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Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria
Email: repository@iiasa.ac.at **Telephone:** +43 (0)2236 807 342

YSSP Report
Young Scientists Summer Program

Global Land Use Change and Food Security Implications of China's Bioenergy Development under 2060 Carbon Neutrality Target

Yazhen Wu
wuyazhen@pku.edu.cn

Approved by

Supervisors: Andre Deppermann, Petr Havlík, Stefan Frank
Program: Biodiversity and Natural Resources (BNR)
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Abstract

Most 1.5-degree climate change mitigation pathways modeled by Integrated Assessment Models (IAMs) require large-scale deployment of negative emission technologies in a medium-to-long turn, especially bioenergy with carbon capture and storage (BECCS). However, the impacts and feasibility of such bioenergy developments are still under heated debate. Moreover, one region's climate actions and bioenergy demand may arouse strong spillover effects via international trade. As the world's top CO_2 emitter, China has just made the 2060 carbon-neutral pledge. In this context, whether it is feasible to produce the bioenergy needed for this target domestically, and what might be the global ecological and economic implications if China imports a certain amount of bioenergy or crops to support the bioenergy development, are important scientific and policy questions.

In this study, the Global Biosphere Management Model (GLOBIOM) was applied to test the impacts of possible production or import portfolios for China's bioenergy demand under the 2060 carbon neutrality target. The study started by collecting the scenario data of China's bioenergy demand under the net-zero emission targets. Then a series of bioenergy production and trade scenarios were designed and input into the GLOBIOM model to estimate the impacts of higher bioenergy production or import demand on the global agriculture and land-use sector. Finally, the effects of rising demand for short-rotation plantation biomass in China on global land cover, greenhouse gases emissions, food production and trade, and the implications for food security were quantitatively assessed.

Our analysis indicates that pursuing high biomass production in any single region could lead to certain sustainability concerns. For example, if the excess biomass for meeting China's increased bioenergy demand under the 2060 carbon neutrality scenario is to be produced and imported from South Asia, the number of undernourished people across the world could increase by 34 million in 2030 and 17 million in 2060. Importing more biomass from Europe would lead to significant spillover impacts, with land-use change and competition for cropland intensified in Latin America and Africa.

It is also found that the induced land-use change and food security impacts might peak around 2030 and 2040, possibly due to population peaking and the technological improvement that would rather relax the markets. Therefore, introducing a large-scale production of biomass as a mitigation option after 2040 might be a better timing for simultaneously attaining multiple sustainable development goals.

Sensitivity analysis indicates that higher bioenergy demand could reduce the feasibility of excess biomass supply and therefore bring greater challenges to sustainable bioenergy development. It should also be noted that the bioenergy demand in other regions except China were assumed to follow the values in the reference climate scenarios in the main analysis above; and if the rest of the world also increases the bioenergy demand to be in line with the 1.5℃ target, the impacts of excess biomass demand on GHG emissions and food security would be slightly intensified.

Furthermore, a more diversified importing portfolio with an optimized regional allocation of global biomass production would be crucial to reduce the negative trade-offs. An optimized bioenergy import portfolio combined with stricter forest regulation could fulfill the increased biomass demand for China, while simultaneously achieving food security and forest protection targets, avoiding 35.5 million (or 17.5 million) cumulative undernourishment from 2030 to 2060 compared with the domestic production scenario (or a fixed global biomass trade scenario). These results could shed some light on designing environmental-friendly, sustainability-coordinated bioenergy strategies for supporting the deep transition toward low-carbon economies.

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About the authors

Yazhen Wu is currently a 3rd year PhD student majoring in Environmental Management at Peking University, China. She received a Bachelor of Science and a Bachelor of Economics from Peking University in June 2019. As a member of the Laboratory of Energy & Environmental Economics and Policy (LEEEP) led by Prof. Hancheng Dai, she is keen to investigate the co-benefits and trade-offs of climate change mitigation in terms of public health and food security. With experience in the energy-economic model (IMED|CGE) and health impact model (IMED|HEL) and by exploring their linkages with the biosphere model (GLOBIOM), she hopes to study the interactions between socioeconomic development and land use.

Abbreviations

Table of Abbreviations

Abbreviations	Full names
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
NDC	Nationally Determined Contributions
GHG	Greenhouse Gas
CO_2	Carbon Dioxide
CDR	Carbon Dioxide Removal
NET	Negative Emission Technology
CCS	Carbon Capture and Storage
BECCS	Bioenergy with Carbon Capture and Storage
SDGs	Sustainable Development Goals
CIS	Commonwealth of Independent States
SSP	Shared-socioeconomic Pathways
RCP	Representative Concentration Pathways
FAO	Food and Agriculture Organization
AFOLU	Agriculture, Forestry and Other Land Use
IEA	International Energy Agency
WMO	World Meteorological Organization
USEPA	United State Environmental Protection Agency
IRENA	International Renewable Energy Agency
IAM	Integrated Assessment Model
LCA	Life Cycle Assessment

Introduction

1. Bioenergy demand for deep mitigation

Deep decarbonization pathways under climate targets

Limiting the global mean temperature rise below 1.5°C by 2100, the goal in the Paris Agreement, is crucial for ensuring the risk of changing climate under control. By 2020, the global mean temperature rise has approached 1.2°C compared to the preindustrial levels (WMO, 2021), of which more than 1°C was induced by human activities (IPCC, 2021), mostly from anthropogenic greenhouse gas (GHG) emissions. Global climate change has brought a variety of direct and indirect negative impacts on the earth's ecosystem and humanity through hundreds of channels, which are likely to be further intensified in the future (O'Brien et al., 2012; Woodward et al., 2014; Massetti et al., 2017; O'Neill et al., 2017; UNEP, 2019).

To achieve this climate target without significant overshoot, the world needs to reach net-zero anthropogenic CO_2 emissions by 2050 and net-zero greenhouse gas emissions by around 2070 (IPCC, 2018). After a long-stagnant period without new milestones in climate ambition and actions around the globe since the Kyoto Protocol, the signing of the Paris Agreement has brought new opportunities and aroused more ambitious climate actions, which have been further strengthened in this post-COVID era due to the unprecedented consciousness of the importance of sustainable development. In 2020, China updated its Nationally Determined Contribution (NDC) target, stressing reaching a carbon emission peak before 2030 and aiming at carbon neutrality before 2060[1], which is followed by the net-zero commitments from South Korea and Japan. EU has also adopted a more ambitious 2030 target of GHG emission reductions; the ratio of committed emission reductions has been raised from 30% to 55% (compared with the 1990 level)[2], further ensuring the steady transition toward the net-zero mid-century.

Achieving the carbon neutrality target would require drastic transformation in almost all production and living sectors. The transition of the energy system toward a zero-emission or net-negative-emission one could be vital, while the rapid transformation of end-use sectors, as well as enhancing carbon sequestration via land-based solutions or other carbon dioxide removal (CDR) technologies, would also be very important. In this context, promoting renewable energy to replace fossil fuels and seeking more nature-based mitigation solutions is undoubtedly crucial.

Bioenergy demand under low-carbon pathways

As zero-emission energy with the potential of net-negative emission when coupled with carbon capture and storage (CCS) technology (BECCS), bioenergy is regarded as important renewable energy for climate change mitigation. The flexibility and abundance in resources make bioenergy a unique substitution in the power sector, road transport sectors, and many hard-to-abate sectors. In particular, the importance of BECCS as one of the most promising negative emission technologies (NETs) has been widely stressed in literature. In the special report *Global Warming of 1.5°C* by IPCC, all 1.5°C scenarios without temperature overshoot simulated by integrated assessment models (IAMs) need to adopt CDR

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[1] The State Council Information Office (People's Republic of China), Xi's statements at UN meetings demonstrate China's global vision, firm commitment. 2020-10-02. http://english.www.gov.cn/statecouncil/wangyi/202010/02/content_WS5f771a17c6d0f7257693d023.html

[2] European Commission. 2030 climate & energy framework. https://ec.europa.eu/clima/policies/strategies/2030_en

technologies to achieve net-zero emissions in the mid-to-long term; while 104 out of 114 scenarios in line with the 2°C target evaluated by IPCC require BECCS in the second half of the century (IPCC, 2018).

Currently, bioenergy has become the largest renewable energy in primary energy production in the world, accounting for 67.2% of the global renewable energy supply (World Bioenergy Association, 2020). While the utilization of bioenergy nowadays is still mostly in the traditional form which is projected to be gradually phased out in the coming decades, the demand for modern bioenergy would grow significantly to meet the climate mitigation targets. According to WWF's *Energy Report*, 60% of the world's industrial fuel and heating demand would be fulfilled by bioenergy by 2050 (WWF, 2011). It is also estimated that bioenergy could account for 15-30% of primary energy and 18% of final energy consumption by 2050 (IRENA, 2021). IPCC's special report *Renewable Energy Sources and Climate Change Mitigation* estimated that the amount of bioenergy in global primary energy by 2050 could reach 120-155 EJ in a medium development scenario, or 265-300 EJ in a high-bioenergy-demand scenario (IPCC, 2011). Rogelj et al. (2018) reviewed a series of 1.5 °C scenarios and pointed out that the spread of global bioenergy demand is between 50-300EJ, and the average bioenergy demand would grow at a rate of 1%-5% in 2020-2050. A multi-model comparison practice (Bauer et al., 2018) has indicated that by 2050, global bioenergy demand could reach 100-280 EJ per year (in the "Very low GHG budget" scenario), which is equivalent to 17%-48% of global primary energy demand in 2019.

2. Bioenergy supply potential and related impacts

Evaluation of bioenergy supply potential

Bioenergy can come from many different feedstocks, including food crops, energy crops, energy forests, agricultural or forestry residues, as well as other wastes (Figure 1). In the history of modern bioenergy development, the first-generation bioenergy, mostly bioethanol and biodiesel from corn or sugarcane, is the most widely-used one. But it is estimated that considering the sustainability and feasibility of scaling up bioenergy around the world, the 2nd generation biofuel from industrial plantations (or energy crops) would be important, as these cellulosic plantations can be produced at larger scales and lower costs, and do not induce direct shocks to the food market (Wang and Lü, 2021). Nevertheless, there could still be indirect impacts of 2nd generation biofuel production on land use and the agricultural system.

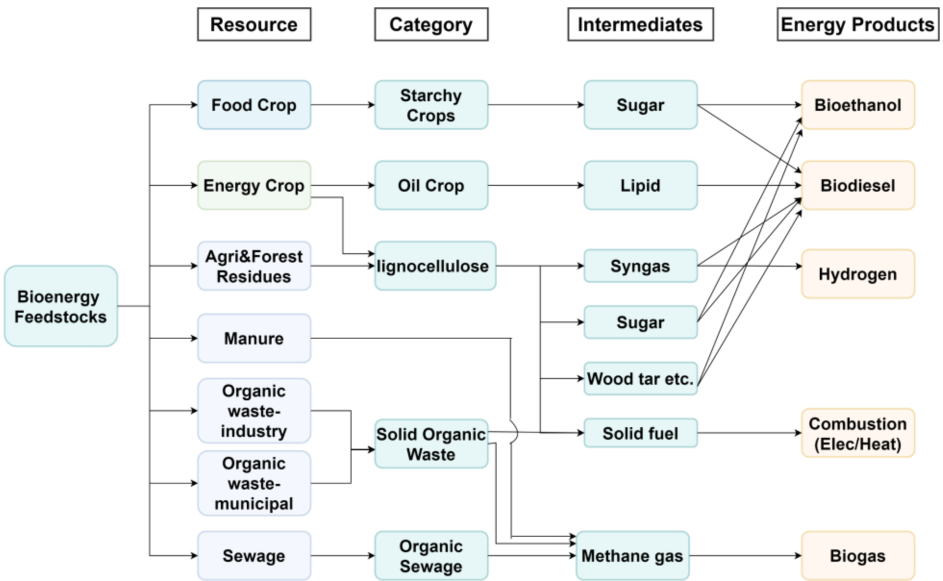

Figure 1 Categories of main bioenergy feedstocks and products

The capability of bioenergy supply is affected by many factors, including the potential of biomass from agroforestry residues, the potential of marginal land, the economy of biomass utilization technology, international trade conditions and trade costs for biomass, as well as policies for protecting biodiversity and forest. Overall, the global bioenergy supply capability is large, but estimations of bioenergy supply potential in different studies vary significantly. Table 1 summarizes several estimations of bioenergy supply capacities for China and the world from different studies. Besides, there also exists significant regional heterogeneity in terms of biomass supply potentials; for example, regions with greater supply capacity of forestry biomass include North America, Latin America, and Commonwealth of Independent States (CIS) countries (Smeets and Faaij, 2007).

Table 1 Bioenergy supply potential (Unit: EJ)

Region	Year	Item	Value	Reference
China	2050	Bioenergy, total	17	(Qin and Hu, 2015)
		in which: residues	6	
		in which: wastes	6	
		in which: energy crops	4	
World	2050	Bioenergy, total, technically available	500	(IPCC, 2011)
	2007	Forest sector, total		(Smeets et al., 2007)
		theoretical	71	
		technically available	64	
		economically available	15	
		sustainable	8	
	2050	Forest residues	11	(Williams, 1995)

Impacts of bioenergy development

Although the theoretical or technical availability of bioenergy supply might be substantial, the prospects of bioenergy for energy transition and climate change mitigation are still under debate, mainly due to the diversified impacts of bioenergy development (Jeswani et al., 2020; Calvin et al., 2021).

On the one hand, as a zero-carbon energy alternative, bioenergy could bring economic as well as ecological benefits. In 2019, the bioenergy-related industry created 3.58 million jobs globally, acting as the second-largest renewable energy sector in terms of employment (World Bioenergy Association, 2020). For mitigation costs, it's estimated that the introduction of BECCS as a mitigation option could lower the carbon prices for meeting the 2°C or 1.5 °C targets by an order of magnitude and avoid most of the consumption losses (reduced to 5% compared with 19% in a no-BECCS narrative) under the 1.5 °C scenario (Fajardy et al., 2021). Besides, replacing fossil fuels with biomass in the power sector could help reduce emissions of air pollutants due to higher combustion efficiency (USEPA, 2010). The development of bioenergy could also increase forest coverage, prevent desertification, and avoid land degradation, especially when biomass is planted in marginal lands.

On the other hand, the development and increased penetration of bioenergy in the energy sector could also lead to negative impacts. The concerns center on three points:

First, bioenergy production, especially large-scale energy crop production, could lead to land-use competition and induced impacts on crop production, food security, and ecosystem protection. This has long been identified as a major limitation of bioenergy or BECCS development. It should be noted that previous research is still largely inconclusive in terms of the impacts of bioenergy development in food security (Zhao et al., 2016). Some argued that bioenergy production wouldn't lead to significant impacts on food price (Gerber et al., 2008). However, some studies did point out the possible negative trade-offs induced by future bioenergy development in an early-warning manner (Hasegawa et al., 2018; Fujimori et al., 2019; Fuhrman et al., 2020). Besides, there also exist trade-offs between bioenergy development and biodiversity protection, mostly due to habitat conversion induced by plantations (Næss et al., 2021).

Second, the induced irrigation water demand for biomass plantation may affect regional water supply-demand balance, intensifying the indicator of water stress. For example, it is pointed out in a recent study that there would be huge water demand for irrigating bioenergy plantation for BECCS implementation under the 1.5°C target; under this circumstances, the population facing severe water shortage would be twice the number of today, even worse than the impacts of a 3°C climate change (Stenzel et al., 2021). When imposing strict restrictions on sustainable water use, the irrigation-based BECCS potential would be largely limited, only accounting for 5-6% of the potential of rainfed-based BECCS (Ai et al., 2021).

Third, the emissions during the whole life cycle of bioenergy production and utilization are also not negligible. Studies based on life cycle analysis (LCA) have revealed that not all bioethanol fuels can achieve carbon abatement in the full life cycle; the bioethanol from corn or wheat could perform poorly in terms of life-cycle CO_2 emissions, while only 2nd generation bioethanol from straws or cellulose energy crops can realize real CO_2 mitigation (Zhang et al., 2008; Jeswani et al., 2020). The losses of soil organic carbon happening during land conversion for biomass plantation might also result in extra CO_2 emissions in the first stages. It is therefore estimated that the "pay-back time" for CO_2 mitigation from bioenergy could be as long as 19 years on average when biomass is used for power generation as a substitute for thermopower (Elshout et al., 2015).

Currently, studies have used different qualitative or quantitative methods to identify the impacts of bioenergy development (Table 2). Common methods include energy system modeling, land-use modeling, and integrated modeling. Each method has unique features and advantages and thus can generate different results in terms of bioenergy potentials and impacts (Calvin et al., 2021).

