Energy Research & Social Science 125 (2025) 104089

Contents lists available at ScienceDirect

Energy Research & Social Science

journal homepage: www.elsevier.com/locate/erss

Perspective

Minimizing trade-offs and maximizing synergies for a just bioeconomy transition

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ARTICLE INFO

Keywords:
Trade-offs
Synergies
Resource sustainability
Biodiversity
Renewable energy

ABSTRACT

The transition to a bioeconomy holds promise for reducing greenhouse gas (GHG) emissions and advancing sustainable development but also presents complex challenges. This perspectives article critically examines the environmental, social, and economic implications of shifting from fossil-based to bio-based resources, addressing key concerns such as land use competition, biodiversity loss, and social equity. Rising biomass demand poses sustainability risks, especially for the Global South, where it may exacerbate food insecurity and ecosystem degradation. Without careful management, this transition could lead to deforestation, biodiversity loss, and increased carbon emissions, undermining its intended benefits. To navigate these challenges, the article outlines pathways for an inclusive and sustainable bioeconomy transition. It emphasizes the need for interdisciplinary approaches that integrate diverse knowledge systems and values to ensure the equitable distribution of benefits and risks. Policymakers should adopt governance frameworks that align sustainable development goals with local realities, fostering a just transition that mitigates socioecological challenges while maximizing long-term sustainability.

At present, various anthropogenically driven threats, including climate change, critical losses in biodiversity, and excessive nitrogen and phosphorus inputs, are intensifying dramatically. This poses severe challenges for the Earth system's ongoing capacity to sustain human life [1,2]. Recent work has suggested that a transition toward a bioeconomy could be key to rethinking how we restore the Earth system and mitigate anthropogenic threats [3], and policymakers in at least 50 countries, globally, have nationally tailored bioeconomy strategies or specific policies [4]. However, the specific components of these strategies vary significantly, reflecting the economic and environmental preferences of each country. The EU defines the bioeconomy as the sustainable use of renewable biological resources to produce food, materials, and energy[1] [5], and its Bioeconomy Strategy adopts a systemic perspective to support climate neutrality and promote environmental, economic, and social sustainability, in alignment with the UN Sustainable Development Goals (SDGs) [8]. In addition, the European Green Deal envisions member states to apply circular economy principles, which the EU promises will make itself carbon neutral by 2050 [9]. Whether or not the

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[1] Bioeconomy visions are generally categorized into three distinct sectors: biotechnology, bioresources, and bioecology [6]. Biotechnology refers to the shift toward incorporating advanced biological technologies and processes into various sectors of the economy, with the goal of improving efficiency, sustainability, and innovation. This transition is characterized by the application of tools such as genetic engineering. Bioresources emphasize the sustainable use and management of biological materials, while bioecology prioritizes ecosystem resilience and biodiversity conservation. Countries like the USA, China, and India have primarily focused on biotechnology, whereas the EU leans toward bioresource- and bioecology-based visions [7]. This discussion will center on these latter visions, which synthesize multiple sectors and intricately link agricultural and industrial activities with land use and resource supply.

https://doi.org/10.1016/j.erss.2025.104089
Received 17 October 2024; Received in revised form 31 March 2025; Accepted 14 April 2025
Available online 26 April 2025

EU can fulfill this promise, particularly considering its global trade relationships, remains unclear.

There is political and economic disagreement on the priorities within a bioeconomy transition, because trade-offs and synergies vary across stakeholders, policy agendas [10], and geographic scope, exacerbating uncertainty regarding social equality [11]. As bioeconomy strategies are complex and interconnected, evaluating these trade-offs and synergies is not straightforward. Current EU bioeconomy strategies are ill-suited to address the complex, interconnected challenges of overconsumption, extractivism, and global socioecological inequalities and injustices [12–14]. The updated EU bioeconomy strategy lacks consideration of issues particularly related to climate justice, carbon emission disparities, and the differing carbon footprints and resource use among sectors of society [8]. Moreover, despite emphasizing the SDGs, there has been no reversal in the trend of expanding biomass production, nor any significant mitigation of its negative socio-ecological impacts [15]. Thus, we suggest placing social justice at the center, in order to more clearly identify and comprehensively assess trade-offs and synergies in a common framework.

