Exploring sustainable food system transformation options in China: An integrated environmental-economic modelling approach based on the applied general equilibrium framework

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Abstract

Our food system drives global environmental change, and differences in environmental concerns of consumers may cause negative environmental 'spillover effects' in less concerned countries. While food system transformation is increasingly recognised as crucial for mitigating such negative environmental spillovers, possible unintended negative environmental consequences in other regions and/or economic sectors have received less attention. Using an integrated environmental-economic modelling framework and scenario analyses, we explored options for more sustainable food systems and to mitigate the negative environmental spillovers from trading partners to China. We found that doubling novel soy-based food (soy-based meat) consumption while reducing pork consumption in China decreased Chinese economy-wide emissions of greenhouse gases (GHGs) by 1% and acidification pollutants by 3%. However, it increased Chinese economy-wide emissions of eutrophication pollutants by 2%, driven by the increased production of soy-based food and other food with relatively high emission intensities of eutrophication pollutants. Combining a dietary shift with the adoption of cleaner cereals production technology for half of the current resources used for cereals production decreased Chinese economy-wide emissions of GHGs by 1%, acidification pollutants by 7%, and eutrophication pollutants by 3%, but required capital reallocation from other sectors. Implementing a unilateral environmental policy in China (i.e., implementing incentive-based emission permits to reduce emissions of all pollutants by 3% annually) increased economy-wide emissions of GHGs in trading partners by 2%. This ‘carbon leakage’ emerges due to the shift of production of products with relatively high emission intensities (i.e., nitrogen fertiliser and livestock) from China to its trading partners through international trade. We demonstrate that indirect environmental impacts are crucial to consider when analysing the economy-wide consequences of food system transformations, as these indirect impacts may inadvertently affect other regions and/or economic sectors that were not initially targeted. Our study offers policymakers insights into designing effective policies for more sustainable food systems and sheds light on trade-offs among competing environmental and economic goals.

Keywords

sustainable food system; sustainable production and consumption; trade; emissions; applied general equilibrium models; integrated environmental-economic modelling.

1. Introduction

The food-land-water-climate nexus concept arises from recurring resource crises, highlighting the interconnectedness of food, land, water, and climate and their broader impacts. A nexus approach aims to enhance resource utilisation efficiency, inter-departmental collaboration, and coherent policy formulation (Doelman et al., 2022). Exploring options for more sustainable food systems in the food-land-water-climate nexus is one of the main global challenges (Griggs et al., 2013), in particular when the demand for animal-based food (meat, milk, eggs) continues to increase (FAO, 2022; UNCCD, 2017). Animal-based food has contributed to over half of the protein supply to humans in developed countries during the last decades, while its consumption is rapidly increasing in developing countries due to population growth, economic growth, and urbanization (FAO, 2022). Our food system, especially the production and consumption of animal-based food, has impacts on climate change, ocean acidification, biogeochemical flows (nitrogen and phosphorus), freshwater use, land-use changes, and biodiversity loss (Springmann et al., 2018). Improving our food system is essential for realising the Sustainable Development Goals (SDGs), especially SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 13 (climate action) (UN, 2015).

Differences in environmental concerns of consumers may cause negative environmental ‘spillover effects’, namely, from trading partners with higher environmental concerns to the region with lower environmental concerns (Hökby & Söderqvist, 2003; Latacz-Lohmann & Hodge, 2003; Zhu, 2004). Food system transformation is increasingly recognised as crucial for mitigating such negative environmental spillovers and achieving multi-dimensional SDGs (Doelman et al., 2022; Newbold et al., 2015). For example, the EAT-Lancet Commission proposed various measures to keep food systems within environmental limits while delivering healthy diets by 2050 (Willett et al., 2019). These measures include dietary structure changes towards healthier and more plant-based diets, improvements in technologies and management, and reductions in food loss and waste (Springmann et al., 2018). Policy instruments, such as a meat tax (Funke et al., 2021) and emission restrictions (Zhu, 2004; Zhu & Van Ierland, 2006; Zhu & Van Ierland, 2005), can help to implement the aforementioned measures in practice. Y. Du et al. (2018) have suggested that adopting a so-called 'green source trade strategy (i.e., importing food and feed from nations with low emissions intensities)' can assist in the realisation of emission mitigation. While the direct environmental benefits of food system transformation are well acknowledged, possible unintended negative environmental consequences in other regions and/or economic sectors have received less attention. For instance, resources freed from one sector may be reallocated to other sectors across the whole economy and may influence other countries through international trade. Moreover, in some cases, these negative environmental spillovers may outweigh the direct benefits of food system transformation. However, many prior studies exploring options for sustainable food systems tend to either focus solely on a specific mitigation measure or analyse a particular environmental impact (mainly global warming potential) within small life cycles rather than adopting an economy-wide perspective. This approach may result in a biased estimation of the environmental benefits derived from food system transformation (Dandres, Gaudreault, Tirado-Seco, & Samson, 2011, 2012).

While the significance of acknowledging the indirect environmental impacts of food system transformation is growing, there remains a lack of quantitative analyses that take an economy-wide perspective to understand the synergies and trade-offs within the food-land-water-climate nexus. This gap may hinder the design of effective policies for sustainable food systems on a global scale. This study aims to explore options for more sustainable food systems and to mitigate the negative environmental spillovers from trading partners to China. We took China as an example, as China is among the largest and most populous countries in the world, and its food system exerts enormous impacts on the environment (FAO, 2022). Our study aims to address two related questions under food system transformation. First, what are the negative environmental 'spillover effects' from trading partners to China? Second, what are the environmental and economic impacts of different food system transformation options in China, and to what extent can these options mitigate the negative spillovers from trading partners to China? This study aims to bridge the gap by using an integrated environmental-economic modelling approach based on the applied general equilibrium (AGE) framework. We have chosen the AGE models for our study because AGE models with a highly structured and comprehensive description of the economy based on microeconomic theory are widely used to assess the economy-wide effects (i.e., production, consumption, and trade) of policy changes and shock events in society (Gatto, Kuiper, & van Meijl, 2023; Mason-D'Croz et al., 2022; Mason-D'Croz et al., 2020; Xie et al., 2018; Yao, Zhang, Davidson, & Taheripour, 2021). Moreover, policymakers can use the AGE models to evaluate the potential socioeconomic and environmental consequences of food system transformation, which allows for feedback to enhance policy design.

In this study, we first discussed how differences in environmental concerns of consumers in different regions (S1) may cause negative environmental 'spillover effects', namely, from trading partners with higher environmental concerns to China. Next, to explore options for sustainable food systems to mitigate negative environmental spillovers, four options for food system transformation related to emission mitigation in China were simulated. (i) Doubling novel soy-based food (soy-based meat) consumption while reducing pork consumption (S2): This scenario is particularly relevant given China's status as the world's largest pork producer and soybean importer. Additionally, China's historical consumption of soy-based food provides a solid foundation for this dietary shift, which has substantial potential to reduce emissions by altering consumption patterns. (ii) Adopting cleaner cereals production technology for half of the current resources used for cereals production (S3): Cereal production efficiency and emission intensities vary significantly between regions, with cleaner and more efficient technologies employed by China's trading partners, such as the United States, in contrast to less efficient and more polluting practices in China. By adopting cleaner cereals production technology used by China's trading partners, China could enhance cereal productivity and reduce emissions. (iii) Combining dietary structure change with cleaner cereals production technology (S4 = S2+S3): The combination of demand-side and supply-side measures may help reduce emissions in China further. (iv) Implementing incentive-based emission permits to contribute to China's carbon neutrality goal and other environmental policies (S5): The introduction of incentive-based emission permits can drive a transition from emission-intensive production to cleaner alternatives. By setting emission limits aligned with China's carbon neutrality goal and other environmental policies, the total emissions from all producers in China could be kept below the specified threshold. We also performed a sensitivity analysis for key environmental, economic behavioural, and technological parameters.

2. Materials and methods

2.1 The integrated environmental-economic model and database

We chose the AGE modelling approach for two reasons. First, due to the significant global implications of supply-side and demand-side measures, as well as environmental policies, facilitated by international trade of food and feed across various countries, our analysis necessitates a model encompassing multiple countries. Second, given the intricate interconnections between food and feed sectors, including intermediate uses and resource competition (e.g., land, water, and fertiliser), employing a multi-sectoral model is essential for this analysis. In short, these considerations point to the use of a multi-country and multi-sectoral economic model that can simulate the effects of the food system transformation across the whole economy. We, therefore, developed a global comparative static AGE model, a modified version of an integrated environmental-economic model (Zhu & Van Ierland, 2004, 2012; Zhu, van Wesenbeeck, & van Ierland, 2006), and calibrated this model with the Global Trade Analysis Project (GTAP) database (GTAP, 2014). The GTAP database covers economic data of 65 sectors and 141 countries, and it has been widely used for analysing global issues related to international trade, the environment, and climate change.