Table 2 Summary of three main modeling methods for assessing impacts of bioenergy development

Model Category	**Description**	**Advantages**	**Disadvantages**	**Representative literature**
Energy system models	Top-down energy-economic modeling based on market equilibrium; or bottom-up energy technology modeling based on cost minimization	Detailed modeling of the energy system dynamics	Only suitable for macro-level analysis; Coarse category classification for bioenergy, and often missing of BECCS; Missing or very coarse depiction of the land-use sector	(Britz and Hertel, 2011; Timilsina et al., 2012; Chen et al., 2016; Victoria et al., 2020)

Model Category	Description	Advantages	Disadvantages	Representative literature
Land-use models	Modeling trends, evolution and spatial-temporal heterogeneity of land use, biomass cultivation, and bioenergy utilization	Detailed modeling of the land system dynamics; Can be applied to both macro and gridded levels	Energy demand is given by exogenous estimation	(Lauri et al., 2014; Deppermann et al., 2018; Zhou et al., 2020; Stenzel et al., 2021)
Integrated Assessment Models (IAMs)	Coupled land-society system modeling with multiple modules and complicated feedbacks	A comprehensive description of the feedbacks between natural and human systems; Can be applied to both macro and gridded levels	High modeling resource demands; Lack of hard-link and two-way linkages between land and economic sectors; Sometimes too much simplification for ensuring efficiency	(Duan et al., 2021; Zhang, A. et al., 2021)

Sustainable bioenergy supply

Viewing under the Sustainable Development Goal (SDG) framework, the development of bioenergy and the induced land demand could lead to conflicts with SDG2 (Zero hunger), SDG6 (Clean water and sanitation), and SDG15 (Life on land) to some extent. The 500EJ of global bioenergy supply potential mentioned by IPCC is only the maximum technically available quantities. In fact, in 2010, all biomass harvested for food, feed, and material usages was only equivalent to 219 EJ (IPCC, 2011). As bioenergy developments could lead to both positive and negative impacts, closing the gap and realizing the supply potential would not only face challenges in technology but also concerns on its environmental and food-security effects as well as challenges from other sustainability dimensions.

The implication is that the scale of bioenergy supply which can be defined as sustainable would depend largely on the footprints of bioenergy production. For example, it is estimated that the global bioenergy potential from marginal lands from the technology perspective could reach 39 EJ/year; however, when considering more SDGs constraints including water resource management and terrestrial biodiversity protection, the potential would be reduced to 5.5 EJ/year (Næss et al., 2021). For bioethanol from crop residues, Holmatov et al. (2021) estimated that the global total potential of bioethanol and co-generated electricity from 123 types of crop residues would be reduced to 8-8.9 EJ when considering the sustainability of residue collection, compared to a 38.4 EJ theoretical maximum. It is also pointed out that when considering biodiversity protection and other SDG targets, global bioenergy supply potential could be reduced by around 30% (Frank et al., 2021). The trade-offs between usages for bioenergy production and straw turnover for keeping the content of soil organic carbon above a sustainable level could also limit the supply potential of agricultural residues (Zhang, B. et al., 2021).

Great uncertainties exist in the estimations of global total bioenergy potential under the sustainability criteria. Krewitt et al. (2009) considered stricter environmental restrictions and estimated that the technically available bioenergy supply without conflicts with other SDGs by 2050 would reach 150EJ, of which more than 50% (88EJ) would be from agricultural and forestry residues. Beringer et al. (2011) indicated that by 2050, global bioenergy supply under the agricultural and environmental constraints would be 130-270 EJ, accounting for 15%-25% of global energy demand; the supply from energy crops would account for 30-50% in total bioenergy supply, with the concrete numbers depending on irrigation conditions. Searle and Malins (2015) gave a relatively lower estimation number, 60-120EJ, of which about 40-110EJ are from dedicated energy crops. Wu et al. (2019) estimated that the technical and economic potentials of global advanced bioenergy production without environmental policies could reach 245 EJ and 192 EJ/year, respectively; and if imposing enhanced biodiversity and soil protection policies simultaneously, the figures would decline to 149 EJ and 110 EJ/year.

Biomass and bioenergy trade

As the distribution of biomass resource potential does not exactly match that of bioenergy demand under climate goals, international trade of bioenergy or biomass might need to play an important role in fulfilling the climate and bioenergy development targets. For example, a study using the Global Change Assessment Model (GCAM) has pointed out that the bioenergy demand in China for achieving the 1.5°C climate target might reach 16-30EJ by 2050, of which around 20% might need to be met by biomass feedstock imports, mostly from Africa and other Asian countries (Pan et al., 2018).

Factors influencing bioenergy trade include the supply-demand balance, trade policy, or sustainability considerations. Currently, the trade of bioenergy or biomass is still in relatively small volumes and accounts for only a low proportion of agricultural and forestry trade. According to U.S. Bioenergy Statistics (USDA, 2021), the shares of imports in the total supply of both bioethanol and biodiesel in US accounted for less than 1% in recent years. It was also pointed out in the *OECD-FAO Agricultural Outlook 2020-2029* that in the past century, the global trade volume of bio-gasoline and biodiesel hardly exceeds 10% of their output, and the international trade of bioenergy is only centered on several countries or regions. But it is also expected that in the coming decade, with the differentiated growing rates of supply and demand of bioenergy in regions, the global trade volumes may change accordingly. For example, the export of biodiesel in Argentina is expected to increase while that in Indonesia might decline (OECD and FAO, 2021). In the context of global climate change mitigation targets and with the corresponding increases in bioenergy demand across the globe, we could expect the trade of bioenergy to become more important for fulfilling the growing demands while reducing the footprints of bioenergy production by optimizing the regional allocation of biomass plantation.

3. Research gaps and scientific questions

Research gaps

By reviewing current literature, it can be found that many projections of energy transition pathways under climate targets by energy system models or IAMs are conducted by optimizing the energy mix considering the economic costs and benefits (Victoria et al., 2020; Cao et al., 2021) without detailed elaboration on implications for the land sectors, or only accounting for land use as another input factor (Masui et al., 2001). Most projections didn't consider the feasibility of bioenergy development in terms of land use and related impacts, especially when the projected bioenergy demand is great. This is possibly due to limited model availability or capacity, which would more or less influence the practical significance when interpreting the scenario results. Another method of dealing with the uncertainty of bioenergy development is to exogenously set the upper boundary of bioenergy supply. For example, in the *Net-Zero America* report released by Princeton University (Larson et al., 2020), the authors directly set a bioenergy supply limit of 13EJ/year by 2050 which indicate no new land can be converted for biomass plantation, with a sensitivity scenario (B+) allowing higher biomass supply (23EJ/year by 2050).

However, ignoring either the induced impacts or the potential improvements from complementary measures could lead to underestimation or overestimation of bioenergy potential and its contribution to decarbonization. Literature has indicated that proactive measures or mechanisms could help improve the sustainability of the land-use and food systems, and avoid the possible conflicts of bioenergy production with food, feed, resource management, biodiversity protection, and ecological conservation. Studies have revealed that in food systems, optimizing measures including improved efficiency by scale production, reduced loss and waste, improved management on irrigation water and fertilizer use, spatial optimization of crop distribution as well as switching to a more plant-based human diet all have the potential to reduce the need for land and resources (Davis et al., 2017; Clark et al., 2020; Folberth et al., 2020; Hu et al., 2020). Likewise, such measures can also reduce the environmental footprints of bioenergy production, but this has not been comprehensively investigated in previous studies.

In particular, there is a lack of analysis of global biomass and agricultural markets in high bioenergy demand scenarios, especially the impacts of potential biomass trading. How will the increased bioenergy demand affect the land-use change and what would be the food security and environmental implications on a global scale? Whether and how could trade or other complementary measures help ease the trade-offs induced by bioenergy production, and thus create a sustainable pathway of bioenergy development? These are important questions yet to be answered comprehensively. Literature has also revealed that trade in the agricultural sector can reduce global hunger and improve consumers' welfare (Janssens et al., 2020). Whether this conclusion can still be held for biomass trade remains uncertain. Therefore, it is necessary to analyze the potential impacts of as well as the improvement by biomass trade, in the context of increasing bioenergy demand for climate change mitigation.

Case study: China's increased bioenergy demand its implications

In China, the scale of bioenergy utilization and its share in the energy system is not as much as other countries that have longer histories of bioenergy development, but biomass power and biofuel production has already grown steadily over the past years. Biomass electricity capacity addition in China exceeded 5GW in 2019, accounting for around 60% of global capacity addition[3]. In 2020, China ranked 5th in biofuel production, after the US, Brazil, Indonesia, and Germany[4].

In China's updated NDC target last year, China proposed to reach "carbon neutrality", which was further explained as "net-zero GHG emission" by China's Special Envoy on climate change, Zhenhua Xie, in the Global Asset Management Forum 2021 Beijing Summit[5] – by 2060. It is estimated that this mitigation target is generally consistent with the global 1.5°C climate target, and by 2050, China's bioenergy demand under the mitigation pathway could reach 15-30EJ (Pan et al., 2018), or even greater than 40 EJ (Duan et al., 2021). Currently, China is promoting higher penetration of bioenergy in the renewable energy system to support the green transition as well as the rural development. China also has been providing subsidies for biomass power projects[6] and biomass heating[7].

To ensure food security, China has also rolled out regulations on bioenergy in the early years of this century, demanding that the development of bioenergy should adhere to the fundamental principle of "not compete with people for grain, not compete with grain for land" [8]. A recent study revealed that

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[3] IEA. Renewables 2020 Analysis and forecast to 2025. https://www.iea.org/reports/renewables-2020

[4] Our World in Data. Biofuel energy production. https://ourworldindata.org/grapher/biofuel-production?tab=table

[5] Wuhan Ecological Environment Bureau. China is designing the timetable and roadmap for carbon peaking and carbon neutrality (in Chinese). 2021-07-27. http://hbj.wuhan.gov.cn/hjxw/202107/t20210727_1748064.html

[6] The State Council Information Office (People's Republic of China). China to optimize subsidy policies on renewable energy generation. 2020-02-03. http://english.www.gov.cn/statecouncil/ministries/202002/03/content_WS5e381fdac6d0a585c76ca584.html

[7] The State Council Information Office (People's Republic of China). Biomass energy to provide heat, fuel. 2021-04-15. http://english.www.gov.cn/news/topnews/202104/15/content_WS60778ff2c6d0df57f98d7d92.html

[8] The Central People's Government of People's Republic of China. China's biomass energy development insists on "Not competing with people for grain, not competing with grain for land" (in Chinese). 2008-10-31. http://www.gov.cn/zxft/ft154/content_1135855.htm

China could produce enough amount of bioenergy for the 2°C target by using only marginal land (Zhang, A. et al., 2021). But would it be similar for the greater bioenergy demand under the deep mitigation target of 2060 net-zero emission, and how the impacts on land use and food system would be different, if the bioenergy is produced domestically, or imported from other regions? In this study, we take China as a case study to assess the impacts of increasing bioenergy demand on global land use and related indicators, to better understand the possible challenges and opportunities for bioenergy development in regions with great quantities of bioenergy demand for achieving the mitigation targets.

Scientific questions in this study

The objective of this study is to explore the impacts of increasing bioenergy production or biomass import for China's net-zero GHG emission targets. By applying the GLOBIOM model developed in IIASA, we would like to address the following main scientific questions: (1) how much land and what kinds of land would be needed for bioenergy in line with China's 2060 net-zero target, if produced in different regions of the world? (2) what would be the direct and indirect impacts of biomass plantation on GHG emissions from the Agriculture, Forestry and Other Land Use (AFOLU) sector? (3) what could be the impacts of China's increased bioenergy demand on the food market, including food production and trade? and finally (4) what are the implications for food consumption and hunger risks? We hope to evaluate the potential risks that could stem from expanded bioenergy production and trade, and identify the optimization strategies for supporting the green energy transition by bioenergy development while holding other important factors, especially land use and food security, within sustainable boundaries.

The remaining part of the report would be organized as follows. Session Two presents the methods used in this research, including an introduction on the GLOBIOM model, scenario settings, and source of the biomass demand data. Session Three highlights the main results obtained in this study. And the report concludes with Session Four in which the key messages are summarized, together with a discussion on limitations and future work.

Methods

1. Overall framework

The study is based mainly on partial equilibrium modeling and scenario analysis (Figure 2). To analyze the local and spillover impacts of scaling up bioenergy production on the agricultural system, food consumption, and the environment, we designed a scenario modeling framework to investigate the differentiated impacts of increasing bioenergy demand in different regions, and thus to help identify the preferable global bioenergy developing strategies.

This modeling research is conducted at a global scale from the year 2000 to 2060 with 10-year intervals, which is corresponding to China's 2060 carbon neutrality target. After collecting scenario data for bioenergy demand and designing different biomass trade scenarios, we used the Global Biosphere Management Model (GLOBIOM) to explore the impact of increasing bioenergy demand on the agriculture and land-use sectors, including the impacts of a demand shock on food markets and AFOLU emissions. Further, we analyzed the induced impacts on food production, trade, and consumption, and finally on food security.

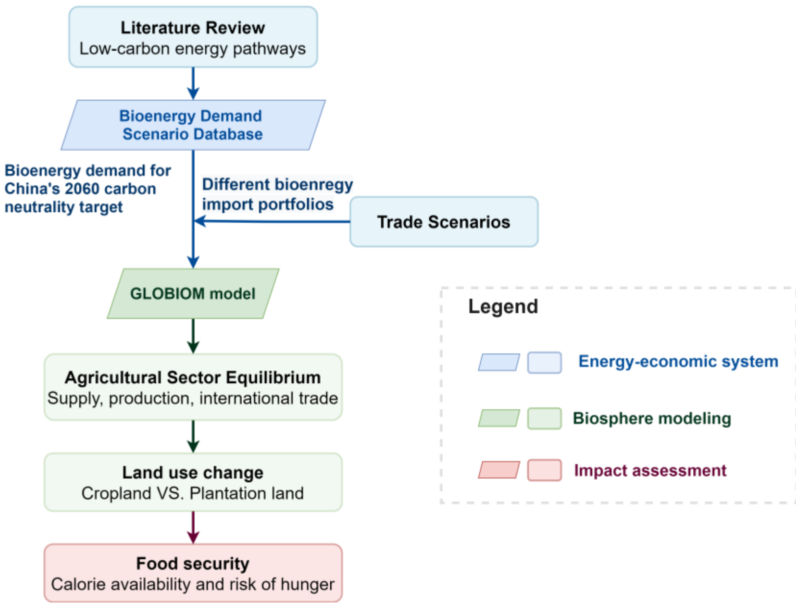

Figure 2 Overall research framework

2. GLOBIOM model

Introduction of the GLOBIOM model

GLOBIOM is a partial-equilibrium model with a global scale, representing various land use-based activities and sectors (Figure 3), including agriculture, forestry, and bioenergy sectors (Havlík et al., 2011). The model is a recursively dynamic model built with bottom-up settings based on detailed gridded land, climate, and agricultural information. It has a detailed representation of the crop production and livestock sectors, accounting for 18 crops, a variety of livestock, forestry commodities, first- and second-generation bioenergy, as well as water and fertilizer use for agricultural products and energy crops. The key mechanism of the GLOBIOM model is to maximize the sum of producer and consumer surplus within the agriculture and land-use sectors, subjective to a series of demand and resource constraints. To optimize the spatial allocation of agricultural and livestock production, a spatial equilibrium modeling approach (Takayama and Judge, 1971) is utilized. Data of technical parameters for gridded simulation are taken from different biophysical models: the parameters for crops are from EPIC (Balkovič et al., 2014), livestock from RUMINANT (Herrero et al., 2013), and forestry from G4M (Kindermann et al., 2008). A more detailed description of the GLOBIOM model can be found in existing literature (Havlík et al., 2011; Havlik et al., 2014; Deppermann et al., 2018; Deppermann et al., 2019; Chang et al., 2021).

The GLOBIOM model has already been widely applied to evaluate the impacts of land-use policies, bioenergy development strategies, and mitigation measures in the agriculture sector on global or regional land use, food market, GHG emissions as well as other SDG indicators (Havlík et al., 2011; Kraxner et al., 2013; Lauri et al., 2014; Deppermann et al., 2018; Frank et al., 2019; Chang et al., 2021). The integrated version of the MESSAGE-GLOBIOM model has also been implemented in a series of integrated assessment studies (Hasegawa et al., 2018; Fujimori et al., 2019; Leclere et al., 2020; Roelfsema et al., 2020).