In the following, we discuss how increasing biomass consumption for industrial purposes within the EU impacts land-use competition, the relationships between land use, climate change and biodiversity, and conflicts between economic viability and social equity across the globe. We do so by focusing on forestry and biofuels, as well as the feedstocks required. We aim to illustrate how centering social justice may improve comprehensive assessments and ensure a just bioeconomy transition.

1. Land use competition

The EU's bioeconomy transition is driving significant demand for land both within and beyond its borders, particularly for first-generation biofuel crops and wood production [16]. The EU is not yet self-sufficient in biomass production but sources the bulk of its biomass domestically from forestry, agriculture, and waste, with key contributions from countries like Germany, Sweden, and Finland [17]. With a focus on transitioning its forestry and agriculture sectors toward a more sustainable, bio-based economy, the EU must move away from traditional industries like pulp and paper production and instead develop advanced biorefineries that can produce a wide range of bioproducts, including biofuels, bioplastics, and other renewable materials [18]. Additionally, the EU has introduced measures to promote biogas and biomethane production as part of the REPowerEU plan, aiming to reduce reliance on imported fossil fuels [19]. However, land availability in the Global North is increasingly limited due to competing demands such as agriculture, urbanization, and conservation, which constrains domestic biomass production and risks undermining environmental goals such as biodiversity preservation and climate change mitigation. As a result, the EU remains heavily reliant on imports, particularly for biofuels, given the growing industrial demand. For instance, biodiesel imports have surged in recent years [20], highlighting the increasing need for feedstocks, such as palm oil, from the Global South to meet the EU's renewable energy targets.

In the Global South, large areas of land are considered available for biomass production, driven by lower land costs and favorable climates for biofuel crops, which incentivize investors. While this theoretically presents economic opportunities for local communities, it also raises significant concerns regarding the clearing of primary forests, threats to community well-being, food security risks, and biodiversity loss [21]. By 2022, palm oil plantations covered a global area of 30 million hectares, mainly concentrated in Indonesia and Malaysia [22]. Since 2000, land acquisitions for other biofuel crops and timber production have surged considerably in low- and middle-income countries. For example, 3 million hectares have been acquired for Jatropha cultivation, 15 million hectares for timber production, and 52 million hectares for forest logging [21].

Timber plantations and certain biofuel crops, such as jatropha, can also grow in agroecological zones that are less suitable for food production and often less densely populated. This can help mitigate risks to food production and reduce potential conflicts with farmers. However, even outside the global agricultural production zones, land remains essential to human livelihoods. Pastoralists rely on extensive grazing areas, and many communities living in remote areas, particularly in the Global South, still depend on diverse ecosystem services for their livelihoods. Timber plantations, in contrast, often provide limited ecosystem services and can restrict the movement of pastoralists by disrupting traditional grazing routes [23]. There are also further constraints in shifting land use to a bio-based economy. In some cases, farmers may still consider their land too valuable for energy crop cultivation [24]. Furthermore, many potential production areas overlap with regions of high biodiversity value [25,26]. Designing landscapes that serve these multiple functions is hence pivotal. This includes, for instance, acknowledging and integrating the needs of local communities that live in these areas, even so their land use might be of low intensity, in land use planning or integrating bioenergy crops and trees into existing farming systems to balance food production with bioenergy needs.

Choosing energy crops with minimal input requirements that do not compete with food crops can help minimize environmental impacts, especially if these crops are suited to the local climate. Incorporating native species into bioenergy systems can enhance biodiversity and ecosystem services, as seen in forest plantations that help protect surrounding unmanaged or sustainably managed primary and secondary forests [26–28]. Furthermore, innovations like second-generation biofuels from agricultural residues or algae can reduce competition for land used for food production. Broadening crop management approaches to include diverse knowledge systems, including indigenous knowledge, can provide valuable insights for steering research toward more adaptive solutions. A holistic approach that integrates diverse knowledge systems, sustainable crop choices, and innovative technologies can enhance both environmental sustainability and social justice in bioenergy development.

