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Enhanced food system efficiency is the key to China's 2060 carbon neutrality target

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Bioenergy with carbon capture and storage, among other negative-emission technologies, is required for China to achieve carbon neutrality—yet it may hinder land-based Sustainable Development Goals. Using modelling and scenario analysis, we investigate how to mitigate the potential adverse impacts on the food system of ambitious bioenergy deployment in China and its trading partners. We find that producing bioenergy domestically while sticking to the food self-sufficiency ratio redlines would lower China's daily per capita calorie intake by 8% and increase domestic food prices by 23% by 2060. Removing China's food self-sufficiency ratio restrictions could halve the domestic food dilemma but risks transferring environmental burdens to other countries, whereas halving food loss and waste, shifting to healthier diets and narrowing crop yield gaps could effectively mitigate these external effects. Our results show that simultaneously achieving carbon neutrality, food security and global sustainability requires a careful combination of these measures.

Bioenergy with carbon capture and storage is pivotal for meeting the ambitious climate mitigation targets set by the Paris Agreement[1,2]. However, large-scale bioenergy deployment to combat climate change triggers multiple land-based sustainability concerns, including food insecurity[3], water scarcity[4,5], greenhouse gas (GHG) emissions[6] and biodiversity loss[7].

As China is the largest GHG emitter globally[8] and a key contributor to global climate governance, proving the feasibility of its carbon neutrality target before 2060 is invaluable for other emerging economies facing growing demand for energy and food. China's remarkable success in feeding 20% of the world's population with only 7% of global arable land[9] relies heavily on its continuous agricultural intensification. However, a 120% increase in domestic grain production has led to a 494% increase in chemical fertilizer consumption[10] from 1978 to 2020. Moreover, substantial yield gaps exist[11] despite food waste and loss of 30%[12], while the shift towards more animal-intensive diets has increased both adverse environmental[13,14] and human health[15,16] impacts. Although the 95% self-sufficiency ratio (SSR) redlines for China's three main staple crops (wheat, rice and corn) have been maintained so far, many other agriproducts are imported, such as soybean, ruminant meat and dairy products[17], which places environmental pressures on China's trading partners[18].

It is thus essential to understand the potential risks for land-based Sustainable Development Goals (SDGs) and the mitigation opportunities from large-scale bioenergy deployment, given China's limited arable land and increasing food demand. Most global integrated assessments have focused on reducing the land pressure from large-scale bioenergy through various measures, including improving agricultural productivity, reducing animal-based product consumption and reducing food loss and waste[3,19–21]. However, globally stylized

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assumptions in such assessments may not suit regional or local circumstances[22,23]. By contrast, national-level studies have typically addressed country-specific food, trade, resource and environmental policies and their domestic impacts[24,25] but have failed to holistically capture global spillover effects, which involve multiple sustainability indicators under multidimensional policies.

Here we use the Global Biosphere Management Model (GLOBIOM)–China model to investigate how large-scale domestic bioenergy production could be compatible with China's carbon neutrality target without imposing adverse effects at home or abroad (Extended Data Figs. 1 and 2). Our study builds a valuable bridge between the top-down view of typical integrated assessments and the bottom-up perspective of national studies by including more realistic country-specific food, trade, resource and environmental policies. We assume that all Chinese energy crops are from domestic short-rotation energy plantations as bioenergy feedstock (Methods). We consider five sustainability impacts on China and its food trading partners, including food security, cropland and pasture expansion, GHG emissions, nitrogen fertilizer use and agricultural irrigation water use. A set of scenarios is established: (1) the baseline scenario (Reference) following the middle-of-the-road pathway, Shared Socio-economic Pathway 2 (SSP2)[26]; (2) a Bioenergy scenario with increasing bioenergy production consistent with China's carbon neutrality target while maintaining the SSR redlines (95%) for wheat, rice and corn; (3) a FreeTrade scenario removing the SSR constraint in the Bioenergy scenario; and (4) four policy scenarios overlaid on the FreeTrade scenario with fine-tuned compensatory measures to reconcile bioenergy production with broader sustainability goals—narrowing crop yield gaps (YieldUp), halving food loss and waste (FoodLossDown), shifting to healthier diets (DietHealth) and combining all three (FoodSystem) (Table 1). We also performed a comprehensive sensitivity analysis considering alternative futures for key parameters.

Table 1 | Scenario narratives and compensatory measures

Scenario name	Narrative	Source
Reference	The Reference scenario follows SSP2 with no additional bioenergy production.	Fricko et al.[26]
Bioenergy	Additional bioenergy for meeting China's carbon neutrality is produced domestically, while the SSRs for the three main staple crops (wheat, rice and corn) are maintained at no less than 95%.	GLOBIOM–MESSAGE model framework[26,41]
FreeTrade	Additional bioenergy for meeting China's carbon neutrality is produced domestically; China's SSR constraints are relaxed, allowing free trade of the three main staple crops.	
YieldUp	China's food crop yield is increased in addition to the FreeTrade scenario. The three main staple crop yields increase to ~75% of their attainable levels by 2060. Other crop yields follow the SSP1 assumptions, increasing faster than those in the FreeTrade scenario.	Ma et al.[64] and Chen et al.[11]
DietHealth	A shift towards less animal-based diets closes 20% of the gap between current consumption quantities and recommended values in China. Other assumptions remain the same as in the FreeTrade scenario.	The Chinese Dietary Guidelines 2022[33] and planetary health diet[73]
FoodLossDown	Food loss and waste in the food supply chain are halved in China. Other assumptions remain the same as in the FreeTrade scenario.	United Nations[67]
FoodSystem	All the above-mentioned compensatory measures implemented in the YieldUp, DietHealth and FoodLossDown scenarios are implemented simultaneously. Other assumptions remain the same as in the FreeTrade scenario.	

Results

Sustainability implications of bioenergy expansion in China

Bioenergy expansion would increase pressure on China's domestic food security. In the Reference scenario, China's crop and livestock production will be 13% and 24% higher, respectively, by 2060 than in 2020 (Supplementary Fig. 6). We project a 15% increase in the domestic average daily per capita calorie intake (from ~2,534 to 2,905 kcal, Supplementary Fig. 7) from 2020 to 2060. Accordingly, cropland increases from 123 Mha in 2020 to 130 Mha in 2040 and then decreases to 120 Mha in 2060 (Supplementary Fig. 8). Over the period, cropland area fluctuates slightly around China's current arable land area redline of 124 Mha[27], driven by continually increasing food demand counteracted by persistent productivity improvements. The total irrigation water use thus increases from 400 km^3 in 2020 to around 420 km^3 in 2030 and then decreases to 380 km^3 in 2060, which is dominated by three main staple crops distributed in the main production regions such as the North China Plain, the northeastern crop production base, and Jiangxi, Guangxi and Sichuan provinces. In the Bioenergy scenario, the area of the bioenergy cropland that expands into land used for other purposes is 51 Mha (mainly distributed in the northeast and southwest of China), equivalent to the entire land area of Thailand, by 2060 (Fig. 1a). China's grassland therefore shrinks by 12% (16 Mha), and other natural vegetation land declines by 32% (15 Mha) in 2060, with cropland falling by 16% to 101 Mha in 2060, in the Bioenergy scenario relative to the Reference scenario. Correspondingly, crop and livestock production in 2060 will be lowered by 15% and 13% (Fig. 1b,c), respectively, which leads to a 23% increase in domestic agricultural product prices and a 242 kcal (8%) reduction in daily per capita calorie intake (to 2,646 kcal) in 2060 relative to the Reference scenario (Fig. 2). The impacts of bioenergy production on food security are even larger than those of climate change itself, which is projected to lower China's per capita calorie intake in an average year by 0.25% in 2050, even under the high-emission Representative Concentration Pathway 8.5 scenario[28]. By comparison, a recent study[3] estimated that a 118 kcal decrease (from 2,736 to 2,618 kcal) in daily per capita calorie intake would result in an additional 9 million people (approximately 0.6% of the current population) being at risk of hunger in China, especially for low-income groups. Compared with the Reference scenario, domestic irrigation water, nitrogen fertilizer and GHG emissions from agriculture, forestry and other land use (AFOLU) will decrease by 5%, 8% and 43%, respectively, in 2060 in the Bioenergy scenario (Fig. 2 and Supplementary Figs. 9–12).

Sustainability trade-offs at home and abroad

China's domestic food dilemma would be halved by removing food trade constraints. Removing the SSR constraints on the three main staple crops in the FreeTrade scenario relieves the tension between domestic food supply and demand caused by bioenergy deployment, largely through increased food imports. In 2060, the daily per capita calorie intake decreases by only 5% (149 kcal) instead of 8% (as in the Bioenergy scenario), and food prices increase by 14% instead of 23% (Fig. 2). Nonetheless, in the FreeTrade scenario, the SSR for wheat is projected to decrease from 96% in the Reference scenario to 66% in 2060; for rice, from 98% to 91%; and for corn, from 98% to 92% (Fig. 1d–f). China's domestic net imports of wheat, rice and corn in 2060 are projected to be 610% (42 Mt), 281% (13 Mt) and 221% (14 Mt) higher, respectively, than in the Reference scenario (Extended Data Fig. 3 and Supplementary Figs. 13 and 14). This would make China the world's largest net importer of wheat and rice and the second-largest net importer of corn.