Our model incorporated two major enhancements, which facilitate the analysis of the food system. First, we enhanced the representation of food-related (i.e., crop, livestock, soy-based food, and other food) and associated non-food (compound feed, nitrogen fertiliser, phosphorous fertiliser, and non-food) sectors. Second, we further added three main environmental impacts of food systems into the model, i.e., global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). Our study extends beyond the traditional focus on global warming potential (GWP) seen in previous AGE models, such as GTAP-E (Burniaux & Truong, 2002), GTAP-AEZ (Lee, 2005), and GTAP-BIO (Golub & Hertel, 2012). We also incorporate acidification potential (AP) and eutrophication potential (EP), which, along with GWP, are key environmental impacts of food systems (Aiking et al., 2006a; Galloway, 2001; Leip et al., 2015; Xue & Landis, 2010). Including these three main environmental impacts of food systems in the AGE framework is crucial, as food systems contribute significantly to AP and EP, even more than to GWP from an economy-wide perspective. The scheme of economy-wide environment impact assessment was provided in Fig. 1.

The basic idea of AGE models is that supply and demand are interconnected throughout the economy, such that changes in one sector or market are transmitted to other sectors and markets. The objective of the model is to maximise the total social welfare of an economy subject to consumer utilities, production technologies, commodity balances, and emissions affecting environmental quality. In general, social welfare is a measure of overall well-being of society, including the economic benefit (i.e., the consumption of goods) and environmental benefit (i.e., the amenity values of the environmental quality) (Zhu & Van Ierland, 2006). AGE models can be presented in various formats (Ginsburgh & Keyzer, 2002), all of which have the same model and lead to the same equilibrium solutions. We chose the Negishi format for our study because it is more effective in addressing tipping points and non-convexities, similar to the start of the era of large-scale integrated assessment models, i.e., dynamic integrated climate-economy (DICE) model (Nordhaus, 1993). This is crucial for addressing sustainability challenges, as many environmental issues involve non-convexities that deviate from conventional economic assumptions. Additionally, the Negishi format of AGE models is widely used to identify optimal options for greater sustainability, enabling efficient resource allocation under social welfare maximisation (G. Fischer et al., 2007; Greijdanus, 2013; Keyzer & Van Veen, 2005; Le Thanh, 2016; van Wesenbeeck & herok, 2006).

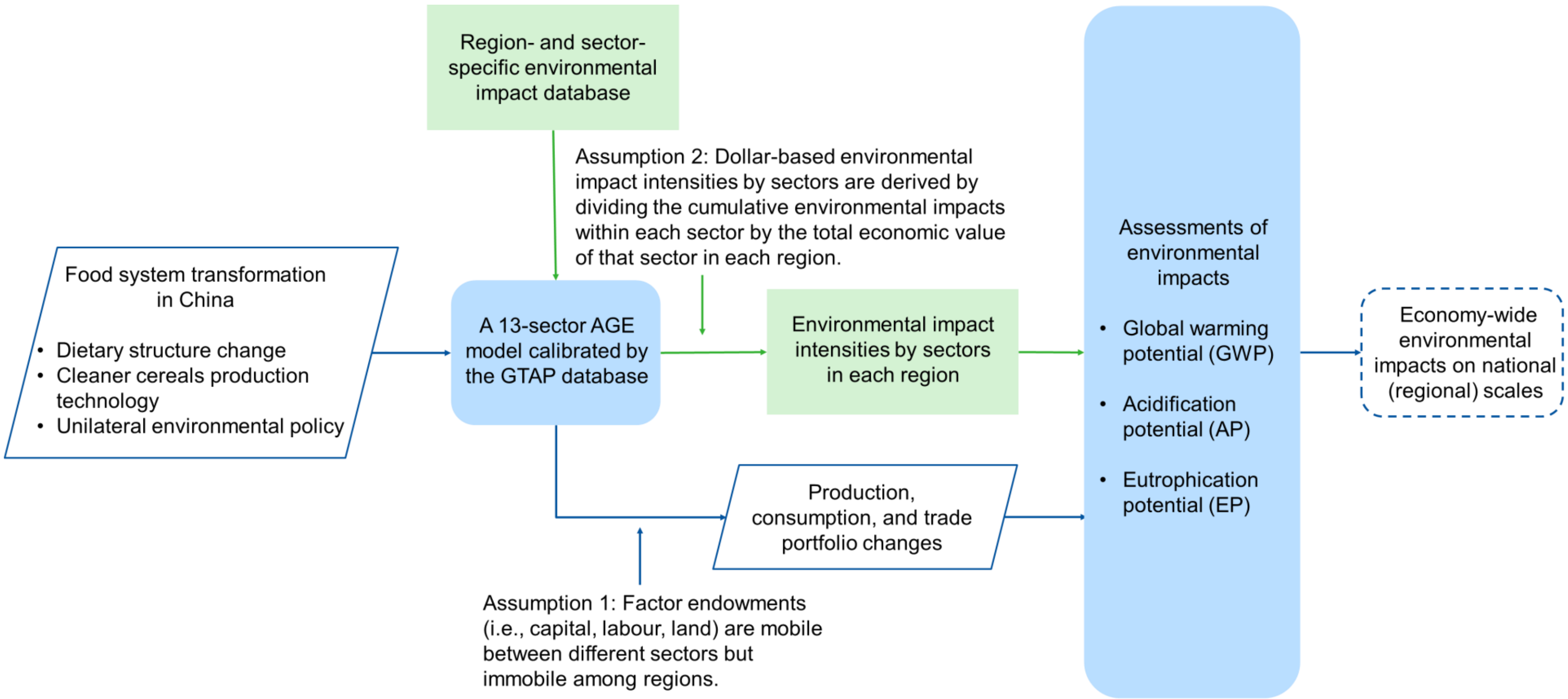

Fig. 1. Scheme of economy-wide environment impact assessment. The blue rounded squares depict the model itself. Parallelograms illustrate the inputs and outputs of the applied general equilibrium (AGE) model, which is calibrated using the Global Trade Analysis Project (GTAP) database. Green rectangles signify the base data used to evaluate various environmental impacts. Rounded squares with dotted lines indicate the different environmental impacts assessed. Arrows show the data flows within the model structure.

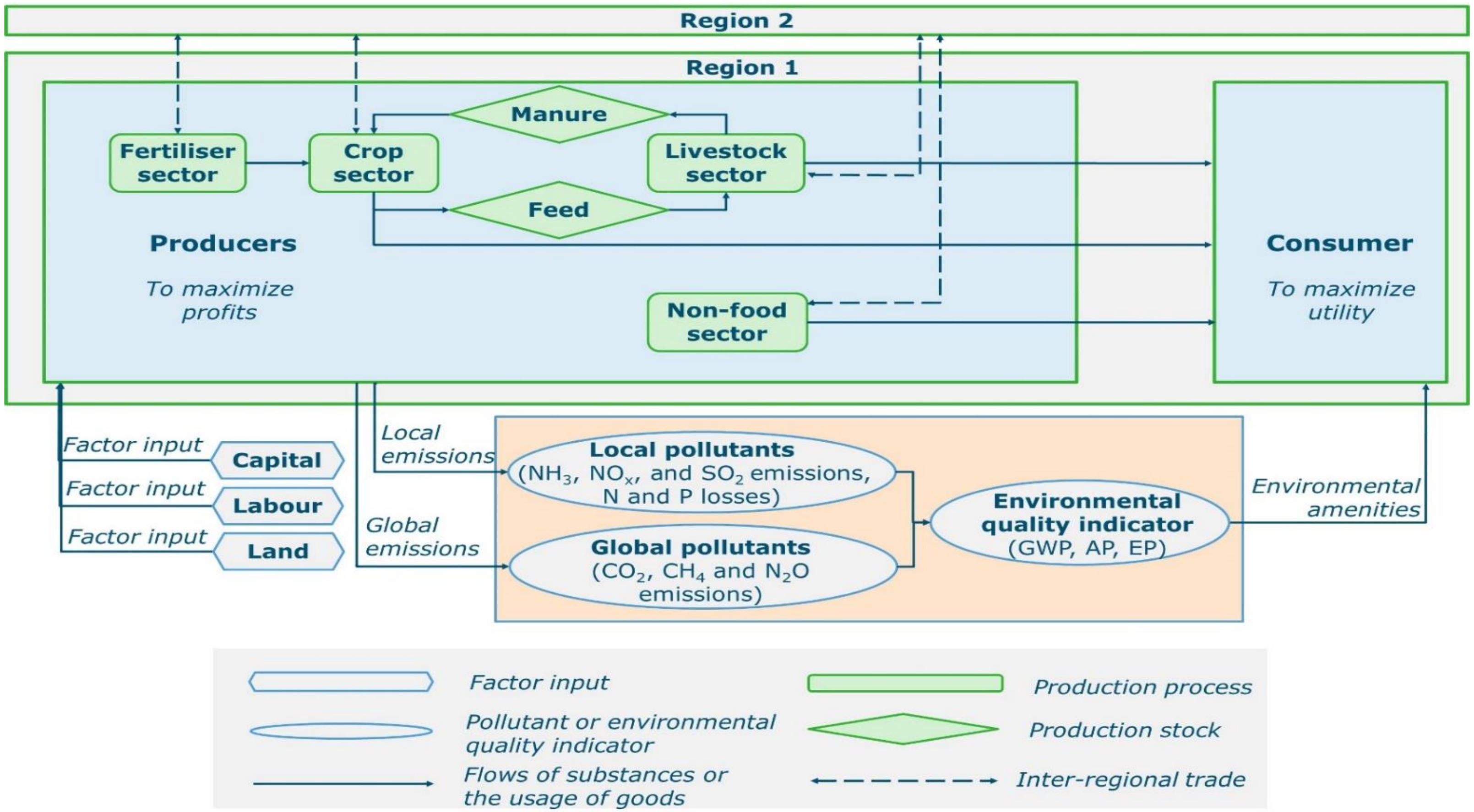

Fig. 2. Economic agents and material flows in the two-region environmental-economic framework. Region 1 is China, and region 2 encompasses the main food and feed trading partners (MTP, including Brazil, the United States, and Canada) of China. The two regions have the 'same' structural outline of the economy-environment interaction framework. GWP = global warming potential. AP = acidification potential. EP = eutrophication potential. CO_2 = carbon dioxide. CH_4 = methane. N_2O = nitrous oxide. NH_3 = ammonia. NO_x = nitrogen oxides. SO_2 = sulphur dioxide. N = nitrogen. P = phosphorus

We used the GTAP version 10 database (GTAP, 2014) based on general equilibrium theory to calibrate our AGE model and provide dollar-based quantities. It covers 65 sectors (agriculture, manufacturing, and services) of the economy and 141 countries. To use the GTAP database for our study, we improved the GTAP database by splitting food-related and associated non-food sectors from existing sectors in the GTAP database. We designed a sectoral aggregation scheme comprising 13 sectors (see Appendix Table B1) from the original GTAP database to produce social accounting matrices (SAM) (see Appendix Tables B2 and B3) in our study. Our sectoral aggregation scheme for GTAP ensured that all competing and complementing sectors for food and feed were present in a disaggregated form. Data on physical quantities of crop and livestock production was obtained from FAO (2022). Feed production was extracted from "Feed" in the FAO food balance sheet. Data on the trade shares matrix was calculated from the data from the UN Comtrade Database (2022). For illustrative purposes, our model distinguishes two regions, namely China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Each region has one representative consumer who consumes rival goods and non-rival environmental quality related to different types of pollutants (Fig. 2.). These trading partners accounted for more than 75% of China's total trade volume related to food and feed in 2014. Our reference year is 2014, which is the latest available year for data in the GTAP database. Factor endowments (i.e., capital, labour, land) owned by consumers are mobile between different sectors but immobile among the two regions according to the GTAP default settings. Producers produce goods with the use of capital, labour, land, and intermediate goods. Products from the livestock and non-food sectors are used for direct human consumption, while crop products are used as food for human consumption and as feed for livestock production. Fertilisers and livestock manure are used for crop production. The model is solved by the general algebraic modelling system (GAMS) software package (GAMS, 2022). Further details about the model are presented in Supplementary Information (SI).

To estimate changes in environmental dimensions, we first established a baseline economy-wide environmental impact database for China and MTP, rather than restricted in certain sectors within the food system. Next, we paired the changes in production simulated by our AGE model with a set of environmental footprints. Detailed commodity mapping was presented in Appendix Tables B2 and B3. Three main environmental impacts include GWP (caused by emissions of greenhouse gases

(GHGs), including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions; converted to CO_2 equivalents), AP (caused by emissions of acidification pollutants, including ammonia (NH_3), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) emissions; converted to NH_3 equivalents), and EP (caused by emissions of eutrophication pollutants, including N and P losses; converted to N equivalents). The conversion factors for GWP, AP, and EP are shown in Table A.1. We obtained data on economy-wide CO_2, CH_4, and N_2O emissions from the Climate Analysis Indicators Tool (CAIT) (2014). All GHG emissions calculations in our model follow the IPCC Tier 2 approach (IPCC, 2006). We derived economy-wide NH_3, NO_x, and SO_2 emissions from L. Liu et al. (2022), Huang et al. (2017), and Dahiya et al. (2020), respectively. We considered NO_x emissions from energy use only, as agriculture's contribution to NO_x emissions is generally small ($\leqslant$2%). We used the global eutrophication database of food and non-food provided by Hamilton et al. (2018) to obtain data on economy-wide N and P losses to water bodies. We first obtained the economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants for the food and non-food sectors in the base year. Then, we allocated the economy-wide emissions to specific sectors according to the shares of emissions per sector in total emissions to unify the emission data from different years. Emissions per sector were calculated based on the emission database mentioned above and additional literature provided in SI by multiplying the physical quantity of an activity undertaken (in tons) and the corresponding emissions coefficient (tons of CO_2, NH_3, or N equivalents per unit of activity undertaken). More detailed information about emissions sources of greenhouse gases, acidification pollutants, and eutrophication pollutants across various sectors of the model was provided in Table B4. The sector-level emissions of GHGs (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents), as well as the US dollar-based emission intensities of GHGs (t CO_2 equivalents million USD^{-1}), acidification pollutants (t NH_3 equivalents million USD^{-1}), and eutrophication pollutants (t N equivalents million USD^{-1}), were presented in Table B5-7 and Table B8-10, respectively.

2.2 Scenarios

Differences in environmental concerns of consumers may cause negative environmental ‘spillover effects’ (Hökby & Söderqvist, 2003; Latacz-Lohmann & Hodge, 2003; Zhu, 2004). The growing environmental concerns over time are evidenced by the increasing environmental expenditures by governments in high-income countries (Eurostat, 2020). Thus, we examined the impacts of differences in environmental concerns of consumers in scenario 1 (S1), i.e., a two times higher expenditure share for improving the environmental quality in MTP than in China. To explore options for more sustainable food systems and to mitigate the negative environmental spillovers (in our case) from MTP to China, we examined four additional scenarios regarding food consumption and production as well as environmental policy, as follows: S2 - dietary structure change, i.e., doubling novel soy-based food (soy-based meat) consumption while reducing pork consumption; S3 - cleaner cereals production technology, i.e., adopting cleaner cereals production technology for half of the current resources used for cereals production; S4 - combining dietary structure change with cleaner cereals production technology (i.e., S4 = S2+S3); and S5 - unilateral environmental policy in China, i.e., implementing incentive-based emission permits to contribute to China's carbon neutrality goal and other environmental policies. These scenarios were further described below and in Table A2 and SI. The results of scenarios S2 to S5 were compared in relation to those of scenario S1, whereas scenario S1 was evaluated relative to the baseline (S0). In S0, environmental quality indicators were set at 100 to facilitate the comparison of environmental quality changes across various scenarios. Thus, if environmental quality indicators in scenarios are higher than 100, it means increases in environmental quality (i.e., decreases in emissions) compared to S0.

2.2.1 Baseline (S0)

The baseline (S0) represents the economies of China and MTP in 2014. Environmental concerns of consumers were not considered in S0 because the original GTAP database does not contain expenditures on environmental programs for improving environmental quality. The substitution elasticity between soy-based food (SBF) and pig (i.e., the ease of substituting pork with SBF for consumption) was 0.5. The expenditure shares of SBF in the pork-SBF protein composite consumption were 25% and 82% in China and MTP, respectively, as calculated based on the SAMs from the GTAP database. These expenditure shares were maintained in all scenarios except for the dietary shift scenario S2.

2.2.2 Differences in environmental concerns of consumers (S1)

Consumers in higher-income countries are more willing to pay for environmental quality than less concerned countries (Hökby & Söderqvist, 2003; Latacz-Lohmann & Hodge, 2003). Environmental concerns of consumers were reflected through their willingness to pay for environmental quality, represented by the utility elasticity within the utility functions in our model. This implies that consumers have to pay for their consumption of environmental quality. Environmental quality is priced by the marginal value of a balance equation, where each individual's consumption equals the total supply of the environmental quality. Environmental quality is “supplied” by the environment and determined by the emissions of pollutants from all producers across the whole economy. Three types of environmental quality indicators related to GWP, AP, and EP were determined in a linear relationship by the associated equivalent emissions of pollutants. The higher the emissions, the lower the environmental quality. Thus, emissions will decrease the utility of consumers by reducing environmental quality. As the model accounts for both the utility from consuming goods and the disutility from environmental pollution, consumers face a trade-off: increasing the consumption of rival goods leads to lower environmental quality, whereas prioritising higher environmental quality requires reducing the consumption of rival goods. In this manner, the emissions from production give a feedback on utility and on the consumption bundle of rival goods and non-rival environmental quality, indirectly influencing the production structure across the whole economy. That is, consumers have the chance to improve environmental quality with reduced emissions due to their cleaner food purchases. In S1, we assumed that consumers in China and MTP were willing to pay 1% and 2% of their total budget for improving environmental quality. Consumers in both regions were assumed to be willing to pay equally for improving the three types of environmental quality indicators related to GWP, AP, and EP as they attach equal importance to the three types of environmental pollutants. Despite Brazil having a relatively lower gross domestic product (GDP) and the United States and Canada having higher GDPs compared to China, we opted to aggregate these three main trading partner countries as a whole. This decision was based on Brazil contributing less than 10% to the combined GDP of these three countries, while the United States and Canada account for over 90%, according to the GTAP database. Moreover, the simple two-region model structure was employed here because some fundamental macroeconomic mechanisms can be better understood in small and aggregated AGE models.

2.2.3 Dietary structure change (S2)

China is a major pork producer and consumer and a significant importer of animal-based products (FAO, 2022). Pork consumption in China has exceeded the recommended red meat consumption ranges reported by the EAT-Lancet diet (Willett et al., 2019) and the Chinese Dietary Guidelines 2022 (Chinese Nutrition Society, 2022). China is also the world's largest importer and consumer of soybeans, which are utilised as both human food, including traditional SBF (tofu, soy milk, tempeh, and soybean oil) and novel SBF (soy-based meat), and livestock feed (soybean meal) (FAO, 2022). It has been shown that if consumers partially replace meat with plant-based food, GHG emissions, land use, and water use can be reduced substantially (Aleksandrowicz, Green, Joy, Smith, & Haines, 2016; Guo, Shao, Trishna, Marinova, & Hossain, 2021; Tong et al., 2022; Yu, Jiang, Cheshmehzangi, Liu, & Deng, 2023; M. Zhang et al., 2022). However, previous studies have not adequately accounted for interactions with other sectors and countries, as they primarily focused on the environmental impacts of dietary shifts within limited life cycles. It is crucial to consider these interactions, as resources saved through dietary shifts may be reallocated elsewhere in the economy, potentially mitigating the environmental benefits of the dietary shift. Aiking et al. (2006b) and Markiewicz (2010) suggested that almost 50% of meat in the diet in terms of protein food expenditure should be replaced by plant-based food in order to achieve a 20-fold reduction of environmental pressure by 2035. In addition, from a nutritional perspective, the protein content in SBF (13-19 grams per 100 grams) is comparable to that in traditional pork and beef (15 grams and 20 grams per 100 grams, respectively) (Yang, 2020). Thus, we explored the impacts of an exogenous dietary shift in consumer demand, i.e., by doubling novel SBF (soy-based meat) consumption while reducing pork consumption in China, driven by the increased consumer acceptance of SBF. The expenditure share of SBF in the pork-SBF protein composite consumption increased from 25% in the baseline (S0) to 50% in S2 concomitant with a decreased pork consumption.

2.2.4 Cleaner cereals production technology (S3)

Interventions in cereals production technology are of interest for sustainable food production and emission mitigation, as China is a major cereal producer, while fertiliser and pesticide inputs are high (FAO, 2022; Zhai et al., 2021). Compared to China's original cereals production technology, MTP's cereals production technology has a better technological performance (i.e., achieving the same output level with fewer inputs) and requires relatively less land, labour, and nitrogen fertiliser but more capital and phosphorus fertiliser to produce one unit of cereals. The cleaner technology also has relatively lower emission intensities of all pollutants than the original technology (see Table B7-9). Technological innovations have been well recommended in China, for example, through the Science and Technology Backyard (STB) platform (An et al., 2024; Cui et al., 2018; W. Zhang et al., 2016). Therefore, in S3, half of the current resource uses (i.e., capital, labour, land, nitrogen fertiliser, and phosphorus fertiliser) were employed using the cleaner MTP technology in cereal production. Technological parameters and input cost shares of the two production technologies are presented in Table A3.

2.2.5 Combination of dietary structure change and cleaner cereals production technology (S4)

In S4, we combined the dietary structure change (S2) and cleaner cereals production technology (S3) to examine to what extent the combination of demand-side and supply-side measures would affect the economy (i.e., production, consumption, and trade) and environment (i.e., emissions of GHGs, acidification pollutants, and eutrophication pollutants).

2.2.6 Unilateral environmental policy (S5)

The primary cause of environmental problems associated with food systems is emissions from economic activities. Therefore, from a policy-making perspective, it is crucial to implement effective measures, particularly economic instruments, to reduce emissions based on principles such as the 'polluter pays principle'. Incentive-based emission permits for GHGs, recognised as one of the most efficient market-based GHG emission mitigation policy instruments, are highly recommended by economists and international organisations (S. Frank et al., 2018; Lin & Li, 2011; Peña-Lévano, Taheripour, & Tyner, 2019; Zhu et al., 2006). The introduction of incentive-based emission permits would motivate producers and consumers to shift from emission-intensive activities, commodities, and technologies to cleaner alternatives. This is because if a producer's emission abatement cost is lower than the market price for emissions, they will actively implement technological solutions to reduce emissions and sell the excess emission permit quota to other sectors or regions. Thus, in a perfectly competitive world, emissions are reduced most cost-effectively in sectors or regions with relatively high emission intensities or significant mitigation potential. Shadow prices of emission permits can be determined based on the marginal value of the emission permit balance equation, where total emissions from all producers across the whole economy should not be above a certain level of emissions. For the specified emission reduction target, the AGE model can endogenously calculate shadow prices of emission permits for different pollutants. The Chinese government has committed itself to achieving carbon neutrality by 2060, in line with the Paris Agreement (NDRC, 2018). To accomplish this goal, China has pledged to reduce the country's carbon intensity (emissions per unit of GDP) by more than 65% in 2030 compared to the 2005 level. The Chinese government has also implemented several environmental policies to address nutrient losses from agriculture and improve water quality. These policies include initiatives such as (i) Zero Fertiliser Growth (MOA, 2015), (ii) Improvement of manure recycling (MOA, 2017), and (iii) Prevention and Treatment of Water Pollution ("Ten-Point Water Plan") (GOV, 2015). In this scenario, we implemented incentive-based emission permits to contribute to China's carbon neutrality goal and other environmental policies for a 3% reduction in emissions of all pollutants annually.

2.3 Sensitivity analysis

Conducting a sensitivity analysis is a way to check the robustness of a simulation model with many uncertain parameters and the sensitivity of model results to these parameters. Results were obtained for key environmental, economic behavioural, and technological parameters. So far, we have assumed that current consumers were willing to pay equally for improving the three types of environmental quality indicators related to GWP, AP, and EP. In the sensitivity analysis, we first run the model by assuming that consumers were willing to pay for improving only one type of environmental quality in both regions. Then, we increased the environmental willingness to pay in China from 1% to 2%, equal to that in MTP. For the simultaneous reduction target of 3% for emissions of all pollutants, we did sensitivity analyses for each type of pollutant. For the value of the economic behavioural parameter, we considered the value of substitution elasticity between pork and SBF in a range from 0.5 to 1.5 because SBF is not a perfect substitute for pork, and, in the short run, it is impossible to replace all pork with SBF. For the value of the technological parameter, we considered the value of the replacement ratio of cleaner MTP technology in a range of 0 to 1. Further details about the sensitivity analysis are summarised in Table A4.

3. Results

3.1 S1 - Differences in environmental concerns of consumers

Differences in environmental concerns of consumers increased environmental quality indicators related to GWP, AP, and EP in MTP relative to S0 by 10%, 34%, and 43%, respectively. Conversely, these indicators experienced a 2% decrease in GWP, a 21% decrease in AP, and a 38% decrease in EP in China (Table A5). The consumption of rival goods decreased by 0.06-4% in China and MTP (Fig. A3.), as increasing environmental concerns in both regions call for reducing consumption of rival goods. Despite the increased expenditure on environmental quality, the overall environmental quality did not increase in China because the willingness to pay for improving environmental quality was higher in MTP than in China (2% versus 1%). Consequently, emission-intensive production was transferred from MTP to China (Fig. 3a), causing negative environmental spillovers from MTP to China, i.e., increased emissions and lower environmental quality in China (Fig. 3b). To be more specific, the production of goods with relatively high emission intensities, such as animal products, soy-based food, and fertilisers, increased by 18-287% in China. The decline in the environmental quality indicator associated with EP surpassed that of the other two indicators, primarily due to the substantial increase in the production of other animals (179%) with high emission intensity of eutrophication pollutants in China. In contrast, MTP obtained environmental benefits by decreasing its domestic production of relatively emission-intensive products, as China increased production and exported these goods to MTP. Concurrently, resources freed from the reduced production of emission-intensive products were reallocated towards increasing the production of vegetables & fruits by 215% and other food by 42% in MTP, respectively. This production shift is because MTP has a comparative advantage in producing these relatively “clean” goods compared to China.

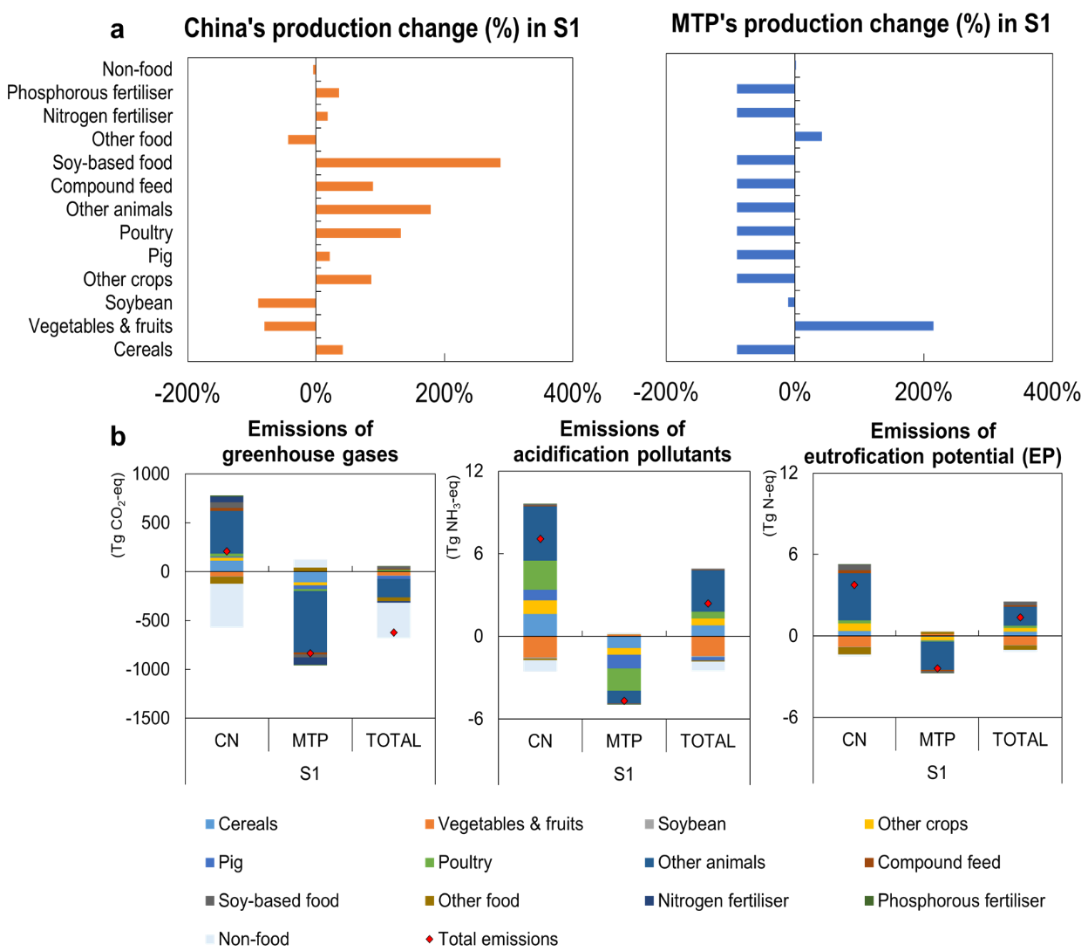

Fig. 3. Changes in (a) production of goods (%) and (b) emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) in China (CN) and its main trading partners (MTP) when there are differences in environmental concerns of consumers (S1). Changes are relative to S0.

3.2 S2 - Dietary structure change

The dietary shift from pork to SBF decreased pork consumption by 33% and increased soy-based food consumption by 102% in China (Fig. A4). This shift resulted in a 1% reduction in GHG emissions and a 3% reduction in acidification pollutants, but a 2% increase in eutrophication pollutants in China relative to S1 (Fig. 4 & 6). The latter increase in emissions was mainly propelled by the heightened production of soy-based food and other food in China, which have relatively high emission intensities of eutrophication pollutants.

Lower pork demand influenced not only the consumers and producers of pork but also had knock-on effects on other sectors across the whole economy. Evidently, the reduction in domestic pork consumption led to a 28% decrease in pig production (Fig. 5a), which subsequently reduced the production of cereals (1%) and compound feed (9%) used to raise pigs. Agricultural inputs freed up from reduced pig production were primarily reallocated to increase the production of plant-based alternatives, such as soy-based food (26%) and other (crop-based processed) food (25%). Soybean production in China remained nearly constant, as increased food use outweighed the decline in feed use, with higher demand met by imports from MTP, where production surged by 21% due to MTP's comparative advantage. The production of vegetables & fruits (23%) and other crops (2%) increased in China due to their increased use as intermediate inputs for other (crop-based processed) food production. Changes in China's crop production structure increased domestic fertiliser demand, raising domestic production of nitrogen and phosphorus fertiliser by 0.5% and 5%, respectively.

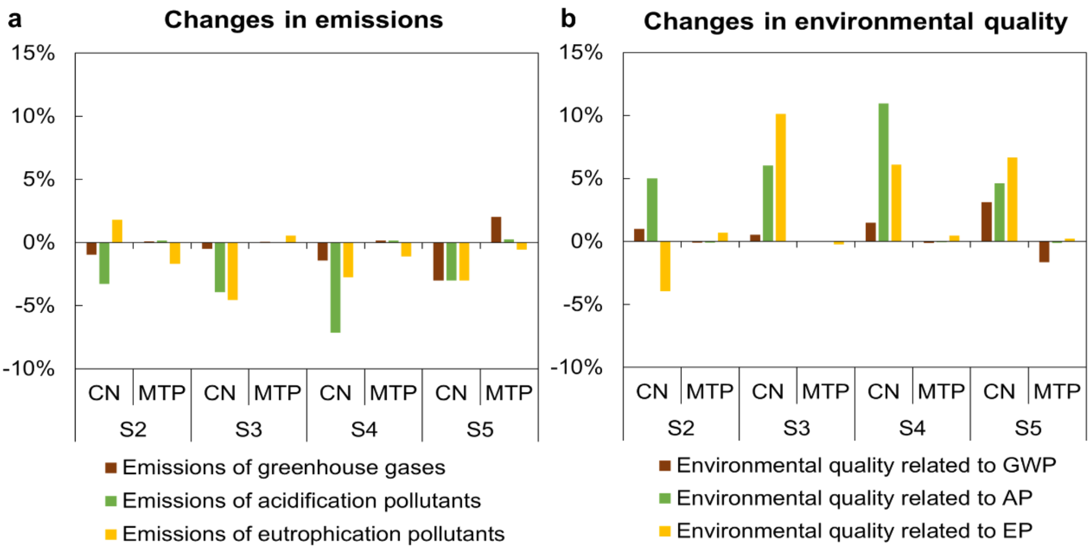

Fig. 4. Changes in (a) emissions of greenhouse gases, acidification pollutants, and eutrophication pollutants and (b) environmental quality indicators related to global warming potential (GWP), acidification potential (AP), and eutrophication pollutants (EP) in China (CN) and its main trading partners (MTP) under scenarios of dietary structure change (S2), cleaner cereals production technology (S3), the combination of dietary structure change and cleaner cereals production technology (S4), and unilateral environmental policy (S5). Changes are relative to S1, in %.

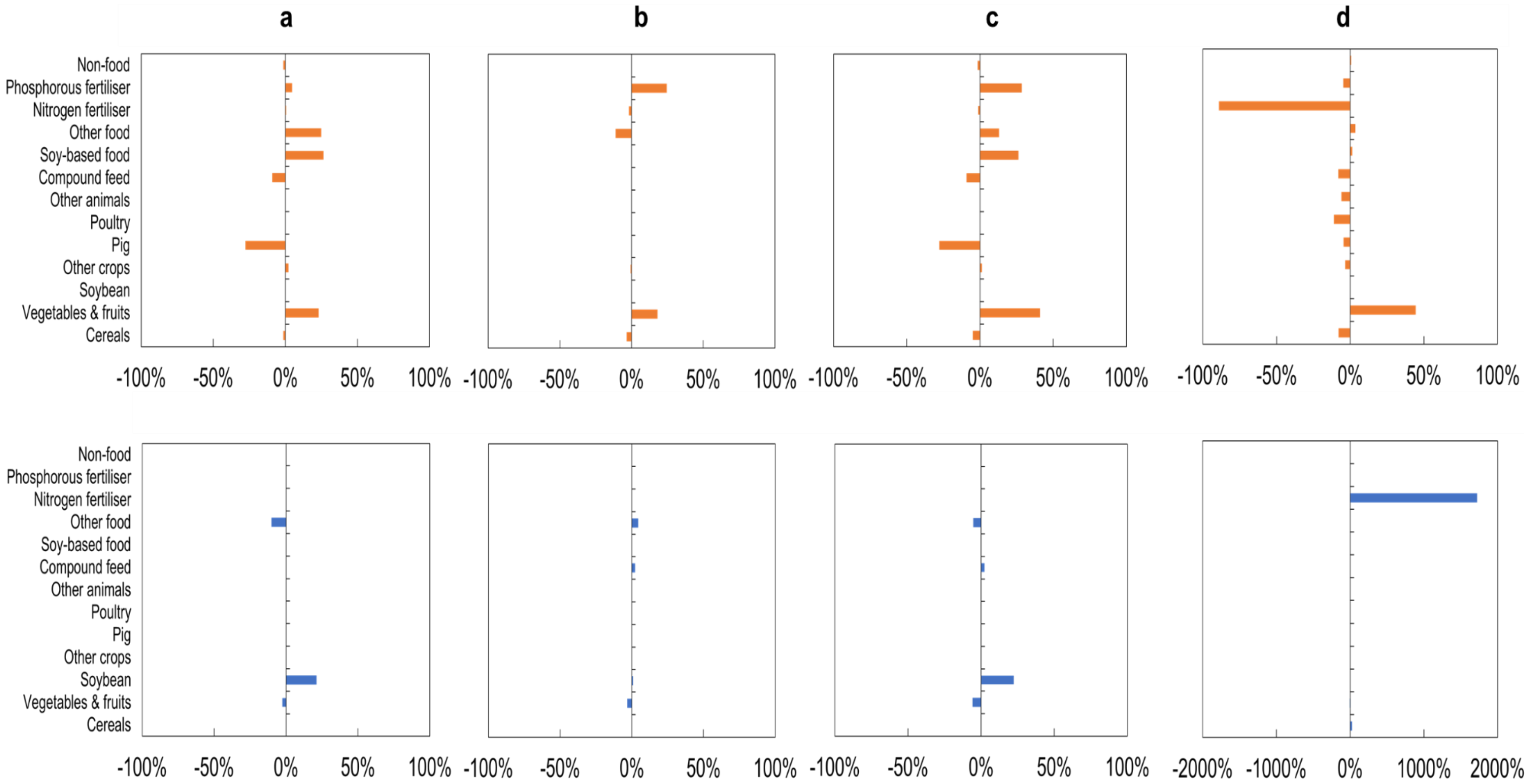

Fig. 5. Changes in the production of goods in China (upper panels) and its main trading partners (MTP, lower panels) under scenarios of (a) dietary structure change (S2), (b) cleaner cereals production technology (S3), (c) the combination of dietary structure change and cleaner cereals production technology (S4), and (d) unilateral environmental policy (S5). Changes are relative to S1, in %.

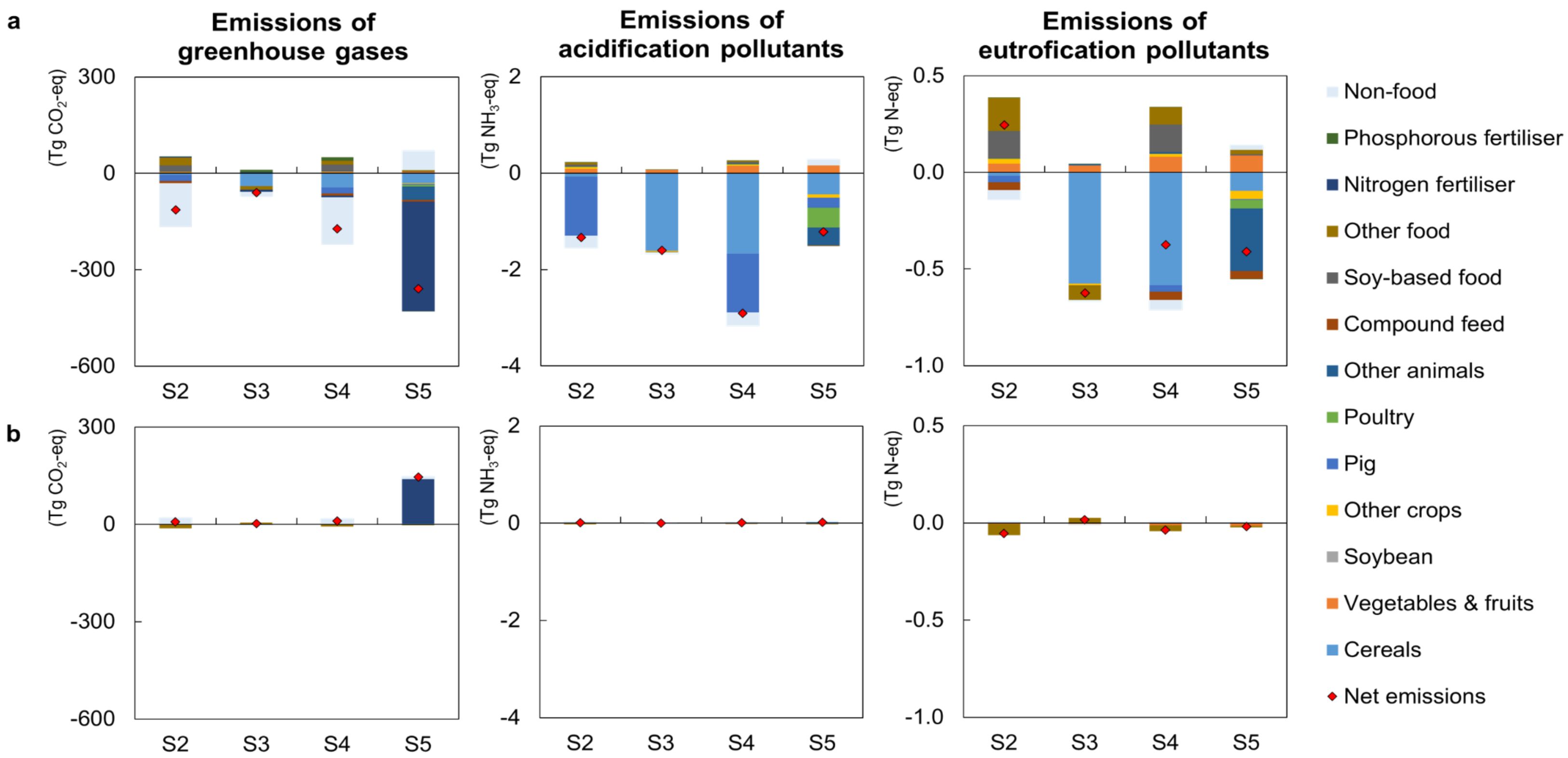

Fig. 6. Changes in emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) in (a) China (upper panels) and (b) its main trading partners (MTP, lower panels) under scenarios of dietary structure change (S2), cleaner cereals production technology (S3), the combination of dietary structure change and cleaner cereals production technology (S4), and unilateral environmental policy (S5). Changes are relative to S1. The red dots in the figures refer to the net emissions in China and MTP, respectively.

3.3 S3 - Cleaner cereals production technology

Adoption of cleaner cereals production technology in China decreased emissions of GHGs, acidification, and eutrophication pollutants in China by 0.5%, 4%, and 5%, respectively, relative to S1 (Fig. 4 & 6). In addition, the adoption of cleaner technology, which requires relatively less nitrogen fertiliser but more phosphorus fertiliser to produce one unit of cereals than the original technology, resulted in a 2% decrease in nitrogen fertiliser production and a 25% increase in phosphorus fertiliser production (Fig. 5b.). This adoption also led to a 3% decrease in cereals production, as the higher costs of increased capital and phosphorus fertiliser use outweighed the savings from reduced land, labour, and nitrogen fertiliser use. The higher production cost of cereals increased cereal prices, resulting in a 3% decrease in cereals consumption in China (Fig. A4.). Higher cereal prices also led to an 11% decrease in the production of other (crop-based processed) food, which rely on cereals as intermediate inputs. Consequently, resources freed as a result of adopting cleaner cereal production technology were reallocated, resulting in an 18% increase in vegetables & fruits production in China and a corresponding decrease in imports from MTP. The structural shifts in China's production also have cross-border impacts, influencing production in MTP through international trade. Specifically, the production of vegetables &fruits in MTP declined by 3%, whereas the production of other food increased by 4%.

3.4 S4 - Combination of dietary structure change and cleaner cereals production technology

Combining dietary changes with cleaner cereals production technology in China decreased emissions of GHGs, acidification, and eutrophication pollutants in China by 1%, 7%, and 3%, respectively, relative to S1 (Fig. 4 & 6). That is, the combination decreased the pollution-swapping effect associated with the dietary shift scenario. This combination resulted in a 5% reduction (2% more than S3) in cereal production in China (Fig. 5c), attributed not only to its increased production costs but also to decreased demand for cereals as feed in the pig sector. Resources freed up by this combination were reallocated, leading to a 41% increase in vegetables &fruits production, along with a 13% increase in the production of other food in China. In contrast, the production of vegetables & fruits and other food in MTP decreased by 6% and 5%, respectively.

3.5 S5 - Unilateral environmental policy

Implementing a unilateral environmental policy in China (i.e., implementing incentive-based emission permits to reduce emissions of all pollutants by 3% annually) increased emissions of GHGs by 2% in MTP with minor impacts on emissions of acidification and eutrophication pollutants relative to S1 (Fig. 4 & 6). The increased GHG emissions in MTP reflect the so-called 'carbon leakage'. This emerges due to the shift of production of products with relatively high emission intensities from China to MTP as there were no emission restrictions in MTP. For example, China experienced reductions in the production of cereals by 8%, other crops by 3%, pigs by 5%, poultry by 11%, other animals by 6%, nitrogen fertiliser by 90%, and phosphorus fertiliser by 5% (Fig. 5d). The percentage change in nitrogen fertiliser production was the most significant because nitrogen fertiliser production has high GHG emission intensity (see Table B7). Therefore, to reduce economy-wide GHG emissions in China, the highest priority should be placed on reducing nitrogen fertiliser production and use. The consumption of goods with relatively high emission intensities also decreased by 2-10% (refer to Fig. A4), as these "dirty" goods became relatively more expensive due to emission restrictions. Meanwhile, China increased the production of products with relatively low emission intensities, such as vegetables & fruits (45%). Although the fertiliser application rate per hectare is about two folds higher for vegetables & fruits than for cereals and soybean (Wang et al., 2021), the dollar-based emission intensities of all pollutants are relatively low for vegetables & fruits (see Table B7-9), which is related to the high prices and yields of vegetables & fruits (FAO, 2022). In contrast, due to MTP's comparative advantage in nitrogen fertiliser production, its output increased by 17 times. The 17-fold increase in nitrogen fertiliser production under S5, relative to S1, was influenced by several factors. Firstly, the significant increase was due to a substantial prior reduction, with nitrogen fertiliser production in MTP decreasing by 90% in S1 and reaching a lower bound of 10% of the original production. This lower bound was set by the model to prevent a strong specialisation effect under free international trade, adhering to the Heckscher-Ohlin assumption that treats domestic and imported goods as perfect substitutes (see supplementary information for details). Relative to the baseline (S0), the increase in nitrogen fertiliser production was only a factor of 1.8. Secondly, in the baseline (S0), nitrogen fertiliser production accounts for less than 0.1% of MTP's GDP. After the 90% reduction in S1, this share become even smaller. Consequently, the 17-

fold increase in nitrogen fertiliser production under S5, compared to the 90% reduced levels in S1, appeared particularly pronounced.

3.6 Sensitivity analysis

Alterations in model results were examined in response to variations in the values of three parameters: environmental concerns, the substitution elasticity between pork and SBF, and the replacement ratio of the cleaner cereals production technology.

First, if consumers only care about one type of environmental quality, the gap between countries with different environmental concerns in that type of environmental quality is larger than the gap in the other two types of environmental quality (Table A5). When countries have equal environmental concerns, the gaps in environmental quality, particularly related to EP, diminish between China and MTP (Table A6). Furthermore, a single emission reduction target for China would improve one type of environmental quality at the expense of the other one or two types (Table A7).

Second, for the substitution elasticity between pork and SBF, the current value was 0.5. Variation in the elasticity in the range of 0.5 to 1.5 did not affect pork consumption under S2 (Fig. A8a) because the expenditure share of SBF in the pork-SBF composite consumption remained fixed. However, a higher substitution elasticity indicates an increased price ratio between SBF and pork, leading to decreased pork production as pork becomes cheaper (Fig. A8b).

Third, increasing the replacement ratio of the cleaner cereals production technology in China decreased cereals production, as well as emissions of all pollutants (Fig. A9). Specifically, raising the technology replacement ratio from 0% to 40% resulted in a significant decrease in cereals production. This is because the cleaner MTP technology necessitates relatively less land, labour, and nitrogen fertiliser but more capital and phosphorus fertiliser to produce one unit of cereals. Reallocating resources raises production costs, as the higher costs of increased capital and phosphorus fertiliser use outweigh savings from reduced cropland, labour, and nitrogen fertiliser use, leading to reduced cereal production. When the ratio exceeded 40%, the model results for cereals production stabilised, reaching a point where no additional capital and phosphorus fertiliser would be available for cereals production. Overall, changes in model parameters had a modest impact on model results, showing the robustness of the model results.

4. Discussion

4.1 Main findings

Our study emphasises the importance of employing an economy-wide modelling approach, rather than a single sector/country approach, in the design of effective policies for sustainable food systems. This broader perspective enables a deeper understanding of the interconnections among different countries, sectors, and environmental impacts, while also shedding light on the trade-offs between environmental and economic objectives.

First, we found that differences in environmental concerns of consumers led to cross-national pollution spillover effects through international trade, a type of telecoupled impact (Hull & Liu, 2018; J. Liu, 2023). Specifically, environmental quality increased more in countries with higher environmental concerns compared to those with lower concerns because the production of 'dirty' products shifted to countries with lower environmental concerns through international trade. This echoes findings by Meyfroidt, Lambin, Erb, and Hertel (2013), who argue that globalisation can benefit developing nations economically but can also lead to negative environmental impacts like carbon leakage and land-use displacement. Our study focused on emissions of GHGs, acidification, and eutrophication pollutants, rather than solely on a specific environmental impact (mainly GWP), as previous studies have done using models such as GTAP-E (Burniaux & Truong, 2002), GTAP-AEZ (Lee, 2005), and GTAP-BIO (Golub & Hertel, 2012). This is significant because food systems contribute more to these pollutants than to GHGs (Aiking et al., 2006a; Galloway, 2001; Leip et al., 2015; Xue & Landis, 2010), yet no studies have explored this aspect within the AGE framework so far. This 'spillover effect' in our study shows that China experienced a decrease of 2%, 21%, and 38% in environmental quality indicators related to GWP, AP, and EP, while MTP experienced an increase of 10%, 34%, and 43%, respectively. It indicates that the production of goods with high emission intensities of eutrophication pollutants was swapped more from MTP to China than those with high emission intensities of GHGs and acidification pollutants.

Second, our results show that shifting towards a more soy-based diet could reduce GHG emissions due to the higher human-edible energy and protein conversion efficiencies of plant-based foods compared to animal products (Eshel et al., 2018; Yu et al., 2023; M. Zhang et al., 2022). Additionally, it has been estimated that a dietary shift towards more plant-based food in China increases total human-edible energy (3-20 times) and protein (1-5 times) deliveries while reducing carbon and nitrogen footprints (Long et al., 2021). A key novel insight of our study is that the reductions in GHG emissions were partially attenuated by increased production in other sectors, such as SBF (26%) and other food (25%). Agricultural inputs, including capital, labour, land, and primary feed (mainly cereals and compound feed), freed up from reduced pig production, were reallocated within the Chinese food system. Relocation of resources across the food system enables more production with the same inputs (increased efficiency), but may attenuate the expected outcome in terms of emission reductions and does not guarantee a decline in total resource use. Specifically, our study showed that the dietary shift from pork to SBF decreased economy-wide emissions of GHGs by 1% and acidification pollutants by 3% but increased emissions of eutrophication pollutants by 2% in China. This is because the interlinkages between production sectors were captured in our integrated environmental-economic framework, and, as a result, we identified the increased production of SBF and other food with relatively high emission intensities of eutrophication pollutants through resource reallocation. Hamilton et al. (2018) confirmed this by showing that processed food sectors, such as SBF and other food, are major contributors to eutrophication, accounting for 19% and 10.3% of global marine and freshwater eutrophication impacts, respectively. Furthermore, changes in China's crop production structure led to a 0.5% rise in nitrogen fertiliser production and a 5% increase in phosphorus fertiliser production domestically. Recently, Mason-D'Croz et al. (2022) assessed the economy-wide impact of adopting plant-based beef substitutes, demonstrating reduced economy-wide GHG emissions and increased fertiliser use in the United States. Our analysis goes further by using a global model, rather than a national one, to consider the cross-border impacts on trading partners through international trade. For instance, our model showed a 21% increase in soybean production in MTP, driven by its comparative advantage in soybean production over China. Additionally, our comprehensive assessment of emissions of GHGs, acidification, and eutrophication pollutants enables us to discern trade-offs and synergies associated with each type of emission.

Third, we provide possible solutions to prevent the pollution-swapping effect associated with the dietary shift scenario. Our analysis illustrated that both combining a dietary shift with cleaner cereals production technology and implementing a unilateral environmental policy (i.e., implementing incentive-based emission permits) decreased emissions of all pollutants in China. However, implementing unilateral environmental policies in China could cause the so-called 'carbon leakage' (Kuik & Gerlagh, 2003). On the one hand, it decreased emissions in China by reducing domestic production of goods with high emission intensities of GHGs (e.g., nitrogen fertiliser), acidification pollutants (e.g., cereal, pig, poultry, and other animals), and eutrophication pollutants (e.g., other animals). On the other hand, it also increased emissions of GHGs in MTP with minor impacts on emissions of acidification and eutrophication pollutants.

4.2 Policy implications

Our study provides insights into minimising the trade-offs and exploiting the synergies in the food-land-water-climate nexus. This is crucial for achieving sustainable food production and consumption not only in China but also in other developing countries similar to China facing similar challenges in food production in the context of globalisation and international trade. Therefore, our findings hold the following policy implications.