Policy plays a crucial role in addressing the stated trade-offs, as demonstrated by the EU's Renewable Energy Directive (RED II), which sets sustainability criteria for biofuels, including restrictions on high-risk feedstocks like palm oil. Additionally, the revised Renewable Energy Directive (EU/2023/2413) [19] strengthens the sustainability criteria for biomass and extends 'no-go areas' to include primary forests, biodiverse secondary forests, and peatlands [29]. The update ensures that biomass use aligns with the EU's biodiversity and climate goals, requiring member states to integrate these principles into their national energy and climate plans. At this stage, the directive does not explicitly address social justice concerns. Starting in 2025, the EU's new regulation on Deforestation-Free Products (EUDR) will also require that any operator or trader placing certain commodities—including palm oil and wood—on the EU market or exporting them must prove that the products do not originate from recently deforested land [30]. However, how such EU policies and strategies steer land competition and subsequent acquisitions within and beyond its boundaries—and therefore impact social justice—remains unclear.

2. Economic viability versus social equity

Land resources are under increasing pressure from multiple global trends, intensifying competition for land and causing social and economic repercussions for populations with insecure land rights. The limited availability of land for large-scale projects in many regions has driven investments into economically remote areas, often exacerbating conflicts with already marginalized communities. This dynamic creates trade-offs between economic viability and social equity. For example, in Europe, competing interests between forestry and reindeer farming in Sweden create significant challenges. Specifically, intensive forestry practices often encroach on grazing lands critical to the livelihoods and cultural heritage of Sami reindeer herders, exacerbating conflicts over resource access and ecosystem sustainability [31]. Similar patterns of conflict exist around the world. Investments in the Global South, exemplified by the biofuel boom, further highlight economic potential but also pose significant human rights and environmental risks, particularly in regions where communal land rights remain unrecognized [32], leading to conflicts over large-scale land acquisitions [23,33,34].[2] Moreover, employment impacts of such investments are often limited, especially for land investments, which typically have low labor intensity and a high degree of mechanization, e.g. for timber plantation and forest logging. The literature shows little optimism regarding development benefits such as technological knowledge spillovers, infrastructure development, and overall local economic development [23], particularly for Indigenous Peoples and Local Communities (IPLCs).While the employment impacts of some biofuel crops are less daunting, positive employment effects often result from cropland expansion at the expense of natural ecosystems [37].

Changes in global food production may increase pressure on food prices, particularly within globalized food markets, which rely heavily on a limited number of producer countries. Recent political developments underscore the crucial role of international treaties in ensuring security and peace, while also exposing the vulnerabilities of these interdependencies. Additionally, global modelling assessments indicate that growth-driven, bioeconomy-focused mitigation strategies could exacerbate food insecurity and poverty—particularly in the most vulnerable regions—potentially surpassing the adverse effects of climate change itself [10].

To progress toward the SDGs, it is essential to implement policy interventions that integrate sustainable climate change mitigation, equitable distribution of carbon sequestration incomes, and simultaneous shifts in energy and dietary consumption patterns. However, many existing plans fail to adequately emphasize the role of sustainable consumption in mitigating these potential negative impacts, despite its significant potential to do so [3]. This also closely relates to the question of whether sustainable development is achievable within the current economic system [31]. This debate aligns with the growing discourse on societal transformation [13] and degrowth, which challenges economic growth as a sustainable measure of progress. Degrowth advocates argue that continuous economic expansion exacerbates resource depletion, environmental degradation, and social inequalities, making it incompatible with the bioeconomy [31,38]. For example, despite the stated goal of equal prioritization, productivity concerns and economic growth often take precedence over social and environmental considerations [39–42]. Achieving the SDGs from this perspective requires reducing the consumption of resource-intensive products, ensuring equitable resource distribution, implementing effective policy interventions, and balancing human well-being with GDP growth [43,44]. Discussions about a just bioeconomy transition emphasize the need to address resource control and power dynamics within bio-based production systems [45]. Holmgren et al. [40] highlight that Sweden's bioeconomy is shaped by a tightly connected network of organisations operating without a formal framework, allowing influential actors to align their interests while blurring the lines between public and private objectives. This lack of transparency and inclusivity marginalizes alternative forest uses, such as biodiversity conservation and cultural values, in favor of maximizing biomass production. Inclusive governance frameworks are essential to integrate diverse perspectives and ensure a sustainable and equitable bioeconomy transition.

[2] Some countries exemplify these trade-offs. For example, the Democratic Republic of the Congo hosts approximately 10 million hectares of concluded land deals for wood and fiber production, according to Land Matrix data [22]. However, these deals overlap with the territories of IPLCs, who often have limited legal means to protect their lands [35,36].