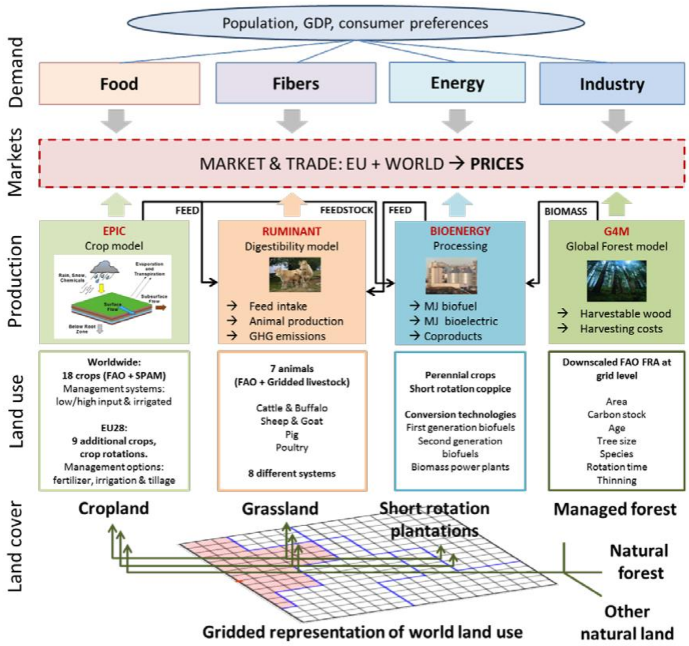

Figure 3 Overview of GLOBIOM model (Source: (Havlík et al., 2018))

In the version used in this study, the GLOBIOM model operates with 10-year intervals and at a spatial resolution of 2° x 2° latitude-longitude grids. Regional aggregated production is modeled at the country level with a total of 179 countries represented. These countries were further aggregated into 37 aggregated regions, whose total demand for agricultural and forestry products is to be matched with the total supply from the countries (and on the bottom level, 2° x 2° grids) within these regions. The modeling for the China region has also been calibrated between 2000 and 2020 to ensure better consistency with historical data, making it better to be used for analyzing the bioenergy development projections for China (Zhao et al., 2021). The calibration for the China region covered the most important modules in the GLOBIOM model, including the afforestation area and related carbon sink, pasture yield and area, international trade volume and trade policies, crop production, livestock production, and food demand. Data sources for calibration include FAOSTAT[9] from the Food and Agriculture Organization (FAO) of the United Nations, as well as China's national statistics and policies.

[9] FAO. FAOSTAT. http://www.fao.org/faostat/en/

Bioenergy in the GLOBIOM model

The GLOBIOM model has a detailed representation of the biomass processing and end-use bioenergy products, including both first and second-generation bioenergy from different feedstocks. Figure 4 summarizes the main biomass feedstocks and the processes related to bioenergy production in the GLOBIOM model version that is used in this study, according to the EU report (Valin et al., 2015) and model codes.

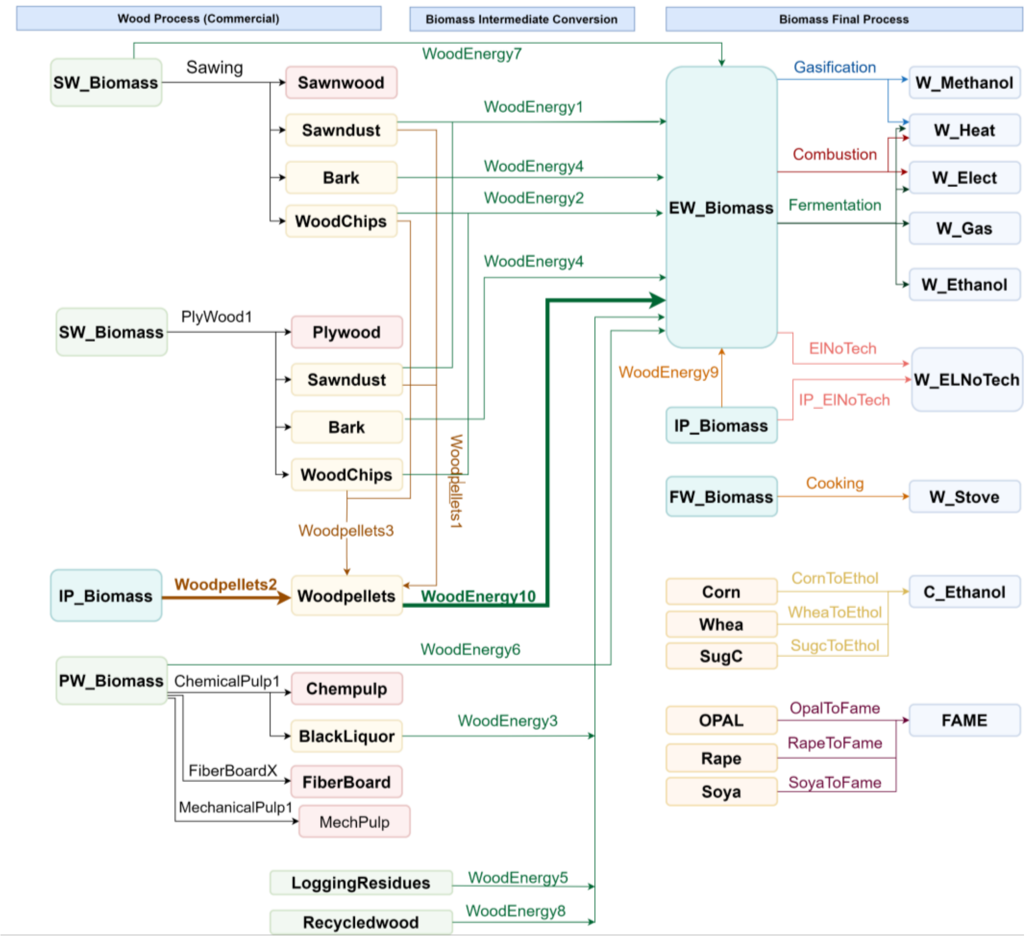

Figure 4 Bioenergy-related processes represented in the GLOBIOM model

Generally, a total of five types of different biomass categories are depicted in the GLOBIOM model:

(1) EW_Biomass: the energy wood biomass from the forestry sector which can be transformed into electricity, heat, or different types of bioenergy products including, biogas and biofuels. This biomass can come from the energy forests (SW_Biomass, which is the abbreviation for sawn wood biomass; and PW_Biomass for plywood biomass), and also forest residues from the sawing process of the SW_Biomass or plywood-making process of the PW_Biomass, including from sawdust, bark, woodchips, and wood pellets. The EW_Biomass can also come from the black liquor in the chemical pulping process.

(2) FW_Biomass: fuelwood biomass (a traditional form of biomass utilization). The FW_Biomass is also a part of the EW_Biomass but has been distinguished for residential cooking usage specially. The activities that supply FW_Biomass include the sustainable harvest of managed forests and deforestation; and together with a demand function, the supply-demand balance of FW_Biomass is modeled endogenously by the model.

(3) IP_Biomass: industrial plantation biomass. This refers to "short-rotation plantations", the plant with a short rotation period, and can be used for the production of 2nd generation biofuel (also referred to as "advanced biofuel" in literature). As an energy crop, this kind of biomass should be planted in arable land (which indicates possible conflicts between plantation land for energy crops, and agricultural cropland). This biomass is also projected by IAMs to become increasingly important in the future to support the higher penetration of bioenergy in the energy system (Duan et al., 2021).

(4) Grain crops and sugar crops: including wheat, corn, and sugarcane. These crops can be transformed into 1st generation bioethanol - crop ethanol (C_Ethanol) - in further process. As the grain crops or sugar crops for biofuel production would compete with those for other usages (food or feed) directly, and thus scaling up the 1st generation biofuel could directly influence the equilibrium of crop markets.

(5) Oil crops: including oil palm, rapeseed, and soybean. These oil crops are used to produce oil, which would be further transformed into FAME (biodiesel).

The GLOBIOM model can simulate the supply-demand balance for each type of biomass or final bioenergy product separately, and would optimize the production of biomass and final bioenergy fuels within each region given the predefined demands for each scenario. In the current model version, the demand for IP_Biomass and EW_Biomass (including FW_Biomass) in each period is exogenously input into the model according to scenario assumptions, and accordingly, the model would choose the best places to plant more short-rotation plantations (IP_Biomass) within the target region, and endogenously optimize the sources of EW_Biomass from the forestry sector to meet the demand. Besides, the minimum level of demand for crop ethanol and FAME is also given for regions with a great quantity of production in the base year, including Brazil, the US, and part of Europe.

3. Scenario and data

Overview of scenario settings

To investigate the domestic and global impacts of increased bioenergy demand under China's 2060 carbon neutrality targets, a reference scenario ("Ref") and a series of "China 2060 carbon neutrality" mitigation scenarios ("CHN1P9") were designed for comparative analysis (Figure 5).

The major difference between the Ref scenario and CHN1P9 scenarios is the underlying assumption on the level of climate change mitigation. In the reference scenario, there is no mitigation policy on top of the baseline socioeconomic trends to mitigate the GHG emissions (in line with the reference RCP climate scenario); while in the CHN1P9 scenarios, it is assumed that the level of mitigation efforts is in line with the +1.9W/m^2 radiative forcing level by the end of the century (the "RCP1.9" climate scenario). This is corresponding to the 1.5°C climate target and the carbon neutrality target by mid-century.

It should be noted that as the focus of our study is on the impact of increasing bioenergy demand on the agriculture and land-use sectors, we interpret the climate mitigation scenario as a "high bioenergy demand" scenario, which means the only difference between the "Ref" and "CHN1P9" scenarios is the bioenergy demand. Under the Ref scenario, the bioenergy demands in China and all other regions are assumed to be produced all domestically and grow at a generally lower speed, as there is no strong incentive to replace fossil energy with biofuel or other renewable fuel. While under CHN1P9 scenarios, the bioenergy demand in China is projected to increase more rapidly to support the decarbonization of the energy system. The excess biomass demand in the CHN1P9 scenario on top of the ref scenario is then assumed to be met by the increased production in different regions (corresponding to a series of bioenergy trade scenarios to be introduced immediately in the next section) to investigate the possible land-use-related impacts. Other parameters and settings, including the carbon prices in the land-use sector, are exactly the same as those in the Ref scenario (no carbon price and no additional land-use regulations in the CHN1P9 scenarios).

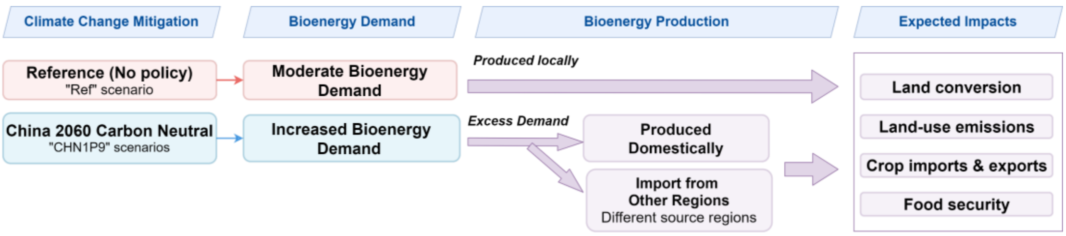

Figure 5 Conceptual diagram for scenario settings

Scenario assumptions

Table 3 summarizes the scenarios analyzed in this study. For all scenarios, the underlying socioeconomic settings are corresponding to those in the "middle of the road" (SSP2) in the SSP scenario framework (O'Neill et al., 2014; Fricko et al., 2017). Altogether there is one reference scenario ("Ref"), one domestic scenario where China is assumed to produce all the excess biomass domestically ("CHN1P9_Domestic"), seven stylized trade scenarios (No.3-9, "CHN1P9") where the excess biomass demand under the carbon neutrality target in China is assumed to be imported from other regions, and three optimization trade scenarios (No. 10-12, "CHN1P9_World_optim") where the model is allowed to endogenously explore the best regions to allocate the production of excess biomass to maximize the global total surplus. These scenarios are not necessarily realistic but can be used to compare the food and environmental impacts of producing more biomass in different regions. Finally, two groups of sensitivity analysis scenarios are set up to better address the possible uncertainties.

Table 3 Scenario Table

<table>
<tr><th>Scenario Group</th><th>No</th><th>Scenario Name</th><th>SSP scenario</th><th>RCP scenario</th><th>Source Regions for Excess Bioenergy Demand</th></tr>
<tr><td>Baseline</td><td>1</td><td>Ref</td><td rowspan="12">SSP2</td><td>RCPref</td><td>-</td></tr>
<tr><td>Domestic</td><td>2</td><td>CHN1P9_Domestic</td><td rowspan="11">RCP1.9 (China)</td><td>China</td></tr>
<tr><td rowspan="7">Stylized Trade Scenarios</td><td>3</td><td>CHN1P9_SouthAsia</td><td>SouthAsia</td></tr>
<tr><td>4</td><td>CHN1P9_LAM</td><td>LatinAmericaCarib</td></tr>
<tr><td>5</td><td>CHN1P9_NrAmerica</td><td>NorthAmerica</td></tr>
<tr><td>6</td><td>CHN1P9_EU</td><td>Europe</td></tr>
<tr><td>7</td><td>CHN1P9_FrmSU</td><td>FormerSovietUnion</td></tr>
<tr><td>8</td><td>CHN1P9_SSA</td><td>SubSaharanAfrica</td></tr>
<tr><td>9</td><td>CHN1P9_World</td><td>World (all regions)</td></tr>
<tr><td rowspan="3">Optimization Trade Scenarios</td><td>10</td><td>CHN1P9_World_optim</td><td rowspan="3">World (endogenous optimization)</td></tr>
<tr><td>11</td><td>CHN1P9_World_optim _noDefor5</td></tr>
<tr><td>12</td><td>CHN1P9_World_optim _freeall</td></tr>
<tr><td colspan="6">Sensitivity analysis 1: Higher bioenergy demand projection for China (from another IAM: GCAM)</td></tr>
<tr><td colspan="6">Sensitivity analysis 2: The rest of the world also increase bioenergy demand in line with the RCP1.9 climate scenario</td></tr>
</table>

First, the demands for EW_Biomass and IP_Biomass under the Ref scenario are derived from a common application of MESSAGE and GLOBIOM (Fricko et al., 2017; Huppmann et al., 2019; Krey et al., 2020). As the MESSAGE model has a relatively coarser regional resolution, the bioenergy scenario analysis in this study is carried out at the same aggregated region level, i.e. the "GGIREGION" which is the regional aggregation used in the MESSAGE model, to ensure internal consistency and avoid the extra uncertainty from additional downscaling. There are 11 aggregated regions in total, i.e. NorthAmerica, WesternEurope, CentralEastEurope, PacificOECD, FormerSovietUnion, PlannedAsiaChina, SouthAsia, OtherPacificAsia, MidEastNorthAfrica, LatinAmericaCarib, and SubSaharanAfrica. The detailed information on these GGIREGIONs can be found on the website of the MESSAGE model [10].

For the group of stylized trade scenarios (scenarios 3-9), we chose some of the regions (e.g. SouthAsia), or aggregations (e.g. Europe is the aggregator of WesternEurope and CentralEastEurope), to be the intended source regions for excess biomass imports based on results of some pre-experiment (feasibility of increasing production by large quantities). Under the CHN1P9_World scenario, all regions including China would increase the production of biomass by the same proportion to meet the new global total demand when China has increased the bioenergy demand. Besides, in the region aggregation, China was originally aggregated with RSEA_PAC (several SouthEastern Asia countries in the Pacific region) in "PlannedAsiaChina". To better represent the impacts of increasing bioenergy demand in China, we separate out China when modeling the bioenergy market balance by re-dividing the RSEA_PAC region into the "OtherPacificAsia" region.

As traditional biomass is gradually being phased out and the biofuel from crops is not promising under land constraints and food-security considerations, the short-rotation plantation (IP_Biomass) is considered in our study as the most important type of modern biomass in the future, which is expected to fulfill most of the increased bioenergy demand in our high-bioenergy-demand scenarios. Therefore, it is assumed that all the excess biomass under the mitigation are from the IP_Biomass instead of woody residues (EW_Biomass) from the forestry sector. Table 4 explains the settings for bioenergy demand in a formula way, where $\Delta Q_{IP\_Biomass}$ equals the excess IP_Biomass demand in China for the RCP1.9 mitigation scenario (compared with the RCPref). In our scenario analysis, we directly modified the bioenergy demand data for the source regions, and assumed the corresponding regions would export the excess amounts of biomass to China; this means that we didn't explicitly model the biomass trade flows between China and other regions, and the underlying assumption is that there are no trade costs for biomass exports. This simplification could be reasonable, as to whether to model the biomass trade flows explicitly won't impact the results in current model settings, and as global biomass trade is now only on a small scale and there are no significant trade tariffs or barriers on biomass.

