Global Land-use and Sustainability Implications of Enhanced Bioenergy Import of China

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Abstract

Most ambitious climate change mitigation pathways indicate multi-fold bioenergy expansion to support the energy transition, which may trigger increased biomass imports from major bioenergy-consuming regions. However, the potential global land-use change and sustainability trade-offs alongside the bioenergy trade remain poorly understood. Here, we apply the Global Biosphere Management Model (GLOBIOM) to investigate and compare the effects of different increasing bioenergy import strategies in line with the 1.5℃-compatible bioenergy demand in China, which is projected to represent 30% of global bioenergy consumption by the middle of the century. The results show that sourcing additional bioenergy from different world regions could pose heterogeneous impacts on the local and global land systems, with implications on food security, greenhouse gas emissions, and water and fertilizer demand. In the worst cases under strict trade settings, relying on biomass import may induce up to 25% of unmanaged forests converted to managed ones in the supplying regions, while in an open trade environment, increasing bioenergy imports would drastically change the trade flows of staple agricultural or forestry products, which would further bring secondary land-use changes in other world regions. Nevertheless, an economically optimized biomass import portfolio for China has the potential to reduce global overall sustainability trade-offs with food security and emission abatement. However, these benefits vary with indicator and time and are conditional to stricter land-use regulations. Our findings thus shed new light on the design of bioenergy trade strategies and the associated land-use regulations in individual countries in the era of deep decarbonization.

Keywords

bioenergy, 1.5℃, international trade, land-use change, GLOBIOM

1. Introduction

Modern bioenergy utilization is projected to play a key role in the global and regional climate agenda. Most 1.5 °C scenarios simulated by integrated assessment models (IAMs) expect a jump in global primary bioenergy demand from less than 60 EJ [1] in 2019 to 100-300 EJ by 2050 and 200-450 EJ by 2100 [2-4] driven by demand for modern bioenergy [5] and bioenergy with carbon capture and storage (BECCS). Even in bioenergy-constrained or BECCS-constrained scenarios, global bioenergy demand may still increase steadily to around or over 100 EJ by 2050 [4, 6, 7]. However, large-scale bioenergy deployment is under debate due to its potential trade-offs with food security, land-based carbon sink, sustainable water use, etc., which have been extensively studied at the global level. For example, Frank et al. [8] revealed that combining increased bioenergy demand with carbon price under the 1.5°C target would lead to a shock in the global food supply, resulting in an 80-300 million additional undernourished population in 2050. Humpenöder et al. [9] pointed out that without complementary environmental policies, large-scale bioenergy expansion would induce 146 Gt additional cumulative greenhouse gas (GHG) emissions between 2010 and 2030. Stenzel et al. [10] estimated that increased irrigation water demand for bioenergy plantations for the 1.5°C target would expose a larger population to severe water shortage than the impacts of a 3°C-climate change. These induced land sustainability risks pose questions on the feasibility of bioenergy development.

Regional bioenergy strategies can bring more complex land-use trade-offs in a global context. For regions, either scaling up the local biomass production or booming bioenergy imports may induce indirect land-use change (iLUC). On the one hand, scaling up domestic biomass production could push up local food prices due to cropland displacement and lead to an increase in net imports of food, feed, and fiber, which may further result in agricultural land expansion into the forest or other natural lands in the exporting regions [11]. On the other, increasing bioenergy imports may trigger similar domino effects on land use in the bioenergy-exporting regions and their trade partners. For example, it is pointed out that by 2050, the bioenergy import demand in Germany triggered by its energy policy targets could lead to an “imported” land area for bioenergy which is as large as 58-80% of Germany’s total land area [12]. As the demand for bioenergy and bioenergy trade is projected to uplift swiftly in a deep-decarbonizing world [13], these potential worldwide iLUC spillovers alongside bioenergy imports deserve further attention and caution.

However, with most existing studies focusing on land-use change under increasing domestic bioenergy production, the direction and extent of land-related impacts induced by possibly growing bioenergy trade were rarely investigated. So far, knowledge is still lacking on global iLUC impacts and sustainability implications triggered by regional bioenergy import. By now, a string of multi-model studies [4, 13-15] has analyzed the demand, supply, and land-use implications of bioenergy expansion at the global level. While timely analyzing worldwide bioenergy pathways in global climate scenarios, these global studies rely heavily on IAMs with coarser regional representation and do not single out the potential iLUC induced by regional bioenergy targets, and thus could provide only limited insights into regional bioenergy strategies [16]. On the other hand, most regional studies are either based on the closed economy assumption [17], or merely focus on economic impacts [18] or domestic land-use change [19, 20]. In some rare cases, the global land-use spillovers originated from bioenergy import in the U.S. [11], EU [21, 22], or Germany [12] are explicitly addressed, but are by applying exogenous land-use narratives or static input-output analyses; these studies did not analyze different alternative bioenergy import schemes from the land-use perspective, and also did not extend to broader sustainability indicators like forest protection or agricultural input demands. Therefore, deeper dives into the evolution of both local and global land-use implications associated with regional bioenergy development under stringent long-term climate targets are needed, because otherwise, policies on regional bioenergy import might become either too conservative (missing win-win opportunity of better coordinating global land-use sustainability) or too aggressive (inducing severe land-related risks across the world by bioenergy import).

To address these research gaps, this study takes China as an example to explore the global land-use impacts of different biomass import schemes in accordance with its ambitious climate target. China is chosen as the case study for three main reasons: First, a sustainable bioenergy deployment strategy is crucial for the feasibility of China's new climate policy. China's climate actions would form an important part of global mitigation efforts, given that China's GHG emissions constituted around one-fourth of total global emissions in 2019 [23]. Existing studies on China's 1.5 ℃-compatible decarbonizing pathways have concluded that bioenergy would constitute at least about 10% of primary energy by the mid-century [24-26]. Such projected bioenergy demand in China would range from 15-30 EJ [27] and, in some cases, even greater than 50 EJ [25], meaning a multi-fold increase from 5.2 EJ in 2019 (with two-thirds being traditional biomass utilization)[28]. However, currently, China is implementing both the "strictest farmland protection policy" [29, 30] (that forbids the expansion of bioenergy into cropland) and a ban on solid biomass waste imports [31]. Hence, it remains unclear how China can fulfill the soaring bioenergy demand with available land resources, and the need for identifying a sustainable bioenergy supply portfolio for China is pressing. Second, the scale of extra bioenergy demand for the climate target in China would be in the upper-middle level among different regions as projected by eight IAM implementations [25, 32, 33]. In most of the 1.5 ℃ scenario results, China's bioenergy demand would be similar to those in Latin America or the OECD region, while slightly greater than those in Southeast Asia or Sub-Saharan Africa, and South Asia. Therefore, the results on the potential global land-use changes under China's increasing bioenergy demand could shed light on other regions' bioenergy strategies under similar climate targets. Finally, China also has its particularity due to its relative land scarcity and active participation in the international agricultural market. In 2020, China ranks first worldwide in both cereal production and soybean import [34]. Zhao et al. [35] further estimated that China's increasing food demand by 2050 would increase domestic and virtually imported agricultural lands upon the 2010 levels by 25 and 63 Mha, respectively. This distinguishes China from other bioenergy-demanding regions (e.g. Latin America, Europe, North America) that are agricultural exporting powerhouses. Additional bioenergy demand in China under climate targets would potentially drive up bioenergy import [13], indicating further effects on global land use. Therefore, proactive analysis of enhanced bioenergy import schemes that reduce global land-use trade-offs would be critical for designing China's bioenergy strategy.

In this study, we explore the global land-use and sustainability implications of different biomass import schemes for China's bioenergy demand under the ambitious 1.5 ℃ climate target, and address the following questions: (i) what could be the major sustainability impacts triggered by increased regional bioenergy demand in different world regions, and what are the underlying mechanisms? (ii) what would be the induced global land-use impacts from different bioenergy import schemes for China? (iii) could a more flexible bioenergy import portfolio alleviate global land sustainability trade-offs? Addressing these multi-facet questions, this study contributes to the existing literature in three aspects. Firstly, we analyzed the spatially explicit long-term impacts on global land-use and multiple sustainability indicators induced by regional bioenergy demand under climate targets, taking advantage of the well-established land-use model of the Global Biosphere Management Model (GLOBIOM). Secondly, we explored the biomass-to-food or biomass-to-fiber cross-system spillovers, and the worldwide cross-regional spillovers through the lens of market-mediated land-use changes. Thirdly, we uncovered the major land-use-related risks in different regions under corresponding bioenergy import schemes.

The remainder of this paper is structured as follows. Section 2 describes the methodology, including the model setup, data sources, and scenario design. Section 3 presents the model results of China's global land-use impacts under different bioenergy import schemes. In Section 4, we discuss the impacts, benefits, and viability of international biomass trade, as well as the limitations of this study. Conclusions are drawn in Section 5.

2. Methodology

2.1 Research framework

We apply the GLOBIOM model [36, 37] to investigate the agricultural and forestry sector dynamics as well as global land-use impacts under different hypothetic bioenergy import schemes in line with China's 2060 net-zero emission target. After deriving consistent bioenergy demand projections, we set up a series of bioenergy import scenarios. These scenarios were then fed into the GLOBIOM model to assess the effects of the rising bioenergy import in China on regional and global land-use sectors and related sustainability indicators (Figure 1).

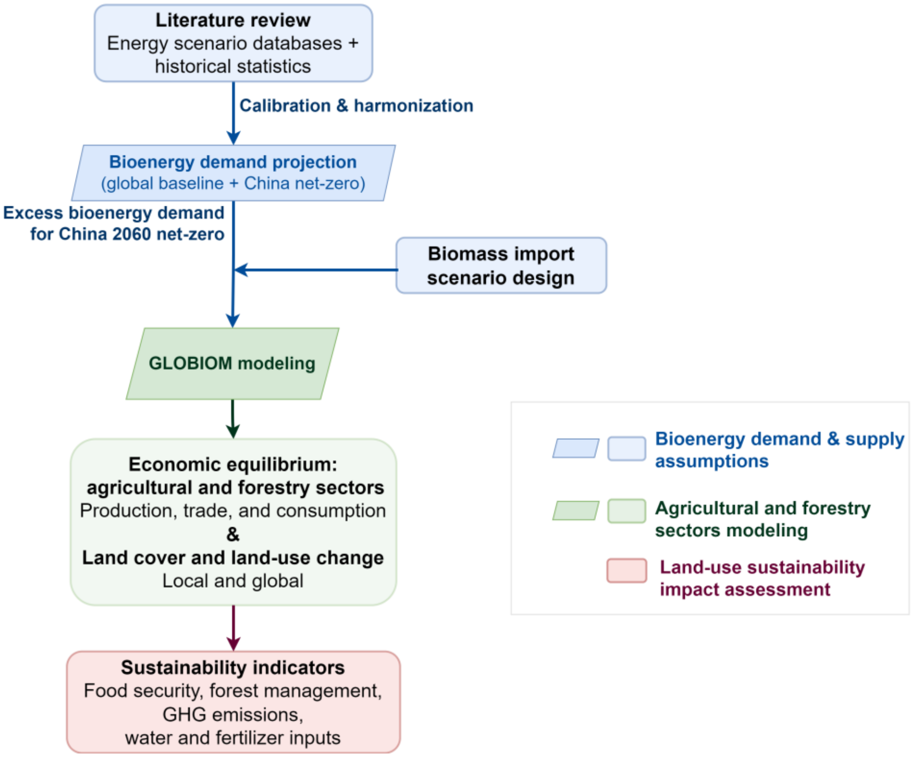


Figure 1 Overall research framework

2.2 Derivation of bioenergy demand pathway

Before applying GLOBIOM for the bioenergy-expansion scenarios quantification, a two-step method was adopted to generate the bioenergy demand pathways for China and other world regions, i.e., calibration of historical bioenergy production, and harmonization of future bioenergy projections from literature with the calibrated historical values.