Removing China's food SSR constraints risks transferring negative environmental burdens to its trading partners, especially countries with large agricultural sectors (for example, Australia, Canada and

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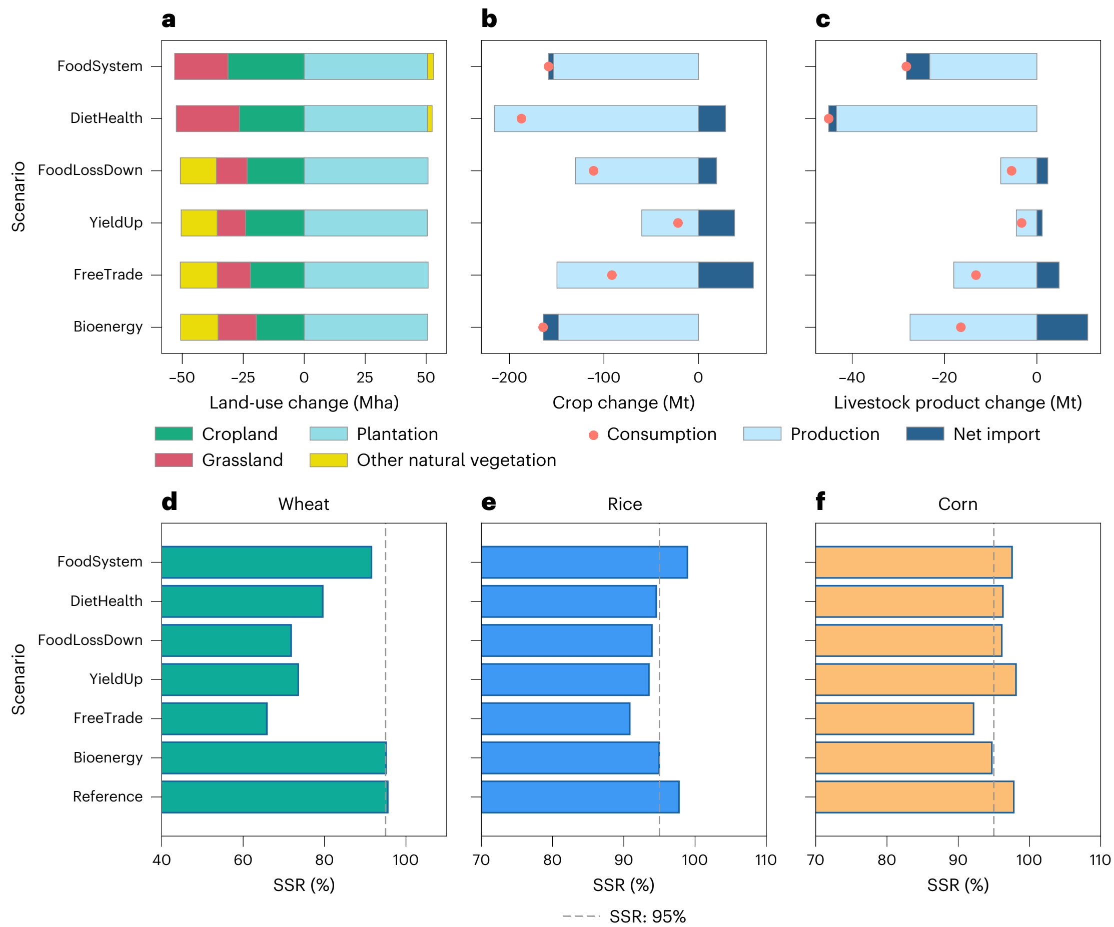

Fig. 1 | Effects of bioenergy deployment in China on domestic land use, production, consumption and trade of agricultural products. a–c, Projected absolute changes in China's land use (**a**); crop consumption, production and net imports (**b**); and livestock product consumption, production and net imports (**c**) in the six higher-bioenergy scenarios relative to the Reference scenario in 2060. **d–f**, SSRs for wheat (**d**), rice (**e**) and corn (**f**) in 2060.

Brazil). In the FreeTrade scenario relative to the Reference scenario, imports in 2060 are projected to increase by 290% for cereals and by 23% for livestock products (Fig. 1b,c, Extended Data Fig. 3 and Supplementary Figs. 13 and 14). In 2060, increased food imports would transfer an additional 23.2 Mha of agricultural land (9% of China's present-day agricultural land area), 16.6 km^3 of irrigation water (4%), 1.7 Mt of nitrogen fertilizer use (7%) and 46.2 Mt of CO_2-equivalent (CO_2e) GHG emissions from AFOLU (6%) to China's trading partners (Fig. 3). For example, wheat imports from Australia are projected to increase by 656% (27 Mt) in 2060, accounting for 46% of Australia's wheat production and 7.9 Mha of its crop area, consuming 0.7 Mt of nitrogen fertilizer and causing 4.5 $MtCO_2e$ of N_2O emissions from cropland soil (Fig. 4). An additional 16.8 km^3 of irrigation water use among China's rice trading partners (for example, Thailand, Myanmar and the Philippines) in 2060 can be attributed to rice production exported to China, accounting for 23% of the combined rice irrigation water use in these regions. Moreover, China's increased food imports would impact the food markets of its trading partners to different extents. Australia would be highly affected, with food prices increasing by 6% in 2060. Under the FreeTrade scenario, the cumulative GHG emissions from AFOLU, including domestic and virtually imported GHG emissions, from 2020 to 2060 are projected to be 30 $GtCO_2e$, which accounts for 7–23% of the remaining carbon budget of 400 ± 220 $GtCO_2e$ imposed to limit global warming to 1.5 °C (Fig. 3 and Supplementary Fig. 15)[29]. Encouragingly, removing the self-sufficiency constraint on the three main staple crops in China would increase global food production (especially through crop and ruminant productivity increases) while reducing the overall global environmental burden, implying that the relocation of crop production away from resource-intensive China to other parts of the world could improve global food supply efficiency. In 2060, in the FreeTrade scenario, China imports more cereal (an increase of 290%, or 69 Mt, instead of 38% as in the Bioenergy scenario relative to the Reference scenario), whereas fewer non-ruminant products (pork and poultry products) are imported (an increase of 123%, or 1.4 Mt, instead of 609% as in the Bioenergy scenario). In the FreeTrade scenario, global food production increases for both crops and ruminant products, resulting in an 11.4 kcal (0.4%) increase in the global total daily per capita calorie intake in 2060 relative to that in the Bioenergy scenario (Supplementary Fig. 16). Moreover, global irrigation water use in 2060 is projected to be 3.2 km^3 (0.11%) lower than that in the Bioenergy scenario. This is because China's partners produce more wheat without irrigation in the FreeTrade scenario, most of which is projected to be exported to China and to replace China's irrigated wheat.

The effects of trade combined with domestic measures

The above results show that it is difficult for China to reconcile its large-scale bioenergy deployment with domestic food security and global sustainability. Thus, in addition to removing the cereal trade constraints, we assess a bundle of sociotechnical measures for the food supply and demand system—namely, halving food loss and waste, shifting to healthier diets and narrowing crop yield gaps (Methods).

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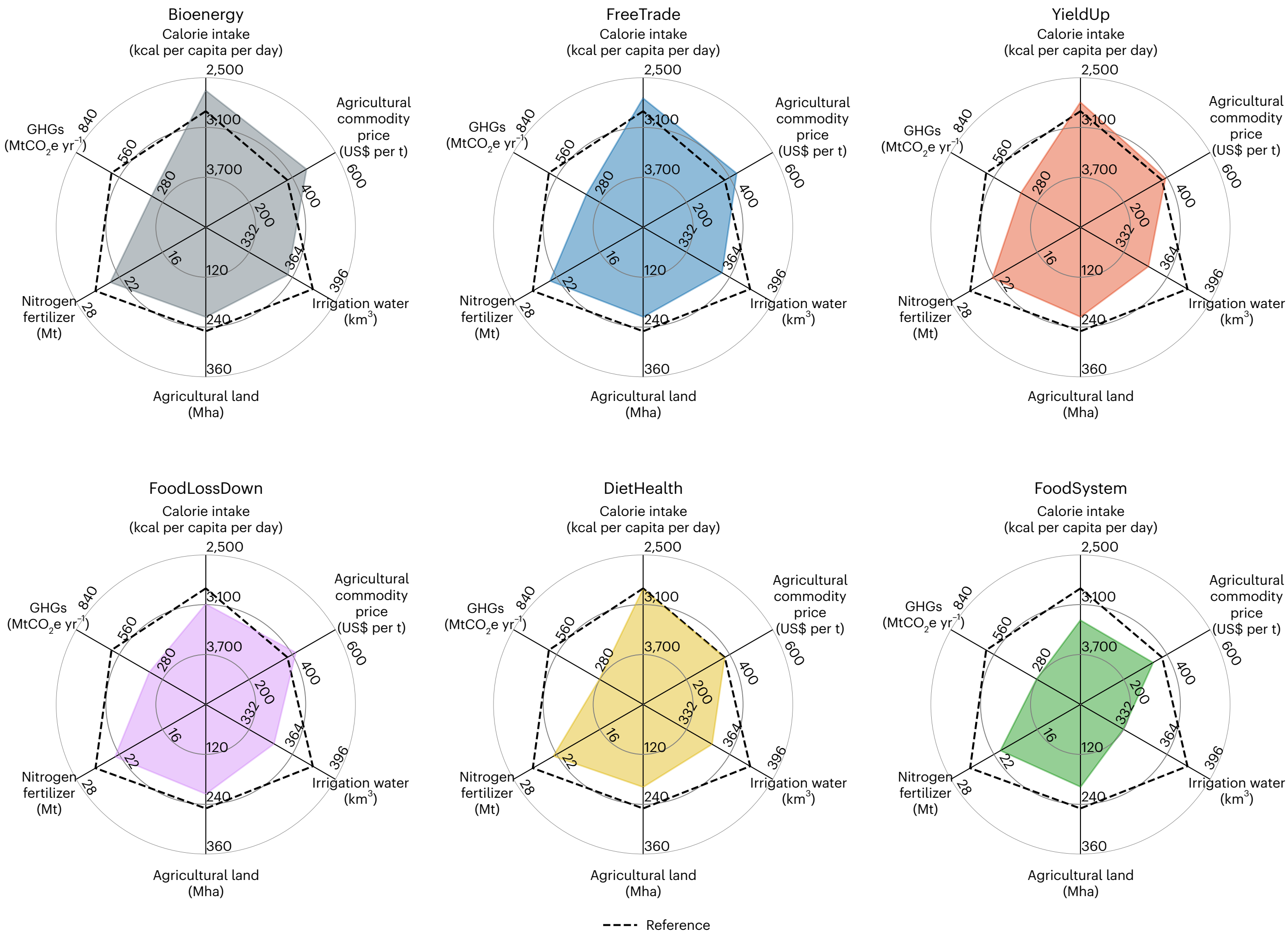

Fig. 2 | Impacts of bioenergy deployment in China on domestic sustainability in 2060. The six sustainability indicators include daily per capita calorie intake, agricultural commodity prices (2000 constant prices), irrigation water, agricultural land (cropland and grassland), nitrogen fertilizer and GHG emissions from AFOLU.