Table 4 Scenario settings for bioenergy demand

Scenarios	Scenario settings
Ref	$Q_{r,\ IP\_Biomass} = Q_{r,\ IP\_Biomass,\ RCPref}$ $Q_{r,\ EW\_Biomass} = Q_{r,\ EW\_Biomass,\ RCPref}$
CHN1P9_Domestic	$Q_{CHN,\ IP\_Biomass} = Q_{CHN,\ RCPref} + \Delta Q_{IP\_Biomass}$
CHN1P9_LAM	$Q_{LAM,\ IP\_Biomass} = Q_{LAM,\ IP\_Biomass\ ,\ RCPref} + \Delta Q_{IP\_Biomass}$
CHN1P9_SSA	$Q_{SSA,\ IP\_Biomass} = Q_{SSA,\ IP\_Biomass\ ,\ RCPref} + \Delta Q_{IP\_Biomass}$
…	…
CHN1P9_World	$Q_{r,\ IP\_Biomass} = Q_{r,\ IP\_Biomass,\ RCPref} * \frac{Q_{world\ total,\ RCPref} + \Delta Q_{IP\_Biomass}}{Q_{world\ total,\ RCPref}}$

Next, the group of optimization trade scenarios (scenarios 10-12) was set up for testing whether there is room for improvement with respect to the spatial allocation of biomass production (Table 5). Different from the CHN1P9_World scenario where all regions increase their production of the industrial plantation biomass proportionally (based on their production amount in the Ref scenario) to meet China's import

[10] IIASA. MESSAGE model regions. https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html

demand, in the CHN1P9_World_optim scenario (scenario 10), the excess bioenergy demand for China's carbon neutrality target is allowed to be produced in any region of the world to reduce the overall cost. While in CHN1P9_World_optim_freeall scenario (scenario 12), not only the biomass demand in China can be allocated endogenously, but all the demand of industrial plantation biomass is assumed to be allowed to freely reallocate in the world. This can be regarded as a drastic optimization scenario that only considers the economic efficiency but not historical distribution. Results for this group of scenarios will be presented in the fifth part of the result session (Session Four).

Table 5 Details in the optimization trade scenarios

Scenario	**IP_Biomass demand**	**How the world meets the total IP_Biomass demand**
ref	scenRCPref	Produce all locally in each GGIREGION
CHN1P9_World	Higher bioenergy demand in China to be in line with RCP1.9	Proportionally scale each GGIREGION's production on top of the Ref scenario
CHN1P9_World_optim		1.World total supply ≥ total demand 2. Regional supply ≥ demand in Ref
CHN1P9_World_optim_noDefor5		Same as CHN1P9_World_optim; but deforestation is also prohibited in LAM and SSA
CHN1P9_World_optim_freeall		Only world total supply ≥ total demand

We also tried to include the observed forest protection policies in our scenario analysis. In all scenarios except the 11^{th} scenario, deforestation is prohibited in China, Europe, and the US, which reflects national or regional policies and recent trends. In other regions, there were assumed to be no restrictions on deforestation, which means the other regions could convert the primary forest land into cropland for producing agricultural products, or plantation land for biomass. To test the possibility of coordinating biomass plantation and forest protection, we further introduced the 11^{th} scenario in Table 4, the "CHN1P9_World_optim_noDefor5" scenario, where all other settings are the same as those in "CHN1P9_World_optim", but prohibition on deforestation are also implemented in Latin America and sub-Saharan Africa regions.

It should also be noted that in current settings, we didn't introduce the land conversion restriction for biodiversity protection (e.g. prohibiting the deforestation, or disallowing conversion from cropland or natural land to cropland or plantation land, when the number of overlapping with biodiversity protection hotspots in a simulation unit excess a certain threshold), to avoid infeasible results. This means that the possible conflicts between biodiversity protection and other land use are currently not fully addressed in this study.

Projections of Bioenergy demand in China

To quantify the excess biomass demand in China under the carbon neutrality target, we took one projection of the bioenergy demand from the MESSAGE model, which is from the built-in database of the GLOBIOM model and was derived by the common application between MESSAGE and GLOBIOM, and another projection from the GCAM model from a multi-model comparison exercise (Figure 6). The projection from the MESSAGE model is used in the main scenarios that are described in Table 3 above, while that from GCAM is used in sensitivity-analysis scenarios. The excess demand for IP_Biomass in China was then calculated by subtracting the corresponding reference values from the values for the RCP1.9 (1.5 ℃) climate scenario.

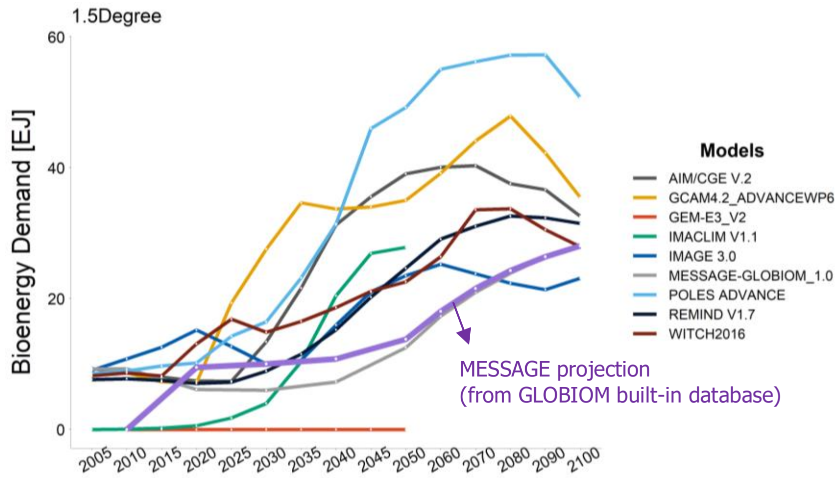

Figure 6 Total bioenergy demand in China under the 1.5 ˚C climate change mitigation scenario (Data source: (Duan et al., 2021) & ADVANCE database[11])

The demands for EW_Biomass in China under the Ref or CHN1P9 scenarios were also taken from the MESSAGE model and were kept the same across all CHN1P9 scenarios. The numbers of quantities of EW_Biomass demand in China under the Ref scenario (0.001EJ by 2060) and the differences between the Ref and CHN1P9 scenarios (0.8 EJ by 2060) are both significantly smaller (Table 6).

Table 6 Demands for IP_Biomass and EW_Biomass under different scenarios

Category	**Scenario**	**Unit**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
IP_Biomass	Ref	EJ/yr	0.00	0.00	0.23	0.80	1.57	2.41	3.25
	CHN1P9	EJ/yr	0.00	0.00	3.56	6.42	9.16	11.75	14.60
	Excess demand	EJ/yr	0.00	0.00	3.32	5.63	7.59	9.34	11.35
EW_Biomass	Ref	EJ/yr	8.98	8.54	6.46	4.63	0.00	0.00	0.00
	CHN1P9	EJ/yr	8.98	8.54	6.35	4.60	0.00	0.00	0.82
	Excess demand	EJ/yr	0.00	0.00	-0.11	-0.03	0.00	0.00	0.82

[11] IIASA. ADVANCE Synthesis Scenario Database.
https://db1.ene.iiasa.ac.at/ADVANCEDB/dsd?Action=htmlpage&page=welcome

Results

1. Land system: land-use change and related emissions for bioenergy

Additional land requirement for biomass plantation

Figure 7 shows the additional plantation land that would be needed in the corresponding producing region for short-rotation biomass plantation in each of the stylized trade scenarios ("CHN1P9" scenarios, the mitigation scenarios with increased bioenergy demand for China's carbon neutrality target), compared with the reference scenario (Ref). The dark blue bars indicate the existing cumulative additional plantation land until the last period, and the bars in other colors indicate the newly added plantation land in the present period. In historical years (2000-2020), the biomass plantation was calibrated to the same amount for both Ref and mitigation scenarios, so the excess plantation land for short-rotation plantations equals zero. Starting from 2030, the area of newly-added plantation land and the cumulative land would be larger in bioenergy trade scenarios in the corresponding regions due to the excess biomass production.

The scale of land conversion for biomass plantation would be different when the excess biomass is assumed to be produced and imported from different regions. To produce the same amount of excess short-rotation plantations to meet the increased bioenergy demand, the FormerSovietUnion region (which includes Russian Federation, Ukraine, and other CIS countries) would need the largest plantation land area. This is due to the relatively lower yields of biomass at high latitudes according to the underlying yield data in the model. For example, the yields of short rotation plantation in tropical regions could reach more than 40,000 m^3/ha (e.g. average in Brazil: 46,067 m^3/ha), while for countries located in the high-latitude, the yields of biomass could be significantly lower (e.g. average in the Russia Federation: 7,940 m^3/ha).

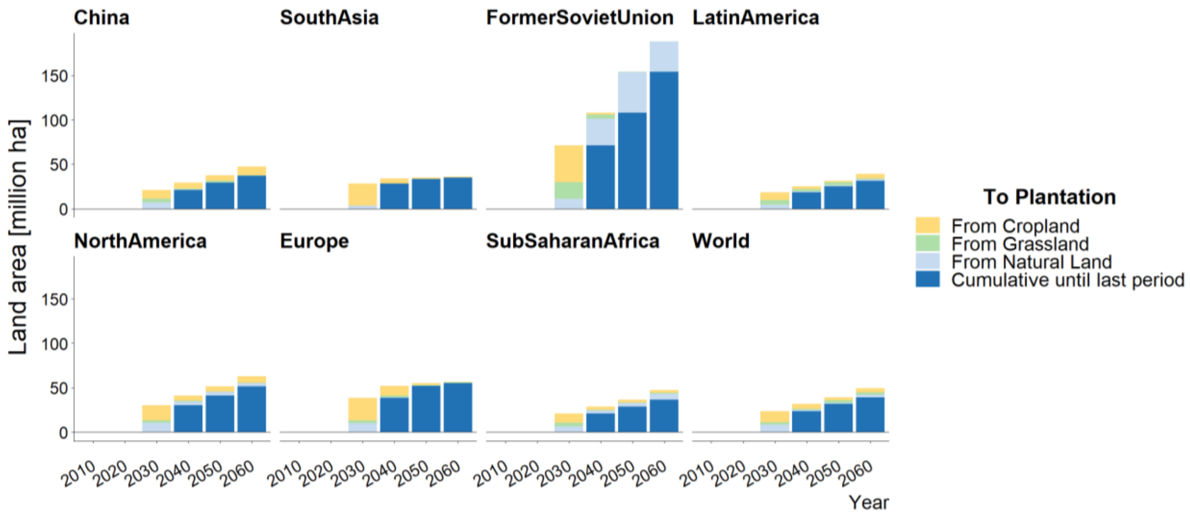

Figure 7 Cumulative land-use change to plantation land in corresponding regions under the CHN1P9 scenarios

Note: The analyzed regions are corresponding to the scenarios. For example, the results in the figure for China are the changes in China under the "CHN1P9_Domestic" scenario, and those for World are global total changes under the "CHN1P9_ World" scenario (similarly hereinafter).

Greenhouse gas emissions from the Agriculture, Forest, and Other Land Use (AFOLU) sector

The Agriculture, Forest, and Other Land Use (AFOLU) sector contributes around one-fifth of global GHG emissions (IPCC, 2014; Crippa et al., 2021; Hong et al., 2021), acting as an important GHG emission sector that attracts wide attention. Figure 8 shows both the changes in emissions in the corresponding local region and the total emission changes in the world, when the excess biomass production is assumed to be located in different regions. Under high-bioenergy demand ("CHN1P9") scenarios, the induced land-use change and the regional relocation of agriculture production by additional short-rotation biomass plantation would lead to certain scales of changes in AFOLU GHG Emissions. For most regions, additional biomass plantation would bring negative emissions due to the carbon sequestration effects in the corresponding periods, which could amount to several hundred Mt CO_2eq in some scenarios; the exact numbers would depend on whether the added plantation land would be converted from cropland or grassland (net negative emissions), or from natural land (could be either positive or negative emissions). It should also be noted that the direct emission changes from biomass plantation would only happen in the period when the short-rotation biomass is planted, but not for the subsequent years, which could be different from the emissions from additional cropland or the forest sector. Meanwhile, there could be significant changes in GHG emissions due to indirect land-use changes (between natural lands, cropland, and grassland) induced by biomass plantation, and also some positive emissions from deforestation in the FormerSovietUnion region or sub-Saharan Africa. Reduced emissions from crop production or livestock due to land crowd-out could also be expected.

Regional spillover effects on the emission changes could be observed by comparing the impacts in local regions and the total of the world. For example, producing more biomass in the FormerSovietUnion region, North America or Europe could lead to a certain level of deforestation emissions in other parts of the world. The regions that could produce biomass with smaller spillover impacts include SouthAsia, FormerSovietUnion, Latin America, and sub-Saharan Africa. The spillover effects are also visualized in Figure A1.

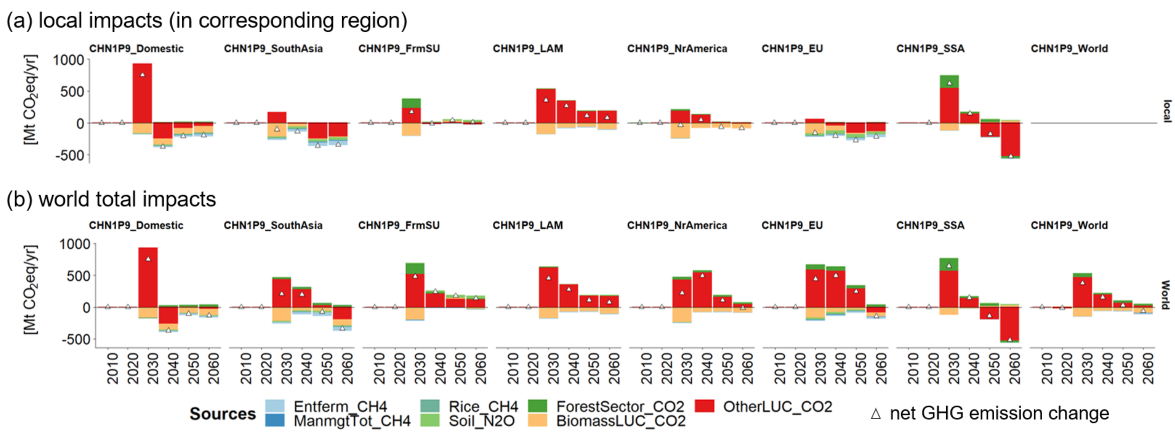

Figure 8 Changes in AFOLU GHG emissions in (a) corresponding local regions and (b) total of the world, under the mitigation ("CHN1P9") scenarios, compared to the Ref scenario

2. Food markets under high-bioenergy-demand scenarios

Changes in food production, import, export, and consumption

Increasing the production of short-rotation plantation biomass could bring significant changes in regional food markets (Figure 9). Generally, the land-use competition between crop production and the additional biomass plantation would increase the land rents, and therefore the corresponding regions would reduce domestic food production and exports while increase imports. It can be found that when producing more biomass in China, South Asia, the FormerSovietUnion region, or Europe, the local region would increase the imports of staple crops (rice and wheat) by large quantities. For example, Europe might reduce the production of wheat by 128 million tons and increase the import by 111 million tons. Soybean trade would also be largely affected at the same time. For example, when producing more biomass in South Asia or sub-Saharan Africa, they would increase the imports of soybean by around 50%; if the excess biomass is to be supplied by North America, which is one of the two major soybean exporting regions in the world (the other one is Latin America), it would tend to reduce much of its soybean production and exports (by almost 50%). The overall impact on food consumption is not significant in both quantity and ratio, as most of the impact caused by land competition could be mitigated by adjustments in imports and exports.

