^[107] projected lower urbanization rates, thus less loss of forest cover and forest carbon storage, due to bioenergy production. However, BEF production could also compete with other land uses such as agriculture. Global analysis by Kraxner *et al.*^[108] warned that humankind may not have enough land to simultaneously conserve natural areas completely, halt forest loss, and switch to 100% renewable energy. Competition between BEF and food production may lead to direct land use changes

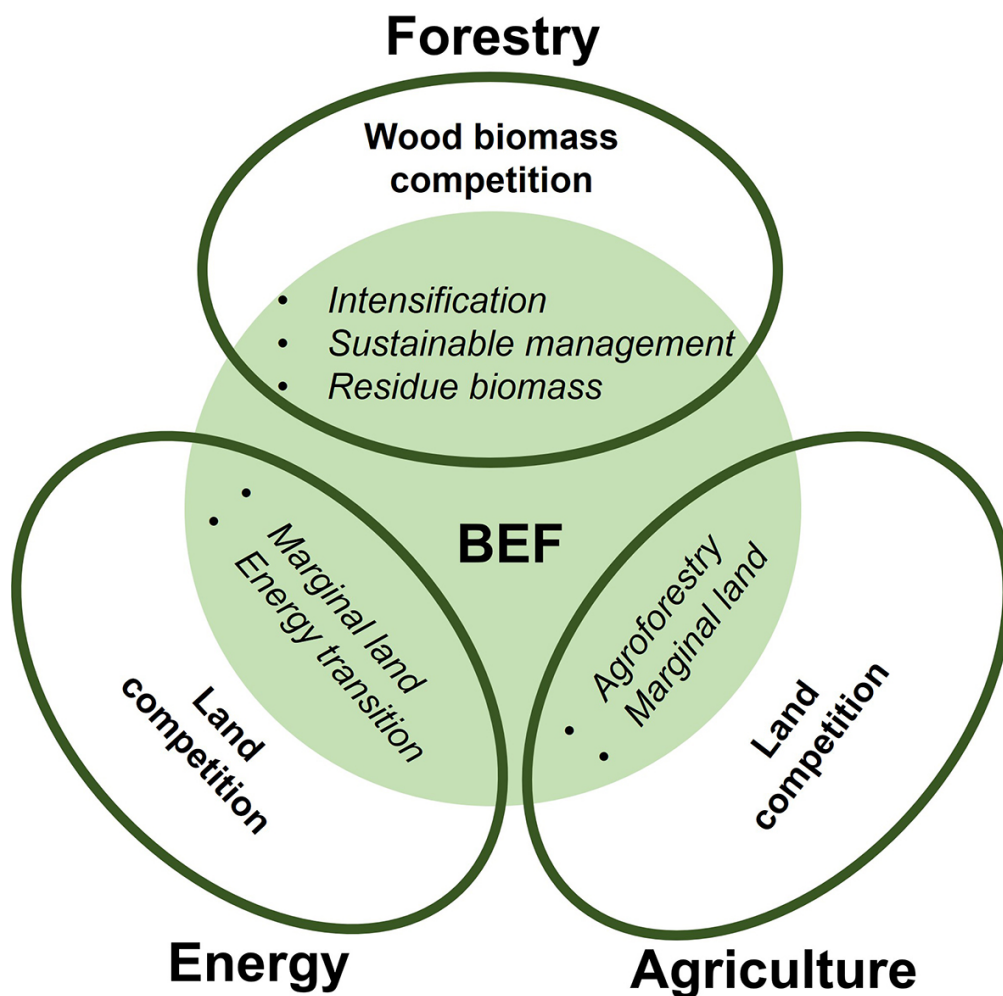


Figure 5. Market conflicts between BEF and other sectors and potential ways of synergy.

(dLUC) of cropland conversion and indirect changes (iLUC) where the displaced crops are produced under less efficiency^[56,109]. Other resource-intensive renewable energy technologies, such as solar farms, would also compete with BEF for land^[110,111]. Current effort tries to reconcile the land conflict with integration (e.g., agroforestry^[112], Figure 1) and segregation strategies (e.g., marginal land^[68,113], Figure 1).

Evaluation of climate effects of BEF systems needs to account for market changes to better address real-world problems such as feedstock supply challenges and policy or industry tradeoffs. Methodological advances in the consequential LCA methodology will be beneficial, such as developing better standardized procedures and incorporating more solid economic modeling^[98]. Comprehensive uncertainty and sensitivity analysis are also crucial to the proper interpretation and communication of climate effects^[99].

ACCOUNTING SOCIAL IMPACTS

The BEF system from wood biomass production to BEF combustion creates ecological and environmental benefits and burdens that, when not distributed equally, could raise strong social and environmental justice concerns. Current research showed emphasis on social aspects through keywords such as “food security” and “governance” [Figure 1]. In Table 3 we summarize potential social impacts based on different stages of the BEF supply chain including biomass harvest^[114-119], processing^[114,119-124], distribution^[82,114,123-128], and bioenergy

Table 3. Potential social risks and co-benefits associated with the BEF supply chain

Life cycle stage	Social risks	Potential benefits
Harvesting	<ul style="list-style-type: none"> • Loss of access to forests for cultural and traditional uses^[114,115] • Land conflicts with agriculture and/or local communities^[116,117] 	<ul style="list-style-type: none"> • Job creation and economic benefits for the local forestry industry^[114,118] • Rural development with improved infrastructure and improved forest management^[119]
Processing	<ul style="list-style-type: none"> • Air and water pollution from dust and chemical emissions^[120,121] • Health and safety risks in and around factories and mills^[122,123] 	<ul style="list-style-type: none"> • Job creation and economic benefits for the local forestry industry^[114,119] • Improved infrastructure and technology due to more investment^[114,124]
Distribution	<ul style="list-style-type: none"> • Geopolitical risks due to reliance on international supply chain^[125,126] • Uneven distribution of economic benefits^[123,127] 	<ul style="list-style-type: none"> • Improvement of transportation infrastructure^[114,124] • Economic benefits for the supplier and energy transition for the consumer^[82,128]
Combustion	<ul style="list-style-type: none"> • Health risks around power plants due to biomass combustion emissions^[120,129] 	<ul style="list-style-type: none"> • Supporting energy security and renewable energy transition^[130,131]

combustion^[120,129-131]. For example, from the production side, Koester and Davis^[122] estimated that wood pellet production facilities in the southeastern United States are 50% more likely to be located in minority communities, making them more likely to suffer negative health impacts^[132]. From the consumption side, the main driver of US's air pollution has shifted from coal combustion-dominated to more biomass combustion^[120], making 2.3 million people live within 2 km of a biomass facility subject to adverse health impacts from their emissions, with disparities to racial and ethnic minority groups^[121]. Yet it is unclear whether the demographic groups at risk also receive benefits from BEF projects^[116], as economic profits of BEF production may not be distributed equally^[127]. On the other hand, many studies highlighted the potential of co-benefits that could improve the current state of unequal and unjust social impacts from BEF. Development of new BEF infrastructures could support wellbeing for indigenous people in areas beyond the sectoral need of energy, such as sustainable forest management, income generation, employment and infrastructures, *etc.*^[114,119].

Climate effect of BEF systems should be evaluated in an integrated socio-economic and environmental assessment framework for more nuanced policy rationales and more socially sustainable strategies. Socio-economic performance of BEF system should include six categories of 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)^[124]. Participatory processes that engage a diverse community of stakeholders including policymakers, industries and researchers are needed to bridge the current gap between policy and tangible implementation^[133,134].

CONCLUSION

This review highlights six key components of the BEF system and the associated methodological choices and assumptions that led to concerns and disagreements related in BEF's climate effects. We demonstrated how these system contexts are critical in determining the accuracy and relevance of the outcomes, and proposed methodological recommendations regarding each key area:

(1) **Definition of system boundaries:** inclusion and exclusion of certain ecological and technical system components or processes greatly change the environmental performance of BEF scenarios.

Recommendation: we recommend accounting key processes such as soil carbon dynamics and transportation, and evaluating the sensitivity of different technical pathways such as biomass treatment and CCS.

(2) **Spatial temporal scales:** spatial heterogeneity and temporal dynamics of BEF systems are prominent contributors to the variations of BEF's climate effects.

Recommendation: we recommend evaluations at spatial scales that reflect the practical scales of forest management strategies and objectives, and adoption of dynamic LCA approaches that capture temporal scales of both climatic and forest ecological processes.

(3) **Reference system:** projected energy and land use systems that the BEF system compares to are crucial in determining the relative performance of the target BEF scenario.

Recommendation: we recommend taking a prospective LCA approach that accounts for the current state and projected energy and land use scenarios, including energy structure, renewable energy development, and land use and land management changes.

(4) **Sourcing of feedstock:** management strategies, harvest practices and the location of forestry wood biomass production will lead to divergent life-cycle climate effects.

Recommendation: we recommend regional-specific considerations that specify the intensive and sustainable forest management strategies adopted, as well as better accounting of the embedded environmental impact of global trade and the risk of carbon leakage.

(5) **Effects of market changes:** consequences of the blooming BEF market and the increasing wood biomass demand are not yet understood in consensus. Increasing demand for wood biomass may conflict with the traditional forestry industry and cause market disruptions to other wood products.

Recommendation: we recommend consequential LCA approaches with accounting of direct and indirect land use changes and potential displacement of market activities of other sectors including food, energy and forestry.

(6) **Accounting social impacts:** social impacts of BEF development are not yet sufficiently accounted for and understood. There are potential justice and equity issues due to the unbalanced distribution of environmental burdens (e.g., pollution) and economic benefits of the BEF projects among ethnic groups.

Recommendation: we recommend development of an integrated socio-economic and environmental assessment framework for more nuanced policy rationales and participatory actions for more inclusive implementations.

FUTURE RESEARCH DIRECTIONS

Here, we propose the following three directions for future research to further reconcile the concerns and disagreements identified in this research:

- **Quantitative synthesis and comparative analysis of methodological choices.** Our understanding of the climate effect of BEF would benefit from more systematic review and meta-analysis to provide a quantitative view of the range of climate effects. For example, effect sizes could be quantified for methodological choices such as the system boundary taken (see section Defining System Boundary) or the time horizons of analysis (see section Spatial and Temporal Scales). Individual assessments should expand their sensitivity analysis to compare plausible methodological alternatives, therefore improve transparency for results' interpretation and avoid bias in the study design.

• **Advancing and standardizing LCA methodologies.** LCA studies of BEF should apply consequential approach (see section Effect of Market Changes), but efforts are needed in developing better guidelines for system expansion and accounting of indirect consequences (e.g., iLUC). Systematic evaluation of forest, soil and climate process models including the incorporation of stochastic disturbances (e.g., wildfire) is urgently needed for the advancement of dynamic LCA (see section Spatial and Temporal Scales) to facilitate the standardization of model selection, therefore improve comparability of results. BEF LCAs should also adopt the prospective LCA framework (see section Reference System) and incorporate the latest development of IAMs to improve relevant to future socio-economic state.

• **Interdisciplinary research and multi-stakeholder engagement.** Although indicator systems are proposed for socio-economic performance of BEF in previous studies (see section Accounting Social Impacts), better guidelines are still needed regarding the categorization of indicators and the evaluation of both quantitative and qualitative indicators. This can only be achieved by interdisciplinary groups integrating social, economic and environmental impacts in a holistic assessment. In addition, wider stakeholder groups need to be included, especially the forest owner, forestry practitioner and local community that are currently underrepresented.

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Author's contributions

Conceptualization, methodology, writing - original draft, writing - review & editing: Liu, W.; Tang, M.

Investigation: Liu, W.

Software, visualization: Tang, M.

Availability of data and materials

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Not applicable.

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Conflict of interest

Both authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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Supplementary Materials

[Supplementary Materials](#)

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