Halving food loss and waste. Surveys conducted in China show that 27% of the food produced annually for human consumption (~349 Mt) is lost or wasted. This waste could be substantially reduced through mitigation strategies such as improving technology, increasing awareness and altering cooking styles[12]. In the FoodLossDown scenario, food loss and waste rates will be halved by 2060 compared with the current levels[30,31]. As a result, domestic daily per capita calorie intake increases by 12% (343 kcal) in 2060 relative to the FreeTrade scenario, while food prices decline by 4%, leading to a decrease in domestic agricultural land, water and fertilizer use and GHG emissions by 0.1% (0.3 Mha), 2.2% (7.9 km^3), 1.5% (0.3 Mt) and 0.8% (3 $MtCO_2e$), respectively (Fig. 2). Moreover, such food-saving efforts also improve global sustainability by reducing the virtual agricultural land, water, fertilizer and GHG emission imports in 2060 by 11.0% (17.1 Mha), 17.3% (9.0 km^3), 21.1% (1.0 Mt) and 16.0% (34.1 $MtCO_2e$), respectively (Fig. 3). Although reducing food loss and waste could somewhat resolve the food–bioenergy dilemma, China's food demand will still require substantial imports, thus continuing to transfer environmental impacts to its trading partners.

Shifting to healthier diets. In China, per capita consumption of animal-based food has increased approximately 12-fold since 1961 (Supplementary Fig. 17)[32]. China's present per capita meat consumption (for example, pork) has already exceeded the level recommended in the Chinese Dietary Guidelines[33]. The rapid transition towards meat-intensive diets has had increasing environmental[13,14] and human health[15,16] impacts. Following the dietary intake recommendations from the Chinese Nutrition Society would improve human health while substantially reducing environmental burdens[16,34]. In the DietHealth scenario, we consider a shift away from animal-based diets that reduces the gap between current and recommended consumption by 20% (Supplementary Table 5). Such a dietary shift will reduce China's livestock product consumption by 15% (32 Mt) in 2060 relative to the FreeTrade scenario (Fig. 1b,c). Although the use of crop products for food increases by 15% (81 Mt), total crop consumption decreases by 8% (96 Mt), driven by a 40% (200 Mt) reduction in the use of crops for feed. A dietary shift also effectively reduces agricultural land use, which helps relieve the land competition between food and bioenergy crops and reduces food security impacts. On the supply side, a reduction in animal-based food consumption reduces domestic livestock and crop production by 13% (25 Mt) and 8% (66 Mt), respectively, in 2060, resulting in reductions in agricultural land, irrigation water, nitrogen fertilizer and GHG emissions of 8% (17 Mha), 2% (7 km^3), 2% (0.5 Mt) and 23% (84 $MtCO_2e$) in 2060, respectively (Fig. 2). Moreover, food prices fall by 13%. Thus, compared with the FreeTrade scenario, the DietHealth scenario results in decreases in net livestock and crop product imports of 25% (6 Mt) and 9% (29 Mt) in 2060 (Fig. 1b,c), reducing the virtual import of agricultural land by 33.5% (51.9 Mha), of water by 18.2% (9.5 km^3), of nitrogen fertilizer by 24.4% (1.1 Mt) and of

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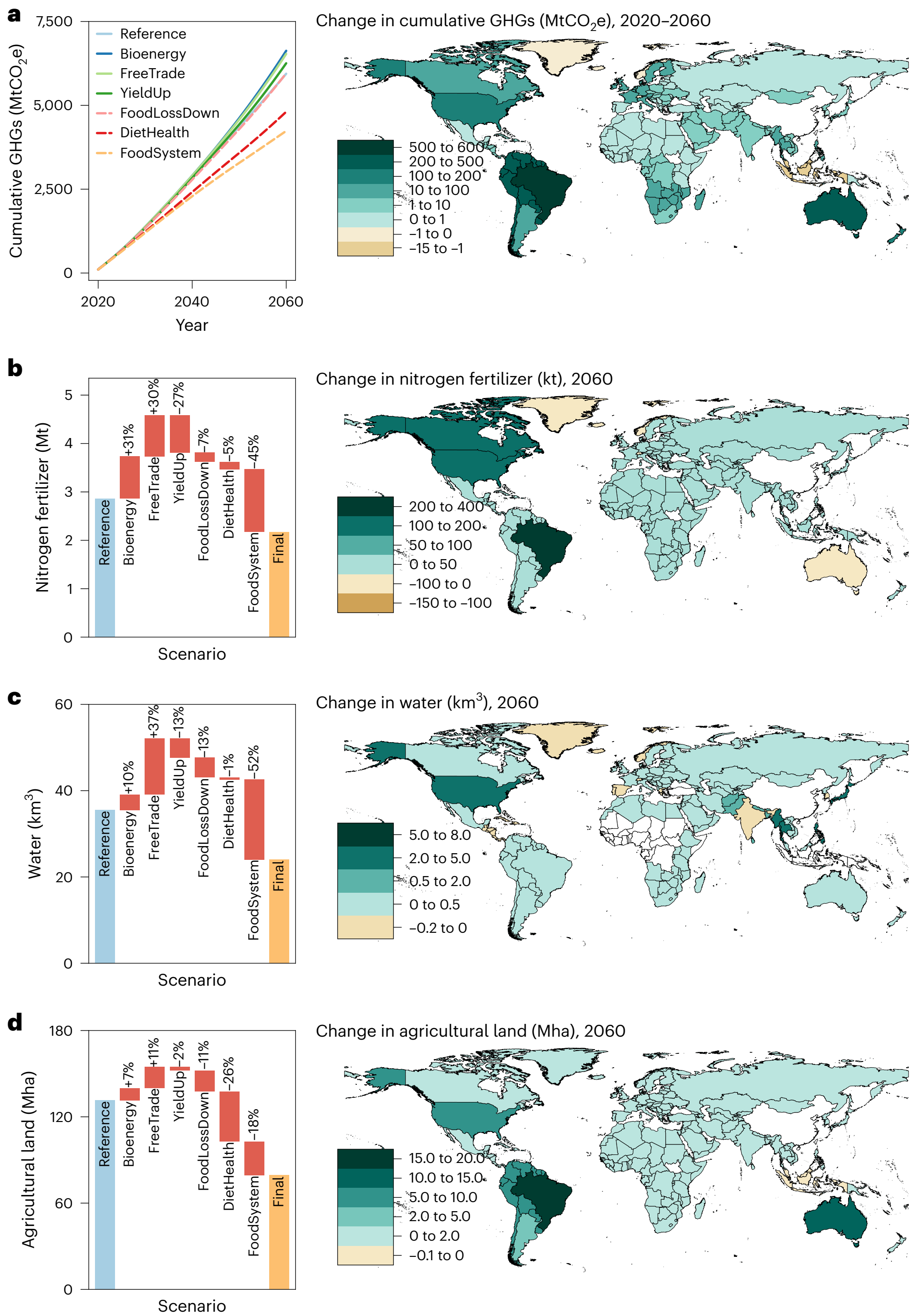

Fig. 3 | Virtually imported environmental impacts from China's trading partners due to agricultural imports. a, Cumulative virtually imported GHG emissions (left) and changes in cumulative virtually imported GHGs from different regions from 2020 to 2060 (right). **b**–**d**, Virtually imported nitrogen fertilizer (**b**), irrigation water (**c**) and agricultural land (cropland and pasture) (**d**) in 2060 (left); and changes in virtually imported nitrogen fertilizer (**b**), irrigation water (**c**) and agricultural land (**d**) from different regions in 2060 (right). In the left panels of **b**–**d**, the heights of the red suspended bars indicate the absolute marginal change in each scenario compared with the scenario to its left; the number above each red bar is obtained by dividing the above-mentioned absolute change by the corresponding value in the Reference scenario. The height of the final bar is the value for the FoodSystem scenario.

GHG emissions by 38.9% (82.8 $MtCO_2e$) in 2060 (Fig. 4). In particular, the substantial reduction in the import of agricultural land (51.9 Mha) is caused mainly by the decreased pasture imports (34 Mha) associated with beef, 12.8 Mha of which are from Brazil, 5.6 Mha from Australia and 3.6 Mha from Argentina (Supplementary Figs. 18–20). In summary, shifting diets is the most effective measure for reducing the impact on China's domestic food prices, agricultural land, GHG emissions and transferred environmental impacts to its trading partners.