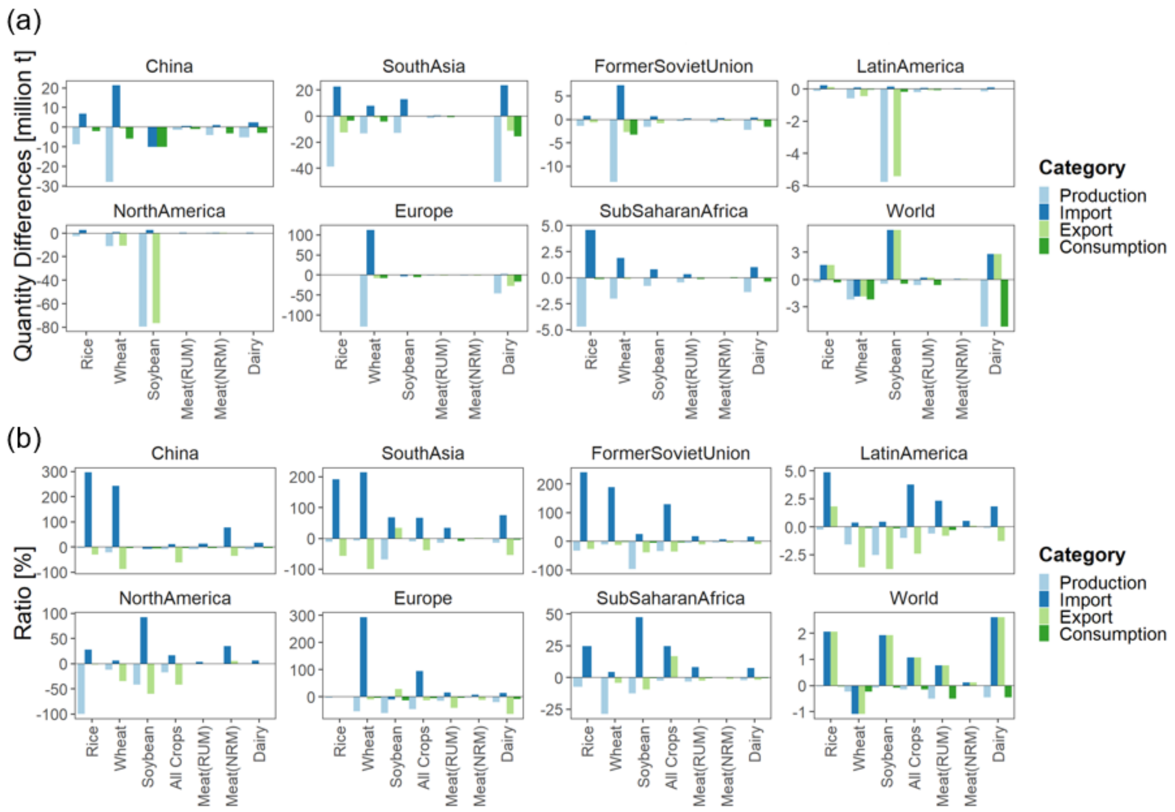

Figure 9 Changes in food production, import, export, and consumption compared with Ref scenario in 2060: (a) in absolute quantities; (b) in ratio

There could also be changes in trade patterns of important agricultural products, represented by the shift in major trade flows. Figure 10 shows the major soybean exporting flows under the Ref scenario and two different stylized biomass trade scenarios. Moving from Ref to CHN1P9_LAM, there would not be significant changes, which is because the Latin American region could deforest more for compensating the occupied cropland for biomass production. While in North America, deforestation is assumed to be prohibited according to local forest laws; this would lead to more intense land competition and therefore, when producing more biomass in North America, the soybean production and exports from North America would be significantly reduced and replaced by those in Latin America.

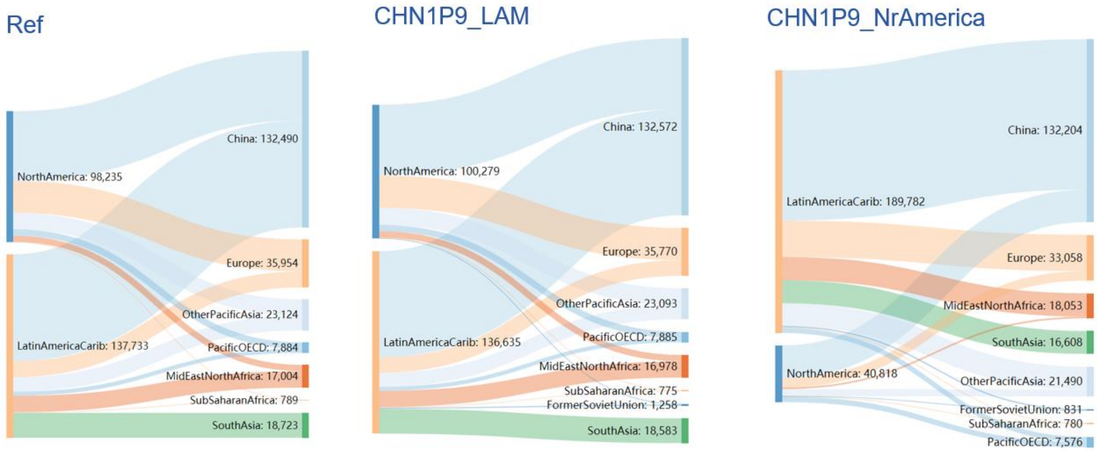

Figure 10 Soybean exports from major exporters in 2060 in selected scenarios

Similar effects could be expected for staple crops. For example, if Europe is to produce more biomass, it would turn from a wheat exporting region to a net-importing one (Figure 11), with the increased imports mostly from the PacificOECD region, North America, and the FormerSovietUnion region. This is due to the competition for the relatively scarce land resources and could have further implications on land use, environment, and food prices in other regions that would export more to or import less from the European countries.

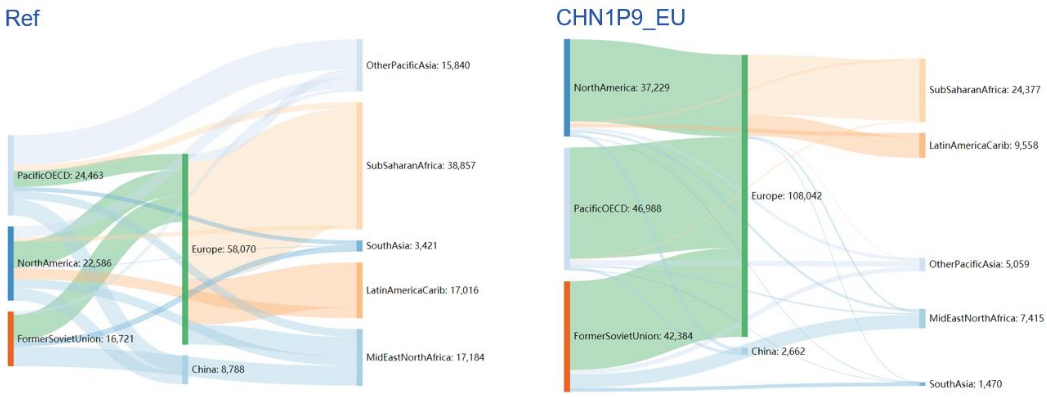

Figure 11 Wheat trade among major importing or exporting regions in 2060 in selected scenarios

Accompanying the shifted trade flows would be the changes in import dependencies. Figure 12 shows that the import dependency rates for some of the major agricultural products could rise significantly in local regions under certain scenarios by 2060. For example, planting more biomass in China would increase the its import dependency rate for wheat from 5.9% to 23.7% in 2060, indicating possible conflicts with one of the China's policy targets on food security that requires the self-sufficiency rate of staple food grains to remain above 95%[12]; while planting more in the FormerSovietUnion region could raise its import dependency rates for soybean and crops by 77% and 26%, respectively. There could also be some spillover impacts in food import dependency. For example, when the biomass is to be produced and imported from Europe (CHN1P9_EU), not only the import dependency rates for wheat will rise in Europe, the FormerSovietUnion region would also have to import a lot more soybean. This is because when Europe produces more biomass and reduces domestic production of wheat, more land in the FormerSovietUnion region which is originally be used to produce soybean would then be used to produce wheat that is to be exported to the European countries.

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[12] The State Council Information Office (People's Republic of China). China's rice, soybean imports top the world in 2017. http://english.www.gov.cn/state_council/ministries/2018/02/02/content_281476033872340.htm

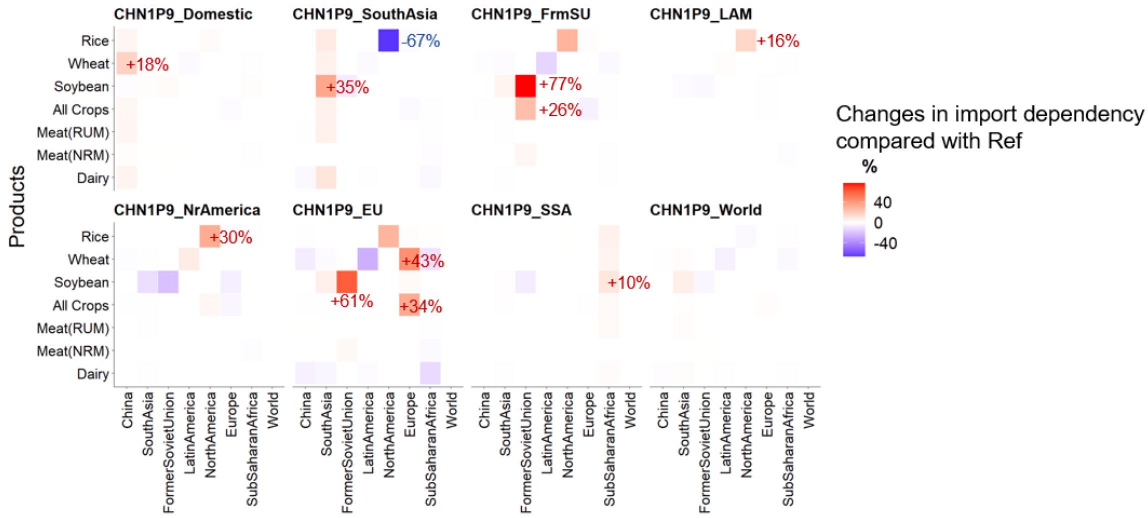


Figure 12 Changes in import dependency rates for different agricultural products in 2060 under different CHN1P9 scenarios

Changes in Food Prices

Similar to the impacts on food consumption, the impact of excess biomass plantation on food price is generally minor, though it could still be significant for certain scenarios and products. For example, there could be significantly increasing signals in the prices of staple crops under the domestic-biomass-production (CHN1P9_Domestic) scenario, where the prices of wheat and rice could increase by 32.3% and 18.8% in 2050 compared with the Ref scenario. The increases in the prices of wheat in the corresponding regions under the CHN1P9_EU, CHN1P9_FrmSU, and CHN1P9_NrAmerica scenarios could also be distinct.

The possible reasons for the diversified effects on prices could be that, generally, the impacts of bioenergy production on the local food supply would be partly or mostly offset by international markets (i.e. importing more food when producing more biomass); however, for several regions, if the supply shock is huge or it is relatively hard to find trade partners with whom the trade costs of crops are still low enough, the increases in prices could be more significant. This means that the international trade could serve as a stabilizer, being conducive to the stability of food price and food security; but it cannot mitigate all the impacts and there could still be certain levels of price increases when pursuing higher biomass production in some of the single regions.

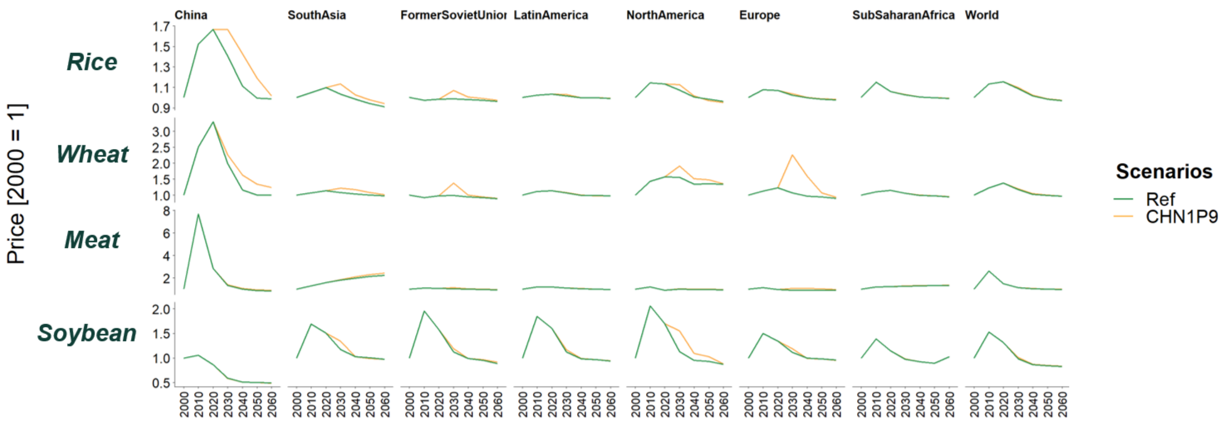
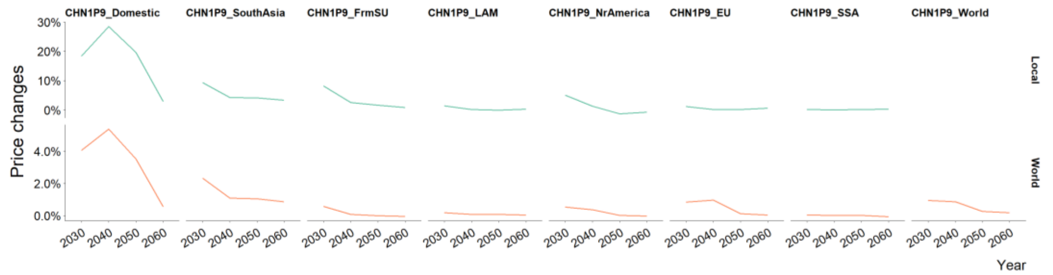


Figure 13 Prices of selected crops and meat under the corresponding mitigation("CHN1P9") scenario

Figure 14 takes rice and meat for example to compare the impacts on local and the global weighted-average food prices. It's natural to find the impacts of excess biomass production on the averaged world prices would be much smaller than those on prices in the local planting regions, but the increase in the global average food prices could still be nonnegligible in certain scenarios (e.g. rice price in CHN1P9_Domestic scenario, and meat price in CHN1P9_EU scenario). Producing more biomass in Latin America (CHN1P9_LAM), Sub-Saharan Africa (CHN1P9_SSA), or in multiple regions in the world (CHN1P9_World) would correspond to smaller impacts on global food prices.

(a) Rice



(b) Meat

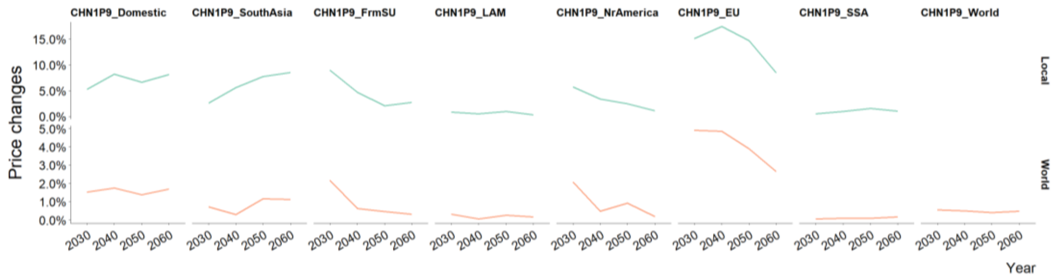


Figure 14 Increases in the price of (a) rice and (b) meat upon Ref scenario, in the local region that produces and exports more biomass to China, and in the whole world (weighted-average prices)

3. Food security impacts

Calorie availability under different scenarios

The changes in food prices and food consumption induced by the additional biomass plantation could have further implications on calorie intake. Figure 15 shows the total calorie availability under the Ref scenario and different CHN1P9 mitigation scenarios. In both scenarios, the calorie availability would keep increasing toward 2060. The impacts of excess biomass production on calorie availability could be more significant in several scenarios, including when producing more biomass in China, South Asia, Europe, and the FormerSovietUnion region. The negative impacts on total calorie availability would be most significant in 2030. Besides, we could also expect unproportioned declines in food intake from different categories (Figure A2), which could imply impacts on population health related to diet.

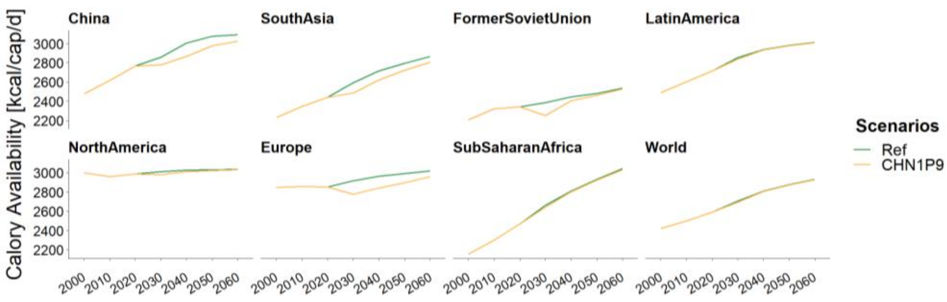


Figure 15 Total calorie availability in corresponding regions under the corresponding CHN1P9 scenario

Implications on hunger risks

The risk of hunger could be increased when the total calorie availability is affected by biomass plantations. Under most scenarios, certain levels of impact on the prevalence of undernourishment could be expected in local regions. By 2030, the induced increment in the undernourishment risks could be as much as 1% compared with the Ref scenario (Figure 16). And in several scenarios including CHN1P9_FrmSU and CHN1P9_EU, significant regional spillover effects on the undernourishment risks could also be observed. Moving toward 2060, the impacts on undernourishment risk would be even lower than those in 2030 (Figure A4).

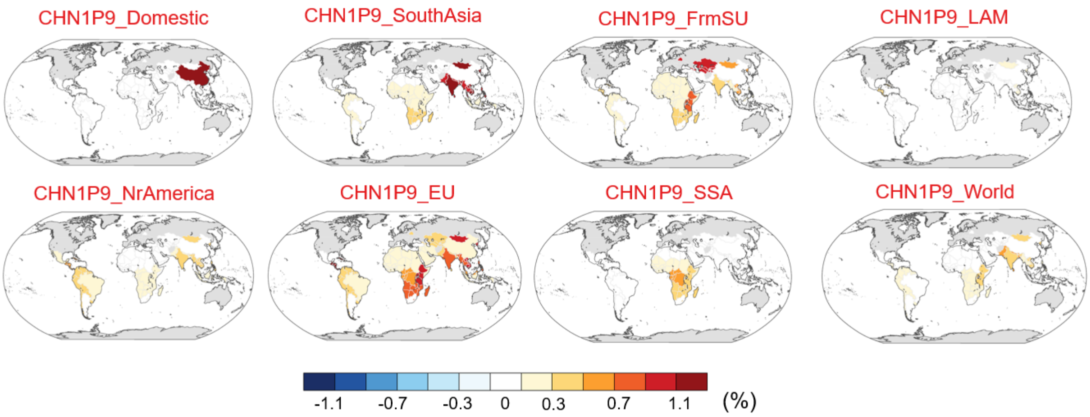


Figure 16 Changes in undernourishment rates in CHN1P9 scenarios compared with Ref in 2030
Note: grey color indicates temporarily no corresponding results or no data for evaluation (similarly hereinafter)

Besides, although there would only be a relatively minor increment (less than or around 1%) in the undernourishment rates (ratio of undernourished people as of total population), there might be significant impacts on the absolute values (number of people undernourished) in some scenarios. The exacerbation of food insecurity would be especially significant under the CHN1P9_EU or CHN1P9_SouthAsia scenarios, where the increases in the number of undernourished people could reach tens of millions of people (Table 7). Under the CHN1P9_EU scenario, stronger regional spillover effects on hunger risk could be observed, as the plantation of biomass in Europe might need to take up more than one-third (37.6%) of the cropland in the Ref scenario, leading to significantly greater import demand in Europe for wheat from the Russia Federation, and for meat from Latin America. This is further because of the limited available grassland and other natural lands that could be converted to plantation land in Europe, given the trend of feed demand and subjective to plantation suitability.

Table 7 Changes in the number of undernourished people in different scenarios (compared with Ref) in different years (Unit: million people)

Scenarios	**2010**	**2020**	**2030**	**2040**	**2050**	**2060**
CHN1P9_Domestic	0	0	18.7	14.36	10.02	6.94
CHN1P9_SouthAsia	0	0	76.66	45.68	20.34	17.39
CHN1P9_LAM	0	0	3.13	0.72	0.54	0.33
CHN1P9_NrAmerica	0	0	15.86	3.84	0.84	-0.6
CHN1P9_EU	0	0	30.81	14.74	4.95	1.98
CHN1P9_FrmSU	0	0	16.03	3.09	0.41	-0.62
CHN1P9_SSA	0	0	3.45	2.11	0.33	1.54
CHN1P9_World	0	0	12.84	4.52	4.11	4.4

While in other scenarios e.g. CHN1P9_LAM, the cumulative additional undernourished people could be limited to 4.72 million. This is because the conflicts between cropland and biomass plantation land would be relatively small in Latin America, with only less than 3% of the cropland under Ref scenario to be converted to plantation land. Similar trends could be observed for the CHN1P9_SSA and CHN1P9_World scenarios, under which the ratios of taken-up cropland in the corresponding region would be only 3.7% and 0.1%, respectively. This indicates smaller reduction in crop production, as well as smaller increments in food import demands and spillover impacts. However, it should also be noted that planting more biomass in sub-Saharan Africa (under the CHN1P9_SSA scenario) would take up large grassland and natural land, reducing the land cover of these two land types by 16.2 million ha and 21.8 million ha, respectively, which further implies possible conflicts with biodiversity or ecosystem protection. These results imply that the regional planning of biomass plantation to meet the higher bioenergy demand in the decarbonizing world would be crucial in bioenergy developing strategies. To minimize the additional hunger risks in terms of the number of undernourished people, allocating the excess biomass plantation in Latin America, sub-Saharan Africa, or in multiple regions of the world might be more preferable.

4. Timing of bioenergy development

Greater impacts in the nearer term

By examining the effects of biomass plantation on food markets and food security in different periods, a phenomenon could be observed that the impacts would be generally greater in the short run, even though the excess biomass demand keeps increasing between 2030-2060. From Figure 17 it can be noticed that the effects of producing or importing more biomass on food prices, calorie availability, and undernourishment risk could all be more severe in the nearer term, especially in 2030. After 2040, the negative impacts could be significantly reduced. This applies to both the domestic and spillover impacts and implies that the induced food security risks from biomass plantation might need more attention in the short-to-medium run.

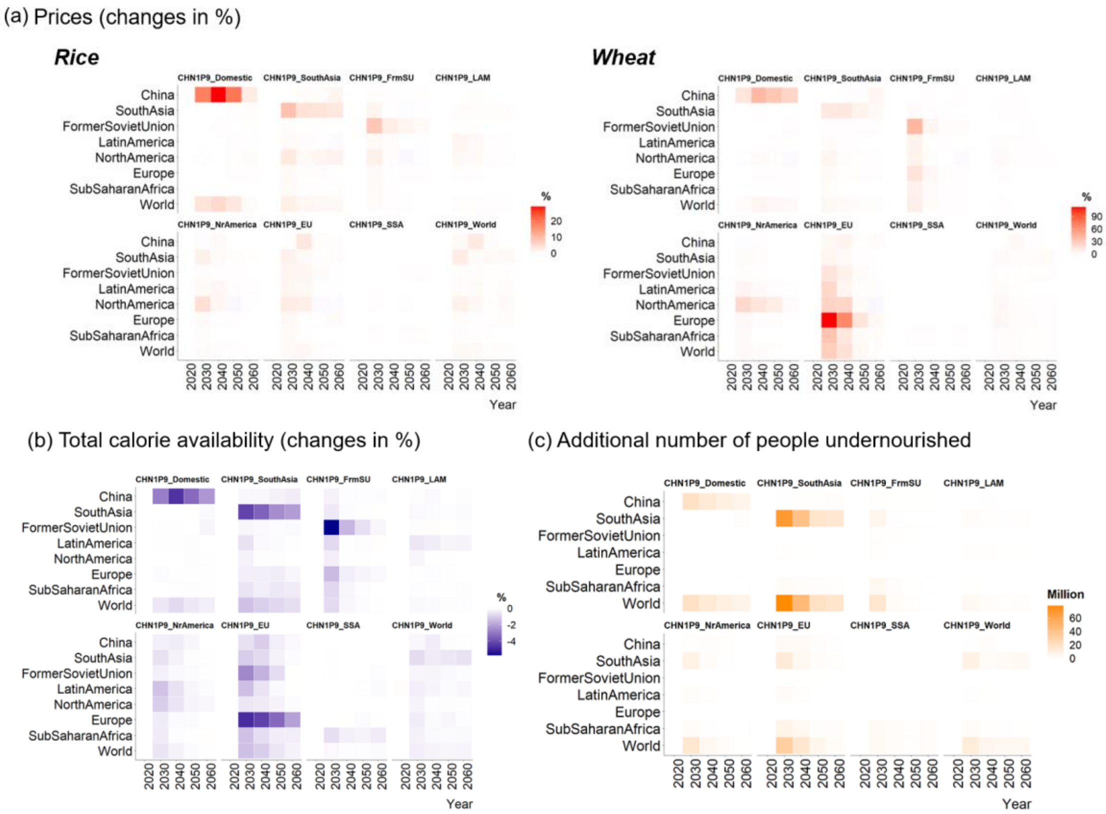


Figure 17 Percentage changes in (a) food prices, (b) total calorie availability, and (c) increment in the number of undernourished people under the CHN1P9 scenarios compared with Ref

Possible reasons: Socioeconomic and technology factors

There could be many underlying factors that drive these "timing effects". We didn't quantitatively explore the driving factors, but some key reasons for this effect could be speculated by examining the related socioeconomic and technology trends. An important factor would be the growth rate of the population. According to projections for the SSP2 scenario (Figure 18), the population in most developed regions and middle-income countries would either peak in around ten years (e.g. China), or grow at very low rates (e.g. Europe), or even show declining trends (e.g. the FormerSovietUnion region). For other developing countries the population may keep growing, but the growth rates would be relatively smaller after the middle of this century in some regions (e.g. South Asia, Latin America). The slowing down of population growth would lead to reduced growth rates of food demand, offering the chances of alleviating the pressure in the food supply through technological progress.

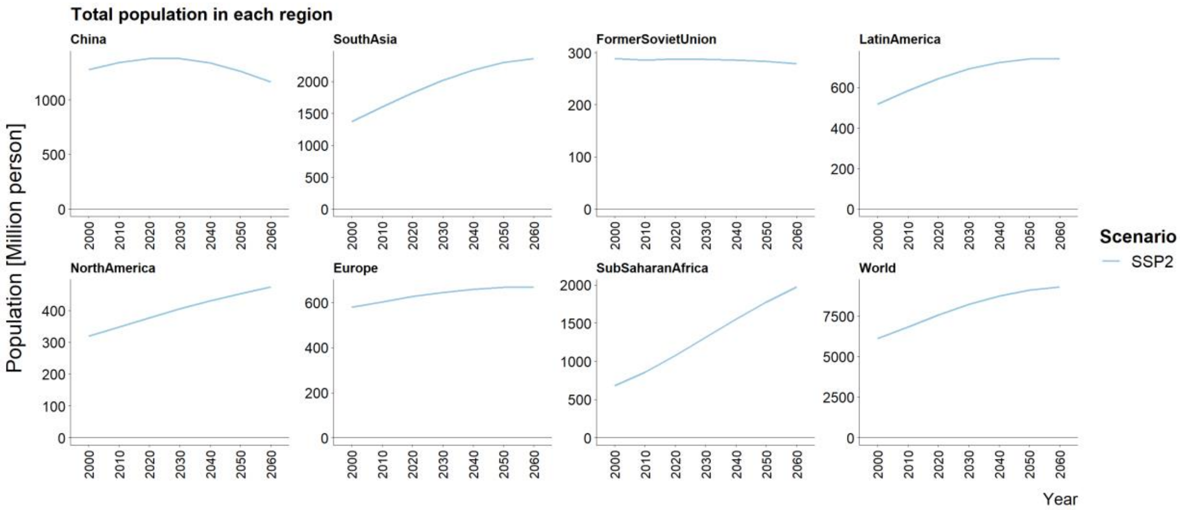


Figure 18 Trend of the total population in each aggregated region from 2000 to 2060

Looking at the yield of crops, it can be found that the crop yields in all regions would keep increasing, especially in the developing regions (Figure 19). For example, by 2060, the yields of rice and wheat in South Asia are assumed to become 3 times as much as those in 2000; similar trends could be expected in Latin America and sub-Saharan Africa. The increasing crop yields would help mitigate the land competition between crop production and biomass plantations and thus help reduce the induced food security risks.

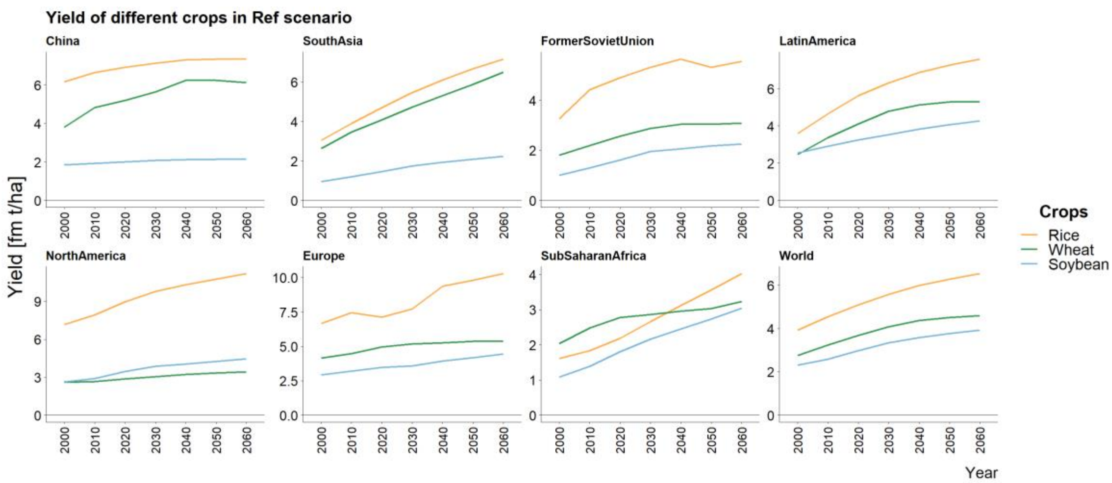


Figure 19 Trend of crop yields in each aggregated region from 2000 to 2060

5. Spatial optimization: Identifying the best supply region

Optimized global bioenergy production could improve food security

Here we analyzed the results from "optimization trade scenarios", where the regional allocation of biomass production has been endogenously optimized by the model based on the least-cost principle. Figure 20 illustrates the spatial redistribution of biomass plantation under the three optimization scenarios, compared with the Ref and the exogenous CHN1P9_World scenario in the main trade scenario group. Moving from the Ref scenario to the CHN1P9_World scenario, all regions would increase the production of short-rotation plantation biomass (IP_Biomass) in the same proportion for meeting the excess biomass demand in China for climate change mitigation. The other three optimization scenarios would have the same amount of global total biomass production, but the places of production would be redistributed to produce the biomass more efficiently.

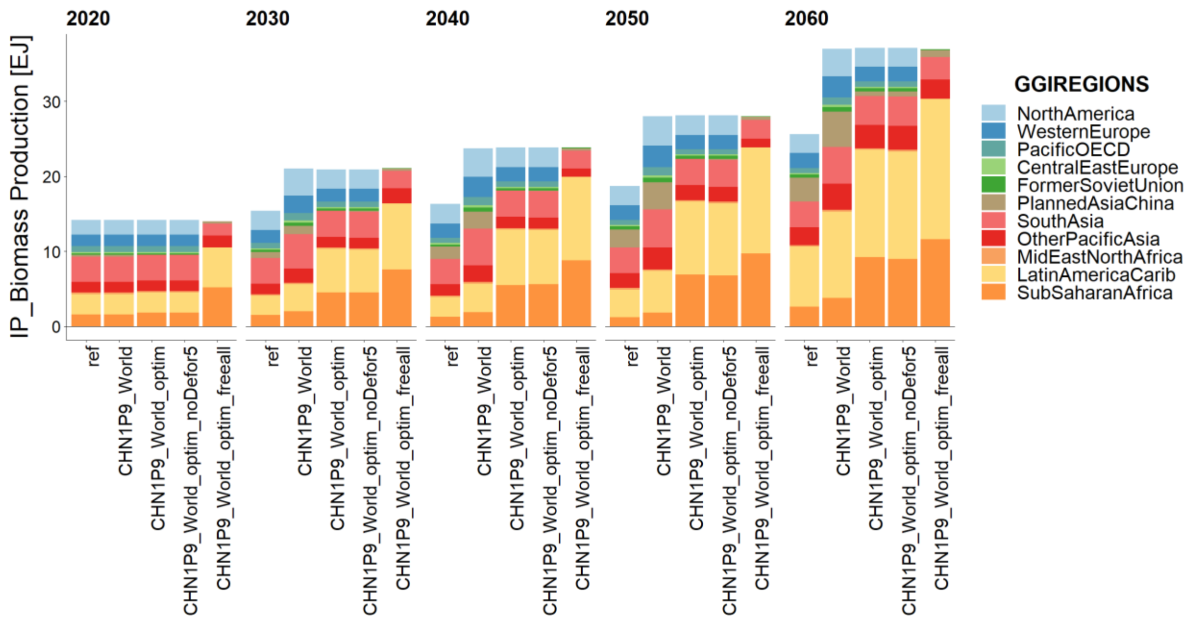


Figure 20 Global distribution of short-rotation plantations in different scenarios

Results show that when the biomass for China's bioenergy demand can be freely imported from any region (under the CHN1P9_World_optim scenario), the sub-Saharan Africa region and Latin America would produce more to fulfill the excess demand, while other regions will only produce the same amounts as in the Ref scenario. When also implementing no-deforestation policies in Latin America and sub-Saharan Africa (the "noDefor5" scenario, which means a total of five regions are not allowed to deforest, as there was already restriction on deforestation in three regions – China, USA, and Europe), the distribution of short-rotation plantation biomass production would be very similar.