For the historical calibration, we match bioenergy production at the feedstock level for each of the 37 aggregated economic regions (that are applied in the GLOBIOM model, to be introduced in Section 2.3) in three modeled historical periods (2000, 2010, and 2020) with available statistics. First, the total bioenergy supply for each economic region is derived from the IEA database [1]. For countries without statistics for the year 2020, the data for 2019 are applied. Next, as GLOBIOM simulates different woody biomass types with different mechanisms, total bioenergy supply data are further divided into different feedstock categories for calibration, based on FAOSTAT data [34] and additional calculations with processing technology parameters (Table 1**Error! Reference source not found.**). For non-woody biomass, its region-level supply in history is estimated as the residual term due to a lack of historical statistics.

The calibrated results show that in 2020, the total bioenergy supply in the 179 countries covered in GLOBIOM was 53.5 EJ (total bioenergy supply in all countries covered by IEA statistics in 2020 = 55.6 EJ), of which 29.2 EJ was from woody biomass (about 50% fuelwood and 50% energy wood biomass) and 24.3 EJ was from non-woody biomass. Most of the modern bioenergy utilization (i.e., energy wood biomass) by 2020 was located in North America, Europe, and China. Results for historical bioenergy supply calibration by region and feedstock categories are shown in Figure S12.

Table 1 Summary of data and method for historical bioenergy calibration

Bioenergy feedstocks	**Data source or estimation method**
1. Woody biomass	Equals to the sum of the following three woody biomass feedstock categories
1.1 Fuelwood	FAOSTAT [34] data for fuelwood in each region, with the underbark estimates corrected to overbark ones
1.2 Energy wood biomass	Estimated endogenously based on FAOSTAT [34] data for forest production levels and technology parameters for utilization of forest residues, following method in [38]
1.3 Short-rotation plantations	The amounts for historical years were set to zero for all regions, given the fact that dedicated energy plantations are still mostly in the experimental phase instead of large-scale commercial application [39, 40]
2. Non-woody biomass	Equals to total biomass subtracted by woody biomass
3. Total biomass	IEA database [1]

For future bioenergy demand projection, this study derived both global baseline (reference) bioenergy trajectories and China’s “excess bioenergy demand” in line with the 1.5°C target. The “excess demand” is defined as the additional primary bioenergy demand in China under the 1.5°C target scenario, on top of the reference scenario where no climate policy is assumed. In this study, projections of demand for different bioenergy feedstocks are derived separately. First, the projections of modern woody biomass (i.e., not including fuelwood) for world regions under both the baseline scenario and the China 1.5°C target scenario are derived from the common application between the MESSAGE and GLOBIOM models [41, 42]. The original values were then harmonized with historical calibration to ensure consistency. Second, future fuelwood demand is exogenously estimated based on historical consumption, projected future socioeconomic trends, and income elasticity for each economic region following the method in literature [38], and is fixed across scenarios. Finally, future non-woody biomass supply (including agricultural residues and other biomass wastes) is assumed to remain constant at the 2020 level in all scenarios, due to the lack of available projections and the limited scale of sustainable supply potential of non-woody bioenergy feedstocks identified in existing literature [43-45]. With this setting, we assume that the excess bioenergy demand under China's 1.5°C target is met by woody biomass feedstocks. More details on bioenergy demand projection are provided in Supplementary Method 1.

Summing up the calibrated projections for different feedstocks, global total bioenergy demand in the reference scenario would be 53.2 EJ in 2030 and 71.1 EJ in 2060, of which 5.9 EJ in 2030 and 8.2 EJ in 2060 for China. The excess bioenergy demand for China for its 1.5°C target is estimated to be 2.7 EJ in 2030 and 13.2 EJ in 2060 (Table 2**Error! Reference source not found.**). In the reference scenario, China would share a stable proportion (around 10%) in global bioenergy demand between 2010 and 2060 (Figure S13); while in the scenario where China implements the 1.5°C target, this proportion would be 15% by 2030 and 30% by 2060. Compared with literature on China's future bioenergy production potential [43, 44, 46, 47] (Table S3), this scale of bioenergy demand exceeds most projections of the long-term availability of dedicated energy crops in China (and even if considered together with non-woody feedstocks), which forms the rationality of considering biomass import as a complementary solution.

Table 2 Core settings and sensitivity scenarios on bioenergy demand in China (Unit: EJ)

Category	Scenario	2000	2010	2020	2030	2040	2050	2060
Total bioenergy demand	Reference	8.1	5.6	5.4	5.9	6.5	7.3	8.2
Excess woody bioenergy demand for 1.5°C target	Core scenarios	0	0	0	2.7	5.6	9.3	13.2
	S1_HighDemand	0	0	0	20.4	23.8	27.2	30.6
	S2_LowDemand	0	0	0	0.4	1	2.5	4.1

Note: "Core scenarios" indicate the scenarios used in the main text (see section 2.5), with a medium level of excess bioenergy demand and default settings on land use and land-use change possibilities.

To put this in a broader context of literature, the projection of excess bioenergy demand in China used in this study is at the lower end of existing IAM projections [25, 32, 33] (Figure S1). Some models, like GCAM, AIM/CGE, and POLES, have reported significantly higher estimations of bioenergy demand in China (>30 EJ in 2060) for the 1.5°C scenario. We also set up two sensitivity tests to address (i) the uncertainty in the projected bioenergy demand under climate targets, and (ii) the uncertainty in the resource potential of non-woody biomass. In the first sensitivity setting (S1 in Table 2), the higher excess bioenergy demand projected by the GCAM model in the study [25] was adopted; in the second sensitivity setting, it is assumed that the supply of agricultural residues and other non-woody biomass could grow steadily to 10 EJ by 2050 (which is in line with a projection from [48] and is further linearly extended to 12.3 EJ by 2060) to represent a case where the resource potential of non-woody biomass energy is fully realized. It thus reduces the excess demand for woody biomass to 4.1 EJ by 2060**Error! Reference source not found.** (S2 in Table2). Compared to the core analysis, these are used as sensitivity sets with high and low woody-biomass-source bioenergy demand for China. Details on sensitivity analysis setup and results are presented in Section 2.5 and Section 3.4, respectively.

2.3 GLOBIOM modeling

The GLOBIOM model is applied to simulate global land-use change and the corresponding land-use sustainability implications accompanying China's additional bioenergy demand. GLOBIOM is a global partial-equilibrium model with coverage of main land-based activities and sectors, and has been extensively applied to evaluate agricultural or nature-based mitigation options [36, 37, 49-54]. Compared with other land-use models (e.g., vegetation models, cellular automata models, and forest sector models) that can also be applied to analyze bioenergy's land-use and sustainability impacts, the most distinguished feature of GLOBIOM is that it is an economic model with spatially-explicit global coverage. This allows for the simulation of the bioenergy-induced land competition with a finer resolution and an endogenous cost-optimization-driven market equilibrium mechanism. The model, therefore, has unique advantages in depicting the cross-sector market interconnections between different production sectors (agriculture, forestry, and bioenergy) and cross-regional spillovers, especially under a dynamic socioeconomic setting.

Operating in a recursive-dynamic way, the GLOBIOM model solves the market equilibrium by maximizing the producer and consumer surplus within each period's agricultural and forestry sectors. GLOBIOM features the market interactions between eighteen crops, a variety of livestock and forestry commodities, and first- and second-generation bioenergy. Different production systems with varied resource input intensities and costs in the agricultural and forestry sectors are characterized, and the production and management decisions are simulated at the pixel level with a spatial equilibrium modeling approach [55]. Seven land cover types are endogenously modeled: cropland for crop production, grassland for livestock farming, unmanaged forest, managed forest, afforested land, energy plantation land, and other natural vegetation lands. Land-use changes are subject to economic profitability and geophysical suitability. Costs represented in the model include production and management cost, processing cost, transport cost, trade costs, and costs of land-use change. In the current version, supply-side activity is modeled at a 2° × 2° spatial resolution, while commodity markets are represented at the level of 37 economic regions (Table S2). A more detailed model description can be found in Supplementary Method 2.1 and www.globiom.org.

With the above economic and land-use settings, bioenergy expansion scenarios are simulated by applying regional bioenergy demand-supply balance equations; in these equations, projections of regional bioenergy demands are exogenous input and serve as lower bounds of bioenergy supply for each of the aggregated economic regions. For China's bioenergy import scenarios in this study, the "excess bioenergy demand" described in Section 2.2 is added to the baseline regional bioenergy demand equations. The GLOBIOM then operates with the optimization principle that this extra bioenergy demand is met at the lowest extra costs within the targeted bioenergy supplying regions. The cost optimization considers fixed costs, variable costs, and opportunity costs (reduced agricultural production, or diverting raw biomass material for energy use) of supplying the additional bioenergy. This cross-sectoral market equilibrium decision simultaneously determines the global agricultural and forestry market dynamics, spatial and feedstock distribution of additional biomass production, and the associated land reallocation and further impacts.

When simulating the bioenergy trade scenarios, we focus on the primary bioenergy supply, which is depicted in detail in terms of feedstock categories and processing flows in GLOBIOM[38, 50]. Three types of woody biomass sources are endogenously modeled: (i) traditional fuelwood consumed in households, (ii) energy wood biomass from the forest sector (utilized in modern forms), and (iii) short-rotation biomass plantations (i.e., dedicated energy crops). Fuelwood is supplied by forest management or deforestation activities. Energy wood biomass can come from lower-cost by-products, including forest residues, logging residues, recycled woods, and forest industry by-products, or it can directly come from round wood, which would compete with material use in the forestry sector and affect the intensity of forest management. Short-rotation energy plantation induces plantation land demand and may compete with cropland or grassland. In the applied simulation, we assume perfect substitution between energy wood and energy plantations, which means the model would endogenously choose between these two feedstocks when scaling up bioenergy based on cost minimization. Non-woody biomass (i.e., biomass from non-woody materials, including first-generation biofuels, agricultural residues, and other forms of waste), is considered exogenously in the applied model version. When modeling future bioenergy import, economic regions were aggregated into 11 aggregated regions (Table S3) to match the regional categorization of the bioenergy projection. A more detailed introduction to bioenergy simulation mechanisms in GLOBIOM and the applied region aggregation is provided in Supplementary Method 2.2-2.4.

The present study applied a calibrated model operating with 10-year intervals from 2000 to 2060. Historical agricultural and forestry production and bilateral trades were calibrated to the FAOSTAT data [34]. Trade volumes of main forestry products in 2000-2020 were further updated based on available data from the product-level international trade database BACI [56]. Characteristics of the Chinese land-use sectors, including crop area, crop yields, food demand, and afforestation area, were also calibrated with available local statistics (see reference [35] for more details). Selected model calibration results are presented in Supplementary Figures S4-S11.

2.4 Scenario framework

To compare the global land-use impacts of China’s excess bioenergy demand when different biomass import portfolios are fulfilled, we designed a scenario framework comprising two trade environment settings and multiple bioenergy-supply portfolios (Table 3). First, a reference scenario (Ref) is simulated, where the reference level of bioenergy demand for each region is applied. Next, we set up a series of stylized bioenergy-supply scenarios with excess bioenergy demand from China in line with its 1.5°C target. In the BioCHN_DOM scenario, it is assumed that the excess demand upon the reference level is assumed to be met by domestic bioenergy production. More details on the reference and the domestic-production scenario are provided in our ongoing work [57]. In the single-region import scenarios (No. 2 – 7), the excess biomass is assumed to be produced exclusively in the respective region and imported to China. Six aggregated regions that are either important bioenergy producers or exporters in history (based on statistics [1, 58]) or with greater biomass yields (based on [59]) are selected as the target regions. Then we introduce a fix-share international biomass supply scenario (BioCHN_World), where all world regions, including China, increase their bioenergy supplies by the same proportion upon the reference levels to meet China's excess bioenergy demand. Finally, in the scenario assumed with a cost-optimized portfolio of biomass imports (BioCHN_Optim), the source regions and their shares of the excess bioenergy import are endogenously determined by the model based on economic efficiency.

Table 3 Scenario settings

Trade setting (Two groups)	**No.**	**Scenario Names**	**Source region of excess biomass**
Reference scenario (Ref), baseline scenario without excess biomass demand			
(1) Fixed trade: Trade of all commodities in all scenarios and time is fixed at the corresponding levels of the reference scenario; **(2) Free trade:** trade of agricultural or forestry commodities (except biomass feedstocks) are free	1	BioCHN_DOM	Domestic (China)
	2	BioCHN_SAS	South Asia
	3	BioCHN_LAM	Latin America and the Caribbean (Hereafter abbreviated as "Latin America")
	4	BioCHN_NAM	North America
	5	BioCHN_EUR	Europe
	6	BioCHN_CIS	The Former Soviet Union
	7	BioCHN_SSA	Sub-Saharan Africa
	8	BioCHN_World	All world regions (equal proportion of supply increases upon reference levels)
	9	BioCHN_Optim	Flexible choice of import sources (endogenously decided by the model with economical optimization)

In bioenergy-import scenarios, biomass trade is implicitly represented by increasing the exogenous bioenergy demand in the target regions (from BioCHN_SAS to BioCHN_World scenarios) or world total bioenergy demand (for BioCHN_Optim), without explicit consideration of trade costs that would occur when trading the additional biomass to China (see Supplementary Method 3 for detail). The main reason for not adopting the market solutions of biomass trade is that the major focus of this study is to compare the heterogeneous land-use impacts when scaling up bioenergy supply in different regions by the same amount; therefore, these stylized scenarios do not represent plausible futures, but are used for diagnosing the marginal effects of bioenergy expansion in different regions. By utilizing these simplified trade representations, our study seeks to analyze whether large-scale biomass trade is practical in terms of global overall land-use implications, especially when market-mediated cross-regional spillovers are simultaneously taken into account.

Each bioenergy-import scenario is simulated under two different international trade settings, which determine whether there would be regional land-use spillovers alongside excess bioenergy import.

In the first case ("Fixed trade"), the trade flows of all commodities between all regions, including crops, livestock, forestry products, and biomass feedstocks, are fixed for the different time steps at the corresponding levels projected in the reference scenario. These scenarios identify and compare the local conflicts with sustainable land use induced by bioenergy deployment in different source regions. In the second case ("Free trade"), the import and export volumes of products other than biomass feedstocks can be endogenously adapted to generate a new global market equilibrium that is economically efficient given the increased bioenergy demand in China. This represents a situation where the adjustments in global production and trade in other agricultural or forestry products are allowed to counterbalance the direct local land competition, and helps reveal the secondary global spillover impacts on land use under different bioenergy import strategies.

We examined multiple land-related sustainability indicators induced by increasing bioenergy supply at the regional and global levels, including food security, GHG emissions, and agricultural input demands for crop and bioenergy production. For food security, we evaluate per capita daily average calorie availability, which is calculated based on food output in each period and the FAO's food balance table for the base year. For GHG emissions, the model covers major GHG sources and sinks in the land-related sectors, including CO_2, CH_4, and N_2O. Water and fertilizer demand is calculated by the EPIC model [60] as input to GLOBIOM and harmonized with national statistics. In this study, only rainfed energy plantations are considered (i.e., no irrigation water use for the plantations).

For all scenarios, we adopt the underlying socioeconomic data from the shared socioeconomic scenario SSP2 ("Middle of the road") [41, 61], which depicts a global future socioeconomic development following a business-as-usual trend. Besides, in spatial modeling, we also activate stringent biodiversity protection by restricting land-use changes that might be detrimental to ecosystem functioning in grids overlapped with predefined biodiversity-protection hotspots, following the method described in the literature [54]. Different from previous studies on global bioenergy demand or trade [4, 13] under climate targets, we do not price the GHG emissions from the land-use sectors for two reasons. Firstly, in our study, the global baseline bioenergy demand is assumed to be on the reference level for examining the effects of China's excess bioenergy demand, and secondly, carbon prices have not become prevailing historically [62] and its implementation in land-use sectors is still under debate. More details about the socioeconomic drivers, land-use change modeling, and evaluation of land-related sustainability indicators are provided in Supplementary Method 2.5-2.8.

2.5 Sensitivity analysis

The land-use and sustainability consequences of bioenergy expansion can be affected by many factors, including bioenergy demand levels, sources of biomass feedstocks, as well as a series of boundary conditions, including land availability or land-use-change regulation settings (Figure 2). Variations in bioenergy demand projections have been discussed in Section 2.2. For feedstock availability, some scholars have argued that policy makers should phase out dedicated land use for bioenergy to avoid possible competition with food production or carbon sequestration [63]. For land availability or land-use regulation, Weng et al. [17] studied China's 2020 bioethanol mandate and pointed out that if marginal land could be reclaimed for biomass cultivation, the competition between bioenergy and cropland would be largely alleviated. Lauri et al. [50] indicated that adding a forest set-aside constraint would reduce the global economic potential of woody bioenergy in 2050 by a quarter, but could avoid 42% of natural forest losses. Similarly, Kraxner et al. [49] found that global bioenergy expansion would lead to much higher land-related GHG emissions by 2050; however, when simultaneously implementing forest and biodiversity protection schemes, the deforestation-induced GHGs could be largely avoided, but at the cost of intensified cropland management which would trigger water stress. This means that the evaluation of bioenergy-related sustainability risks should, on the one hand, be conducted with systematic assessment tools that have finer spatial representation and cover the interconnected land-use sectors; on the other hand, the underlying assumptions on biomass feedstocks and baseline land-use conditions should be carefully considered.

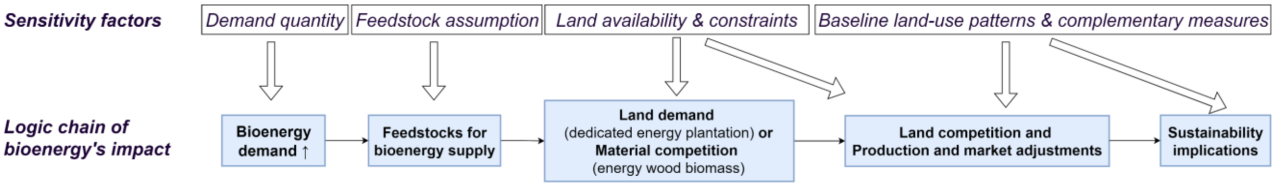


Figure 2 Sensitivity factors affecting the land-use implication of bioenergy demand

To address these uncertainties, we set up nine sensitivity analysis groups (Table 4) to test the sensitivity of the resulting global sustainability implications induced by excess bioenergy demand. These nine groups can be divided into two categories, (1) testing the sensitivity to assumptions on biomass demand and feedstock availability (set 1) and (2) testing the sensitivity to assumptions on land-availability or environmental/land-use constraints (either more relaxed – set 2, or stricter – set 3). For each sensitivity analysis group, ten bioenergy-supply scenarios, the same as described in Table 3 (the Ref scenario and nine scenarios with additional bioenergy supply for China), are simulated under the "Free trade" setting. While the global land-use results under the Ref scenario for some sensitivity analysis could be different from those in the Core setup due to alternative parameterization and model specifications, we focus on comparison across scenarios, i.e., the changes induced by excess biomass production compared with the Ref scenario. The results of the sensitivity analysis are presented and discussed in Section 3.4.

Table 4 Setup of the sensitivity analysis

Sensitivity analysis group	Description
Core scenario group	**Central settings (as presented in Section 2.4) and assumptions, including:** • **Bioenergy demand:** China's excess bioenergy demand for the 1.5℃ target follows the "Core scenarios" trajectory in Table 2; other regions' bioenergy demands follow those under the reference climate scenario • **Bioenergy feedstocks:** flexible choice between dedicated energy plantations and energy woods • **Land-use assumption:** no carbon price; strict biodiversity protection; forbid deforestation in China, EU, U.S., Sub-Saharan Africa and Latin America after 2020; implementing neither "forest set-aside" nor compulsory "food first" policy
Sensitivity set 1: assumptions on bioenergy demand or availability of feedstocks	
S1_HighDemand	Assume higher bioenergy demand for China for the 1.5-degree target (S1 in Table 2), using projection from the GCAM model in the ADVANCE project [32, 33]
S2_LowDemand	Assume low demand for woody biomass for China for the 1.5-degree target (S2 in Table 2), in line with a higher projection of non-woody biomass potential
S3_NoEnerCrop	Disallow dedicated energy plantations
S4_World1P9	Assume high baseline bioenergy demand (in line with the 1.5℃ target) for all scenarios in all global regions except China (2060 global baseline demand = 122.3EJ; China's excess demand is still 13.2EJ)
Sensitivity set 2: more relaxed land-use regulations	
S5_NoBioProt	Deactivate the restriction on land-use change in biodiversity hotspots
S6_AllowDefor	Deactivate the restriction on deforestation
Sensitivity set 3: more stringent land-use regulations	
S7_WithCarbonTax	Activate the carbon price in line with 1.5-degree climate targets since 2030 in all regions (2030=71\$/tCO_2, 2040=116\$/tCO_2, 2050=188\$/tCO_2, 2060=307\$/tCO_2). The carbon price data were from the same MESSAGE-GLOBIOM implementation whose bioenergy projection was taken as the initial projection in the Core scenario
S8_ForestSetAside	Prohibit deforestation or additional forest management since 2010
S9_FoodSecurity	Implement a "food first" policy, requiring global average calorie availability no less than the level of the Ref scenario

3. Results

3.1 Heterogenous sustainability implications in different world regions

First, we analyzed the structure of bioenergy feedstocks under different bioenergy-import scenarios when all other trade flows are fixed to the levels of the reference scenario (“Fixed trade”), since feedstock choices act as the primary and decisive drivers of bioenergy’s land-use implications. As shown in Figure 3**Error! Reference source not found.**, regions with different land endowments would differ in the feedstock structure to supply the same amount of excess biomass. In general, dedicated energy plantations would prevail in most scenarios, accounting for 47.9%-98.0% of the excess supply. For example, under the BioCHN_LAM scenario, energy plantation will take up 73.5% of the excess supply in 2030, and more than 96.6% in 2040 and onward. This mainly results from the limited supply potential of wood for energy and forest sector residues, as well as the high opportunity cost of diverting roundwood for energy. Note that most forest residues in China would already be used for energy but only equivalent to less than 1 EJ under the reference scenario by 2060; simultaneously, the global total roundwood for material use would be 2803 Mm^3, the equivalent energy content being only 20 EJ.

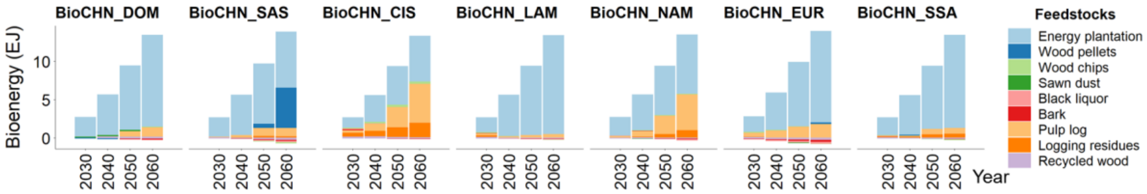
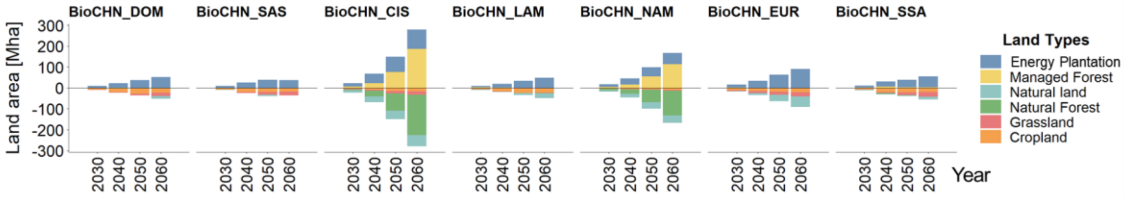


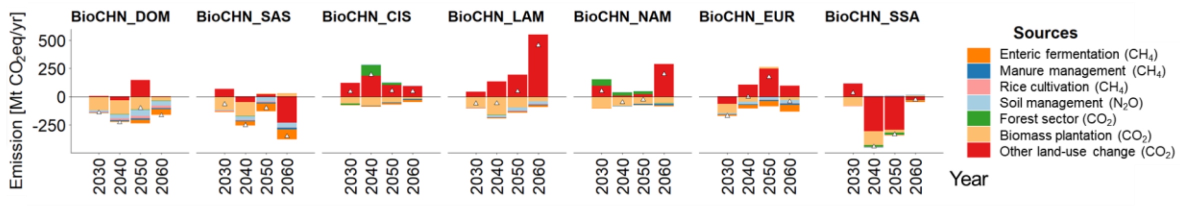
Figure 3 Feedstocks of excess biomass production in different bioenergy-import scenarios under “Fixed Trade”

Nevertheless, regions with competitive forest sectors and large forest management potential would also rely partly on energy wood to supply the excess biomass in our scenarios. If China imports the excess biomass from the Former Soviet Union or North America, around 30-50% of excess bioenergy would come from energy wood in 2050 and 2060. The reason is that when the demand for bioenergy further increases in these regions, round wood usage for bioenergy would become cost-effective, compared with establishing larger dedicated energy plantations that may induce drastic land demand (due to low energy crop yields) and compete with agricultural production.

(a) Changes in land cover



(b) Changes in GHG emissions



(c) Calorie availability

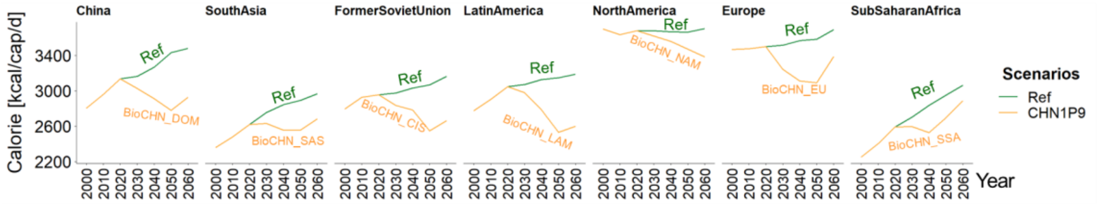


Figure 4 (a) Cumulative changes in land cover and (b) changes in GHG emissions in different scenarios compared with Ref, and (c) calorie availability in Ref and single-region-supply scenarios. Changes are for the supplying region under corresponding scenarios. The triangles in (b) indicate the net differences.

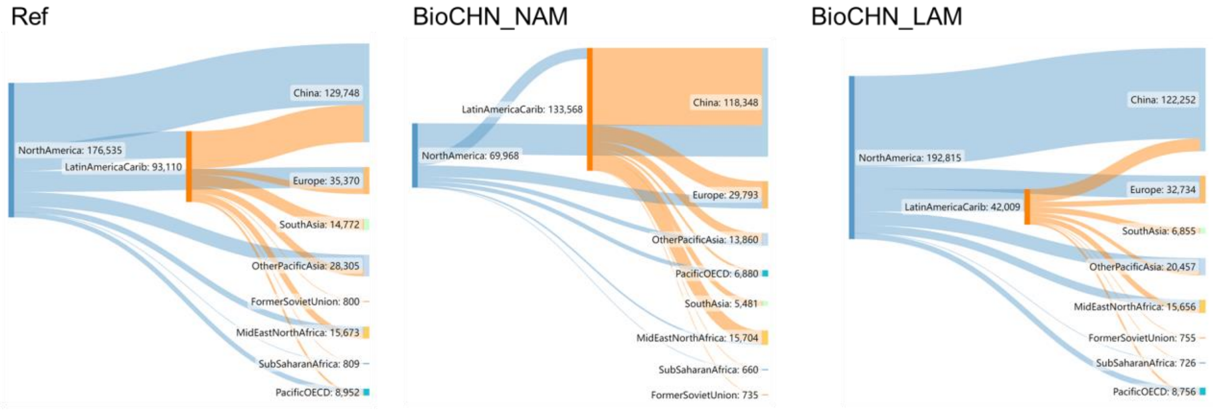
Figure 4 shows the impacts on land use, GHG emissions, and food supply in corresponding supplying regions in different scenarios under the fixed trade setting. If the excess biomass is imported to China, land reallocation and sustainability concerns regarding GHG leakage and food security will emerge in corresponding supplying regions. Owing to low biomass yields, importing excess bioenergy from the Former Soviet Union or Europe would require establishing new energy plantations by 92.7 Mha and 90.7 Mha by 2060, respectively (Figure 4**Error! Reference source not found.**a), which would be almost as large as 70% of China’s current cropland area (127.9 Mha by 2019 [64]). Besides, when importing biomass from the Former Soviet Union or North America, an even larger area of unmanaged forest would be converted to the managed forest by 2060 (corresponding to 25% and 17% of unmanaged forest area in 2000 in these two regions, respectively), indicating potential biodiversity risks and losses of carbon storage if not operated properly. Induced GHG emissions (originated mainly from the intensified land competition and the expansion of energy crops or food crops into natural land with higher carbon content) will become a major concern if Latin America or North America is to supply the excess biomass, reaching 447.3 MtCO$_2$eq/yr and 185.0 MtCO$_2$eq/yr by 2060, respectively (Figure 4**Error! Reference source not found.**b). These levels of GHG leakage would equal approximately 1/2 or 1/5 of China’s GHG emissions in the agricultural sector (=829.8 MtCO$_2$eq/yr in 2014 [65]). Besides, importing the excess biomass from almost all aggregated regions (except North America or Europe) would also induce a significant drop in local calorie availability (exceeding 500 kcal/cap/day in most scenarios; Figure 4**Error! Reference source not found.**c), which would induce severe food security concerns, especially for regions with a relatively lower baseline level of food supply (e.g., South Asia and Sub-Saharan Africa).

3.2 Comparison of local and global spillover land-use effects

With relaxed trade restrictions (“Free trade”), adjustments in the trade flows of agricultural and forestry products alongside the excess bioenergy import will mitigate the land competition in the supplying (=exporting) regions, meanwhile introducing spillover sustainability implications worldwide via indirect land-use changes. While the structures of feedstocks for excess biomass are similar to those under fixed trade settings (Figure S14), the intended bioenergy-exporting regions would adjust the production and trade of key food and forestry products (Figure S15-S17) as a counterbalance to the cropland taken-up or competition with wood material use, leading to large outsourcing of agricultural and forestry production. Figure 5 takes the soybean and wheat trade volumes as examples to illustrate the potential adjustments in global bilateral agricultural commodity trade flows under specific bioenergy-import scenarios. Figure 5a shows that under the reference scenario, net soybean exports from North America and Latin America to other regions would be 176.5 Mt and 93.1 Mt, respectively. If the excess bioenergy is assumed to be supplied in either of these two regions, the targeted region would significantly reduce soybean production and its soybean export would be largely replaced by another. Similarly, if Europe is to supply the excess biomass for China, it would drastically increase wheat import from the Former Soviet Union and North America by 2060 (Figure 5b), turning from a wheat-exporting region (net export = 58.3 Mt) in the Ref scenario, to a net-importing one in the BioCHN_EUR scenario (net import = 32.9 Mt).

Such trends can also be found in the forestry sector. With global total round wood (saw log, pulp log, and other logs) production being only 2.94 Gm^3 by 2060 under the reference scenario, the additional sawn wood imports would exceed 750 Mm^3 in South Asia under the BioCHN_SAS scenario, or 400 Mm^3 in Europe under the BioCHN_EUR scenario (Figure S16), indicating large shocks to the global timber market.

(a) Soybean



(b) Wheat

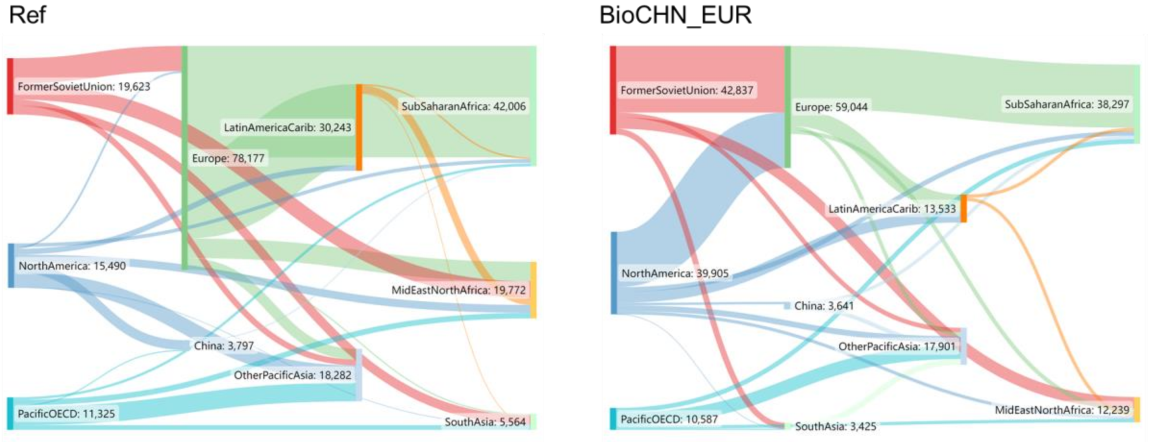


Figure 5 Trade flows for (a) soybean and (b) wheat among major importing or exporting regions in 2060 in selected scenarios (Unit: 1000 t). Trade flows within net exporting regions (on the far left) or minor flows (smaller than 15 thousand tons) are not visualized. Data in the diagram are the values for the dominating trade direction (i.e., total export for net-exporting regions; total import for net-importing regions).

These worldwide agricultural and forestry trade adjustments, alongside excess bioenergy import for China, further indicate comparable scales of indirect land-use change in regions other than the supplying ones. Figure 6 compares the changes in local and global land-related indicators under different biomass-supply scenarios by 2060, including cropland demand, forest management, food security, GHG emissions, and agricultural resource inputs. Results show that global land-use spillovers in other world regions (aggregated as “rest of world”, or ROW) could be similar or even greater than the direct impact in excess biomass supplying regions. On cropland demand (Figure 6a), with the area of local cropland taken up by dedicated energy plantations ranging across 21.4-35.7 Mha in 2060, additional cropland of 3.6-13.8 Mha would be needed in ROW for providing compensatory crop production and exports. On forest land use (Figure 6b), intensification of forest management in ROW to compensate for reduced local forestry production was identified, which is driven by increases in demand for wood imports in supplying regions. More details on the global versus local iLUC effects, and the spatial distribution of extra forest management under different scenarios, are presented in Figure S18-Figure S20. The spillover effects were also found for food supply, induced GHG emissions, irrigation water demand, and fertilizer demand (Figure 6c-Figure

6f), where the impacts in ROW typically exacerbate the global GHG footprints, or largely offset the local reduction of irrigation or fertilizer inputs. For example, supplying excess biomass in Europe would be accompanied by a reduction of nitrogen fertilizer input of 1.56 Mt by 2060 in Europe while an increase of 3.26 Mt in the rest of the world, leading to a net increase in global fertilizer demand.

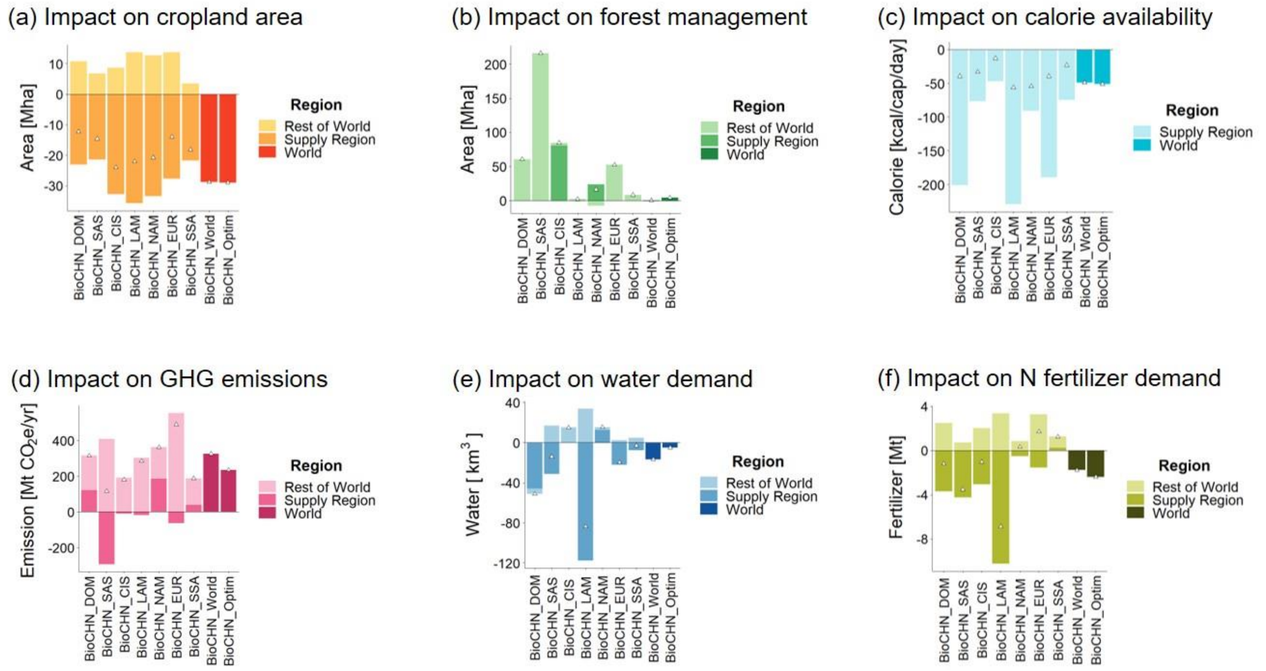


Figure 6 Impact of excess bioenergy supply on local and global (a) cropland area, (b) managed forest area, (c) average calorie availability, (d) GHG emissions, and (e) water and (f) nitrogen fertilizer demands in different bioenergy supply scenarios (compared with the Ref scenario) in 2060.

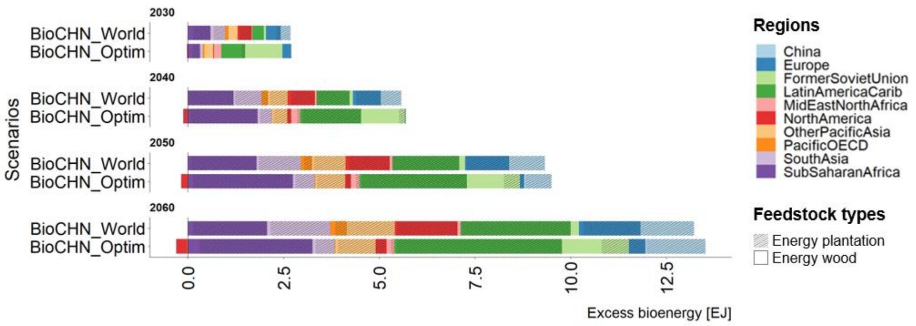
Note: triangles indicate net effects (or population-weighted average for calorie availability) at the global level. “Supply region” indicates the region for excess biomass supply in the single-source-region scenarios, while “Rest of World” indicates the aggregation of all other regions except the supply region. For the BioCHN_World and BioCHN_Optim scenarios, aggregated results for the whole globe (“World”) are shown, as the excess biomass is supplied by multiple world regions in these two scenarios. Only values for corresponding local regions are shown for induced changes in calorie availability, as the average calorie availability in any two regions cannot be directly summed up.

3.3 Economic optimization of bioenergy imports and alleviated sustainability trade-offs

Moving from single-region supply scenarios to multi-region supply scenarios (BioCHN_World, BioCHN_Optim), the source regions of excess bioenergy import are significantly diversified. In the BioCHN_World scenario, regions with greater baseline bioenergy production are assumed to supply greater parts of China’s excess bioenergy demand, while in the BioCHN_Optim scenario, the supplying regions and quantities are fully determined by the model based on economic efficiency. As shown in Figure 7, China itself would only produce about 10% of the excess biomass by 2060 in both scenarios, with the remaining bioenergy demand imported from Latin America, Sub-Saharan Africa, and eight other supplying regions.

Different from single-region import scenarios, a larger part of excess bioenergy would come from energy wood instead of energy plantations in 2030 in both multi-region scenarios (Figure 7a). This is because forest residues and recycled wood distributed in different world regions would be available after fulfilling local regions' baseline bioenergy demand. When biomass imports from multiple regions are allowed, these low-cost feedstocks would be favored. However, dedicated biomass plantations would again become dominant by 2050 and 2060, constituting >85% of the excess biomass supply. The reason is that forest residues are limited in scale, and therefore when the excess bioenergy demand grows larger in the long term, energy plantation instead of round wood will again prevail owing to its greater resource potential and cost-efficiency. Besides, compared with the BioCHN_World scenario, the additional biomass plantation would be more concentrated in Latin America in the cost-optimized scenario BioCHN_Optim (Figure 7b), mainly due to higher bioenergy yields, larger national territory areas, and lower average population density and food demand in Latin America, which imply lower opportunity costs to establish biomass plantations in this region.