Narrowing crop yield gaps. Agricultural intensification has substantially increased the main staple crop yields in China (Supplementary Fig. 21) during the past few decades[17]. However, the yield gaps (current agricultural yields minus attainable yields for a given region) are still enormous. Site–year-level field experiments show that adopting recommended practices can further improve rice, wheat and corn yields in China (to 8.5 Mg ha^{-1}, 8.9 Mg ha^{-1} and 14.2 Mg ha^{-1}, respectively) without increasing nitrogen fertilizer use[11]. In the YieldUp scenario, we assume

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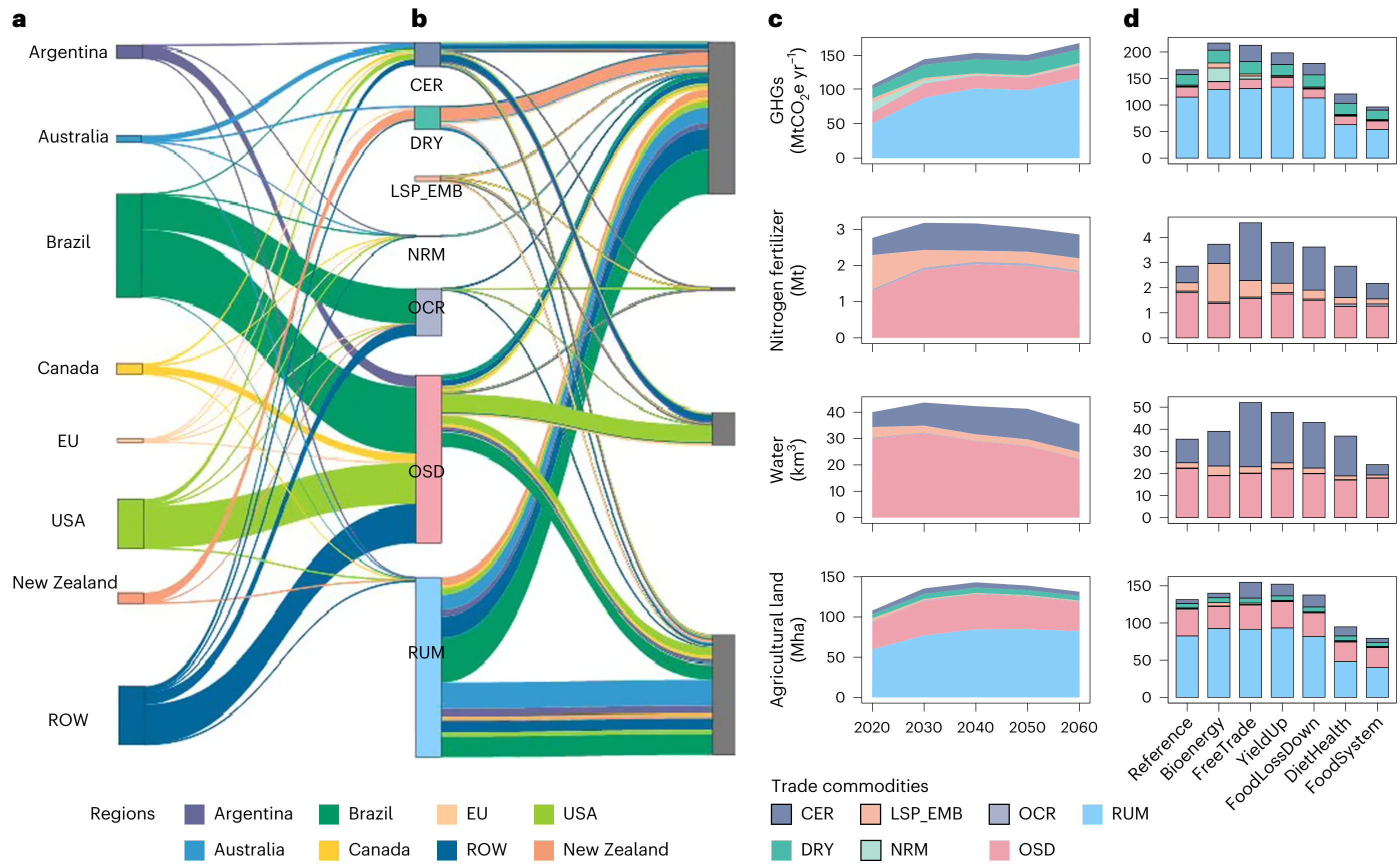

Fig. 4 | Agricultural product import and embedded environmental impacts. **a**–**d**, Agricultural product import (**a**) and virtually imported environmental impacts embedded in food imports (**b**–**d**) from China's trading partners and the remainder of the world (ROW; regions except for China and its seven trading partners). The values in **a**,**b** are for 2060 in the Reference scenario, the impacts in **c** are under the Reference scenario and the impacts in **d** are for 2060. The unit in **a** is million tons (Mt). In **c**,**d**, agricultural products are further decomposed into dairy products (DRY), ruminant meat (RUM), pig and poultry products (NRM), cereals (CER), oil crops (OSD), and other crops (OCR). Environmental impacts from feed crop production for livestock products (LSP_EMB) are also included.

that rice, wheat and corn yields gradually increase from their present levels to approximately 75% of the attainable yield, resulting in a 1.8% (~48 kcal per capita per day) increase in domestic calorie intake and a 9.1% reduction in food prices in 2060 relative to the FreeTrade scenario (Fig. 2). Increased domestic crop yields increase the affordability of crops used for livestock feed, leading to lower livestock production costs in China and increases in livestock product consumption. Consequently, domestic livestock product output increases, and imports decrease. In the YieldUp scenario, net livestock product and crop imports decrease by 14% (3.7 Mt) and 6% (20 Mt), respectively, in 2060 relative to the FreeTrade scenario (Fig. 1b,c). Accordingly, total virtual agricultural land, irrigation water, nitrogen fertilizer and GHG emission imports decline by 2% (2.5 Mha), 9% (4.4 km^3), 17% (0.8 Mt) and 6.7% (14 $MtCO_2e$), respectively, in 2060 relative to the FreeTrade scenario (Fig. 3). Due to yield improvements, the environmental impacts transferred to trading partners would be reduced substantially, although not entirely removed.

Combination of measures. In the FoodSystem scenario, combining all sustainability measures enables the provision of extra bioenergy without hindering sustainability or imposing resource or environmental pressures on China's trading partners. In doing so, domestic per capita calorie intake per day increases to 3,294 kcal by 2060 (20% (538 kcal) higher than that under the FreeTrade scenario and 14% (389 kcal) higher than that under the Reference scenario) (Fig. 2). By 2060, food prices become 22% and 12% lower than under the FreeTrade and Reference scenarios, respectively. Relative to the Reference scenario, domestic agricultural land, irrigation water, nitrogen fertilizer and GHG emissions decrease by 21% (53 Mha), 13% (48 km^3), 17% (4 Mt) and 12% (44 $MtCO_2e$), respectively, in 2060. Moreover, the SSRs are effectively increased to 92% for wheat (from 66% in the FreeTrade scenario, only slightly lower than the 95% redline), 99% for rice (from 91%) and 98% for corn (from 92%) in 2060 (Fig. 1d–f). Virtual agricultural land imports in the FoodSystem scenario are 79 Mha in 2060 (49% lower than in the FreeTrade scenario and 40% lower than in the Reference scenario) (Fig. 3). This decrease is mainly driven by decreased virtual agricultural land imports from Australia (24 Mha), Brazil (20 Mha) and Argentina (5 Mha) due to decreased beef imports relative to the FreeTrade scenario. By 2060, virtual irrigation water, nitrogen fertilizer and GHG emission imports in the FoodSystem scenario will be 24 km^3, 2 Mt and 96 $MtCO_2e$ in 2060 (Figs. 3 and 4), respectively.

Robustness of results

The model results are relatively more sensitive to the assumptions on population, trade and dietary shift; moderately sensitive to those on bioenergy supply level, bioenergy composition and crop yield; and less sensitive to those on gross domestic product (GDP) and bioenergy supply in the remainder of the world (Fig. 5 and Extended Data Fig. 4). Lower trade barriers under the FreeTrade-1 assumption result in increases in virtual agricultural land and water imports of 7.2% (11.1 Mha) and 7.3% (3.8 km^3) compared with the FreeTrade scenario in 2060, while higher trade barriers under the FreeTrade-3 assumption lead to decreases in the above indicators of 18.7% (28.9 Mha) and 31.8% (16.5 km^3). Lowering animal-based food consumption by 10% (under DietHealth-H) leads to a decrease in domestic agricultural land, irrigation water, nitrogen

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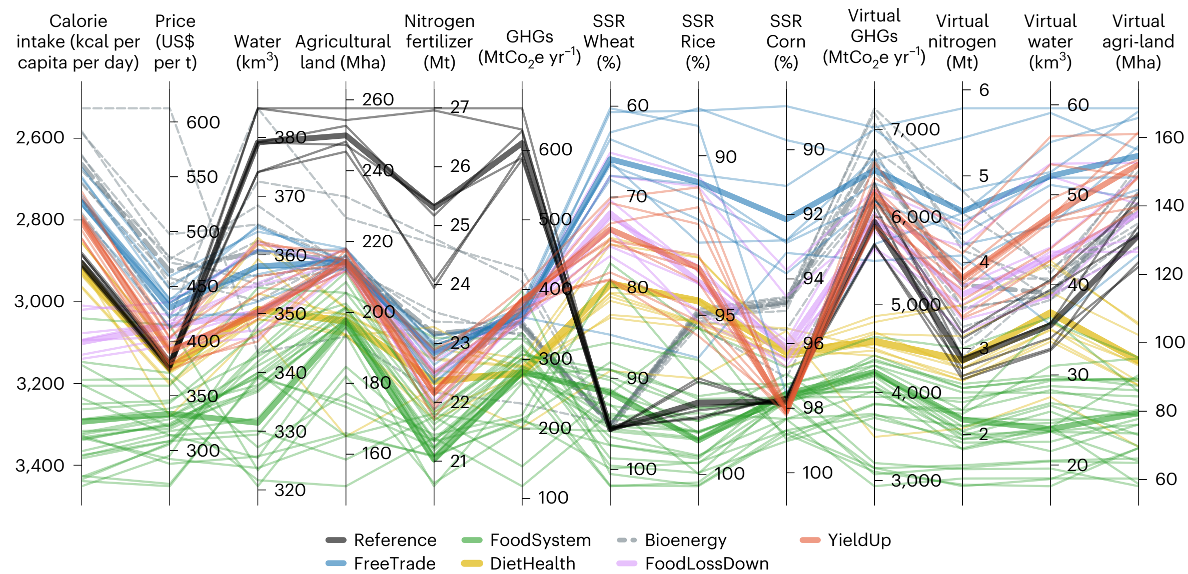

Fig. 5 | Sustainability impacts of bioenergy deployment in China under different alternative futures in 2060. The first nine indicators represent China's domestic sustainability, including daily per capita calorie intake, agricultural commodity prices (2000 constant prices), irrigation water, agricultural land (cropland and grassland), nitrogen fertilizer, GHG emissions from AFOLU, and SSRs for wheat, rice and corn. The last four indicators are virtually imported environmental impacts from China's trading partners, including virtually imported cumulative GHG emissions, nitrogen fertilizer, irrigation water and agricultural land (cropland and pasture). There are multiple lines for each of the seven scenarios due to different assumptions for the uncertain parameters, including GDP, population, trade, crop yield, dietary shift, bioenergy supply (composition) and their various combinations (Methods).

fertilizer and GHG emissions in 2060 by 16.4%, 1.0%, 0.5% and 28.0%, respectively, while virtual agricultural land, water, nitrogen fertilizer and GHG emission imports decrease by 26.6%, 25.3%, 27.7% and 26.3%, respectively (Extended Data Fig. 4). Detailed information on the robustness of the results can be found in the Supplementary Discussion. Nevertheless, even though the alternative sustainability impacts differ considerably from the seven core scenarios, our conclusion that enhancing food system efficiency is the key to achieving China's carbon neutrality while maintaining global sustainability remains valid, and the policy implications developed on the basis of the numerical findings are also plausible.