Further, if the limits of minimum production amounts for IP_Biomass (as in Ref scenario) were eliminated (the CHN1P9_World_optim_freeall scenario), North America, Europe, and the PacificOECD regions would not produce any IP_Biomass; instead, these regions with higher yields of crops but lower yields of biomass would use the land to produce more crops, and the global biomass demand would be fulfilled mostly by the production in Latin America and sub-Saharan Africa.

The land area that is needed for short-rotation biomass plantation could be partly saved by global optimization of production (Figure 21). In the default global production scenario CHN1P9_World, there would be 49 million ha of additional plantation land needed compared with the Ref scenario by 2060. Through global spatial optimization of biomass production, about 9 million ha excess plantation land could be saved (in the CHN1P9_World_optim scenario); while under the scenario with more drastic optimization (CHN1P9_World_optim_freeall), as much as 20 million ha plantation land could be saved.

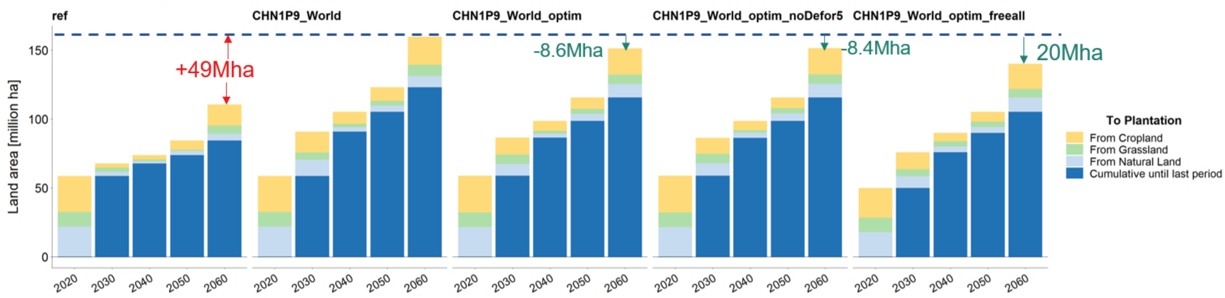


Figure 21 Global total plantation land needed for short-rotation biomass production in different scenarios

The global optimization of biomass plantation would help ease the induced risks in food security to a large extent (Figure 22). Under the default scenario CHN1P9_World, there would be significantly larger numbers of undernourished people (+12 million in 2030, and + 4 million in 2060) compared with the Ref scenario. Pursuing optimized regional distribution of biomass (CHN1P9_World_optim scenario) would help reduce large parts of the risks, with the cumulative number of undernourished people avoided between 2030 and 2060 amounting to 20.4 million compared with the CHN1P9_World scenario, or 35.5 million compared with the CHN1P9_Domestic scenario. And in the CHN1P9_World_optim_freeall scenario, the cumulative reduction in the number of undernourished people would be as many as 17.5 million.

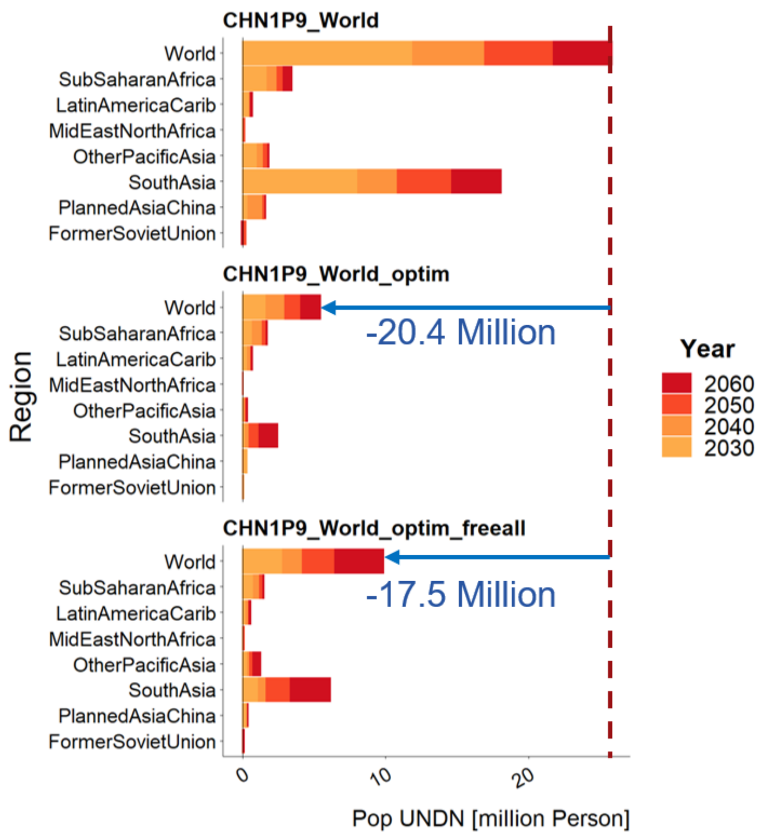


Figure 22 Changes in the number of undernourished people in optimization scenarios compared with Ref

More stringent forest protection would further ease the trade-offs

In the baseline settings, deforestation is only prohibited in China, Europe, and the US to reflect the policy trends in the real world. The level of forest protection in other regions is relatively low and probably inadequate under this default setting. It's observed that the global cumulative additional deforestation between 2030-2060 due to increased biomass plantation could amount to more than 7.5 million ha in the CHN1P9_World scenario (compared with Ref). Under two optimization scenarios (CHN1P9_World_optim and CHN1P9_World_optim_freeall), the deforestation area could even be larger, as converting the forest land into plantation land might be more efficient from an economic perspective (Figure 23). And deforestation would be most prevalent in Latin America and sub-Saharan Africa.

Therefore, in the CHN1P9_World_optim_noDefor5 scenario, we simulated the impacts when also prohibiting deforestation in these two regions. It is found that the stringent forest protection policy would help eliminate most of the deforestation while still fulfilling all the excess biomass demand, contributing substantially to sustainable land use.

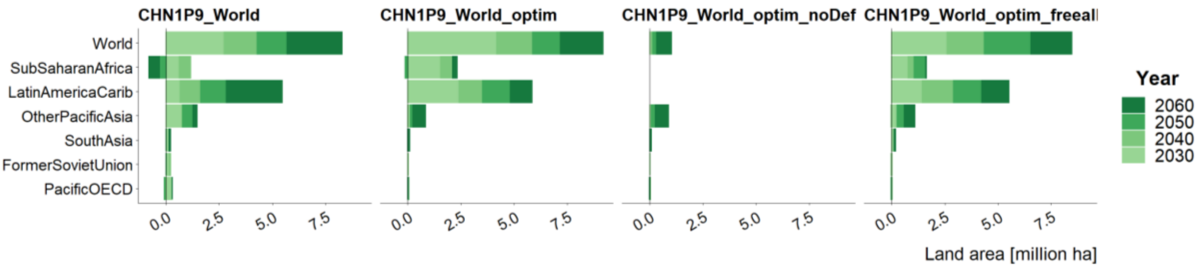


Figure 23 Additional deforestation in optimization scenarios compared with the Ref scenario

With stricter forest protection, the additional CO_2 emissions from deforestation could be mostly eliminated, and certain levels of mitigation of AFOLU GHG emissions could also be reached in the long term (Figure 24). While the emissions from other land-use changes are roughly the same or a bit higher than those in other scenarios before 2050, under the "noDefor5" scenario, the negative emissions from the land-use change of natural lands by 2060 could reduce the net GHG emission by around 0.5 Gt by 2060 compared with the Ref scenario.

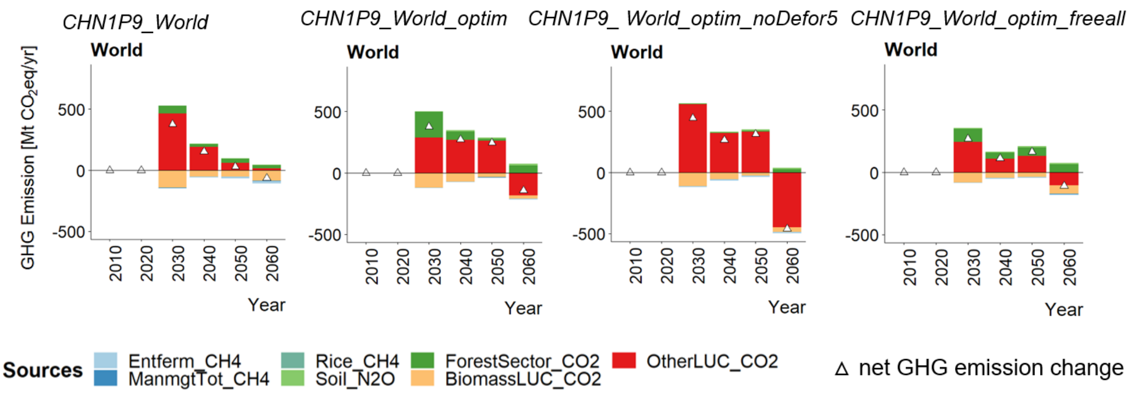


Figure 24 Changes in GHG emissions in optimization scenarios relative to the Ref scenario

In terms of food security, there would indeed be some bounce-back increases in the number of undernourished people with stricter forest regulations in place in Latin America and sub-Saharan Africa, but the increment is relatively small when compared to the default global scenario CHN1P9_World (Figure 25). The reason why the number population at risk of undernourishment in the sub-Saharan African region would be relatively greater in the "noDefor5" scenario might be that there would be less available cropland in sub-Saharan Africa, as there is less land conversion from other land types to cropland if deforestation is not allowed in this region. Comparing the overall impacts under the CHN1P9_World_optim_noDefor5 with other scenarios, the implication might be that the endogenous allocation of excess biomass production with strong protection of the forest might be the global optimum strategies, which can not only significantly reduce the induced food security risks but help to mitigate the trade-offs with other SDGs.

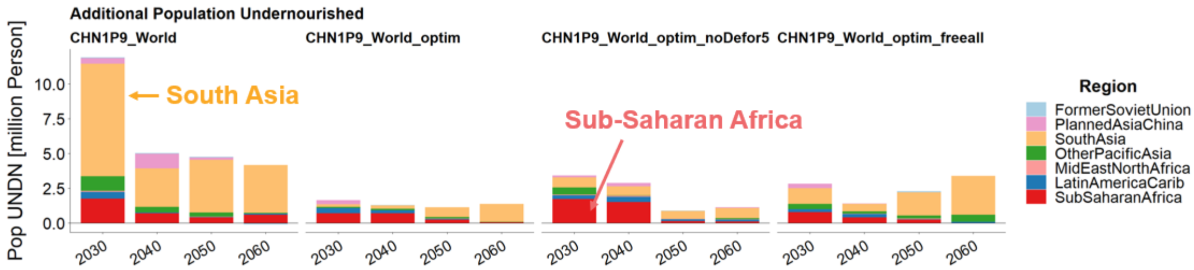


Figure 25 Excess number of people at risk of undernourishment in optimization scenarios

6. Sensitivity Analysis

Higher bioenergy demand could reduce the feasibility

Using the projection of bioenergy demand in China for the 1.5°C target from the GCAM model, which is greater than the numbers from the MESSAGE model that are used in the main scenario group, the scarcity of land resources and competition between biomass plantation and food production would be more prominent. Scenario results indicate that when the bioenergy demand in accord with the 1.5°C target becomes even higher (referred to as "CHN1P9" scenarios with the suffix "_high"), in the current set-up of the GLOBIOM model, China could not produce all the short-rotation plantation biomass domestically due to constraints in land availability and suitability. By 2030, as much as 7.3 EJ out of 26.4 EJ biomass could not be produced domestically, and the number would increase to 16.0EJ in 2060 (Table 8).

Table 8 Bioenergy demand in China and feasibility of domestic production

Data or result	Unit	2010	2020	2030	2040	2050	2060
Bioenergy demand in China from the GCAM model (1.5°C scenario)	EJ/yr	8.5	7.2	26.4	27.8	29.0	33.8
Domestically infeasible amount	EJ/yr	0	0	7.3	12.2	12.6	16.0

This could imply the possible necessity of biomass imports if China is dedicated to supporting the energy transition by promoting high penetration of bioenergy and biofuels in the energy system. If the excess bioenergy demand under the 1.5°C target is to be imported from other regions, then only importing from Latin America (CHN1P9_LAM_high) or multi-region of the world (CHN1P9_World_high) would be feasible. And under both the CHN1P9_LAM_high and CHN1P9_World_high scenarios, there would be significantly greater deforestation globally compared to the Ref scenario, especially in Latin America (Figure 26).

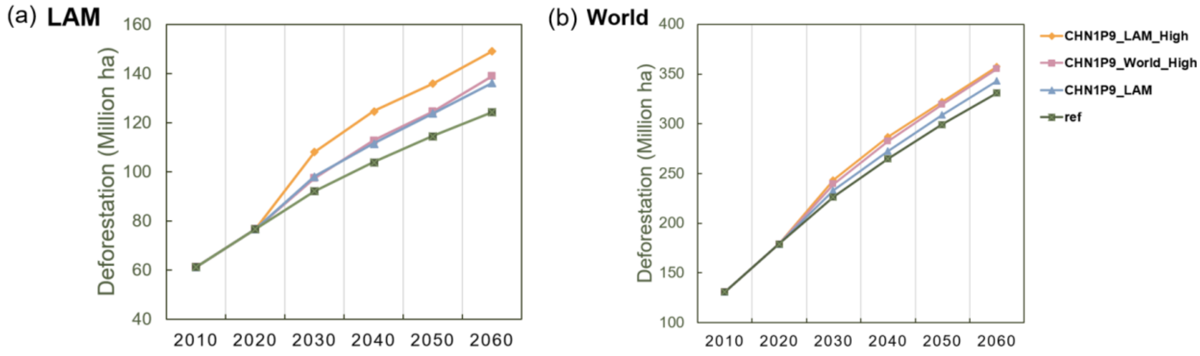


Figure 26 Area of deforestation in (a) Latin America and (b) total of the world under different scenarios

Impacts of increasing bioenergy demand in a denser global market could be more distinct

In the second group of sensitivity analysis, we analyzed the impacts when not only China but also the rest of the world all increase bioenergy demand for 1.5°C mitigation. With this setting, there would be great demands for bioenergy in all regions except China as a baseline under the "Ref" scenario, with the demands in all the other regions corresponding to the projection for the RCP1.9 climate pathway. Then, similar to the main scenario group, the excess biomass demand for RCP1.9 for China is introduced in the new "CHN1P9" scenarios and is assumed to be produced in (and imported from) different places. This means that under the CHN1P9_Domestic scenario, the number of bioenergy demands in all regions would be in line with the RCP1.9 scenario; while in other "CHN1P9" scenarios, it is similar with the main scenarios and the excess biomass would be produced and imported from other source regions, making the bioenergy demand in the source region even higher.

It is found that when there are already high bioenergy demands in all other regions in the world, the impacts of excess biomass demand for China on AFOLU GHG emissions and food security would be moderately intensified. In a global market that is already denser at the baseline, several "CHN1P9" biomass trade scenarios would become infeasible due to land resource constraints. With the updated baseline, importing the excess biomass from South Asia, the FormerSovietUnion region, Europe, or sub-Saharan Africa region would be infeasible. In the remaining four scenarios which are still feasible, the induced impacts on GHG emissions and food security could be more or less intensified in certain regions (Figure 27) compared with results from the main scenario group, but the trends and spatial distribution of the impacts would still be similar. The impacts on GHG emissions would be more distinct than those on undernourishment rates, probably due to the situation that by 2060, the calorie availability in the baseline would already be significantly improved due to yield increases, making the food system more resilient to possible supply shocks from excess biomass demand.

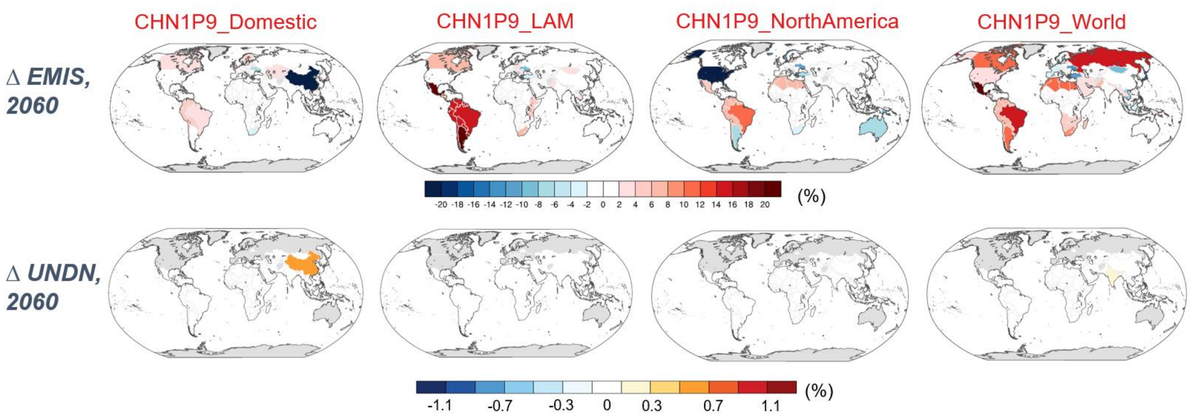


Figure 27 Changes in GHG emissions and increases in undernourishment rates compared with Ref scenario

Conclusions and Discussion

1. Conclusions

In this study, we applied the GLOBIOM model to evaluate the potential impacts of increasing biomass imports from different regions for China's growing bioenergy demand under its 2060 carbon neutrality target. A series of stylized biomass trade scenarios were designed to quantify the possible effects of increasing domestic production or imports for short-rotation plantation biomass in China on global land-use change, GHG emissions from the land, food system, and implications on food security.

Scenario analysis indicates that pursuing high biomass production in any single region could lead to certain sustainability concerns, with the level and distribution of negative effects varying greatly across scenarios. If the excess biomass for China's increased demand is to be produced and imported from South Asia, the number of undernourished people across the world could increase by tens of millions, mostly in India. Importing more biomass from Europe would lead to significant spillover impacts, with land-use change and competition for cropland intensified in Latin America and Africa. While the American region, especially Latin America, could act as an important source region for China's increased bioenergy demand, producing more biomass in Latin America regions would lead to the least extent of compromise with food security and GHG emissions.

Furthermore, a more diversified importing portfolio with an optimized regional allocation of global biomass production would be crucial to reduce the negative trade-offs between bioenergy supply and sustainable land use and food production. An optimized bioenergy import portfolio combined with stricter forest regulation could fulfill the increased biomass demand for China, while simultaneously achieving food security and forest protection targets, avoiding 35.5 million (or 17.5 million) cumulative undernourishment from 2030 to 2060 compared with the domestic production scenario (or a fixed global biomass trade scenario).

The timing of introducing bioenergy could also be very important, as remarkable technology advances could be expected in the next several decades, creating the window for biomass to enter without bringing about severe trade-offs with food security and other SDG targets. It is found that the induced land-use change and food security impacts would be most severe in 2030 and 2040 and then gradually weakening, even if the excess biomass demands keep increasing. This is possibly due to the slowing down or peaking of population growth in the developed and some developing regions, and the increases in crop yields that help release the conflicts between crop production and biomass plantation. Therefore, introducing large scales of biomass as a mitigation option after 2040 might be better timing for simultaneously attaining multiple SDGs.

Finally, sensitivity analysis indicates that higher bioenergy demand would reduce the feasibility of excess biomass supply and therefore bring greater challenges to sustainable bioenergy development. And when the rest of the world also increases the bioenergy demand, the impacts of excess biomass demand on GHG emissions and food security would be slightly intensified. These results could provide some implications on designing environmental-friendly, sustainability-coordinated bioenergy strategies for supporting the deep transition toward low-carbon economies.

2. Discussion and future work

By implementing scenario analysis in the GLOBIOM model for the increased biomass demand in China under the carbon neutrality target, we found that there are chances to increase biomass supply without prominent conflicts with food security targets or GHG emission mitigation. For example, when implementing biomass production in the Latin America region, the excess plantation land demand, increases in food prices, induced AFOLU GHG emission, and additional risks in food security could all be relatively minor. Furthermore, a "global optimization" of bioenergy production and imports together with more stringent forest protection policies could help achieve multiple SDGs while fulfilling the excess biomass demand in China, making the "global optimum" strategy. We even didn't consider more opportunities for coordinating sustainable bioenergy development and food production from both the production side (e.g. more rapid increases in crop yields) and the consumption side (e.g. reduced food waste and diet change), which could further help ease the possible trade-offs. This implies the chances of promoting bioenergy development while safeguarding other sustainable dimensions.

In this study, China is taken as an example to examine the possible domestic and global land-use change and related impacts that correspond to the more rapid development of bioenergy, as China has updated its mid-century carbon neutrality targets and the bioenergy demand in China is expected to grow significantly for supporting the deep decarbonization, according to the multi-model comparison exercise (Duan et al., 2021). Results indicate that the place to grow biomass is decisive to the level of impacts. It could be possible to develop bioenergy without significant compromise with food security, but careful design of the regional allocation of excess biomass production should be in place to avoid the potentially severe adverse impacts under certain scenarios. Moreover, a diversified and more flexible bioenergy import portfolio might contribute to the sustainability and feasibility of China's bioenergy development. Similar conclusions could also be held for other regions with high bioenergy demand in the context of global climate change mitigation.

There also exist major limitations in the current study, which need attention when interpreting the scenario results. First, we only considered a small set of land-use regulations (e.g. no deforestation in specific regions) and didn't include more local land use regulations, e.g. ecosystem protection hot spots or "red-lines" for minimum cropland. In future analysis, we would try to introduce more local land use regulations to better represent the reality and improve the practical significance of this study.

Another caveat is that the land-use regulations for biodiversity protection were not yet considered in our scenario analysis, and therefore there could be unrevealed conflicts between biodiversity protection and biomass production. For example, producing more biomass in the sub-Saharan Africa region seems also practicable, as the induced additional number of undernourished people would be next to the lowest; but a large proportion of the newly added plantation land would have to come from grassland, which might imply possible impacts on biodiversity. Therefore, in the next stage, we would like to introduce the regulations for biodiversity protection in the scenario simulations, to better investigate whether it is feasible to coordinate food security and bioenergy development targets under strict protection of biodiversity and forest.

Besides, more thorough validation of input data would still be needed for key indicators in the food and environment systems. By now, the most important data and parameters in terms of agricultural production and trade for China in the current version of GLOBIOM have been carefully calibrated by our collaborating colleagues (Zhao et al., 2021). However, as we intend to use this model to depict the impact of biomass production on international food markets and trade flows, similar validation exercises should also be done for major economies in the world.

Finally, we would like to add the explicit depiction of agricultural residues in the current model version, as the agricultural residue is regarded as an important source of bioenergy in China. Currently, biomass from the agricultural residues accounts for the largest part of China's bioenergy feedstock (NDRC, 2020), and it is also estimated to be promising in the low-carbon future (Shi, 2011; Xie et al., 2020).

Appendix

Additional figure on GHG emissions

Figure A1 shows the spatial distribution of GHG emission changes (in percentage) induced by biomass plantation in different mitigation scenarios compared with the Ref scenario in 2060. The level of local and spillover impacts diverges in different scenarios. Significant regional spillover impacts in GHG emissions could be observed under CHN1P9_SouthAsia and CHN1P9_EU scenarios where the local region would reduce the food exports or increase imports when producing more biomass, further leading to emission changes in other regions. In terms of minimizing additional GHG emissions and the spillover impacts, allocating the production of short-rotation plantation biomass in China, Latin America, North America might be more preferable, as the global overall and spillover impacts would be smaller.

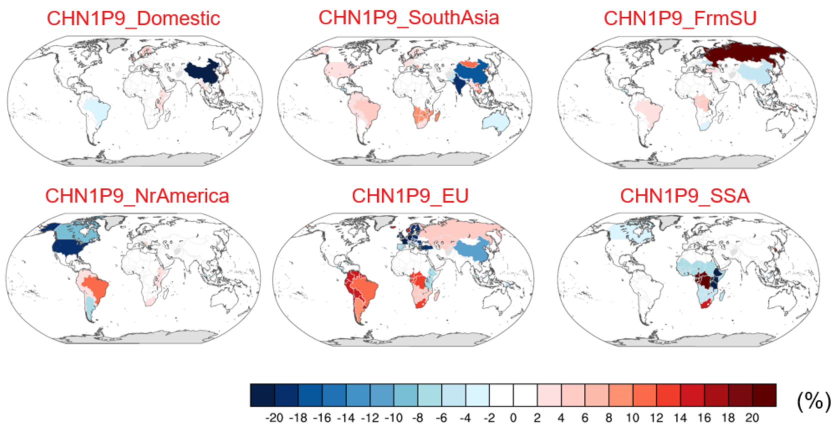


Figure A1 Changes of AFOLU GHG emissions in percentage in 2060, compared with the Ref scenario

Additional figures on food consumption and food security

Figure A2 shows the changes in calorie availability by different food categories under the CHN1P9 mitigation scenarios. It can be found that for almost all scenarios, there would be an uneven reduction in calorie availability from different food categories. For example, producing more biomass in South Asia could significantly reduce the local consumption of potatoes; while producing more in the European region would substantially reduce the milk intake. This could imply further impacts related to dietary health.

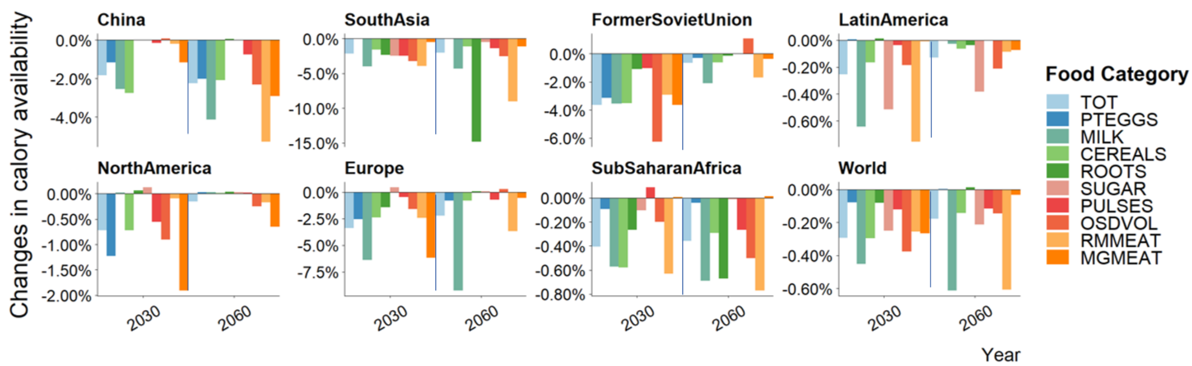


Figure A2 Calorie availability by category, in corresponding regions under different scenarios

Note: "TOT" = total calorie availability from all kinds of food; "PTEGGS" = eggs; "MILK" = milk; "CEREALS" = cereals including rice, wheat, corn, and other grains; "ROOTS" = potatoes, sweet potatoes, and cassava; "SUGAR" = sugarcane; "PULSES" = dry beans and sweet chickpea; "OSDVOL" = other oilseed products and vegetables, including groundnut, soybean, rape, and oil palm; "RMMEAT" = beef meet and sheep meet; "MGMEAT" = pig meat and poultry meat.

Figure A3 shows the undernourishment rates in different regions under the Ref scenario. It can be seen that in 2010, the undernourishment risks were especially significant in Asia and sub-Saharan Africa. Due to advances in agricultural technology and thus increases in crop yields, there would be an already great improvement in the prevalence of undernourishment, with the undernourishment rate all reduced to below 5% level.

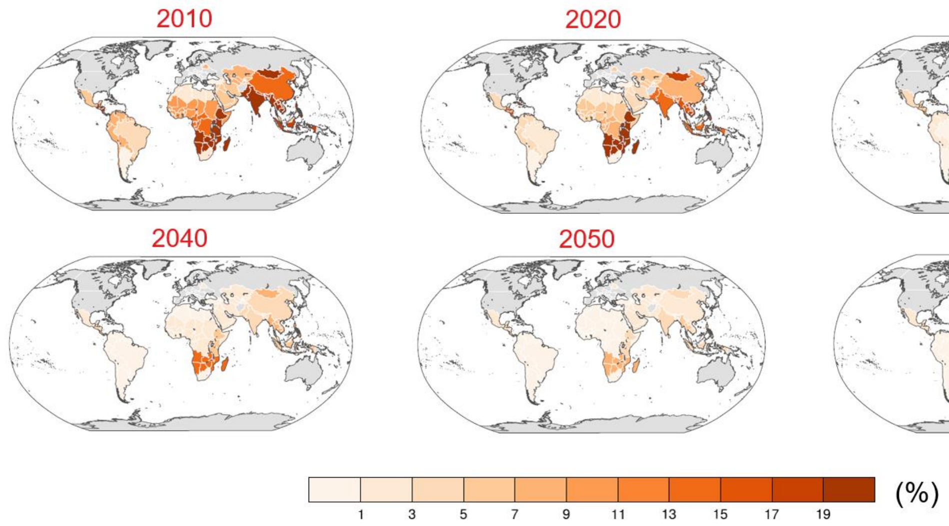


Figure A3 Prevalence of undernourishment (as a ratio in population) under the Ref scenario

Note: gray color indicate there is no undernourishment or currently there are no data for evaluation of undernourishment in these regions

Figure A4 shows the changes in the prevalence of undernourishment in different mitigation scenarios compared with Ref in the year 2060. By 2060, the baseline food security risk would be at a very low level, and the induced impacts from additional biomass plantation on the undernourishment rate would also be much smaller.

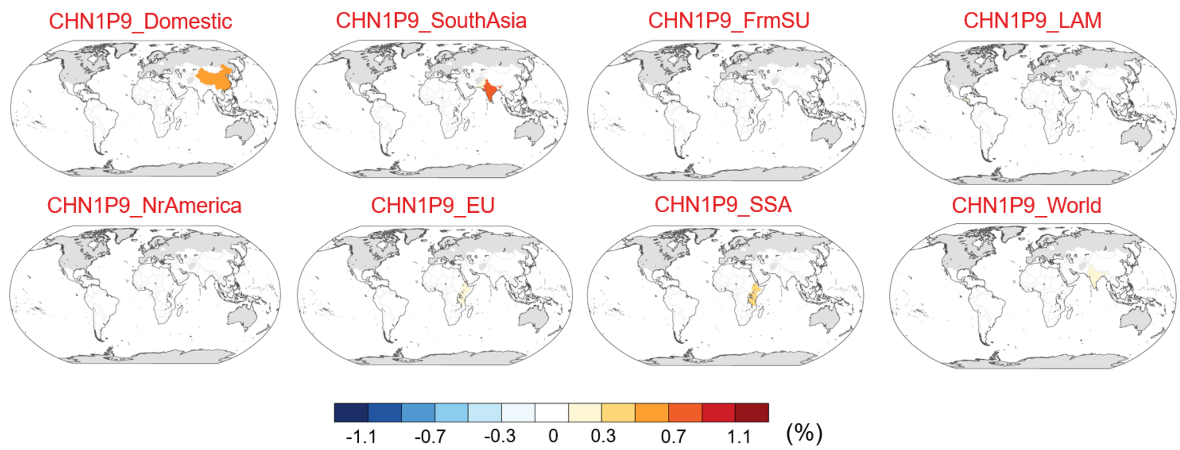


Figure A4 Changes in prevalence of undernourishment in different scenarios compared with Ref by 2060

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