First, our findings show that developed countries typically gain environmental benefits at the expense of developing countries, which bear the environmental burdens through international trade. This is partly because higher environmental concerns among consumers and stringent environmental regulations in developed countries tend to shift emission-intensive production to developing countries (Wiedmann et al., 2015; Xu et al., 2020). The 'spillover effects' caused by differences in environmental concerns of consumers cannot be ignored as such effects could hinder the environmental quality of countries with lower environmental concerns. Our analysis shows that when countries have equal environmental concerns, the gaps in environmental quality, particularly concerning EP, diminish between China and MTP. To mitigate global environmental disparities, it is essential to bridge the gap between consumers in countries with different environmental concerns. Potential solutions include enhancing the environmental awareness of consumers through educational programs and promoting corporate social responsibility (CSR) initiatives. Educational programs could integrate environmental issues into curriculum and community outreach to foster global environmental awareness. Concurrently, CSR efforts could incentivise companies to adopt higher environmental standards across their supply chains, as consumers are increasingly inclined to purchase products or services from companies with strong CSR commitments (S. Du, Bhattacharya, & Sen, 2010).

Second, our economy-wide analysis shows that the environmental benefits of the dietary shift from pork to SBF were smaller than previous narrower studies have estimated (Eshel et al., 2018; Long et al., 2021; Yu et al., 2023; M. Zhang et al., 2022). This is because resources freed up from pig production were repurposed for other economic activities, such as intensifying soybeans used as inputs for soy-based food production. This underscores the risks of policies focusing on a single sector and the need for comprehensive policies to address potential spillover effects on food systems and the broader economy. China has a long history of soy-based protein food, with traditional SBF (tofu, soy milk, tempeh, and soybean oil) dating back thousands of years. While novel SBF (soy-based meat) differ in flavour from traditional SBF, both are derived from soybeans, creating a strong foundation for market growth (Academy of Global Food Economics and Policy, 2024). However, shifting dietary habits in China is challenging to achieve in the short run (Bai et al., 2018), since pork consumption is a culture-related issue. There is a need to promote environmental concerns among consumers and provide information about the environmental benefits of SBF for sustainable food consumption and production. Advertising campaigns and providing consumers with carbon labels linked to the life cycle of food can enhance environmental concerns among consumers (Aiking et al., 2006b; Camilleri, Larrick, Hossain, & Patino-Echeverri, 2019). Additionally, providing food labels that inform consumers about the health benefits of products they purchase, in addition to their environmental advantages, can also motivate the dietary shift (Markiewicz, 2010). Technological improvements in taste, texture, and variety of SBF (Bonny, Gardner, Pethick, & Hocquette, 2017; Megido et al., 2016; Verbeke, Sans, & Van Loo, 2015), along with price mechanisms such as meat tax or lower prices for meat substitutes (Latka et al., 2021) could encourage the dietary shift. Promoting dietary guidelines, carbon taxes, and environmentally friendly behaviours can also help reduce meat consumption and GHG emissions (Bonnet, Bouamra-Mechemache, Réquillart, & Treich, 2020; C. G. Fischer & Garnett, 2016).

Third, we demonstrate that adopting cleaner cereals production technology in China can mitigate emissions of all pollutants but demands capital reallocation from other sectors. Climate change agreements could incorporate technology transfer and support initiatives from developed countries to encourage the widespread adoption of cleaner production technologies (S. Frank et al., 2018). Additionally, policy instruments such as agricultural subsidies could expedite the adoption of cleaner production technologies. For example, providing direct subsidies to compensate for potential income losses from increased adoption costs could reduce the financial burden on cereals farmers, making it more feasible for them to transition to cleaner production technologies (Luo, Wang, & Qin, 2014). Also, the Science and Technology Backyard platform, which fosters direct engagement with farmers through equal dialogue and actively incorporates their feedback into technology design, has been shown to significantly enhance the widespread adoption of sustainable practices and technologies (An et al., 2024; Cui et al., 2018; W. Zhang et al., 2016).

Fourth, our study indicates that the unilateral environmental policy (i.e., implementing incentive-based emission permits) in China can lead to 'carbon leakage' by outsourcing the production of emission-intensive goods to MTP. The global effects of this leakage depend on emission intensities across regions. Avetisyan, Hertel, and Sampson (2014) contend that reducing emissions of GHGs through consumption diversion to local goods is only achievable in regions with relatively low emission intensities. Policymakers should carefully consider the consequences of implementing unilateral environmental policy as it might inadvertently redirect economic activities in ways that exacerbate environmental pressures elsewhere. Implementing a carbon border adjustment mechanism (CBAM) by charging a carbon price on imports of emission-intensive goods could help reduce carbon leakages (Bellora & Fontagné, 2023). In addition, a globally coordinated mitigation policy could also buffer the emission leakages associated with the unilateral environmental policy (Stefan Frank et al., 2021). For example, the Paris Agreement sets a unified global carbon emission reduction target, aiming to limit the increase in global temperatures to well below 2°C above pre-industrial levels, with an ideal target of 1.5°C (IPCC-WGIII, 2014; UNFCC, 2015). This collective target aligns the emission reduction efforts of all participating countries in the world, ensuring a coordinated and consistent approach to addressing climate change on a global scale while mitigating the risk of carbon leakages. Thus, achieving sustainable food production and consumption requires joint efforts from consumers and producers as well as coordinated environmental policy across countries in the world.

4.3 Limitations of the study

Our model, like all AGE models, simplifies reality and operates at a high level of aggregation, which may limit its ability to represent an economy out of equilibrium and primarily view behaviour through an economic lens. Further, the linear relationship between emissions and environmental quality indicators in our model is a simplified representation of the real world. Also, our study assumes free international trade, full mobility of factor endowments (capital, labour, and land) across sectors, and constant income elasticities for all consumption goods. Neglecting trade barriers may overestimate the extent of international trade of feed and food. Barriers to the movement of factor endowments across sectors could be included, for example, by introducing separate labour and capital markets for agricultural and non-agricultural sectors or allowing for land shifts within agroecological zones with similar soil, landform, and climatic features, as demonstrated by the MAGNET (Woltjer et al., 2014) and GTAP-AEZ (Lee, 2005) models. Last but not least, our static model, which does not consider technological and resource changes over time, limits its applicability to short-term policy analysis. A dynamic AGE model (Babatunde, Begum, & Said, 2017) may help to better understand the food systems in the context of climate change. Despite these limitations, AGE models are among the best tools currently available for assessing the economy-wide effects of policy changes and shock events in society. While AGE models may not capture the internal technology flow or operational processes within specific sectors, they facilitate bridging the micro- and macroscopic agents to understand the trade-offs between environmental and economic objectives within the food-land-water-climate nexus by fully considering the teleconnections of different sectors and regions. Thus, our study offers valuable insights into the complex policy effects across the whole economy.

5. Conclusions

In our study, we discussed how differences in environmental concerns of consumers could cause 'spillover effects' of emissions, namely, from trading partners with higher environmental concerns to China. We further explored options for more sustainable food systems with minimal spillover effects by simulating a partial dietary shift from pork to novel soy-based food (soy-based meat), cleaner cereal production technology, and unilateral emission restrictions.

Differences in environmental concerns of consumers greatly influenced production patterns and emissions. The environmental quality increased more in trading partners with high environmental concerns than China because the production of ‘dirty’ products was transferred to China through international trade. This ‘spillover effect’ was noted for emissions of all pollutants.

A partial dietary shift from pork to novel soy-based food (soy-based meat) in China decreased emissions of greenhouse gases and acidification pollutants but increased emissions of eutrophication pollutants because of the increased production of soy-based food and other (crop-based processed) food in China. The adoption of cleaner cereals production technology in China decreased emissions of all pollutants but required capital reallocation from other sectors. Combining a dietary shift with cleaner cereals production technology decreased emissions of all pollutants further and also decreased the pollution swapping from trading partners to China. Implementation of unilateral emission restrictions in China caused ‘carbon leakage’ to trading partners, as nitrogen fertiliser and livestock production were transferred from China to trading partners.

These findings highlight the importance of accounting for the indirect environmental impacts of food system transformations, which may inadvertently affect other regions and/or economic sectors that were not initially targeted. The integrated environmental-economic modelling framework used in this study enables us to analyse the environmental consequences of food system transformations from an economy-wide perspective. Our study, thus, offers policymakers insights into designing effective policies for more sustainable food systems and sheds light on trade-offs among competing environmental and economic goals.

Author contribution statement

W.L., X.Z., H.P.W., O.O., and Y.H. designed the research; W.L. and X.Z. developed the model; W.L., X.Z., O.O., and Y.H. analysed data; W.L., X.Z., H.P.W., O.O., and Y.H. wrote the paper. All authors contributed to the analysis of the results. All authors read and commented on various drafts of the paper.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI in scientific writing

During the preparation of this work, the author(s) used Artificial Intelligence (in our case, ChatGPT) in order to polish the English writing of paragraphs in this paper. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Appendix A and B. Supplementary data

Details about the data, methods, and framework are presented in Supplementary Information (SI).

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