Discussion

Our study has far-reaching implications not only for China's carbon neutrality and food security policies but also for other populous emerging economies facing high pressure to meet carbon neutrality targets with limited agricultural land and growing demand for energy and food. Reconciling large-scale bioenergy production, domestic food security and global sustainability is challenging. Bioenergy expansion under 95% food SSR constraints would increase land rents and food prices, while removing SSR constraints may transfer environmental burdens to China's food trading partners. Distribution- and demand-side measures are therefore vital components of a desirable policy mix.

First, halving food loss and waste from 27%[12] could reduce domestic calorie intake losses and free up 40 Mha of cropland, which covers 79% of the bioenergy plantation area in China in 2060. In practice, the Chinese government has issued a series of policies to reduce food loss and waste, including educational campaigns and regulatory policies such as the 'Eight Rules' issued in 2012, the 'Clean Plate Campaign' in 2020 and the Anti-Food Waste Law of China in 2021. Second, a healthier dietary shift is crucial in reducing agricultural-land-use-related burdens. Even though the current per capita consumption of animal-based food (108.46 kg in 2019) is much lower than that in most developed countries, especially the United States (375.77 kg in 2019)[32], our results suggest that shifting towards diets that are less dependent on animal-based food is cheaper and feasible without reducing per capita calorie intakes. Meanwhile, replacing staple foods with potatoes is an alternative measure that could be considered to increase food security[27]. In reality, a dietary shift is challenging and impacted by many socially inertial factors (Supplementary Discussion), which requires long-lasting efforts that combine incentive, mandatory and economic measures.

Narrowing the yield gaps is possible and practical. Agricultural land use could decline by 22% (20 Mha) if the main staple crop yields reach 80% of the attainable level[11]. However, although the main staple crop yields in China have increased substantially (rice, +10%; wheat, +50%; corn, +37%) during the past two decades, they are still considerably below the attainable levels[11] (Supplementary Fig. 21) due to technological and management deficiencies by smallholder farming patterns[35,36], which could be improved by green revolutionary technologies and enhanced management knowledge[11].

Implementing any of the above individual compensatory measures alone cannot eliminate the negative impacts on global sustainability triggered by deploying sufficient bioenergy. Instead, the triple dividend of carbon neutrality, food security and global sustainability can be reached only by additional well-blended efficiency-enhancing measures in food production and consumption systems, coupled with slightly relaxing the 95% SSR constraint to 90% for wheat. A holistic food system approach is thus needed when designing policies for the broader sustainable development agenda, which requires us to apply integrated modelling tools that allow us to use a consistent framework to consider producers and consumers, general climate and environmental effects alongside social and economic effects, and the domestic implications as well as implications for trading partners. Moreover, it is necessary to carefully design and implement measures to avoid diminishing marginal or rebound effects from the simultaneous implementation of multiple measures.

Despite the integrated and holistic approach, this study has limitations that necessitate further investigation. For instance, it is unclear how carrying out additional afforestation to increase terrestrial carbon sinks would intensify land competition with bioenergy production. Moreover, in addition to using per capita calorie intake to measure food security, the health impacts of the dietary shifts in terms of nutritional adequacy could be explicitly considered. Finally, future studies could assess the impacts of importing bioenergy rather than food when better data on the bilateral biomass trade are available. The Supplementary Discussion presents more aspects.

Methods

Research framework

In this study, we assumed energy plantations (short-rotation plantations), which are derived from the Model for Energy Supply Strategy Alternatives and Their General Environmental Impact (MESSAGE)–GLOBIOM model, as bioenergy feedstock to meet China's 2060 carbon neutrality target (Extended Data Fig. 2). Land-use change and the corresponding direct sustainability impacts, which are driven by changes in the production, consumption and trade of agricultural products resulting from increasing bioenergy cropland, are modelled within the GLOBIOM model. Environmental impacts (agricultural land, irrigation water, GHG emissions and nitrogen fertilizer use) embodied in international trade are calculated on the basis of environmental intensity and food trade quantity projected by the GLOBIOM model. Accompanying compensatory measures, including narrowing crop yield gaps, halving food loss and waste and shifting to healthier diets, are implemented by adjusting the key related parameters in the GLOBIOM model. Finally, we performed a comprehensive sensitivity analysis by varying related parameters within reasonably uncertain ranges in the GLOBIOM model.

GLOBIOM basic model. GLOBIOM[37,38] is a global, bottom-up, recursive and dynamic partial equilibrium economic model of agriculture (including livestock), forestry and bioenergy. The model calculates a market equilibrium in ten-year time steps from 2000 to 2060 by maximizing welfare (the sum of consumer and producer surplus) through a physical representation rather than the monetary representation of variables in general equilibrium models, subject to technological, resource and political constraints. It includes 18 major crops (barley, dry beans, cassava, chickpeas, corn, cotton, groundnut, millet, potatoes, rapeseed, rice, soybeans, sorghum, sugarcane, sunflower, sweet potatoes, wheat and oil palm) and 7 livestock products (meat and milk from cattle and buffalo, meat and milk from sheep and goats, pork, poultry, and eggs). In addition, bilateral trade flows are optimized according to each region's marginal production prices and transportation costs by minimizing total trading costs.

Energy plantations are short-rotation tree plantations covering short-rotation (that is, two to five years) coppice and longer-rotation (approximately ten years) forestry for producing energy wood, such as poplar, willow or eucalyptus. The establishment of plantations is limited to cropland, grassland and other natural vegetation areas. Land suitability is based on aridity, temperature, elevation, population and land-cover data. More details are provided in Havlík et al.[37], Lauri et al.[39] and Li et al.[40]. More information about the model can be found at www.globiom.org.

The model has been widely used for the integrated assessment of land-based sustainable development issues, such as food security[41–44], land-based GHG emissions and climate change mitigation efforts[3,45–47], bioenergy[40,48,49], nitrogen fertilizer use[30,50], water use[3,18,37], biodiversity impacts[51,52], the nexus and trade-offs among sustainability indicators[3,41,53,54], and the impacts of international trade on sustainable development[55,56].

GLOBIOM–China model. The GLOBIOM–China model has been extensively modified and calibrated[18] to improve its representation of China's specific situation via the localized quantification of key parameters such as diet, yield and food loss based on a thorough literature review. At the same time, relevant Chinese agricultural policies, such as the 'zero chemical fertilizer growth by 2020' policy[57]; maintenance of the wheat, corn and rice SSRs at 95%[58] policy; and transition of monogastric production structure policy, were included in the GLOBIOM–China model to better capture the trends in the Chinese agriculture sector. Moreover, the model was carefully calibrated over the 2000–2020 period by narrowing the discrepancies between model outcomes and statistical data such as FAOSTAT and the National Bureau of Statistics of China. The model's projection performance by 2030 was aligned with the mainstream Organisation for Economic Co-operation and Development–Food and Agriculture Organization Agricultural Outlook projections[59]. The model behaviours in contrast to relevant statistics and outlooks regarding crop yield and area, per capita calorie consumption, food demand, production, and trade processes are shown in Supplementary Figs. 22–28. Moreover, the projected food demand also compares well to those in other studies (Supplementary Table 6).

Calculating virtual trade flows in environmental impacts

Virtual trade flows refer to resources or pollution embodied in international trade[18]. Four virtual environmental indicators were used as examples: agricultural land (cropland and grassland), GHG emissions from AFOLU, agricultural irrigation water use and nitrogen use. China's seven major trading partners representing 70% of the value of China's agricultural imports were highlighted: Argentina, Australia, Brazil, Canada, New Zealand, the United States and the European Union (Supplementary Fig. 29). Environmental impacts were calculated using equations (1)–(6) on the basis of the output of the GLOBIOM–China model, including bilateral trade quantities and the estimated environmental intensity. Virtual agricultural-related GHG emissions (N_2O and CH_4) originate from fertilizer, rice paddies, enteric fermentation, manure management, manure on pastures, rangelands and paddocks and were estimated on the basis of N_2O emission coefficients of nitrogen fertilizer from the Intergovernmental Panel on Climate Change[60], CH_4 emission factors of rice from FAOSTAT[61] and emissions intensity parameters from the global livestock production systems database[62]. In addition, environmental impacts caused by feed production are included in the virtual trade flows related to livestock products:

$$\begin{aligned}\mathrm{Virtual\_area}_{R,P,T} &= \mathrm{BilateralT}_{R,P,T} \times \mathrm{Land\_intensity}_{R,P,T}\\ &= \mathrm{BilateralT}_{R,P,T} \times \frac{\mathrm{AREA}_{R,P,T}}{\mathrm{PROD}_{R,P,T}}\end{aligned} \tag{1}$$

$$\begin{aligned}\mathrm{Virtual\_N}_{R,P,T} &= \mathrm{BilateralT}_{R,P,T} \times \mathrm{N\_intensity}_{R,P,T}\\ &= \mathrm{BilateralT}_{R,P,T} \times \frac{\mathrm{N\_input}_{R,P,T}}{\mathrm{PROD}_{R,P,T}}\end{aligned} \tag{2}$$