3. Relationships between land-use change, climate change mitigation and biodiversity

The increasing pressure on land driven by the bioeconomy transition will significantly impact land access, determining who can use land, where, and for what purposes. While shifting to a bioeconomy can reduce dependency on fossil fuels and lower GHG emissions, it may also lead to environmental challenges, including deforestation, soil degradation, and increased water consumption due to the intensive agricultural practices required for biomass production on a global scale [10,46,47].

Climate change and current production practices are already driving species extinction, shifting species ranges, and disrupting overall ecosystem stability [48,49]. Protecting biodiversity is crucial for maintaining ecosystem functions and preserving genetic resources essential for both human and ecosystem adaptation. Reforestation efforts are increasingly impacted by climate change, as juvenile tree stands experience higher mortality due to frequent droughts and heat spells compared to mature forests [28]. Additionally productivity recovers only gradually after replanting [50]. Currently, trees or plants used for replanting often lack the adaptive traits needed to withstand climate extremes, traits that have been naturally selected over generations in species adapted to environmental changes [51–53].

Land acquisition and conversion to plantations or agriculture can critically impact biodiversity and climate resilience [56,57] and less diverse biofuel and forest plantations also store significantly less carbon than unmanaged forests (primary and secondary) in both the Global North and Global South [54,55]. Moreover, large amounts of stored carbon from soils (and woody plants) are released into the atmosphere during land-use changes [58]. While the loss of these carbon pools occurs rapidly, their restoration takes significantly longer. Furthermore, land-use changes toward monocultural ecosystems, combined with climate change, create a complex feedback loop that intensifies threats to biodiversity, as ecosystems struggle to adapt and generally decreases the provision of ecosystem services (Fig. 1). To mitigate these negative impacts, strict land-use planning and adherence to sustainability criteria at all scales are essential to prevent biodiversity loss [26–28].

Overexploitation of natural resources and climate change have already led to significant losses in freshwater quality and quantity, as well as grazed lands, which are vital for biodiversity and human needs [59–62]. Of the approximately 1.4 million lakes ($\geq$10 ha) worldwide [63], many play a fundamental role in securing biodiversity and in providing humans with water and food [62]. Protecting groundwater reserves for aboveground biodiversity, as well as feedstock and biofuel production, is crucial [64], especially as climate change increasingly impacts water availability, exacerbates heat stress, shifts the range of deciduous tree species, and increases the mortality of broadleaf trees, which is essential to regulating microclimates [65].

The transition from fossil-based materials to bio-based materials should, in theory, contribute to the reduction of GHG emissions by capturing and utilizing carbon dioxide during plant growth. When properly managed, this process creates a carbon cycle that results in a net reduction in overall emissions compared to burning fossil fuels [66,67]. Moreover, bioeconomy initiatives focus on converting organic waste streams into valuable products [68,69]. Processes such as anaerobic digestion can transform organic waste into biogas, a renewable energy source, while composting produces nutrient-rich soil amendments [70]. This approach helps reduce methane emissions from organic waste decomposition in landfills and generates nitrogen rich fertilizers, reducing the need for mineral nitrogen fertilizer. Thus, it contributes to waste valorisation and a circular economy that aligns with farmers' practices [71]. However, the transition to bioenergy and the associated changes in land use, such as deforestation, can release stored carbon, offsetting the initial carbon savings. This process also contributes to biodiversity loss —for example, the increase in carbon dioxide emissions during the transition period, which, for forest habitats, can take decades

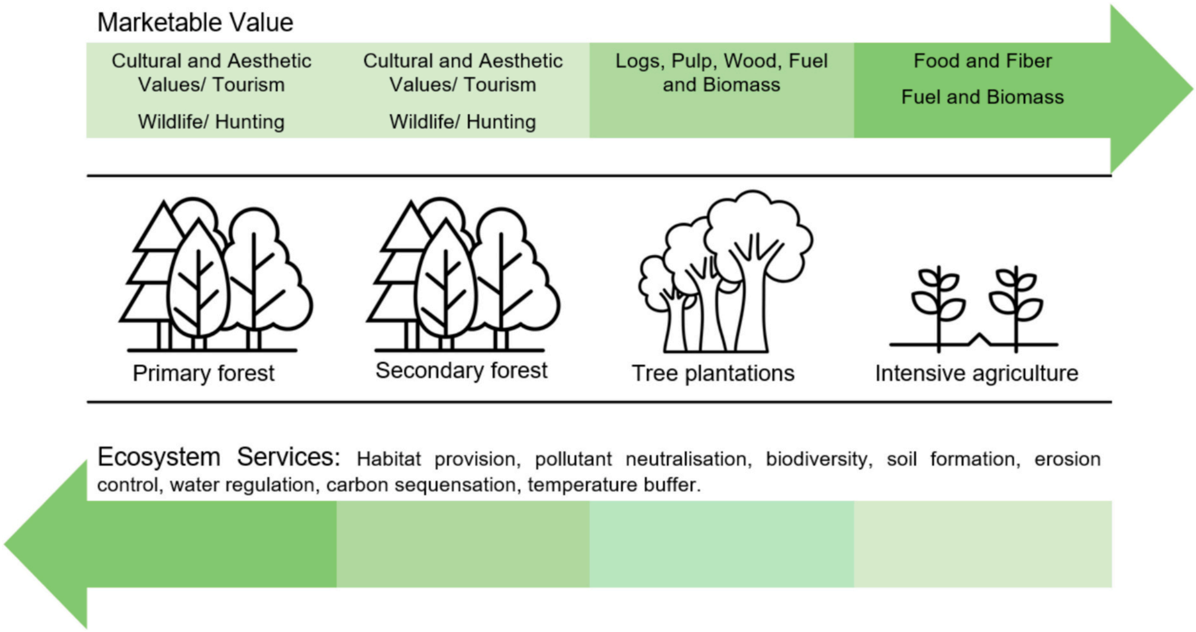

Fig. 1. Overview of the necessary balance between changes in marketable values and ecosystem services along a land-use gradient ranging from primary and secondary forest to agricultural field. The color gradient represents these changes, with dark green indicating the highest values (e.g., ecosystem services and favorable market values) and light green indicating the lowest. Own elaboration, with images sourced from the Noun Project. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

or even centuries to progress from seedlings to full-grown trees [56,72] (Fig. 2).

To mitigate these challenges, protecting biodiversity is essential for land-based production systems [73], as it ensures stable ecosystem functioning and safeguards genetic resources critical for adaptation and future survival [74–77]. This can be achieved by maintaining, enhancing, or increasing structural heterogeneity and diversity in ecosystems and across landscapes, such as in forests [78], grasslands [79] and arable farming systems [80].

Bioenergy production practices, such as agroforestry and the cultivation of energy crops on marginal lands, can promote sustainable land use and be designed to mimic biodiverse ecosystems. Well-planned bioenergy landscapes can also enhance ecological connectivity by providing wildlife corridors, mitigating habitat fragmentation, and preventing deforestation [81–84]. Sustainable biomass production that incorporates agroecological and regenerative practices can enhance