(a) Regional and feedstock distribution for excess bioenergy



(b) 2060 Plantation, Ref (c) 2060 ΔPlantation, BioCHN_World (d) 2060 ΔPlantation, BioCHN_Optim

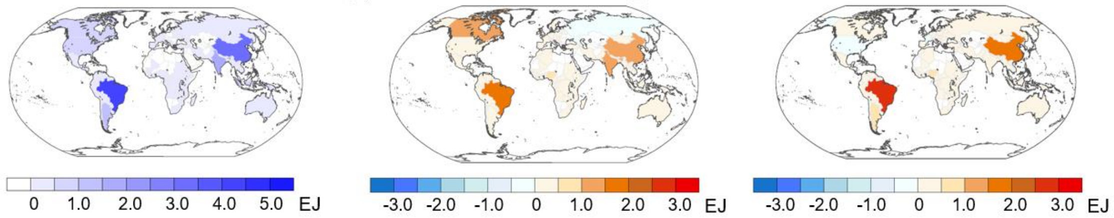


Figure 7 (a) Bioenergy feedstock distribution in BioCHN_World and BioCHN_Optim scenarios in 2030-2060; (b) spatial distribution of biomass energy plantations in Ref scenario in 2060; and (c) additional biomass plantation in BioCHN_World and (d) BioCHN_Optim scenario in 2060

An economically optimized bioenergy import portfolio can potentially reduce land-use sustainability trade-offs, but the impacts vary with indicator and time. Figure 8 shows the trends of land-use-related indicators as global aggregated or average effects. First, regarding food security, greater diversity in biomass import sources will be conducive to easing the trade-offs between bioenergy expansion and food supply, but this improvement only exists before 2040. Under both BioCHN_World and BioCHN_Optim scenarios, reduction in global cropland area and loss in average calorie availability induced by excess bioenergy import would be in the lower end across all scenarios by 2040; after 2040, with dedicated plantations becoming the prevailing feedstock, loss in calorie availability could reach near 50 kcal/cap/day, relatively higher than most of the single-region-supply scenarios (Figure 8d; Figure S23).

In terms of forest protection, economic optimization of bioenergy import (BioCHN_Optim) would imply almost the smallest area of total conversion from unmanaged forests to managed ones by 2060 (=86.8 Mha since 2020; Figure 8b), only slightly greater than that in the Ref (=73.6 Mha) or BioCHN_LAM (=76.1 Mha) scenarios. Besides, induced global GHG emissions would be limited to a lower extent in BioCHN_Optim (-98.8 $MtCO_2eq/yr$ compared to 2020) compared to most of the other scenarios throughout the whole period Figure 8c). Finally, demand for water and fertilizer would be moderate under the BioCHN_Optim scenario, although this scenario corresponds to the lowest agricultural land area by 2060 (=cropland+grassland) driven by extensive plantation expansion. This is because of the more widespread switch from lower-input production systems to higher-input ones under economic optimization.

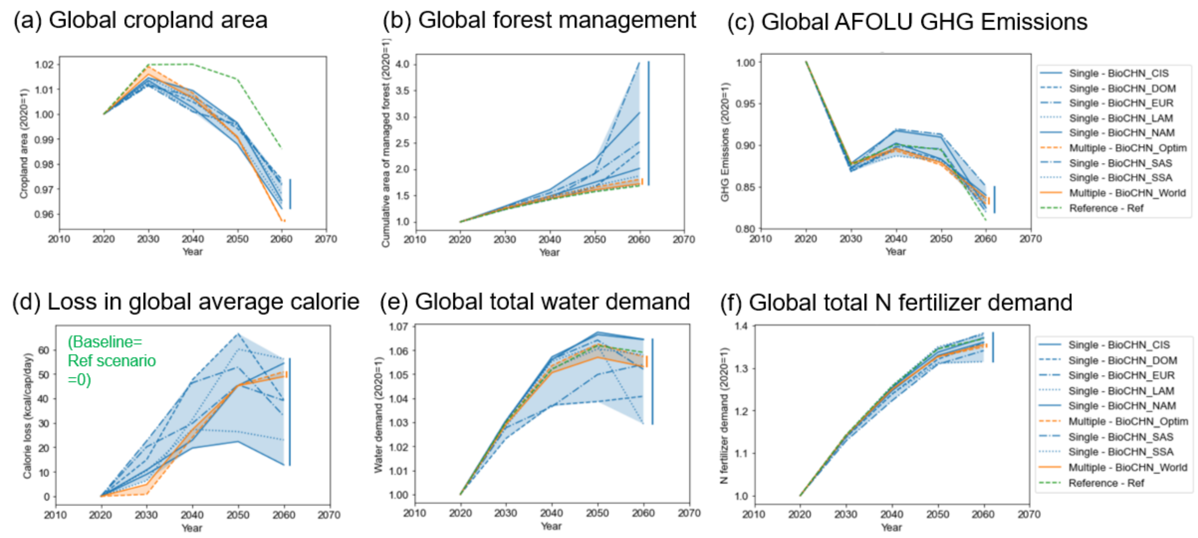


Figure 8 Comparison of aggregated global land-related indicators in different biomass-supply scenarios

Note: “Single” indicates single-region-supply scenarios (plotted in blue); “Multiple” indicates the two scenarios (BioCHN_World, BioCHN_Optim), assuming the excess biomass to be imported from multiple regions (plotted in orange). For figure (d), results from the Ref scenario are used as a baseline to calculate the differences in global average calorie availability. For other subfigures, standardized values (values scaled to the 2020 levels) are presented.

3.4 Sensitivity analysis

By conducting sensitivity analysis as described in Section 2.5, the results of bioenergy’s impact on global land use are found to be sensitive to both assumptions on bioenergy demand/feedstock and assumptions on environmental or land-use regulations. While most qualitative conclusions and the sign of effects on sustainability indicators would still hold, the magnitude of impact on global land use and ordering of consequences across scenarios could vary widely under different settings.

Figure 9 shows that both the amount of excess bioenergy demand under the 1.5℃ target in China and the assumption on biomass feedstock availability could be decisive to the induced land-use impacts and hence the feasibility of bioenergy development. With a two-fold increase in excess bioenergy demand by 2060, induced global average calorie loss under specific scenarios would be significantly intensified (e.g., from -49 kcal/cap/d in BioCHN_World scenario under the Core setting to -128 kcal/cap/day in the same scenario under S1_HighDemand; Figure 9a). On the contrary, if a major advance in non-woody biomass utilization reduces the excess woody bioenergy demand to 4.1 EJ by 2060 (S2_LowDemand), the impact on agricultural land and forest use and sustainability indicators would all be the minimum. Disallowing the establishment of energy plantations (i.e., all excess bioenergy supplied by energy wood) is identified as infeasible by 2060, even under the Ref scenario. In this case, the absence of energy crops eliminates the negative impacts on agriculture or food security. However, in the meantime, all global unmanaged forests outside protected areas would be converted to harvested ones (>600 Mha) while still yet to fulfill global baseline bioenergy demand by 2060 (targeted quantity = 71.1 EJ, in which the infeasible quantity = 6.5 EJ), with no room for supplying additional biomass energy.

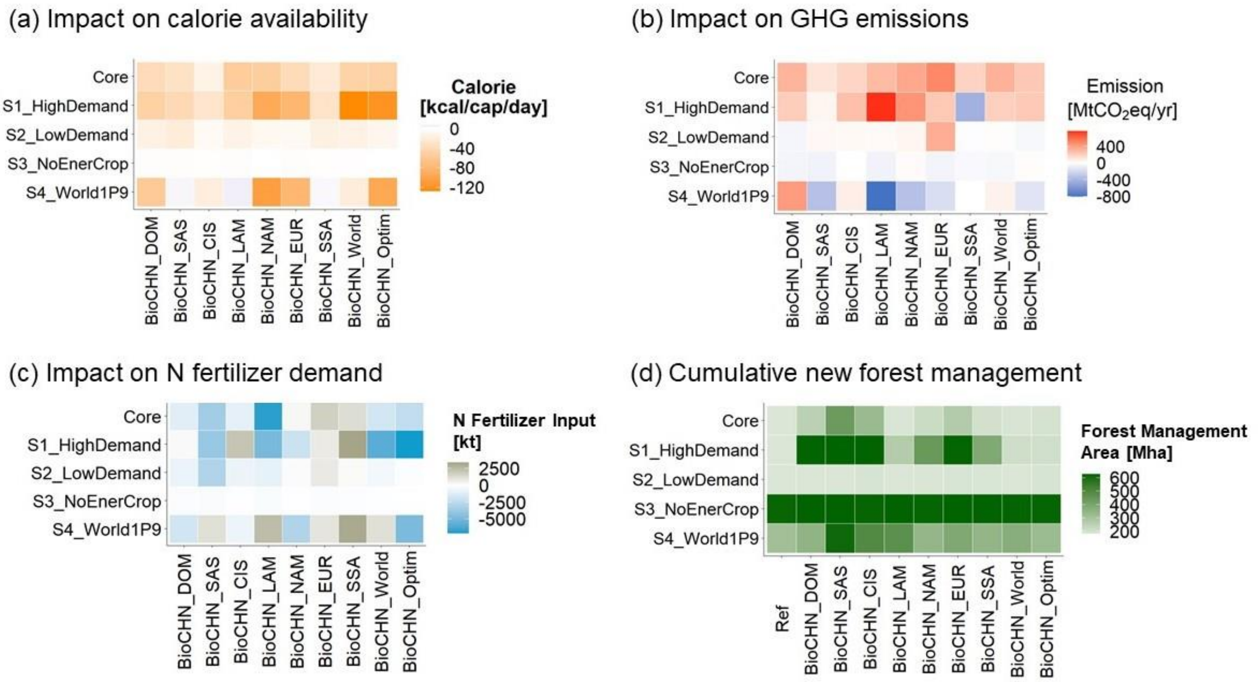
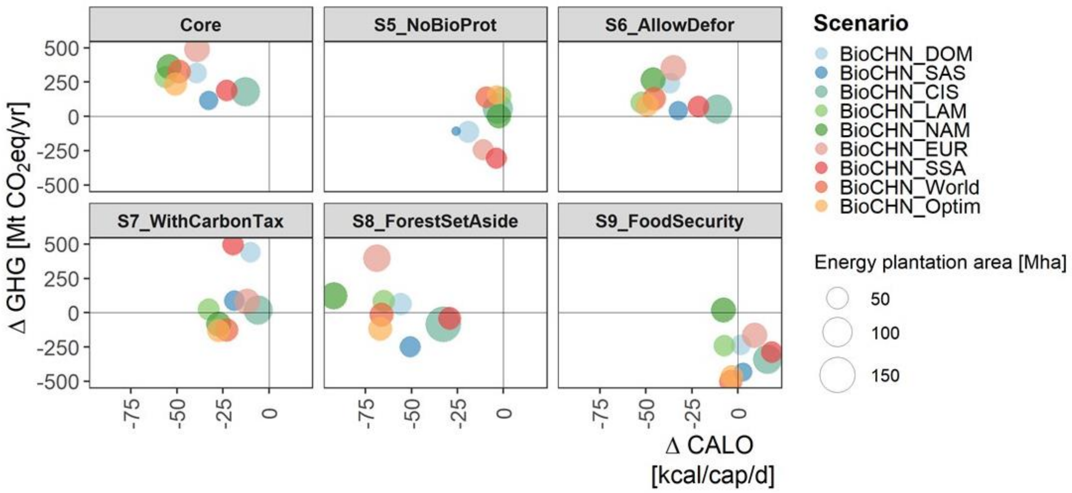


Figure 9 Impact of excess bioenergy import on (a) global average calorie availability, (b) net land-use GHG emissions, (c) nitrogen fertilizer demands in different scenarios (compared with the Ref scenario) in 2060; and (d) cumulative new forest management between 2000 and 2060 in Ref and different bioenergy-import scenarios, under different assumptions on bioenergy demand or feedstocks

Figure 10 shows that variations in land-use regulation settings potentially lead to trade-offs (or in some rare cases co-benefits) in sustainability indicators in the context of an increased bioenergy demand, which is consistent with findings in existing literature, as mentioned in Section 2.5. For example, relaxing biodiversity protection constraints (S5_NoBioProt) would alleviate land stress and reduce the loss in calorie availability (by near or more than 50 kcal/cap/day in BioCHN_LAM, BioCHN_NAM, and BioCHN_Optim scenarios), but the implicit threat to biodiversity is uncertain. Adding a forest set-aside constraint would reduce GHG emissions and eliminate natural forest losses, but induce much greater shocks to the global food supply. By contrast, implementing a GHG tax in land-use sectors or a “food-first” policy could potentially mitigate GHG emissions, as well as reduce forest management (S7_WithCarbonTax) or cropland takeup (S9_FoodSecurity), respectively.

(a) Impact on global calorie availability and GHG emissions



(b) Impact on global cropland and unmanaged forest

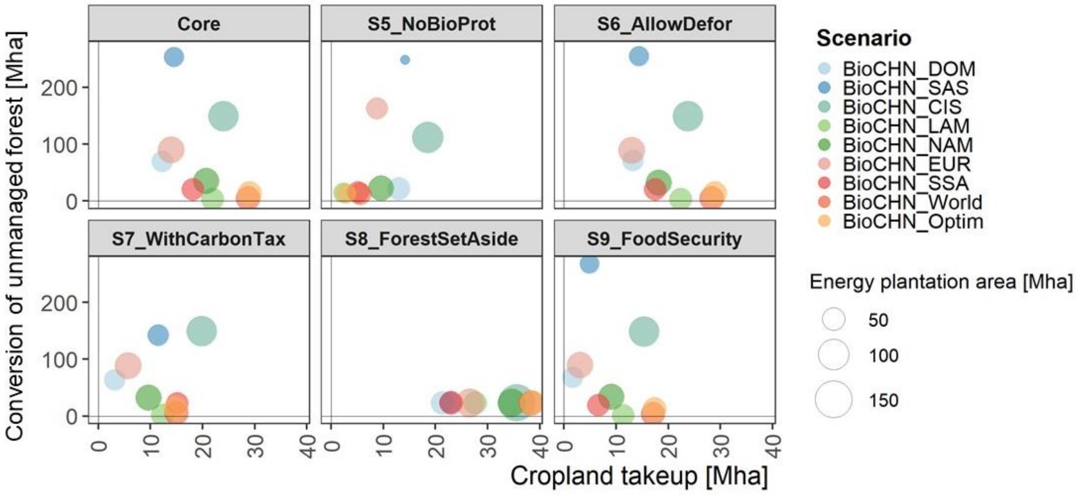


Figure 10 Impact of excess bioenergy imports on (a) global average calorie availability and net GHG emissions and (b) cumulative cropland takeup and natural forest loss by 2060 in different scenarios (compared with Ref), under different assumptions on land-use regulations. The areas of circles indicate total excess energy plantation areas in different scenarios. CALO = calorie availability.

Last but not least, the comparative advantage of the flexible bioenergy trade scheme would generally hold regardless of which specification on bioenergy or land use is applied (Figure 11). More specifically, under almost all sensitivity tests, global overall sustainability trade-offs in BioCHN_Optim could be more or less reduced compared to other stylized bioenergy import scenarios. This is particularly evident for natural forest protection, for the impact on forest management in the BioCHN_Optim scenario is typically the lowest across scenarios. Moreover, with stricter land-use regulations (e.g., taxing GHG emissions, or implementing a “food first” policy), this flexible bioenergy import portfolio (the BioCHN_Optim scenario) has better chances to mitigate the sustainability trade-offs at a global scale, especially for GHG mitigation, fertilizer demand, and natural forest protection. For example, the induced GHG emission in the BioCHN_Optim scenario would be in the middle of all scenarios under the Core setting; but with stricter land protection (S7~S9), net GHG changes would typically be in the lower end. While under the more relaxed setting S5_NoBioProt, where the restrictions on land use for biodiversity hot spots are removed, larger induced GHG emissions and fertilizer demand could make the BioCHN_Optim scenario no longer desirable. In terms of food supply, it should be noted that the flexible bioenergy importing scheme cannot help alleviate the shock of excess bioenergy production on food security, owing to the prevailing energy crop expansion in high-biomass-yield regions in the BioCHN_Optim scenario. This indicates that more complementary measures to improve the global food system and land-use efficiency would be needed to promote the co-achievement of food security and bioenergy targets.

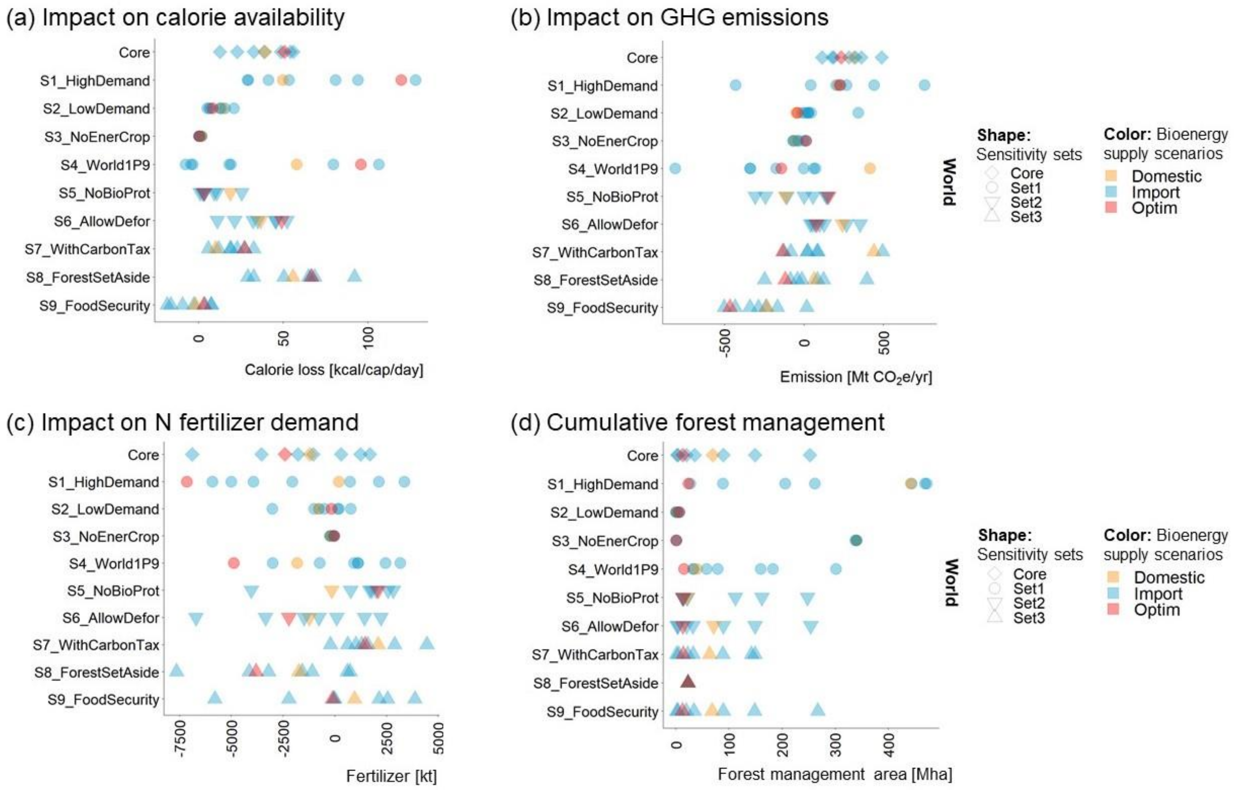


Figure 11 Comparison of the impact of different bioenergy-import scenarios on (a) global calorie availability, (b) net GHG emissions, (c) global nitrogen fertilizer demand, and (d) cumulative cropland takeup and forest management by 2060, under different sensitivity scenarios. The results shown are changes in each supply scenario compared with the Ref scenario. “Domestic” in the legend refers to the BioCHN_DOM scenario, “Import” refers to stylized bioenergy import scenarios (No.2-8 in Table 3), and “Optim” refers to the BioCHN_Optim scenario.

4. Discussion

4.1 Rationality of bioenergy import scenario settings

This study takes China as an example and sets up a series of bioenergy import scenarios to evaluate the compatibility of bioenergy targets with global land-use sustainability. On the one hand, it provides a deep dive into regional bioenergy strategies and explicit comparison of different biomass trade schemes; on the other hand, it gives insights into China's biomass demand in light of its climate neutrality targets. Also, it extends from static, closed-economy analysis to dynamic, global-scale assessment, including both direct and indirect impacts.

While it may seem a giant leap to analyze large-scale biomass import in a world where bioenergy trade is only happening on tiny scales [58, 66, 67] (= 1.25 EJ, equivalent to 2% of global bioenergy production or 1% of global crude oil trade by 2015 [58]), this scenario setting holds certain rationality. The global decarbonization scenario indicates that with the demand for fossil fuel substitution and negative emissions swiftly uplifting, global bioenergy trade would significantly ramp up [68] driven by the mismatch between regional bioenergy demand and supply potential. The quantity of traded biomass for energy could account for up to 25% of global bioenergy demand in 2050 [69]. China, North America, and Europe were projected to be biomass importers by 2050, while Latin America, the Middle East and Africa might be the biomass exporters [13]. Therefore, it is of significance to evaluate the possible impacts of regional bioenergy import strategies, especially when biomass-demanding 1.5°C targets are incorporated in most countries' policy agendas. For China, the government is promoting a bio-economy with increased biofuel utilization in its newly released 14th Five-year Plan [70], but the detailed bioenergy development roadmap and how to align it with domestic land constraints remains unclear, making it important to investigate bioenergy import scenarios and compare with domestic-production ones to cover a broader range of supply schemes.