$$\begin{aligned}\mathrm{Virtual\_water}_{R,P,T} &= \mathrm{BilateralT}_{R,P,T} \times \mathrm{Water\_intensity}_{R,P,T}\\ &= \mathrm{BilateralT}_{R,P,T} \times \frac{\mathrm{Water}_{R,P,T}}{\mathrm{PROD}_{R,P,T}}\end{aligned} \tag{3}$$

$$\begin{aligned}\mathrm{Virtual\_Agri\_GHG}_{R,P,T} &= \mathrm{BilateralT}_{R,P,T} \times \mathrm{Agri\_GHG\_intensity}_{R,P,T}\\ &= \mathrm{BilateralT}_{R,P,T} \times \frac{\mathrm{Agri\_GHG}_{R,P,T}}{\mathrm{PROD}_{R,P,T}}\end{aligned} \tag{4}$$

where R is the exporting region, P is the product, T is the year, $\mathrm{BilateralT}_{R,P,T}$ is the net bilateral trade quantity from R to China for product P, $\mathrm{PROD}_{R,P,T}$ is the total production of product P, $\mathrm{AREA}_{R,P,T}$ is the total harvested area for P, $\mathrm{N\_input}_{R,P,T}$ is the total nitrogen fertilizer use, $\mathrm{Water}_{R,P,T}$ is the total irrigation water use, and $\mathrm{Agri\_GHG}_{R,P,T}$ is the total agricultural-related GHG emissions.

Virtual emissions from deforestation were calculated on the basis of forest loss and deforestation attributable to cropland and pasture expansion using a top-down indirect allocation approach[63] (equations (5) and (6)):

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$$\text{Virtual\_defor\_emission}_{R,T} = \text{Defor\_emis\_crop}_{R,T} \times \frac{\Delta\text{Crop\_area}_{R,P,T}}{\sum_{P=1}^{P} \Delta\text{Crop\_area}_{R,P,T}} \times \frac{\text{Virtual\_Crop\_area}_{R,P,T}}{\text{Crop\_area}_{R,P,T}}, \forall\Delta\text{Crop\_area}_{R,P,T} > 0 \quad (5)$$

$$\text{Virtual\_defor\_emission}_{R,T} = \text{Defor\_emis\_live}_{R,T} \times \frac{\Delta\text{Pasture}_{R,P,T}}{\sum_{P=1}^{P} \Delta\text{Pasture}_{R,P,T}} \times \frac{\text{Virtual\_Pasture}_{R,P,T}}{\text{Pasture}_{R,P,T}}, \forall\Delta\text{Pasture}_{R,P,T} > 0 \quad (6)$$

where $\text{Defor\_emis\_crop}_{R,T}$ and $\text{Defor\_emis\_live}_{R,T}$ are deforestation emissions due to the expansion of cropland and pasture, respectively; $\text{Virtual\_Crop\_area}_{R,P,T}$ is the virtual crop area embodied in the food trade; $\text{Crop\_area}_{R,P,T}$ is the crop area; $\Delta\text{Crop\_area}_{R,P,T}$ is the expanded crop area; $\text{Virtual\_Pasture}_{R,P,T}$ is the virtual pasture embodied in the food trade; $\text{Pasture}_{R,P,T}$ is the pasture; and $\Delta\text{Pasture}_{R,P,T}$ is the expanded pasture.

Scenario design

To investigate the potential risks to other SDGs and mitigation opportunities from large-scale bioenergy deployment, we designed seven scenarios on the basis of bioenergy demand and the maintenance of the SSRs for the three main staple crops (wheat, rice and corn) above 95%, coupled with different compensatory measures (Table 1 and Supplementary Figs. 30–33).

Reference is the baseline scenario following the middle-of-the-road scenario, SSP2 (ref. 26), which extends historical trends in population growth, dietary preferences, trade and agricultural productivity. Bioenergy comes from energy plantations (Supplementary Methods). In the other six intervention scenarios, we assume that China's bioenergy supply gradually increases after 2020 to 15.6 EJ per year in 2060 (Supplementary Fig. 33) to meet the bioenergy demand[26,41], in line with the carbon neutrality target, thus accounting for approximately 17% of the total primary energy by 2060. However, large-scale bioenergy production could hinder domestic food security if food system efficiency improvements remain incremental while maintaining a minimum SSR of 95% for the three main staple crops (wheat, rice and corn). The bioenergy demand for the rest of the world remains the same as that in the Reference scenario.

In the Bioenergy scenario, increasing the bioenergy supply while maintaining the three main staple crop SSRs above 95% is in line with China's current food self-sufficiency policy. To explore how the international food trade can help relieve domestic dilemmas and affect global sustainability, we assume that there are no SSR constraints in the FreeTrade scenario. In addition, four scenarios were designed on top of the FreeTrade scenario, essentially assuming additional compensatory measures implemented in China in either single-action or combined-action bundles, with implementation levels increasing gradually from 2020 to 2060. The compensatory measures for China are (1) increasing food crop yields without using more fertilizer or other inputs by adopting knowledge and technologies that are currently available according to recent field studies[11,64], (2) halving food loss and waste in the food supply chain, (3) shifting towards a less animal-based diet, and (4) simultaneously implementing all of the above compensatory measures. The additional scenarios correspond to each bundle separately (single-action scenarios: YieldUp, FoodLossDown and DietHealth) or an integrated action portfolio (FoodSystem). Detailed descriptions of the compensatory measures are provided below, and the values of the key scenario drivers for China are provided in Supplementary Table 7.

Crop yields. The main staple crop yields (rice, wheat and corn) in China have increased substantially in recent decades due to agricultural intensification[18]. However, the rate of increase has decreased (Supplementary Fig. 21). The agricultural landscape in China is dominated by risk-averse smallholder farmers who lack agronomic knowledge and poorly understand the market, leading to management deficiencies and yields that are substantially below the attainable levels. Moreover, China has been rapidly and continuously urbanizing[65]. As young farmers move to cities and older farmers exit the labour force, the decline in agricultural knowledge could further limit crop yields[11,36]. Site–year field experiments show that adopting integrated soil–crop system management (ISSM) practices can increase average yields for rice, wheat and corn in China to 8.5 Mg ha^{-1}, 8.9 Mg ha^{-1} and 14.2 Mg ha^{-1} (the attainable levels), respectively, without any increase in nitrogen fertilizer[11]. Hence, in the YieldUp scenario, we assume that the average rice, wheat and corn yields (the three main staple crops, which together accounted for 98.4% of China's cereal production in 2020) increase from their current levels to ~75% of the attainable yield by 2060 through the adoption of ISSM practices. Specifically, the average yields of rice, wheat and corn in 2060 relative to 2020 will increase by 13.3% (from 7.0 to 7.8 Mg ha^{-1}), 33.0% (from 5.2 to 6.9 Mg ha^{-1}) and 71.4% (from 6.4 to 11.0 Mg ha^{-1}), respectively (Supplementary Fig. 31). The yields for other crops follow the assumption in SSP1—that is, yields increase by ~20% by 2060 relative to their 2020 values[64,66].

Reduced food loss and waste. Large-scale field surveys were conducted between 2013 and 2018 in China to quantify food loss and waste along the farm-to-fork chain (production, postharvest handling and storage, processing, distribution, retailing, and consumption)[12]. The results show that 27% of food produced for human consumption annually (~349 Mt) is lost or wasted. This figure can be substantially reduced by implementing mitigation strategies such as advancing technology, increasing awareness and altering cooking styles. In the FoodLossDown scenario, we assume that food loss and waste in the food supply chain can be halved by implementing such mitigation strategies, which align with the SDGs[67]. As a result, food loss and waste in China could linearly decrease from the current rate by 50% by 2060[67].

Dietary shift. Dietary risks are among the top five risks for attributable deaths worldwide[68,69]. Shifting towards plant-based diets—that is, consuming more plant food and less animal food—has been recommended for its health and environmental benefits[70–72]. In China, per capita animal-based food consumption has grown approximately 12-fold since 1961 (Supplementary Fig. 17)[32]. Although China's animal-based food consumption per capita (108.46 kg in 2019)[32] is lower than that of most developed countries (375.77 kg in 2019 in the United States), the per capita meat consumption, especially that of pork, has already exceeded the level recommended in the Chinese Dietary Guidelines 2022 (Supplementary Table 5)[33]. A rapid transition towards meat-intensive diets has increased the substantial impacts on the environment[13,14] and human health[15,16] in China. Following the dietary intake recommendations from the Chinese Nutrition Society would improve human health while substantially reducing environmental impacts[16,34].

Here, in the DietHealth scenario, we assume a shift towards less animal-based diets, closing 20% of the gap between current consumption quantities and the recommended values (Supplementary Fig. 32) based on the Chinese national dietary guidelines and the planetary health diet[33,73], which advocates for a more balanced and healthier diet. Accordingly, animal-based calorie consumption gradually decreases from current levels to the calorie target in 2060, while calories from crops gradually increase to keep the total calorie consumption consistent with that in the Reference scenario. More detailed conditions for the dietary shift are listed in Supplementary Table 5.

Sensitivity analysis

To quantify the sensitivity of the results to the key assumptions on socio-economic development and bioenergy supply, we performed an extensive sensitivity analysis covering seven groups of key parameters: (1) higher or lower levels of animal-based food consumption per capita, (2) enhanced or reduced food crop yields, (3) higher or lower overall demand for bioenergy and its differing specific compositions,

(4) increased bioenergy demand that is consistent with 1.5 °C in all world regions (significantly affecting global bioenergy supply and land-use tension), (5) higher or lower food trade barriers, (6) higher or lower future population size, and (7) higher or lower future GDP. These parameters significantly affect food supply and demand and land competition with bioenergy production.