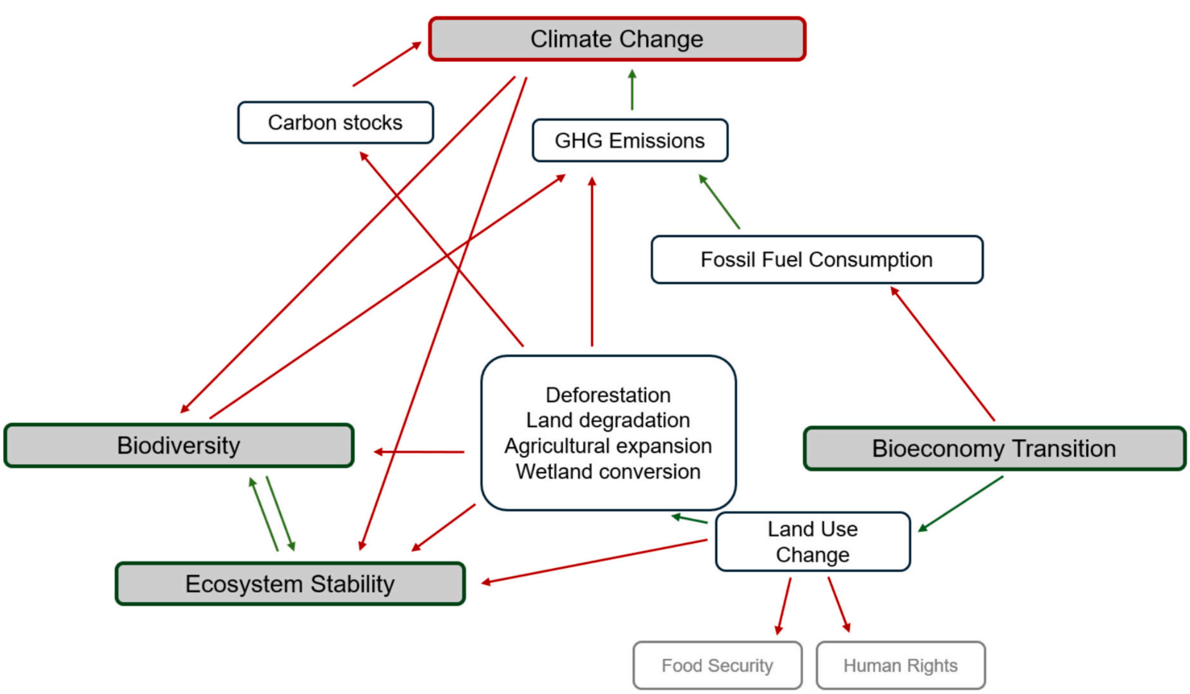

Fig. 2. An illustrative representation of the bioeconomy transition, highlighting the complex interactions between bioeconomy transition, climate change, biodiversity, and ecosystem stability. Red arrows indicate negative associations, while green arrows indicate positive associations. Own elaboration. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ecosystem resilience and protect biodiversity [85–87]. Likewise, increasing the diversity of forest stands is already a key strategy for mitigating drought susceptibility in Europe and should also be considered in intensively managed plantations [88,89].

Integrating native species into bioenergy systems enhances biodiversity and improves ecosystem services [26,27]. Expanding knowledge exchange across regions and stakeholders can support adaptive replanting and perennial vegetation management [52]. Linking bioeconomy research with ecosystem functioning under climate and land-use changes is critical for adapting to climate fluctuations [61]. This is evident in cases where historic land-use changes have led to significant carbon losses, while restorative agricultural practices—such as reduced tillage, organic circular fertilizers, cover cropping, and agroforestry—offer potential ways to recapture lost carbon stores [90]. These practices can improve soil health and enhance carbon sequestration in agricultural soils. Thereby, such agroecological practices enhance the provision of ecosystem services while maintaining the use of managed land (see gradient in Fig. 1). Policy strategies aimed at carbon sequestration must prevent leakage and ensure long-term benefits aligned with sustainable development goals [91,92]. Additionally, bioeconomy initiatives that convert organic waste into renewable products like biogas can help reduce methane emissions and support a circular economy [93]. While the transition to bioenergy offers potential GHG reductions due to its carbon-neutral nature, careful and holistic assessments are essential to ensure that its overall environmental impact—particularly on climate and biodiversity—remains positive [44,72,91–95]. However, this will largely depend on who has the agency to drive land-use changes in a sustainable direction.

4. Conclusion and outlook

The bioeconomy, in its current form, is emerging as a major source of revenue in both the Global North and South, aiming to support the renewable production of bio-based energy and materials. However, in most cases —particularly within EU programs—it lacks a comprehensive environmental and social justice assessment. The request for such evidence does not imply that bioeconomy strategies inherently conflict with global commitments to food security, poverty alleviation, or environmental and biodiversity conservation. Rather, it calls for a systematic and cross-scale understanding of how bioeconomy strategies impact sustainability as a whole. Some initial efforts have emerged from the "Integrated Assessment Modelling" community, exploring comprehensive sustainable development pathways while incorporating social justice to some extent [44,92] (e.g., Shape). Further, more refined assessments will require both interdisciplinary and transdisciplinary research approaches that incorporate comprehensive, cross-system and cross-scale thinking. Specifically, such efforts should aim to capture global drivers and trade-offs while integrating national-level policy interventions and localized knowledge to better understand decision-making regarding technological interventions and production choices within flattened hierarchies. The recent Food System Economics Commission report outlines a comprehensive pathway for food system transformation, incorporating bioeconomy demands and social inclusion while linking global analysis with national and local case studies [96].

However, more detailed quantitative assessments of the bioeconomy's implications for social justice are needed. Understanding distributional effects is crucial at all scales —across world regions, sectors, actors, and groups. Finally, advancing approaches and concepts that integrate transdisciplinary research with state-of-the-art modelling and monitoring-based science will be essential to supporting stakeholder processes and fostering innovation. A justice lens helps assess the social sustainability of the bioeconomy and the associated biodiversity challenges, which stem from decades of unsustainable agricultural production. The uncertainty surrounding future social, economic and environmental risks presents an additional challenge to both bioeconomy policy-making and the bioeconomy itself [1]. Risks can only be identified when the main aims and visions of a growing bioeconomy are clearly defined, and transition pathways are negotiated among all concerned parties—especially those whose values and knowledge systems are often excluded from simplified economic trajectories based solely on GDP growth. A comprehensive assessment is also needed to address the lack of policy coherence in fostering a just bioeconomy transition. In the EU, as in most other countries and regions, policy fields related to forests, agriculture, energy, and industry are often poorly integrated. The disconnect between policies focused on climate change mitigation, game hunting, recreational functions, and biomass production can undermine the consistency and effectiveness of policy instruments [97]. In addition, trade-offs exist between the EU's agro-food and bioeconomy policies [98]. In the Global South, a limited understanding of the economic development potential of a bioeconomy transition can result in misalignments between policies aimed at poverty alleviation and food security and those promoting a global bioeconomy.

Increasing international collaboration on bioeconomy policies must be fostered to address global challenges and share best practices. This includes cooperation on access to land, R&D, technology transfer, capacity-building, and governance improvements to implement the most effective regulations with minimal bureaucratic burden. A bioeconomy that heavily relies on land-based investments in the Global South poses significant risks related to human rights, social inclusion, and environmental impacts, all of which must be addressed. Specifically, an EU-driven bioeconomy has external footprints, particularly in the Global South. Such risks could be addressed through sustainable supply chains that identify, prevent, mitigate, and account for the potential negative impacts of upstream production. A case in point is the emerging due diligence regulations at both national and EU levels. These regulations, however, are limited in scope when focused solely on deforestation and not on potential degradation of other ecosystems, or when they apply only to direct suppliers and regulate only large-scale companies. Thus, the risks associated with a bioeconomy approach cannot be sufficiently addressed by the current set of due diligence regulations.

A just bioeconomy transition requires the engagement of a diverse community of stakeholders. Policymakers (at the EU, national and regional levels), the private sector (including large corporations, small- and medium-sized enterprises, and investors), sectoral associations, researchers, civil society actors (such as non-governmental organisations and non-profit organisations), and consumers should be brought together through targeted forums such as global summits, regional conferences, and participatory approaches. It is essential to emphasize the co-creation of solutions, showcase successful collaborations, and align agendas with pressing global challenges such as climate change, food security, and social equity. A recent report, *Enhancing Stakeholder Involvement in the EU Bioeconomy Policy*, highlights current best practices and presents seven strategic recommendations [99].

We have emphasized that a just bioeconomy transition must address environmental impacts, biodiversity preservation, and social equity—-three interconnected transitions. Given the transdisciplinary knowledge required, we advocate for integrating bioeconomy within a broader research framework encompassing both Earth and societal systems. This perspective promotes: (i) a holistic understanding of the complex, heterogeneous, and dynamic interlinkages across spatial and temporal scales, (ii) the development of science-based references, such as planetary boundaries, for societal decision-making and assessments; and (iii) the identification of capacities, key actors, and innovation pathways for sustainability transformations [100]. Embedding the bioeconomy into this framework enables the development of systemic approaches for managing biological resources, environmental factors, and socio-economic dynamics, the determination of normative references for assessing the bioeconomic status, and the creation of transformation pathways through more inclusive and collaborative transdisciplinary approaches. In this way, the bioeconomy can evolve as a core catalyst for a sustainable Anthropocene, combining social well-being and economic prosperity within the planet's safe operating space.

CRediT authorship contribution statement

Anette Ruml: Writing – original draft, Conceptualization. **Cheng Chen:** Writing – original draft, Conceptualization. **Christoph Kubitza:** Writing – original draft, Conceptualization. **Maria Kernecker:** Writing – original draft, Conceptualization. **Hans-Peter Grossart:** Writing – original draft, Conceptualization. **Mathias Hoffmann:** Writing – original draft, Conceptualization. **Maire Holz:** Writing – original draft. **Ludger A. Wessjohann:** Writing – original draft, Conceptualization. **Hermann Lotze-Campen:** Writing – original draft, Conceptualization. **Maren Dubbert:** Writing – original draft, Conceptualization.

Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

No data was used for the research described in the article.

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