Also noteworthy are the quantities of excess woody biomass imports assumed in the stylized scenarios, which are substantial compared with historical wood production and trade. For example, if around 90% of the excess biomass is imported to China as suggested by the BioCHN_World or BioCHN_Optim scenarios, the quantity of equivalent wood import would reach ten-fold as much as China's total wood imports in 2017 (Figure S24). Pulpwood harvest for excess biomass exports could exceed the supply regions' historical total pulp wood production levels in specific scenarios (Figure S25). Therefore, it deserves further investigation whether China's or worldwide scale of energy wood import could approach or exceed historical total wood trade volumes. However, it should be noted that the stylized biomass trade scenarios are not meant to represent plausible futures, but are used for identifying and comparing the marginal effects of bioenergy expansion, which allows an isolating and better understanding of the challenges when sourcing biomass from different geographies. On the other hand, large-scale solid bioenergy trade is not impossible with advances in global long-distance bioenergy shipping technologies, which have been projected to drive down the high transport cost [71], indicating opportunities for increased bioenergy supplies from historically active biomass exporters and emerging markets.

4.2 Sustainability concerns with regional bioenergy targets

This study reveals the outstanding regional land-use sustainability concerns with increasing bioenergy production. The results indicate that fulfilling China’s ambitious climate target could trigger excess bioenergy demand of 13.2 EJ by 2060, contributing to a 20% increase in global reference bioenergy level (≈70 EJ) and may induce non-negligible food security and other sustainability concerns worldwide. This is because all world regions could face significant (although differential) land resource constraints when the biomass demand is drastically uplifted, especially without an open international trade environment that allows for adjustments in agricultural and forestry trades. If the excess biomass is imported from selected regions, a significant expansion in managed forests or large-scale induced indirect GHG emissions in the land-use sector may largely offset bioenergy utilization's potential climate mitigation benefit. The results thus help identify the adverse impacts in different regions and the prioritized complementary measures.

Moreover, this integrated analytical framework and the findings on global land-use implications also have certain reference values for bioenergy development strategies in other world regions than China. With the implicit biomass trade representation and comparable land-use impact assessment, the simulated impacts in the source regions for China’s bioenergy import schemes could be viewed from another angle as the impacts of a similar-scale increase in local bioenergy production in the corresponding exporting regions. Hence the analyses help understand the possible directions and magnitude of bioenergy’s land-use impacts for regions with increased bioenergy demand in similar scales as China in the context of the 1.5℃ target (including Sub-Saharan Africa, North America, and Southeast Asia, as indicated by existing IAM implementations [25, 32, 33]). It should be noted that the projected global total bioenergy demand in the “very low carbon budget” scenario could reach 100-280 EJ by 2050 and 230-440 EJ by 2100 [4]; this means that the increase over baseline bioenergy levels would be well above the extra demand from China’s climate target (<15EJ) that could already indicate widespread land sustainability trade-offs. Therefore, when more regions are to increase the bioenergy demand in line with the 1.5℃ target, possibly unintended sustainability trade-offs should be carefully assessed when designing the bioenergy strategies.

4.3 Opportunities and challenges from global bioenergy trade

Bioenergy trade can ease the global land-use sustainability trade-offs if implemented wisely. Since global land-use sectors are highly interconnected, increasing biomass import may induce adjusted agricultural or forestry trade and secondary land displacement in other regions. Our results show that a flexible biomass import portfolio can be conducive to forest protection and GHG mitigation, and ease the tension between bioenergy expansion and food security before 2040 thanks to the full utilization of forest residues. This implies bioenergy trade has a chance to improve global land-use efficiency and sustainability, just as a more open food trade which has been identified in previous studies as a critical climate change adaptation measure [72, 73].

Therefore, the option of increasing bioenergy imports for the 1.5°C target should not be completely ruled out. While it is argued that rapid efficiency improvement in the local food system (e.g., diet change [59, 74]) or scaling up alternative feedstock utilization (e.g., agricultural residues[75], energy crops in marginal land [47]) could boost domestic bioenergy supply, such solutions could face specific challenges. In this case, sustainable implementation of biomass trade can serve as a complementary scheme to fortify bioenergy's growing role in substituting fossil fuels and provide desired negative emissions without compromising global sustainability. Over the last two decades, bioenergy trade has increased steadily, especially in Europe [58, 69]. Besides, other countries in East Asia, especially Japan and South Korea, have also been actively promoting the import and utilization of solid biomass, with a significant increase in the projected imports of wood pellets in the coming years [76, 77]. Thus, for countries facing land constraints, such as China, the opportunity of combining local bioenergy production with import to promote more sustainable global land use deserves further attention.

Nonetheless, only when potential leakage effects are addressed by adequate and reasonable land-use regulations could bioenergy trade be secured from threatening global land-use sustainability. Our results also reveal that without further complementary measures, the competition of bioenergy expansion with food production could be exacerbated after 2050 under the scenario with the most flexible bioenergy trade (BioCHN_Optim). Furthermore, sensitivity analysis indicates that stricter land-use regulations could make flexible biomass import more favorable in terms of mitigating global land-use spillovers, while relaxing environmental regulations will imply greater sustainability spillovers worldwide induced by open biomass trade. Therefore, the magnitude of possible iLUC under biomass trade schemes is worthy of attention. Nowadays, countries and regions are already practicing and improving land-use regulations to address the potential risks. For example, the EU has rolled out policies to address the iLUC that may arise with increased biomass production or bioenergy trade and has been advancing the sustainable certification of bioenergy [78]. Future regional bioenergy strategies should be designed along with effective land-use regulations and supporting schemes to reconcile the conflicts with local and global sustainable land management.

4.4 Limitations and future directions

Our current analysis identified the global land-use impacts of different bioenergy import schemes. However, by implicitly using a representation of bioenergy trade in the scenario settings, this study did not feature the transport costs or trade costs associated with bioenergy import, which could be the key logistic obstacles affecting bioenergy trade in practice. Therefore, future studies can elaborate on cost, substitution elasticity, as well as institutional and other barriers of biomass trade to better explore the feasibility and optimization of bioenergy import portfolios.

Besides, in this study, future bioenergy projections are derived from existing IAM practices and treated as fixed exogenous input. It, therefore, did not figure in the potential backward feedback of land-related GHG emissions on bioenergy demand. Induced GHGs from land-use change or the “opportunity cost of carbon sink” due to competition between bioenergy plantation and afforestation/reforestation [79, 80] could influence the global or regional carbon budget and, therefore, the bioenergy demand under the same climate target. In a limited number of global studies with IAMs [81, 82], these interactions are partly featured by solving the fully integrated assessment system iteratively. Future regional studies on bioenergy implications can include these interactions by better depicting the competition of different land-based mitigation strategies endogenously (e.g. [83]), and applying IAMs with a finer regional resolution to factor in the energy-land nexus.

Our study put predominant attention on the potentially unintended risks for land use sustainability and how the land-use trade-offs induced by regional bioenergy expansion could be reduced. However, developing modern bioenergy could also bring economic and ecological benefits. In 2019, the bioenergy-related industry created 3.58 million jobs globally, acting as the second-largest employment-generating renewable energy sector [84]. It is also estimated that the availability of BECCS as a mitigation option could lower the carbon prices for meeting the 2℃ or 1.5 ℃ targets by order of magnitude and avoid 70% of the consumption losses under the 1.5 ℃ scenario [85]. Replacing fossil fuels with biomass in the power sector could also reduce air pollutants emissions thanks to higher combustion efficiency [86]. Additionally, the development of bioenergy has a chance to increase forest coverage, prevent desertification, and avoid land degradation, especially when the new biomass is planted in marginal lands. Therefore, further investigations on the feasibility and systematic impact of bioenergy development could also consider including relevant economic and environmental benefits in the analysis, and compare them with the potential land-use trade-offs to identify a solution of multi-objective optimization.

Finally, a more refined representation of biodiversity protection and localized land-use regulations in modeling the land-use-related impacts induced by bioenergy could help provide more practicable insights for regions. On the one hand, the controls on biodiversity protection in our study may have been overexerted by prohibiting all major land-use changes in places overlapped with biodiversity hotspots. On the other hand, we haven’t considered the impacts of forest management on the ecosystem functioning in the forest [87], or the vulnerability of monocultural biomass plantation systems [88], which means there could be neglected trade-offs with biodiversity. Additionally, when calculating GHG flows from the land-use sector, we only considered the carbon sequestration impacts from living biomass, without considering the impacts on soil organic carbon (SOC) storage, which have been found considerable albeit uncertain [39, 89]. Nevertheless, the findings of this study could shed new light on the outlook of environmental-friendly, sustainability-coordinated bioenergy strategies for both China and the world in the context of climate change mitigation and deep decarbonization of the energy system.

5. Conclusion

In this study, we explored the diversified global land-use implications of biomass import portfolios for China's increasing bioenergy demand by 2060 under the 1.5°C target. We found that a two-fold increase in China's bioenergy imports without largely compromising other regions' land-use sustainability is possible, but would require more flexible international trade and stricter land-use regulations that address potential environmental leakage effects. More specifically, the following conclusions can be drawn.

Relying on any single region to feed China's increased appetite for bioenergy at such a large scale could be infeasible when global trade adjustments are strictly limited. The extra bioenergy import would inevitably lead to land-use trade-offs and related sustainability issues, in the form of either competition with local crop production, or intensified occupation of natural forests and other natural lands. According to our calculations, importing biomass from specific regions could induce a loss of more than 15% of unmanaged forests converted to managed ones in these regions by 2060 if not complemented by regulations on natural forest protection. When adjustments in trade flows of other agricultural or forestry products are allowed, large-scale bioenergy import may also induce significant land-use changes in the supplying regions, as well as secondary effects in other parts of the world through market-mediated iLUC spillovers.

By contrast, an economically optimized import scheme with flexible choices on bioenergy source regions suggests that 90% of the excess bioenergy demand for China be fulfilled by biomass import to achieve better economic-wise global land-use efficiency. With diversified feedstock sources and full utilization of forestry residues and recycled wood, this strategy could largely avoid undermining global land-use sustainability. Correspondingly, global forest management activity (86.8 Mha since 2020) and induced GHG emissions from excess bioenergy import (-98.8 $MtCO_2eq/yr$ since 2020) would be limited to almost the lowest extent across all the examined supply schemes; food security risks in the form of reduced calorie supply may arise after 2040 when energy plantation becomes the predominant bioenergy source.

Sensitivity analysis suggests that high bioenergy demand for 1.5°C targets, as indicated by some IAM studies, may lead to severe shocks to the land-use sectors without a game-changing breakthrough in technology or management. Besides, second-generation dedicated energy crops can be indispensable for fulfilling the uplifted bioenergy demand by the middle of the century. More importantly, when stricter land-use regulations are simultaneously implemented, the flexible and economically optimized bioenergy import portfolio would have a greater opportunity to stay in line with global land-use sustainability targets.

To summarize, a combination of local bioenergy production and biomass import can better reconcile regional bioenergy strategy with global land-use sustainability targets, on the condition that it is implemented meticulously, and an open international trade environment is attainable. With global bioenergy demand and bioenergy trade expected to ramp up in deep mitigation scenarios, sophisticated bioenergy import schemes and other proactive land-use regulations should be in place to address the possible land-use spillovers, so as to tackle climate change without threatening the overall global land-use sustainability.

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