The one-at-a-time and two-at-a-time methods were used to investigate the sensitivity of sustainability impacts to changes in the above-mentioned key parameters (Supplementary Tables 8–10). The one-at-a-time method has been extensively used in investigating the responses of results to changes in input values[74,75] by introducing marginal variations in one input variable and maintaining the other inputs constant. The change in results yields the effect of the target input variable on the results. The larger the elasticity, calculated as the ratio of the relative change in the output to the relative change in the input (Supplementary Methods), the more sensitive the results are. Similarly, the two-at-a-time method was performed by varying multiple input variables, which enable us to provide alternative plausible results of different combinations of assumptions on socio-economic development. The quantification of input variables is described below and shown in Supplementary Figs. 30–33 and Supplementary Table 11. We recalculated the corresponding results when the input variables followed the alternative assumptions presented in Fig. 5, Supplementary Discussion, Extended Data Fig. 4 and Supplementary Tables 12–14.

Population, GDP and trade. For assumptions on population, GDP and trade, we used the well-established SSP framework, which includes narrative and quantitative information with respect to distinct socio-economic drivers. In addition to the SSP2 pathway assumptions in the seven core scenarios (Table 1), we used two contrasted assumptions from the SSP framework—that is, the 'sustainability pathway' (SSP1)[76] and the 'regional rivalry pathway' (SSP3)[77]—to cover the range of uncertainty in future population size, GDP and international trade (Supplementary Fig. 30). SSP1 assumes lower population growth, faster GDP growth and lower trade barriers (trade costs; Supplementary Methods 2). In contrast, SSP3 has higher population growth, slower GDP growth and higher trade barriers (trade costs). Population, GDP and international trade are key factors that determine future food security conditions and land use.

Crop yield growth. We assumed two alternative yield pathways in which the average yields of the three main staple crops increase from their current levels to ~70% (YieldUp-L, inadequate) and ~80% (YieldUp-H, beyond expectation) of the attainable yield in China by 2060 (Supplementary Discussion). Notably, adopting proper system management practices makes it possible to reach 80% of the attainable yield[11,35].

Dietary shift. Future diets are impacted by many factors and thus involve uncertainty. On the basis of the difference between the projected animal-based food consumption level under the Reference scenario and the latest recommendations of the Chinese Dietary Guidelines released in 2022, we set two alternative animal-based food consumption levels, which are 10% higher (DietHealth-L) and 10% lower (DietHealth-H) than that under the DietHealth scenario, while maintaining total calorie consumption consistent with that in the Reference scenario by increasing calories from crops (Supplementary Fig. 32).

Bioenergy supply and its composition. There is a wide range of bioenergy demand that has been estimated by different integrated assessment models to achieve China's carbon neutrality target[78]. Moreover, agricultural and forestry residues are two alternative bioenergy feedstocks[79–81] that can be substituted for partial energy plantations. China's additional bioenergy demand under the six higher-bioenergy-demand scenarios (Table 1) was obtained from the GLOBIOM–MESSAGE framework under the 1.5 °C target and was assumed to originate from energy plantations. We set three alternative bioenergy assumptions to explore the uncertainty of the bioenergy supply level and its composition. The higher bioenergy (Bioenergy-H) assumption considered that energy plantation supply could increase by 30% compared with the Bioenergy scenario, which is comparable to the bioenergy demand estimated by the World Induced Technical Change Hybrid model[78]. In contrast, the Bioenergy-L scenario was set up with a 25% (4 EJ yr^{-1}) lower bioenergy demand in 2060 to reflect two outcomes. First, enhanced use of crop residue may reduce the demand for energy plantations. For example, if the current crop residues used as fuel (11%) or directly burned in the open air (22%) could be collected and used properly[80], a total of 4 EJ bioenergy could be supplied. Second, GHG emissions in the DietHealth and FoodSystem scenarios are lower when driven by adopting compensatory measures, which could reduce demand for negative emissions from bioenergy with carbon capture and storage and the corresponding bioenergy.

We also tested an assumption (Bioenergy-ROW) that bioenergy supply in both China and the remainder of the world is consistent with the 1.5 °C target, while other assumptions remained the same as those in the Bioenergy scenario. Under the Bioenergy-ROW assumption, the bioenergy supply of the remainder of the world would increase to 115 EJ yr^{-1} by 2060, as estimated by the MESSAGE model. Of the supply, 34% originates in Latin America, 26% originates in sub-Saharan Africa and 16% originates in South Asia. From the perspective of biomass composition, a Bioenergy-C scenario was set up, assuming that approximately 15% (approximately 2.5 EJ yr^{-1}) of energy plantations were replaced by forestry residues[79] (Supplementary Discussion). In addition, to prevent large areas of unmanaged forest from being converted into managed forest, we assumed a sustainable amount of available forestry residue supply (approximately 2.5 EJ yr^{-1}), which is comparable to available levels in other studies[79,80]. Both energy plantations and forestry residues were simulated in GLOBIOM.

Combination. We set different combinations of bioenergy supply, trade, yield growth and dietary shift following the two-at-a-time method (Supplementary Tables 9–10). For example, in the FoodSystem-1-H-H scenario, the default settings in the FoodSystem scenario switch to lower trade barriers (1), high yield growth (H) and high dietary shift (H) assumptions. In contrast, in the FoodSystem-BioH-1-H-H assumption, bioenergy also shifts to the high supply (BioH) assumption in addition to the above-mentioned variations. The same rule applies to other sensitivity scenarios, as shown in Supplementary Tables 8–10 and Extended Data Fig. 4.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

The data supporting the findings of this study are available within the Article and Supplementary Data. Source data are provided with this paper.

Code availability

The code used to present the results in this study is available from the corresponding author upon request. The documentation for the GLOBIOM model is available online at https://iiasa.github.io/GLOBIOM/.

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Author contributions

M.R., H.D. and P.H. designed the study. M.R. ran the model and performed the analysis with the help of A.D. and S.F. C.H. drew the figures. M.R., H.D. and P.H. wrote the manuscript with major contributions from all co-authors.

Competing interests

The authors declare no competing interests.

Additional information

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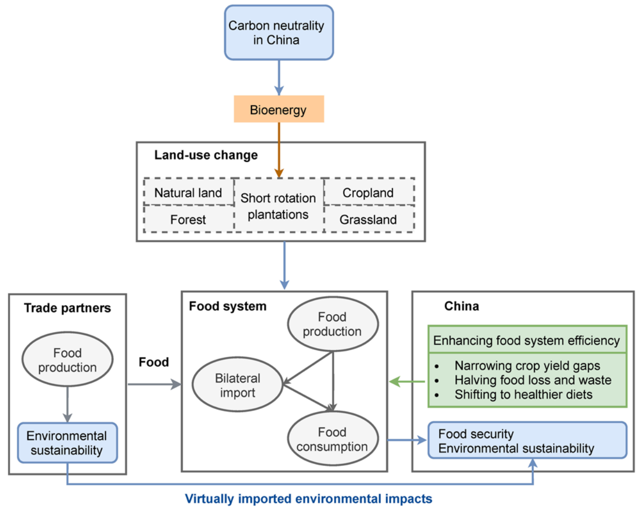
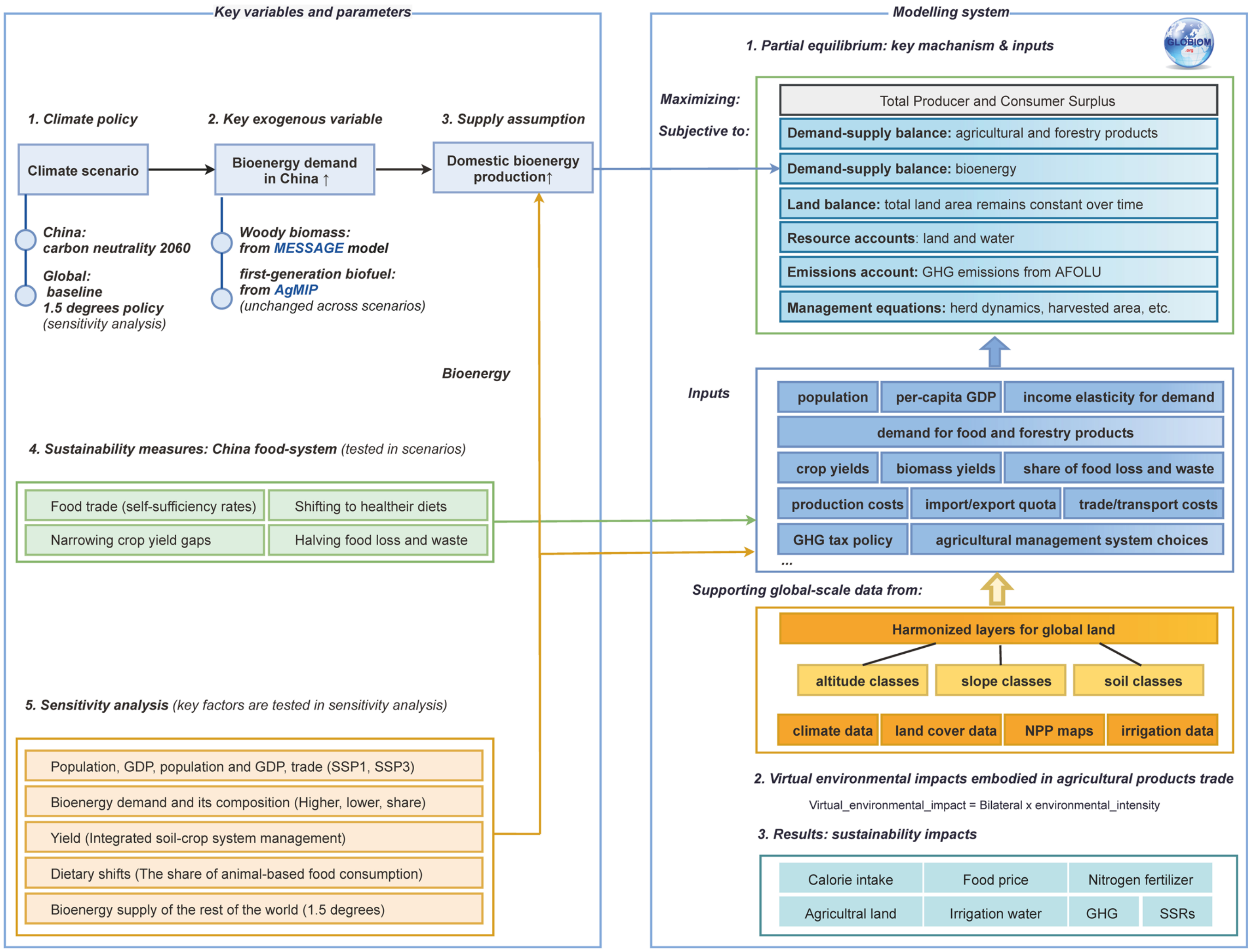


Extended Data Fig. 1 | The conceptual research framework of interconnected impacts of bioenergy deployment on selected sustainability indicators.

https://doi.org/10.1038/s43016-023-00790-1



Extended Data Fig. 2 | Overview of detailed modeling framework.

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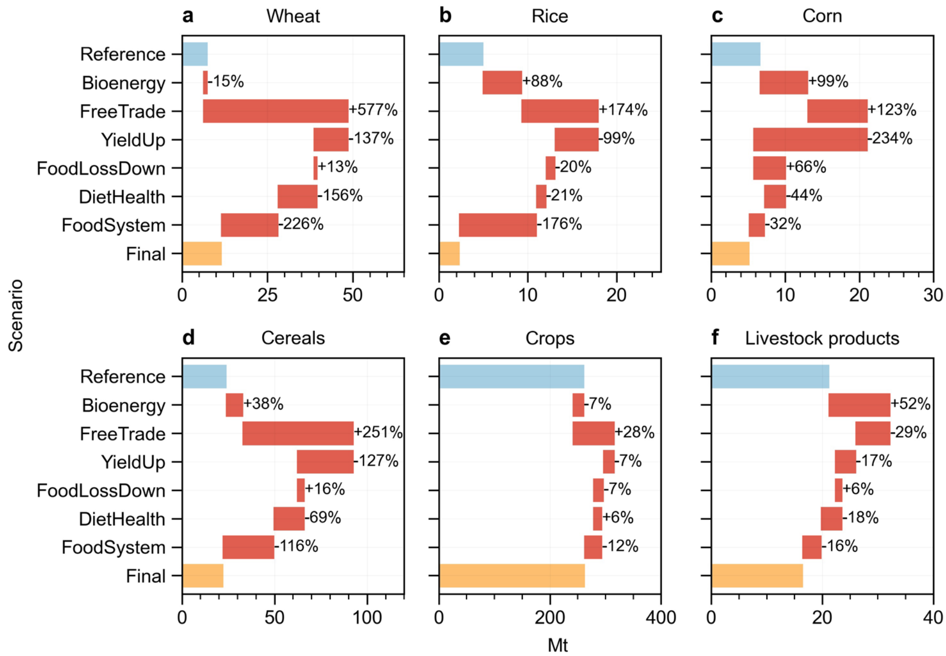

Extended Data Fig. 3 | Projections of China's agricultural imports in 2060. **a**–**f**, The lengths of the red suspended bars indicate the absolute marginal change in each scenario compared with the scenario to its above; the number beside each red bar is obtained by dividing the abovementioned absolute change by the corresponding value in the Reference scenario. The length of the final bar is the value for the FoodSystem scenario.

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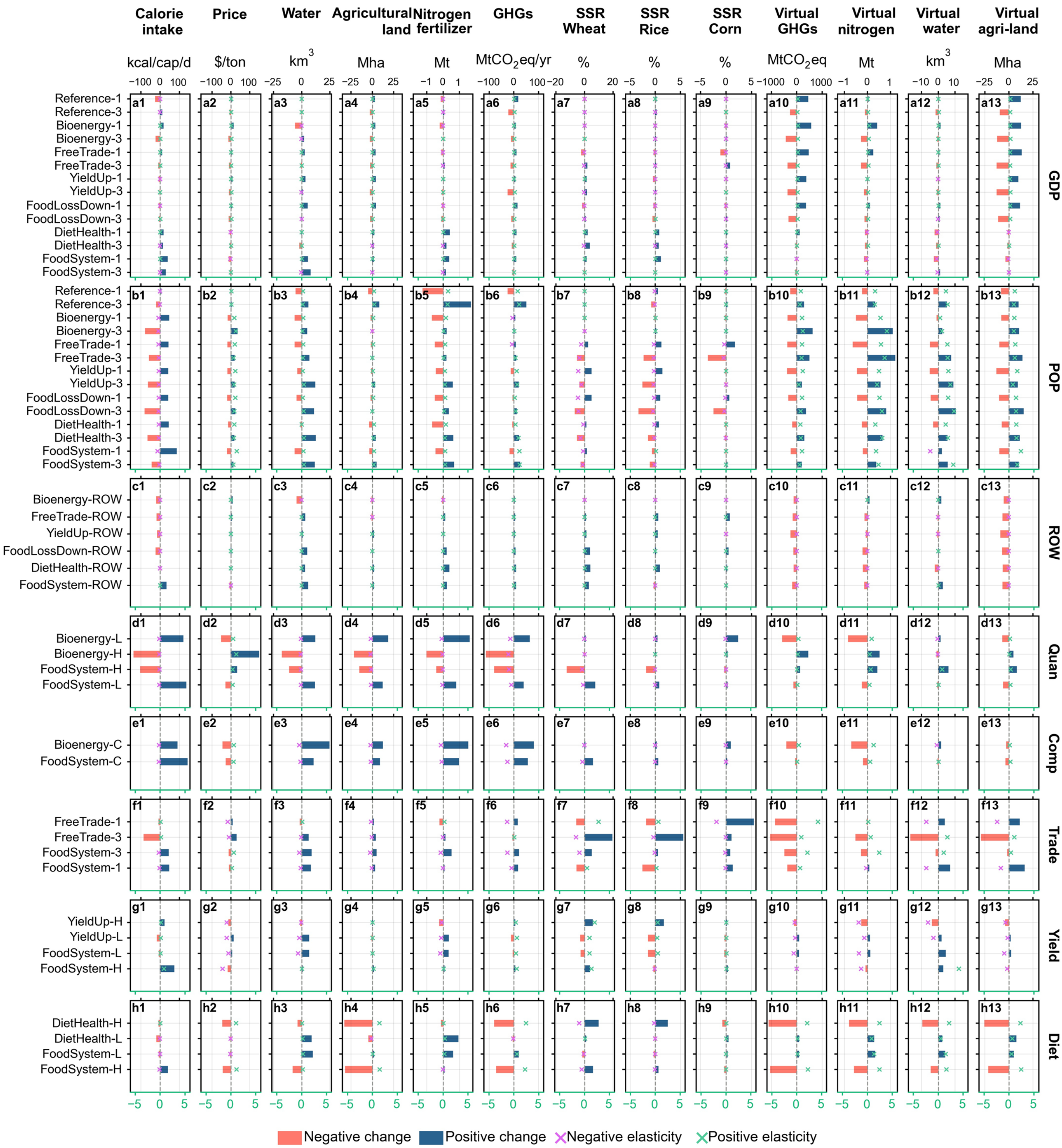

Extended Data Fig. 4 | Sensitivity of sustainability impacts to changes in uncertain input variables. Absolute changes (top) in sustainability indicators and elasticity (bottom) in 2060. The mapping of sensitivity scenarios, baseline scenarios, and inputs and the proxy variables of inputs for calculating elasticities is shown in Supplementary Table 11. Methods and Supplementary Table 8 present sensitivity scenarios in further detail. The right side shows the uncertain input variables and the left side shows the sensitivity scenarios. The first six indicators (top) are China's domestic sustainability, and the last four indicators are virtually imported environmental impacts from China's trading partners.

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Software and code

Policy information about availability of computer code

Data collection	No specific software was used for data collection. The analysis relies on harmonized databases used by the large-scale agrieconomic models (GLOBIOM).
Data analysis	The software used for the analysis in the GLOBIOM models is GAMS (GAMS25.0.3). The results analysis was done by using the open-source software R (R-4.0.2) and Python-3.9.15

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Data supporting the findings of this study are available within the article and its Supplementary Information files.The code used to present the results in this study is available from the corresponding author upon request. The documentation for the GLOBIOM model is available online at https://iiasa.github.io/GLOBIOM/. Supplementary data and source data for each figure will are also published with the final version of the paper.

Human research participants

Policy information about studies involving human research participants and Sex and Gender in Research.

Reporting on sex and gender	No human research participants were involved
Population characteristics	No data
Recruitment	No data
Ethics oversight	No data

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Our study, based on the GLOBIOM-China model, which features a thoroughly validated depiction of China's AFOLU sector and its bilateral trade flows, quantifies how measures to enhance food system efficiency could mitigate the potential adverse domestic and global sustainability impacts of bioenergy deployment to help China successfully transition to a carbon neutral future. The results have far-reaching implications for not only China's carbon neutrality and food security policies, but also for other populated emerging economies facing high pressure to meet carbon neutrality targets with limited agricultural land and growing demand for energy and food.
Research sample	This study is based on economic model simulation (with GLOBIOM built upon existing database); no sampling process was conducted.
Sampling strategy	Sampling strategy is not applicable to this study.
Data collection	The study largely builds on the datasets available in the standard GLOBIOM model. The additionally collected data for model calibration, scenarios and sensitivity analysis collected from literature are listed in Table 1, Suppl. Table 1, Suppl. Table 8, Suppl. Figs. 31-33 including the reference of the data.
Timing and spatial scale	The modeling base year is 2000 and calculated at 10-year steps until 2060, covering global scale.
Data exclusions	No data were excluded from our analysis.
Reproducibility	All the analyses were based on available models and well-defined methods, so the results can be reliably reproduced.
Randomization	Randomization was not relevant for this study.
Blinding	Blinding was not relevant for this study.

Did the study involve field work? ☐ Yes ☒ No

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We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging