Land-use emission leakages from China's dietary shift and afforestation amplify food insecurity and economic losses under the 2 °C target

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Abstract

Shifting to healthy diets and afforestation can reduce greenhouse gas (GHG) emissions and enhance carbon sequestration. However, when implemented unilaterally by China, the world's largest agricultural producer and GHG emitter, these measures may support domestic carbon neutrality while triggering emission leakages through trade-induced land-use changes. Using an integrated environmental-economic model, we find that China's dietary shift with less meat and more dairy leads to an additional 14 Mha of agricultural land use abroad and causes 364 Tg CO_2-eq of emission leakage, more than tripling the domestic mitigation. Similarly, China's afforestation policy expands food production overseas, resulting in 16 Mha of additional agricultural land use and 424 Tg CO_2-eq of emission leakage, largely offsetting the domestic reduction. These emission leakages, primarily driven by land-use change, necessitate more stringent mitigation in non-agricultural sectors to meet the 2 °C target. Without coordinated global actions, China's unilateral measures amplify pressures on carbon tax (36%), food price (65%), the population at risk of hunger (145 million people), and economic losses ($74 billion) under the 2 °C target.

Keywords

diet shift; afforestation; food security; land-based mitigation; climate change mitigation.

Main

Food systems exert tremendous pressure on planetary boundaries (PB) regarding climate change, ocean acidification, biogeochemical flows, and land-use changes [1]. Within food systems, the agriculture, forestry, and other land use (AFOLU) sector plays a central role, accounting for 20-25% of global greenhouse gas (GHG) emissions [2] and serving as a major source of pollutants that drive acidification and eutrophication [1]. For example, livestock production and fertiliser use emit methane (CH_4) and nitrous oxide (N_2O), which contribute to global warming; ammonia (NH_3), which leads to acidification; and nitrogen (N) and phosphorus (P) losses, which cause eutrophication [1,2]. Given its contribution to both climate change and air pollution, the AFOLU sector is increasingly recognised as a critical component of global mitigation strategies. This is particularly relevant in the context of the Paris Agreement, which seeks to limit global warming to well below 2°C and possibly below 1.5°C above pre-industrial levels [3]. While energy system decarbonisation remains central to this goal, growing evidence suggests that these temperature thresholds are unattainable without concurrent mitigation in the AFOLU sector [4].

As the world's largest agricultural producer and importer, and the largest GHG emitter, and with just 7% of global arable land supporting 19% of the global population [5], China's actions in the AFOLU domain play a pivotal role in global food system sustainability. In line with its 2030 carbon peaking and 2060 carbon neutrality goals [6], China has recently proposed two key demand-side and land-based mitigation measures in the AFOLU domain: (i) a dietary transition toward healthier, less meat-intensive consumption [7], which may reduce domestic agricultural emissions and free up land for afforestation; and (ii) a large-scale afforestation program provides direct negative emissions through carbon sequestration [8]. However, when implemented unilaterally, such measures may support domestic carbon neutrality while inducing environmental spillovers abroad. For example, Cai et al. [9] show that the dietary shift toward the Chinese Dietary Guidelines (CDG) nearly triples dairy consumption, potentially triggering emission leakage through trade-induced land-use changes. Likewise, China's afforestation policy [10] may displace food production to other countries, offsetting domestic mitigation gains.

Despite growing recognition of these risks, few studies have comprehensively assessed the cross-border impacts of China's demand-side and land-based mitigation measures. Implementing a global uniform carbon tax is widely recognised as the most cost-effective policy instrument for reducing GHG emissions and preventing emission leakage [11,12]. However, the carbon tax is often criticised as regressive, as it places disproportionate burdens on low-income and vulnerable populations, thereby conflicting with the principle of equity and common but differentiated responsibilities [13]. Recycling carbon tax revenues to households via lump-sum transfers can help ease these equity concerns and mitigate adverse impacts on food security caused by the carbon tax [13,14]. Nevertheless, how these aforementioned measures interact with the Sustainable Development Goals (SDGs) [15], particularly SDG 2 (zero hunger), SDG 13 (climate action), and SDG 15 (life on land), remains underexplored. For instance, China's unilateral actions intended to reduce domestic emissions may inadvertently drive deforestation abroad, thereby amplifying food insecurity and economic losses under the 2 °C target. These outcomes underscore the systemic risks of isolated mitigation measures, and call for a nexus framework to achieve sustainable development and avoid shifting burdens across borders or sustainability domains.

The interconnections between food, land, and climate require an approach that integrates multiple interconnected sectors spanning various dimensions of sustainable development and global environmental change to advance understanding of synergies and trade-offs within the food-land-climate nexus [16,17]. Although nexus approaches have been applied at the global level to explore sustainability challenges related to food, energy, and water [18,19], few studies have applied quantitative methods to analyse the interactions among food, land, and climate under various mitigation measures, particularly in emerging economies such as China [15]. In particular, little attention has been paid to how unilateral climate actions by a major GHG emitter, such as China, interact with globally coordinated mitigation measures. Expanding applied general equilibrium (AGE) models or linking them with partial equilibrium (PE) approaches offers a promising pathway to examine such systemic interdependencies at both national and global scales [18-20].

To address these gaps, our study provides a food-land-climate nexus framework that balances food security, land sustainability, and climate goals. Specifically, we develop an integrated environmental-economic model based on an AGE framework [21] and link our AGE model with the

Global Timber Model (GTM) [22,23], a partial equilibrium, dynamic optimisation model representing the global forestry sector, by calibrating the forest carbon sequestration component of the AGE model, to assess the environmental and economic impacts of China's dietary shift and afforestation under the 2 °C target. Both domestic impacts in China and cross-border effects on its major food and feed trading partners (MTP, i.e., Brazil, the United States, and Canada) are captured in our study. This study makes four key contributions. Firstly, unlike previous studies that analyse individual climate mitigation measures in isolation, it integrates four distinct scenarios (dietary shift, afforestation, carbon tax with revenue recycling, and combined measures) to understand their cumulative and interactive effects. Secondly, while most studies focus on domestic impacts, it examines how China's unilateral measures affect MTP, revealing hidden leakage effects, such as increased deforestation abroad. Thirdly, it identifies counterintuitive trade-offs, for example, how China's dietary shifts and afforestation reduce domestic GHG emissions but trigger emission leakages through trade-induced land-use changes. Fourthly, it presents an enhanced AGE model that improves the representation of modelling biophysical flows, land use change, and forest carbon supply, integrates biophysical data (i.e., land cover, fertiliser use, and emissions), and incorporates a food security module into the economic analysis. This enables a more holistic assessment of climate mitigation measures and supports the design of more coherent and globally aligned sustainability strategies.

In this study, we focus on the improvement of one or more components in the food-land-climate nexus. Five scenarios are examined: one baseline (S0) scenario, three scenarios focusing on improving one nexus component, and one combined scenario focusing on improving all nexus components. The baseline (S0) represents the economic and environmental conditions of all sectors (including agriculture, industries, and services) in the entire economies of China and MTP in 2014. The food scenario (S1) aligning with SDG 2 (zero hunger) indicates China's dietary shift towards a less animal-based diet, closing 20% of the gap between current food consumption and the recommended targets in the Chinese Dietary Guidelines (CDG) 2022 diet [24]. The land scenario (S2) supporting SDG 15 (life on land) represents China's afforestation policy based on China's National Forest Management Plan (2016-2050) [10], which aims to expand forest land in China by 23 Mha (equivalent to 4% of China's agricultural land) by 2030. The climate scenario (S3), in line with

SDG13 (climate action), presents a global uniform carbon tax with revenue recycling via lump-sum transfers to achieve the 2 °C climate target set by the Paris Agreement [3], which aims to reduce net total GHG emissions in China and MTP by 25% by 2030. The combined scenario (S4: S1+S2+S3) integrates China's dietary shift (S1) and afforestation policy (S2) with the implementation of a global uniform carbon tax with carbon tax revenue recycling (S3). Key food security (food price, food affordability, food availability, and the population at risk of hunger) and environmental sustainability (cropland and pastureland use, nitrogen and phosphorus fertiliser use, and economy-wide emissions of GHGs, acidification poulltants, and eutrophication pollutants) and economic (sectoral employment and gross domestic product (GDP)) indicators are assessed for China and MTP. Detailed scenario assumptions and are provided in the Supplementary Information (SI).

Results

China's dietary shift causes carbon leakage that is more than triple the domestic mitigation.

In line with the CDG dietary guidelines, the dietary shift in China (S1) reduces the intake of cereal grains (5%), roots & tubers (10%), and sugar crops (15%) (**Supplementary Table 10**), directly lowering cropland demand. It also decreases the consumption of non-ruminant meat (11%) (**Supplementary Table 10**), which indirectly eases cropland pressure by reducing demand for feed crops. However, the dietary shift leads to only a marginal decline in domestic cropland (0.06%; 0.08 Mha) and fertiliser use (0.63%; 0.4 Tg) (**Supplementary Fig. 4a**; **Fig. 1f**) due to increased intake of oilseeds & pulses (10%) and vegetables & fruits (6%) (**Supplementary Table 10**). Similarly, although the reduced intake of ruminant meat (13%) lowers pastureland demand, this effect is largely offset by the increased dairy consumption (52%), resulting in a -0.86% (3 Mha) reduction in domestic pastureland use (**Supplementary Table 10**; **Supplementary Fig. 4e**). The freed agricultural land is converted into a 3.04% (3 Mha) increase in domestic forest land for afforestation (**Supplementary Fig. 4i**). Outside China, pastureland expands by 3.29% (15 Mha), primarily at the expense of forest land (2.95%; 14 Mha) and cropland (0.38%; 0.98 Mha) (**Supplementary Fig. 4a,e,i**). The largest expansion occurs in the United States, mainly driven by a 10.23% (14.63 Mha) increase in pastureland used for ruminant meat production, while the increase in pastureland for dairy production is relatively small (0.09%; 0.11 Mha) (**Fig. 2a**; **Supplementary Fig. 4e**). This is because China almost offsets rising dairy demand through domestic expansion, but reduces ruminant meat production more than consumption, resulting in a 32% increase in the net import rate of ruminant meat (**Fig. 1b,e,h**).

While China's dietary shift delivers domestic co-benefits by reducing agricultural emissions of GHGs, acidification pollutants, and eutrophication pollutants, these reductions are partially or fully offset by cross-sectoral and cross-border emission leakages, with carbon leakage more than tripling the domestic reductions, whereas leakages of other pollutants remain relatively smaller. We find that China's dietary shift reduces domestic GHG emissions from crop and livestock production by 1.7% (6 Tg CO_2-eq) and 18.3% (59 Tg CO_2-eq), respectively (**Supplementary Fig. 8a, 9a**). Afforestation of freed-up agricultural land from the dietary contributes an additional 53 Tg CO_2-eq reduction in domestic GHG emissions (**Fig. 2b**). However, these reductions are partially offset by a 0.2% (26 Tg CO_2-eq) increase in non-agricultural emissions (**Supplementary Fig. 10a**), as labour saved from the agricultural sectors is reallocated to the expansion of non-agricultural production (**Supplementary Fig. 16a**). As a result, China's economy-wide GHG emissions decline by only 0.8% (93 Tg CO_2-eq) (**Fig. 3a**). Since agricultural activities account for a larger share of economy-wide emissions of acidification and eutrophication pollutants than of GHGs, the dietary shift results in even greater reductions in these pollutants, i.e., 3.47% (1.17 Tg NH_3-eq) and 4.20% (0.42 Tg N-eq), respectively, in China's economy-wide emissions (**Fig. 3e,i**). Meanwhile, China's dietary shift also triggers emissions leakage abroad due to trade-induced land-use changes. Economy-wide emissions leakage amounts to 393% for GHGs, 5% for acidification pollutants, and 18% for eutrophication pollutants, relative to the corresponding domestic reductions in China (**Fig. 3a,e,i**). The substantial carbon leakage is primarily driven by deforestation in the United States, which increases GHG emissions from land-use change by 342 Tg CO_2-eq (**Fig. 2b**).

China's dietary shift also raises food security concerns. It leads to a 5.6% (168 kcal capita^{-1} day^{-1}) reduction in domestic food availability (**Supplementary Fig. 3a**) and increases the population at risk of hunger in China by 77 million people (**Fig. 4b**). Although China consumes less of certain foods under the dietary shift, the global average food price (including primary food products and processed food) increases by 0.12% (**Supplementary Table 17**), primarily due to a 0.37-0.83%

increase in land rents in both China and MTP (**Supplementary Fig. 11a**). Considering that prices reflect only part of the picture in assessing food affordability, we estimate changes in food affordability by subtracting changes in the average wage across the entire economy from fluctuations in cereal prices, given the role of cereals as a primary calorie source for low-income households. We find that the dietary transition reduces food affordability in both China and MTP by 0.15-0.22% (**Fig. 4a**), driven by a 0.15% increase in global cereal prices and a 0.003-0.070% decline in wages (**Supplementary Fig. 12a, 13a**).

China's afforestation induces carbon leakage that offsets domestic reduction.

Under China's afforestation policy (S2), domestic forest land expands by 20% (23 Mha), primarily through the conversion of 6% (22 Mha) of pastureland and 0.42% (1 Mha) of cropland (**Supplementary Fig. 4a,e,i**). This reduction in agricultural land decreases crop and livestock production in China by 2% and 4%, respectively, leading to increases in net import rates by 1% for crops and 8% for livestock (**Fig. 1**). The decline in crop production also leads to a 4.60% (2.6 Tg) reduction in domestic fertliser use (**Fig. 1f**). Outside China, pastureland expands by 3.85% (17 Mha), largely at the expense of forest land (3.43%; 16 Mha) and cropland (0.46%; 1.20 Mha) (**Supplementary Fig. 4a,e,i**). The United States accounts for the majority of this expansion, driven primarily by a 7.90% (11.29 Mha) increase in pastureland for ruminant meat production and a 2.53% (2.90 Mha) increase for dairy production (**Fig. 2b**; **Supplementary Fig. 4f**).

Although carbon leakage from China's afforestation is smaller than that from dietary shifts, it fully offsets domestic GHG reductions, whereas larger leakages of acidification and eutrophication pollutants offset nearly half of the domestic domestic mitigations, as land-use change only contributes to GHG emissions rather than these pollutants. We find that China's afforestation reduces domestic GHG emissions from land-use change by 352 Tg CO_2-eq (**Fig. 2d**), alongside additional reductions of 4.9% (18 Tg CO_2-eq) and 9.2% (30 Tg CO_2-eq) from crop and livestock production, respectively (**Supplementary Fig. 8b, 9b**). However, part of the emission reductions is offset by a 0.2% (25 Tg CO_2-eq) increase in non-agricultural emissions (**Supplementary Fig. 10b**)., as labor released from the agricultural sector is redirected to expand non-agricultural activities (**Supplementary Fig. 16e**). Consequently, China's economy-wide GHG emissions decline by 3.4%

(374 Tg CO_2-eq) (**Fig. 3b**). This also yields co-benefits by reducing domestic economy-wide emissions of acidification and eutrophication pollutants by 3.51% (1.18 Tg NH_3-eq) and 2.24% (0.22 Tg N-eq), respectively (**Fig. 3f,j**). Furthermore, China's afforestation induces emissions leakage abroad, offsetting 113%, 49%, and 47% of domestic reductions in economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants, respectively (**Fig. 3b,f,j**). The carbon leakage is primarily driven by deforestation outside China, which increases GHG emissions from land-use change by 330 Tg CO_2-eq in the United States, 66 Tg CO_2-eq in Brazil, and 10 Tg CO_2-eq in Canada (**Fig. 2b**). In contrast, the leakages of acidification and eutrophicatiojn pollutants are mainly attributed to increased livestock production in the United States (**Fig. 3f,j**).

China's afforestation has relatively smaller adverse impacts on food security compared to the dietary shift scenario. As it does not alter consumers' dietary patterns, it has no effect on food availability (**Supplementary Fig. 3b**) and the population at risk of hunger (**Fig. 4d**). Although afforestation creates competition between agricultural and forest land in China, and typically pushes up domestic food prices. Given that our model adopts the Heckscher-Ohlin (H-O) assumption, which treats domestic and imported goods as perfect substitutes, it captures only changes in global average prices. The resulting increase in China's domestic prices can be attenuated by expanded agricultural production in MTP, leading to modest global price increases or even slight declines, depending on global supply. We find that the global average food price declines slightly by 0.02% (**Supplementary Table 17**) under China's afforestation, reflecting the combined effect of falling and rising prices across food categories. Specifically, dairy and ruminant meat prices decrease by 0.16% as production shifts from China to MTP with relatively higher yields, while crop and non-ruminant meat prices rise by 0.02-0.03% due to their relocation to MTP regions with lower yields compared to China (**Supplementary Fig. 12b**). Food affordability in China and MTP declines by 0.02-0.05% (**Fig. 4c**), reflecting the combined effects of rising global cereal prices (0.03%) and wage changes, exacerbated in China by a 0.024% wage decrease and slightly alleviated in MTP by wage increases of 0.001-0.008% (**Supplementary Fig. 12b, 13b**).

A global uniform carbon tax with revenue recycling causes substantial economic losses.

Under the 2 °C climate target (S3), a global uniform carbon tax of \$43 t CO_2-eq^{-1} is required to achieve a 25% (4752 Tg CO_2-eq) reduction in net total GHG emissions in China and MTP (**Fig. 3c**). This global uniform carbon tax incentivises the production of each good to concentrate in regions with lower emission intensities and away from GHG-intensive sectors. The target is met through a 31% (3408 Tg CO_2-eq) reduction in China and a 17% (1344 Tg CO_2-eq) reduction across MTP (**Fig. 3c**), indicating that China bears a relatively larger share of the GHG mitigation burden. Among all regions, China achieves the largest absolute GHG emissions reduction, followed by Brazil, the United States, and Canada (**Fig. 3c**). The largest contribution to total GHG emissions reduction comes from non-agricultural sources in China, especially the non-food sector (3283 Tg CO_2-eq) (**Fig. 3c**; **Supplementary Fig. 10c**). Within the non-agricultural sectors, the fertiliser sectors in China account for the second-largest reduction (314 Tg CO_2-eq) (**Fig. 3c**). Within the AFOLU sectors, the most significant reductions stem from land-use changes associated with forest carbon sequestration in Brazil (760 Tg CO_2-eq) and the United States (188 Tg CO_2-eq) (**Fig. 3c**), owing to their relatively high sequestration intensities and large areas of accessible forest land compared to other regions (**Supplementary Tables 3, 13**). Among livestock products, ruminant meat has the highest GHG intensity and therefore contributes the most to emission reductions (486 Tg CO_2-eq) (**Supplementary Fig. 9c**; **Appendix Table 10**). Ruminant production declines in China (90%), Brazil (90%), and Canada (90%), while it increases in the United States (38%), which benefits from its relatively lower GHG intensity (**Supplementary Figs. 9c**, **15i-l**). In terms of crop sectors, cereal grains exhibit the highest GHG intensity and account for the largest emissions reduction (36 Tg CO_2-eq) among crops (**Supplementary Fig. 8c**). Cereals production expand in Brazil (297%), where GHG intensity is relatively low, while contracting in China (7%), the United States (90%), and Canada (90%) (**Supplementary Figs. 8c**, **15i-l**). The global uniform carbon tax also generates co-benefits by reducing total emissions of acidification and eutrophication pollutants in China and MTP by 12% (5.64 Tg NH_3-eq) and 5% (0.79 Tg N-eq), respectively (**Fig. 3g,k**). Notably, total emissions of eutrophication pollutants in China even increase by 6% (0.61 Tg N-eq) (**Fig. 3k**), reflecting the pollution-swapping effect. These relatively smaller reductions, or even increases in China, compared with GHGs are primarily due to the expansion of non-ruminant meat (98%) and processed food (155%) production in China (**Supplementary Figs. 9g**, **10k**, **15i-l**), which have relatively low GHG intensities but relatively high acidification and eutrophication intensities (**Appendix Tables 10-12**). These shifts in production structure result in GDP losses of 4.9% ($185 billion) for China, 0.4% ($5 billion) for Brazil, 0.1% ($10 billion) for the United States, and 0.4% ($4 billion) for Canada (**Fig. 5e,f**).

Despite the rise in global food prices and worsened food affordability under the carbon tax, revenue recycling to households via lump-sum transfers helps mitigate the adverse food security impacts of a global uniform carbon tax aimed at the 2 °C target. The global uniform carbon tax leads to a 162% increase in the global average food price (**Supplementary Table 17**), with particularly sharp increases in "dirty" agricultural sectors, such as cereal grains (220%) and ruminant meat (212%) (**Supplementary Fig. 12c**). The price of cereals surpasses that of ruminant meat, primarily due to the sharp rise in nitrogen fertiliser prices (474%), as nitrogen fertiliser has the highest GHG intensity among all sectors (**Supplementary Fig. 12c**; **Appendix Table 10**). Food affordability in China and MTP declines by 226-275% (**Fig. 4e**), reflecting the combined effects of soaring cereal prices and falling wages (6-54%) (**Supplementary Figs. 12c, 13c**). The global uniform carbon tax also encourages consumers to shift from "dirty" food products (e.g., cereal grains and ruminant meat) to "clean" food products (e.g., sugar crops and non-ruminant meat) (**Supplementary Fig. 3c**). While such a tax is generally expected to reduce food availability due to higher production costs and food prices, we observe a notable increase in China (7%; 221 kcal capita^{-1} day^{-1}), in contrast to declines in Brazil (18%; 617 kcal capita^{-1} day^{-1}), the United States (23%; 746 kcal capita^{-1} day^{-1}), and Canada (4%; 127 kcal capita^{-1} day^{-1}) (**Supplementary Fig. 3c**). This counterintuitive outcome in China is largely due to the concurrent revenue recycling via lump-sum transfers. In China, the recycled carbon tax revenue amounts to 0.21% of GDP, higher than in Brazil (0.06%), the United States (0.05%), and Canada (0.07%) (**Supplementary Fig. 19**), thereby mitigating the adverse effects on food availability. As a result, the population at risk of hunger decreases by 102 million people in China but increases by 37 million people in Brazil (**Fig. 4f**). Following the FAO approach, risk of hunger is not applied to high-income countries; thus, no changes are reported for the United States and Canada.

Combined measures amplify food insecurity and economic losses under the 2 °C target.

Combined measures (S4) undermine the feasibility of the 2 °C climate target (S3) due to emission leakages, primarily driven by land-use change, from China's dietary shift (S1) and afforestation (S2), which raise the global uniform carbon tax by 36%, from \$43 t CO_2-eq^{-1} in S3 to \$59 t CO_2-eq^{-1} in S4. This is because these emission leakages increase pressure on CO_2 emissions in the energy system to achieve the same 2 °C climate target, thereby necessitating more stringent mitigation in non-agricultural sectors (an additional reduction of 296 Tg CO_2-eq relative to S3) (**Fig. 3c,d**). This heightened constraint on the energy system results in a 12-384% increase in non-agricultural sector prices, particularly for nitrogen fertiliser (384%) and non-food goods (99%) (**Supplementary Fig. 12c,d**). While still meeting the same 2 °C climate target, the combined measures (S4) result in additional reductions in total emissions in China compared to S3: 7% (764 Tg CO_2-eq) for GHGs, 8% (2.75 Tg NH_3-eq) for acidification pollutants, and 4% (0.41 Tg N-eq) for eutrophication pollutants. In contrast, MTP sees increases in total emissions relative to S3: 10% (764 Tg CO_2-eq) for GHGs, 0.2% (0.03 Tg NH_3-eq) for acidification pollutants, and 1% (0.07 Tg N-eq) for eutrophication pollutants (**Fig. 3c,d,g,h,k,i**). Despite these regional disparities, the combined measures (S4) deliver co-benefits by reducing total emissions of acidification and eutrophication pollutants in China and MTP by an additional 6% (2.72 Tg NH_3-eq) and 2% (0.33 Tg N-eq), respectively, compared to S3 (**Fig. 3g,h,k,i**). These additional reductions largely stem from the 127% (215 kcal capita^{-1} day^{-1}) lower China's non-ruminant meat consumption in S4 compared to S3 (**Supplementary Fig. 3c,d**), resulting from the dietary shift (S1). In contrast to S3, where the carbon tax alone promotes consumption substitution from ruminant to non-ruminant meat, S4 avoids the resulting increase in emissions from non-ruminant meat, which has relatively high acidification and eutrophication intensities.

Without coordinated global actions, combined measures (S4) amplify food insecurity and economic losses under the 2 °C target (S3). The global average food price increases by an additional 65% compared to S3 (**Supplementary Table 17**), with the most pronounced increases observed in cereal grains (73%) and ruminant meat (166%) (**Supplementary Fig. 12c,d**). Food affordability in China and MTP declines by 73-86% compared to S3 (**Fig. 4e,g**), driven by surging cereal prices and wage reductions (0-14%) (**Supplementary Figs. 12c-d, 13c-d**). Food availability in China falls by 13% (389 kcal capita^{-1} day^{-1}), while it increases in Brazil (17%; 584 kcal capita^{-1} day^{-1}), the United States (21%; 680 kcal capita^{-1} day^{-1}), and Canada (10%; kcal capita^{-1} day^{-1}) relative to S3 (**Supplementary Fig. 3c,d**). The decline in China is mainly due to the dietary shift (S1), while the increases in MTP reflect a 0.01-0.02% higher share of recycled carbon tax revenue relative to GDP in S4 (**Supplementary Fig. 19**), due to the higher carbon tax compared to S3. Consequently, the population at risk of hunger rises in China (179 million people) but falls in Brazil (35 million people), relative to S3 (**Fig. 4f,h**). Combined measures (S4) also lead to additional GDP losses relative to S3: 1.5% ($57 billion) in China, 0.2% ($3 billion) in Brazil, 0.1% ($10 billion) in the United States, and 0.5% ($4 billion) in Canada (**Fig. 5e,f,g,h**).

Discussion

Emission leakages through trade-induced land-use changes

In this study, we provide a food-land-climate nexus framework that balances food security, land sustainability, and climate goals. Specifically, we analyse the synergies and trade-offs arising from individually implemented mitigation measures (dietary shift, afforestation, and carbon tax with revenue recycling) as well as their combined application. Synergies reflect mutually enhancing effects, while trade-offs indicate competing outcomes that constrain the desirability of the measures [25]. Our comprehensive analysis underscores the importance of accounting for land-use emission leakages from China's unilateral mitigation measures to facilitate coordinated global actions in reducing GHG emissions, particularly in the context of global climate challenges and interconnections of global food systems through international trade. This is because emission leakages through trade-induced land-use changes undermine the feasibility of the 2 °C climate target, thereby amplifying food insecurity and economic losses.

Our findings should not be interpreted as a dismissal of mitigation measures, nor as a suggestion that they may do more harm than good. Rather, they serve as a caution against relying on policies that target a single goal, thus highlighting the need to carefully combine mitigation strategies to minimise unintended consequences. Among the measures analysed, China's dietary shift and afforestation complement the global uniform carbon tax in reducing domestic GHG emissions. While these benefits are consistent with previous findings [9,11,26], our study further reveals competing mechanisms that trigger land-use emission leakages, which are overlooked in earlier studies. We find that China's dietary shift with less meat and more dairy leads to an additional 14 Mha of agricultural land use abroad and causes 364 Tg CO_2-eq of emission leakage, more than tripling the domestic mitigation. Similarly, China's afforestation policy expands food production overseas, resulting in 16 Mha of additional agricultural land use and 424 Tg CO_2-eq of emission leakage, largely offsetting the domestic reduction. These emission leakages due to unilateral climate actions echo the findings of Zhong et al. [27], who showed that meeting the 2030 agricultural and forestry targets of the European Green Deal (EGD) could raise demand for agricultural land outside the EU by 24 Mha and result in 759 Mt CO_2-eq of land-use emissions, more than doubling the EGD's carbon removal target for land, land-use-change and forestry sectors. We demonstrate that a global uniform carbon tax to meet the 2 °C target increases the food price by 162% and reduces food affordability in China and MTP by 226-275%. This aligns with Hasegawa et al. [11], who found that stringent climate mitigation policy would negatively affect food security. Additionally, we find that recycling carbon tax revenues to households via lump-sum transfers leads to heterogeneous food security outcomes: China sees improved food availability (7%; 221 kcal capita^{-1} day^{-1}) and reduced population at risk of hunger (102 million people), whereas Brazil faces declined food availability (18%; 617 kcal capita^{-1} day^{-1}) and increased population at risk of hunger (37 million people). These disparities are driven by differences in recycled carbon tax revenue as a share of GDP, with China at 0.21% and Brazil at 0.06%. Given that land-use emission leakages require more stringent mitigation in non-agricultural sectors to meet the 2 °C target, we reveal that, without coordinated global actions, China's unilateral measures amplify pressures on carbon tax (36%), food price (65%), the population at risk of hunger (145 million people), and economic losses ($74 billion) under the 2 °C target. These unintended trade-offs highlight the need for more integrated and holistic measures to reduce emissions without amplifying food insecurity and economic losses.

Possible measures to mitigate unintended trade-offs

To mitigate emission leakages due to China's unilateral measures, additional or alternative measures are needed. Firstly, one promising approach is to align global dietary patterns with the EAT-Lancet recommendations, rather than the CDG, to further reduce demand for animal-based food. In the food (S1) scenario, land-use emission leakage is primarily driven by China's attempt to close 20% of the gap between current consumption and the CDG target, requiring a 52% increase in dairy intake. The CDG recommendation of dairy intake (300-500 g day^{-1}) may be unrealistic, given the high prevalence of lactose intolerance and bone fractures in China compared to Western populations [7]. By contrast, the EAT-Lancet diet recommends a considerably lower dairy intake (250 g day^{-1}). Guo et al. [28] showed that adopting the EAT-Lancet diet in China would reduce life-cycle GHG emissions and land-use carbon opportunity costs by 24% and 47%, respectively, compared to the CDG diet, due to the EAT diet's smaller increases in dairy intake and greater reductions in red meat consumption. Furthermore, Sun et al. [29] demonstrated that shifting to the EAT-Lancet diet in high-income countries could reduce agricultural emissions from their diets by 61% and sequester 98.3 Gt CO_2-eq, about 14 years of global agricultural emissions, by sparing agricultural land for ecosystem restoration. A recent study by Humpenöder et al. [30] found that a global shift to the EAT-Lancet diet could increase the 1.5 °C-compatible peak carbon budget from 500 to 625 Gt CO_2-eq, thereby enhancing the feasibility of achieving 1.5 °C pathways under the Paris Agreement. Nevertheless, shifting consumer behaviour toward healthier diets remains challenging. In upper-middle- to high-income countries, healthy diets are estimated to be 22-34% cheaper than current diets, whereas in low- to lower-middle-income countries, they are 18-29% more expensive [31]. Targeted educational programs, behavioural nudges, and informative labeling, such as carbon and health labels, can raise consumer awareness of sustainable food choices and promote sustainable dietary transitions [32,33]. Financial support, such as transfer payments or revised food distribution schemes, is also crucial in providing economic incentives for the adoption of healthy diets [30]. Secondly, agricultural intensification and afforestation on abandoned cropland could help mitigate land-use emission leakages. In the land (S2) scenario, such leakages are primarily driven by competition between agricultural and forest land within China, which reduces domestic food production and increases reliance on imports, thereby triggering agricultural expansion abroad. On the one hand, agricultural intensification could reduce agricultural land use, thereby alleviating the pressure from large-scale afforestation. Direct global forest protection has been shown to be more effective than the deforestation-linked import restrictions, which may be undermined by emissions leakage and economic losses [34]. However, large-scale global afforestation may exacerbate competition between agricultural and forest land, raising concerns over potential trade-offs between climate goals and food security [35]. Doelman et al. [36] found that globally large-scale land-based mitigation (~600 Mha by 2050) could raise food prices by 11%, reduce food availability by 230 kcal capita^{-1} day^{-1}, and put 230 million more people at risk of hunger, but these negative impacts on food security could be offset by a 9% increase in crop yields and 3% intensification in ruminant production. Nevertheless, the feasibility of future crop yield increases remains uncertain due to the negative impacts of climate change on crop yields [36]. On the other hand, afforestation on abandoned cropland could also alleviate the competition for land. Wu et al. [37] found that China had 31 Mha of abandoned cropland, 83% of which (26 Mha) was suitable for recultivation, exceeding the 23 Mha afforestation target by 2030 in S2. Therefore, afforestation on abandoned cropland in China even surpass China's 2030 afforestation goal. However, abandoned cropland can serve diverse purposes beyond afforestation, such as recultivation, bioenergy with carbon capture and storage, and natural vegetation regrowth, offering various benefits for climate mitigation, ecosystem restoration, and biodiversity conservation [37,38]. Thus, a more pragmatic strategy is to balance these objectives rather than dedicating all abandoned land solely to afforestation [39].

Combining climate policies with mixed carbon tax revenue recycling schemes and technology transfer initiatives may support climate mitigation goals while mitigating increased food insecurity and economic losses. In the climate (S3) scenario, we find that recycling carbon tax revenues to households via lump-sum transfers helps mitigate the adverse food security impacts of a global uniform carbon tax aimed at the 2 °C target, but this still comes at the cost of substantial economic losses. Critics argue that a global uniform carbon tax may be unrealistic and inequitable, conflicting with the principle of equity and common but differentiated responsibilities [40]. Frank et al. [41] found that targeting carbon taxes at land-rich, low-population countries could achieve mitigation with minimal food security impacts. However, Hasegawa et al. [42] warned that exempting certain regions or sectors from the carbon tax could shift a greater and often more costly mitigation burden onto the rest of the economy, potentially jeopardizing the achievement of ambitious climate targets.

Therefore, complementary measures are needed to mitigate these negative impacts. For example, de Bruin and Yakut [14] found that combining carbon tax with allocating carbon tax revenues between sales tax reductions and household transfers can achieve a triple dividend by reducing emissions, increasing GDP, and enhancing income equality. Additionally, including the transfer of land- and emission-saving production technologies from developed to developing countries in climate agreements could support global mitigation efforts while fostering economic development [43].

Despite its integrated approach, this study has some limitations that necessitate some follow-up. Firstly, model simplifications, such as fixed budget shares for consumers, fixed cost shares for producers, and the absence of trade barriers, may represent an upper bound of possible changes, yet remain appropriate for exploring potential synergies and trade-offs within the food-land-climate nexus. Secondly, our model includes only China and MTP (i.e., Brazil, the United States, and Canada), which may underestimate land-use emission leakages from China's dietary shift and afforestation. This, in turn, could lead to an underestimation of the resulting food insecurity and economic losses under the 2 °C target. Although MTP accounts for over 75% of China's total food and feed trade value, expanding the model to include the rest of the world, especially China's main importers of dairy products and ruminant meat, such as Australia and New Zealand, could provide a more comprehensive assessment. Nonetheless, the omission is expected to result in limited underestimation, given Oceania's small contribution (0.3%) to the global accessible forest land area [44]. Thirdly, our analysis does not account for crop yield shocks under alternative climate scenarios, that is, the Representative Concentration Pathways (RCPs) [45]. Crop yields are generally projected to decline under both RCP 8.5 (food and land scenarios) and RCP 2.6 (climate and combined scenarios), with more severe impacts under RCP 8.5 due to higher radiative forcing and greater variability in temperature and other climate variables [46,47]. Excluding climate-induced yield losses may lead to an underestimation of food insecurity and economic losses under the 2 °C target, as declining productivity would likely exacerbate food shortages and price increases [48]. Nonetheless, this exclusion is justified by the findings of Hasegawa et al. [11], who demonstrated that, under RCP 2.6, the adverse effects of climate change on crops are substantially smaller than the impacts associated with mitigation efforts. Moreover, omitting climate change impacts allows for a better assessment of the individual contributions of mitigation measures. While this limitation does not alter our main conclusion, future research could strengthen the analysis by incorporating crop yield shocks in the food-land-climate nexus. Fourthly, our static modelling framework reflects current economic conditions and does not capture long-term dynamics (e.g., population growth, economic development, evolving trade policies) or external shocks (e.g., African swine fever, the US-China trade war, the Russia-Ukraine war, COVID-19) that may reshape agri-food systems. Future work could address these gaps through dynamic modelling and additional scenario analyses. Further details on these limitations are elaborated in the Supplementary Discussion. Nevertheless, our main conclusion that land-use emission leakages from China's dietary shift and afforestation amplify food insecurity and economic losses under the 2 °C target remains valid. Our analysis is intended to inform policymakers, not to downplay the importance of mitigation, but rather to highlight the adverse side effects of mitigation measures. It underscores the need for targeted interventions that ensure climate goals are met without triggering unintended trade-offs in food security and economic well-being.

Methods

The integrated environmental-economic model and database.

We developed a global comparative static applied general equilibrium (AGE) model, a modified version of an integrated environmental-economic model, [21] and improved the representation of agriculture, forestry, and other land use (AFOLU) (6 crop types, 3 livestock categories, and 1 forestry sector) and non-agricultural (compound feed, food processing by-products, processed food, fertilisers, and non-food) sectors. While the static nature of the model limits its applicability to short-term policy analysis, previous studies have demonstrated that it allows us to isolate the impacts of external shocks or policy interventions from other complex and uncertain factors, such as future population and economic growth, by grounding the analysis in current economic conditions [48]. Although such interactions are important, they are beyond the scope of this study. Moreover, dynamic models require extensive assumptions on these factors, which can complicate the interpretation of climate-induced impacts and increase uncertainty [49].

AGE models, grounded in microeconomic theory, represent the entire economy by integrating utility-maximising consumers, profit-maximising producers, and market-clearing conditions, where relative prices adjust to equate total supply (domestic production and imports) and total demand (intermediate use, household consumption, and exports), under perfect competition. For international trade, our AGE model adopts the Heckscher-Ohlin (H-O) assumption, treating domestic and imported goods as perfect substitutes, leading to specialised production in countries with comparative advantages where goods can be produced most efficiently. A comprehensive description of our AGE model specifications is provided in the Supplementary Information (SI).

In contrast to the previous version, which combined Brazil, the United States, and Canada into a single region representing China's main food and feed trading partners (MTP), the current version of our model disaggregates them into separate regions. This four-region framework, including China, Brazil, the United States, and Canada, allows for a more detailed representation of bilateral trade flows and enhances the model's capacity to assess context-specific impacts of land-use change. We select 2014 as the reference year, as it is the most recent year in the Global Trade Analysis Project (GTAP) database [50] at the time of our study. Our model is solved using the general algebraic modelling system (GAMS) software package [51]. The rest of the world (RoW) is excluded from our analysis, as GTAP [50] trade flow data indicates that, in 2014, over 75% of China's total food and feed trade value was concentrated with MTP, whereas trade with RoW accounted for only 25%. This highlights the central role of China's domestic food production in shaping its trade balance with MTP, and our model can effectively capture the most significant trade flows influencing China's food system.

To enable the simulation of one of our key scenarios, China's dietary shift towards the Chinese Dietary Guidelines 2022 [24], we enhance the model's representation of biophysical flows, thereby improving its ability to track changes in food demand. Following Gatto et al. [52] and Chepeliev [53], we convert dollar-based quantities (million USD) to physical quantities (Tg; 1 Tg = 10^6 tons) to trace biophysical flows throughout the global economy. GTAP version 10 database [50] is used to calibrate our AGE model and provide dollar-based quantities. We designed a sectoral aggregation scheme comprising 18 sectors (see **Appendix Table 1**) based on the original GTAP database to produce social accounting matrices (SAM) (see **Appendix Tables 2-5**) in our study. In the SAMs from the GTAP database, dollar-based material balances for the reference year ensure that dollar-based production quantities for each commodity across countries equal the sum of dollar-based intermediate demand across sectors, dollar-based final demand from the representative consumer, and dollar-based net exports. Dollar-based bilateral trade quantities in the GTAP database are constructed based on the reconciled UN Comtrade Database [54], while physical bilateral trade quantities are obtained from FAOSTAT [5] trade data. To construct bilateral trade flows in physical quantities, we prioritise FAO-reported imports over exports, assuming that import data is more reliable since importers have a stronger incentive to provide accurate trade records for tax purposes. We then apply the RAS approach (also referred to bi-proportional balancing) [55] to balance physical bilateral trade quantities, ensuring consistency between FAO-reported totals for exporting and importing countries. Physical production quantities of crops, livestock, and fertilisers (see **Supplementary Table 2**) are obtained from FAOSTAT [5]. In addition to primary food products, we also account for food processing by-products, which include cereal bran, alcoholic pulp (including distiller's grains from maize ethanol production, brewer's grains from barley beer production, and distiller's grains from liquor production), and oil cakes (including soybean cake and other oil cakes). Physical production quantities of food processing by-products (see **Supplementary Table 2**) are estimated by multiplying the production quantities of primary food products by FAO technical conversion factors for various by-products [56]. Physical feed production quantities are extracted from the "Feed" category in the FAO Food Balance Sheet (FBS). Since the FAO does not provide feed data by livestock type, following Gatto et al. [57], we allocated the physical production quantities of feed across livestock sectors based on dollar-based feed demand shares across livestock sectors in the SAMs from the GTAP database. To establish the link between dollar-based and physical quantities, we define material intensity coefficients (kg USD^{-1}) for each commodity at the regional level as the ratios of physical production quantities from FAO to dollar-based production quantities from GTAP, estimating these coefficients using reference year data. This approach allows us to compute physical material balances once dollar-based material balances are determined after each model run. However, physical material balances may not hold for all commodities and countries. To address this, we adjust physical production quantities to ensure that the supply of each commodity aligns exactly with FAO-FBS data for further comparisons. This adjustment ensures consistent tracing of material flows in both dollar-based and physical quantities for each commodity across countries. For simulations using the static AGE model, physical material flows change proportionally to the corresponding dollar-based material flows in response to an exogenous shock.

Modelling land use change and forest carbon supply.

In our model, the allocation of land is determined through a constant elasticity of transformation (CET) function, which has been widely used in the previous literature [48,49,58,59]. The rent-maximising landowner initially determines the allocation of land among three land cover types, i.e., cropland, pastureland, and forest land, based on relative returns to land. Subsequently, the landowner allocates cropland among various crops and pastureland between dairy products and ruminant meat. A three-tier structure of land supply is provided in **Supplementary Fig. 1**. Physical area of cropland, pastureland, and forest land is obtained from FAOSTAT [5]. Following the GTAP land use and land cover database [44,60,61], we align the land cover data in our AGE model with FAO land cover data (see **Supplementary Table 3**). We classify forest land into accessible and inaccessible categories based on the country-specific shares of accessible forest area, using data provided by Sohngen et al. [62] and Baldos and Corong [61]. Accessible forests include both managed (timber-producing) and unmanaged forests. Following Golub et al. [49], inaccessible forest land is excluded from our modelling. We assume that deforestation only occurs on the accessible forest land, which is less costly to access than the remaining inaccessible forest land. Crop sectors account for 100% of total cropland, while livestock sectors use 100% of total pastureland. Dairy and ruminant meat production are assumed to use pastureland, whereas non-ruminant livestock production does not use land. The forestry sector uses 100% of the accessible portion of total forest land cover. While we acknowledge that other land types (SavnGrasslnd, Shrubland and inaccessible forests) are also potentially cultivable, Golub et al. [49] have demonstrated that this modelling approach captures the majority of land classified by the FAO as potential arable land.

We link our AGE model with the Global Timber Model (GTM) [22,23], a partial equilibrium, dynamic optimisation model representing the global forestry sector, by calibrating the forest carbon sequestration component of the AGE model. The calibration procedure aims to ensure that both models produce consistent forest carbon sequestration responses under the same carbon tax rate. The calibration is performed by adjusting the incremental annual forestry carbon sequestration intensities to mimic the GTM's assumptions. In line with GTM, we assume that one hectare of new forest sequesters the same amount of carbon, regardless of whether it is converted from cropland or pastureland. Following Hertel et al. [58] and Golub et al. [63], forest carbon stocks can be increased by increasing the biomass on existing forest acreage (the intensive margin) or by expanding forest land (the extensive margin). Annual forestry carbon sequestration intensities (see **Supplementary Table 13**), derived from Nguyen et al. [64] and China's National Forest Management Plan (2016-2050) [10], are distributed evenly over a depreciation period of 20 years, as suggested by Intergovernmental Panel on Climate Change (IPCC) [65] and BSI [66]. Additional details are provided in Supplementary Methods.

Environmental impact assessment.

While the previous version of our model accounted only for production-related emissions across all sectors in the entire economies of China and MTP, the current version expands the scope to include greenhouse gas emissions from land-use change, specifically emissions associated with net forest conversion (i.e., changes in forest carbon stocks). Detailed information about emission sources across sectors is provided in **Appendix Table 6**.

Three main environmental impacts of food systems are distinguished, i.e., global warming potential (GWP, caused by greenhouse gas (GHG) emissions, including carbon dioxide(CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions; converted to CO_2 equivalents), acidification potential (AP, caused by pollutants leading to acidification, including ammonia (NH_3), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) emissions; converted to NH_3 equivalents), and eutrophication potential (EP, caused by pollutants leading to eutrophication, including nitrogen (N) and phosphorus (P) losses; converted to N equivalents). The conversion factors for GWP, AP, and EP are derived from Goedkoop et al. [67]. Data on CO_2, CH_4, and N_2O emissions are obtained from the Climate Analysis Indicators Tool (CAIT) [68]. GHG emissions calculations in our model follow the IPCC National GHG Emission Guidelines [65]. We derive NH_3, NO_x, and SO_2 emissions from Liu et al. [69], Huang et al. [70], and Dahiya et al. [71], respectively. We consider NO_x emissions from energy use only, as agriculture's contribution to NO_x emissions is generally small ($\leq 2\%$) [72]. We use the global eutrophication database of food and non-food provided by Hamilton et al. [73] to obtain data on N and P losses to water bodies. Emissions of food processing by-products (i.e., cereal bran, alcoholic pulp, oil cake) are derived from Mackenzie et al. [74]. We attribute the environmental impacts between the main (e.g., cereal flour) and joint products (e.g., cereal bran) according to their relative economic values (see **Supplementary Table 8**). We derive nitrogen and phosphorous fertiliser use by crop types and countries from Ludemann et al. [75]. The total emissions of GHGs, acidification pollutants, and eutrophication pollutants for the food and non-food sectors in the base year are calculated first. Then, we allocate the total emissions to specific sectors according to the shares of emissions per sector in total emissions to unify the emission data from different years. The sectoral-level emissions 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}) are presented in **Appendix Tables 7-12**.

Food security indicators.

The Food and Agriculture Organization (FAO) [76] defines food security as encompassing four key dimensions: availability (adequate food supply), access (sufficient resources to obtain food), utilisation (nutritious and safe diets), and stability (consistent access to food over time). We focus on the first two dimensions. Firstly, food availability is defined as "calories per capita per day available for consumption". "Population at risk of hunger" refers to the portion of people experiencing dietary energy (calorie) deprivation lasting more than a year following the FAO-based approach [77]. In essence, the population at risk of hunger is estimated by multiplying the prevalence of undernourishment (PoU) by the total population [78]. According to the FAO, the PoU is based on dietary energy availability calculated by our model, the mean minimum dietary energy requirement (MDER), and the coefficient of variation (CV) of the domestic distribution of dietary energy consumption in a country. It is assumed that there is no risk of hunger in high-income countries; consequently, the population at risk of hunger is not applied to the United States and Canada. Secondly, the access dimension is tied to people's purchasing power, which depends on food prices, dietary habits, and income trends. We calculate the average food price (including primary food products and processed food) and estimate changes in food affordability by subtracting changes in the average wage across the entire economy from fluctuations in cereal prices.

Definition of scenarios.

We examined five scenarios: one baseline (S0) scenario and four scenarios of improvements in the food-land-climate nexus components. The latter four scenarios were compared to the 2014 baseline (S0) scenario. The scenarios are further described below and in **Supplementary Table 1**.

S0 - Baseline. The baseline (S0) represents the economic and environmental conditions of all sectors (including agriculture, industries, and services) in the entire economies of China and MTP in 2014. It corresponds to the Representative Concentration Pathway (RCP) 8.5 [45], the worst-case climate change scenario in which emissions continue to increase with no mitigation. Note that the potential negative impacts of climate change on crop yields are not considered in this study; therefore, uncertainties associated with crop yield responses under alternative climate scenarios (that is, RCPs) assessed in previous research [11,48] fall beyond the scope of our analysis.

S1 - Food scenario: A dietary shift in China. Shifting towards less animal-based and more plant-based diets is the most effective demand-side option to mitigate climate change [79]. Meat consumption in China has exceeded the recommended consumption levels reported by the EAT-Lancet diet [80] and the Chinese Dietary Guidelines (CDG) 2022 [24]. While the EAT-Lancet diet offers a widely recognised global benchmark for healthy and sustainable eating, its limited consideration of cultural, age-, and gender-specific dietary needs presents challenges for national-level implementation [80]. In scenario S1, we focus on the CDG diet [24], which offers culturally tailored dietary recommendations and promotes healthy Eastern dietary patterns that are more compatible with Chinese preferences than global guidelines. Specifically, we simulate an exogenous dietary shift in China toward the CDG diet recommendations. We first estimate the gap in food consumption between current levels in China and the recommended targets in the CDG diet. Subsequently, we adjust China's food consumption patterns to close 20% of this gap. Detailed information about the dietary shift in China is provided in **Supplementary Table 10**.

S2 - Land scenario: An afforestation policy in China. Afforestation, with its potential for negative GHG emissions, is widely recognised as a cost-effective and readily available climate change mitigation option [26]. In line with its commitment to achieving carbon neutrality by 2060, the Chinese government has proposed an ambitious afforestation target to support this goal. In scenario S2, we simulate an afforestation policy in China based on the National Forest Management Plan (2016-2050) [10]. This plan outlines an ambitious tree-planting program to expand forest land in China by 23 Mha (equivalent to 4% of China's agricultural land) by 2030.

S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling. Implementing a global uniform carbon tax on economy-wide GHG emissions (i.e., total emissions from all sectors in the entire economy) is considered an effective policy instrument to identify the most cost-effective mitigation pathway to achieve the climate targets outlined in the Paris Agreement [11,12]. In scenario S3, we implement a global uniform carbon tax to achieve a 25%

reduction in net total GHG emissions in China and MTP by 2030. This aligns with the 2°C climate stabilisation target [81] outlined in the Paris Agreement [3], which corresponds to the RCP2.6 and requires global GHG emissions to peak by 2025 and decline by 25% by 2030. We select the 2°C target instead of the 1.5°C target because Matthews and Wynes [82] have demonstrated that while current global efforts are insufficient to limit warming to 1.5°C, they provide a greater than 95% chance of staying below 2°C. However, the carbon tax entails economic trade-offs, as it raises production costs, reduces output and welfare, and imposes greater distortions with deeper emission reductions [14]. Moreover, the carbon tax is often criticised as regressive, as it places disproportionate burdens on low-income and vulnerable populations, thereby conflicting with the principle of equity and common but differentiated responsibilities [13]. Recycling carbon tax revenues to households via lump-sum transfers can help ease these equity concerns and mitigate the adverse impacts on food security caused by the carbon tax [14]. Therefore, we combine a global uniform carbon tax with revenue recycling via lump-sum transfers in S3, which could help advance social equity and support a just climate transition.

S4 - Combined scenarios: S1+S2+S3. In the combined scenario S4, all measures are combined to examine their potential synergies or trade-offs in the food-land-climate nexus. This scenario integrates China's dietary shift (S1) and afforestation policy (S2) with the implementation of a global uniform carbon tax with carbon tax revenue recycling (S3).

Data availability

The data and parameters that support the economic model in this study are available from the GTAP version 10 database (https://www.gtap.agecon.purdue.edu/databases/v10/). The other data that support splitting agriculture, forestry, and other land use (AFOLU) (6 crop types, 3 livestock categories, and 1 forestry sector) and non-agricultural (compound feed, food processing by-products, processed food, fertilisers, and non-food) sectors from the original database GTAP 10 are publicly available at FAOSTAT (http://www.fao.org/faostat/en/#data) and the UN Comtrade Database (https://comtrade.un.org/data). The authors declare that all other data supporting the findings of this study are available within the article and its Supplementary Information files or are available from the corresponding authors upon reasonable request.

Code availability

The authors declare that the GAMS codes for producing the results of this study are available from the corresponding authors upon reasonable request.

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Acknowledgements

We acknowledge financial support from the National Natural Science Foundation of China [no. 32272814] (Y.H.), the High-level Team Project of China Agricultural University (Y.H.), the Agriculture Green Development Program sponsored by China Scholarship Council [no. 201913043] (W.L.), and Junior Researcher Grant from Wageningen School of Social Sciences (WASS) [no. 24-014] (W.L.). Artificial Intelligence (in our case, ChatGPT) has been used to polish the English writing of paragraphs in this paper. After using this tool/service, we reviewed and edited the content as needed and took full responsibility for the content of the publication.

Author contributions

W.L., X.Z., Y.H., and L.M.P. designed the research. W.L., X.Z., and L.M.P. developed the model. W.L. ran the model and performed the analysis. W.L. collected and analysed data. W.L. wrote the paper with contributions from X.Z., Y.H., L.M.P., L.G., and K.B.. All authors contributed to the interpretation of the results and commented on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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

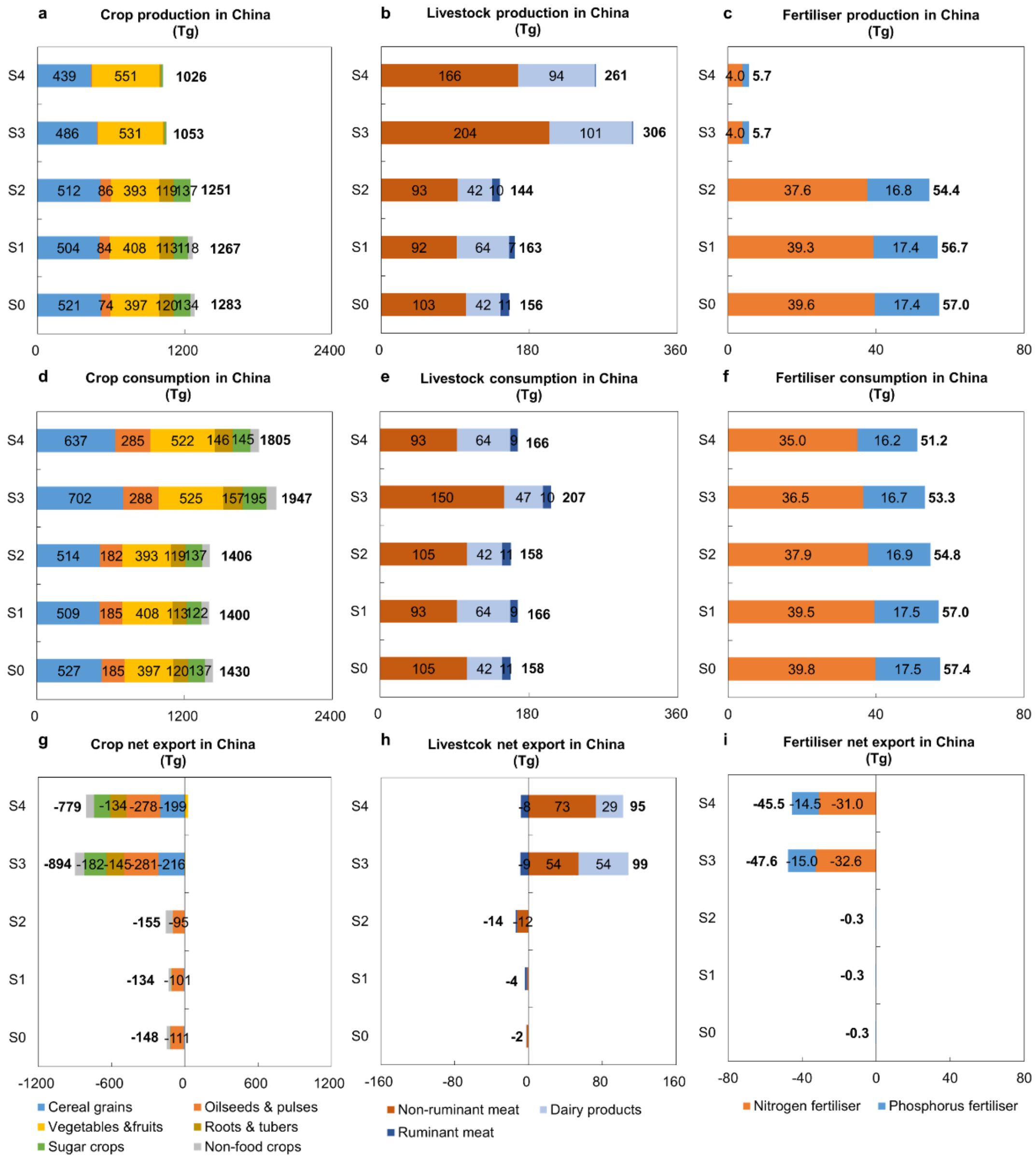

Fig. 1 | Impacts of mitigation measures on domestic production, consumption, and net export of total crop, livestock, and fertiliser. Total (**a**) crop, (**b**) livestock, and (**c**) fertiliser production (Tg) in scenarios. Total (**d**) crop, (**e**) livestock, and (**f**) fertiliser consumption (Tg) in scenarios. Total (**g**) crop, (**h**) livestock, and (**i**) fertiliser net export (Tg) in scenarios. Total crop production excludes discarded food waste and food processing by-products (see **Supplementary Table 2** for detailed data). Total crop consumption includes crop used for intermediate use (i.e, feeding crops, compound feed, food by-products, processed food) and direct consumption (i.e., primary fresh food) (see **Supplementary Fig.5** for detailed data). Definitions of scenarios (S1 - Food scenario: A dietary shift in China; S2 - Land scenario: An afforestation policy in China; S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling; S4 - Combined scenarios: S1+S2+S3) are described in **Supplementary Table 1**.

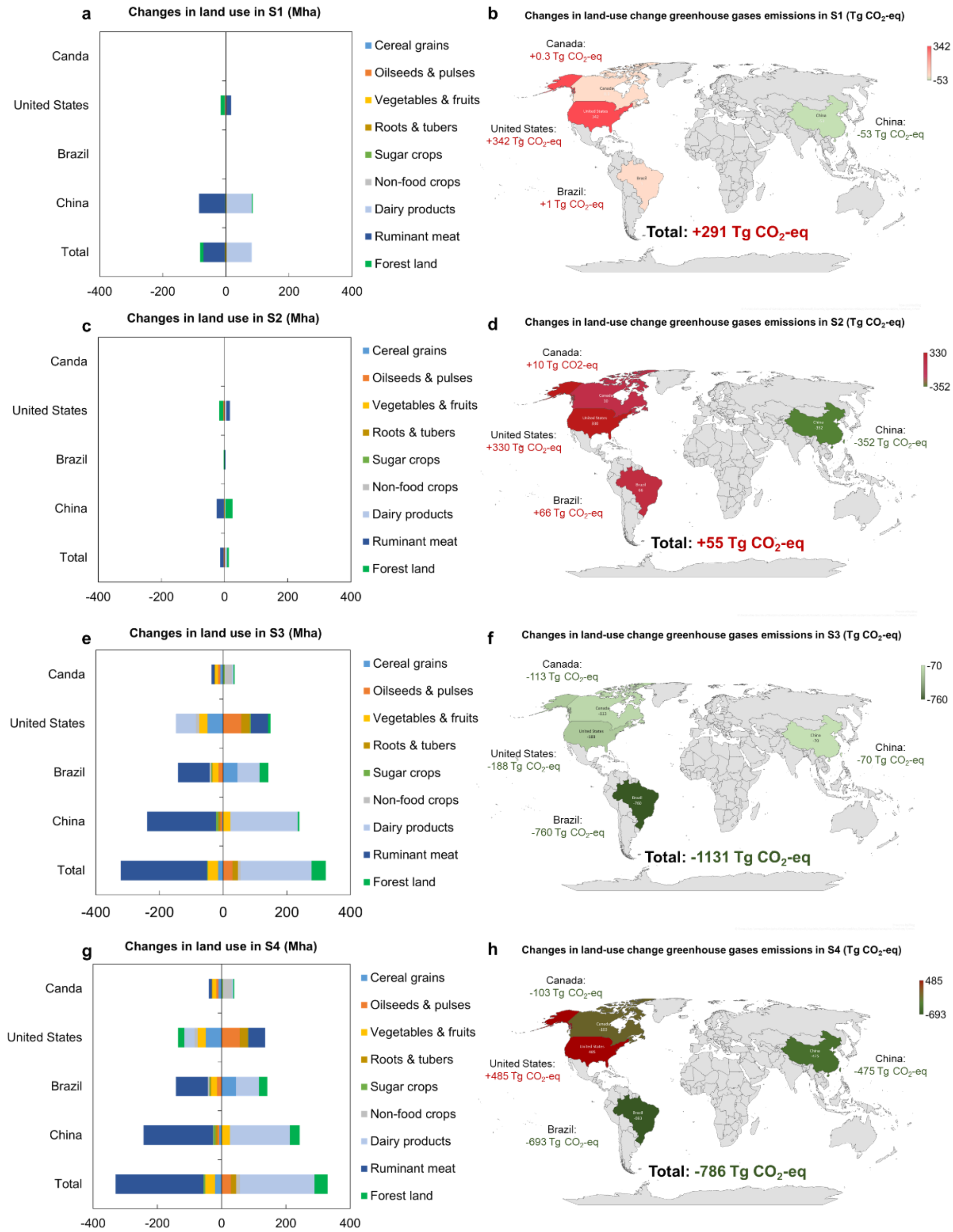

Fig. 2 | Impacts of mitigation measures on land-use changes and land-use change greenhouse gases emissions in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in land use (Mha) in China and MTP in scenarios (**a**) S1, (**c**) S2, (**e**) S3, and (**g**) S4 with respect to the baseline (S0). Changes in land-use change greenhouse gases emissions (Tg CO_2-eq) in China and MTP in scenarios (**b**) S1, (**d**) S2, (**f**) S3, and (**h**) S4 with respect to the baseline (S0). Definitions of scenarios (S1 - Food scenario: A dietary shift in China; S2 - Land scenario: An afforestation policy in China; S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling; S4 - Combined scenarios: S1+S2+S3) are described in **Supplementary Table 1**.

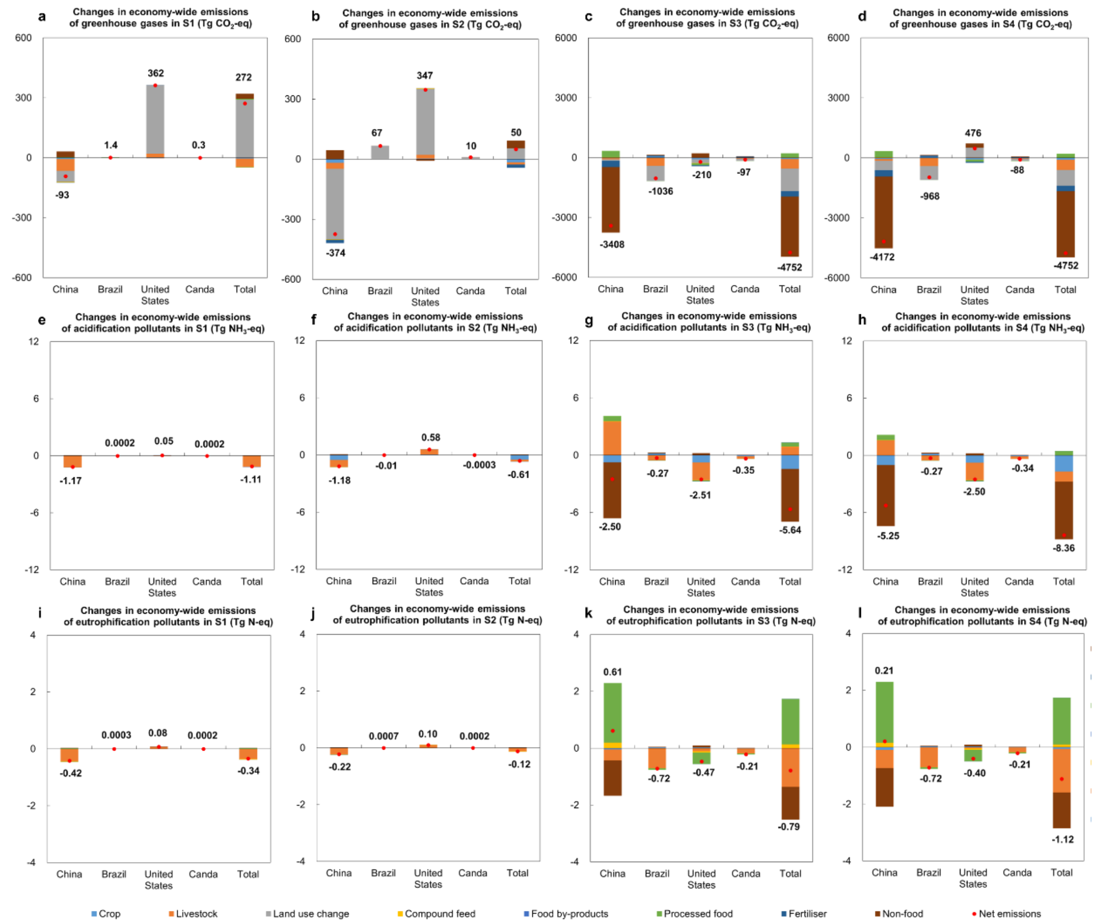

Fig. 3 | Impacts of mitigation measures on economy-wide emissions in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in economy-wide emissions of greenhouse gases (GHGs) (Tg CO_2-eq) in China and MTP in scenarios (**a**) S1, (**b**) S2, (**c**) S3, and (**d**) S4 with respect to the baseline (S0). Changes in economy-wide emissions of acidification pollutants (Tg NH_3-eq) in China and MTP in scenarios (**e**) S1, (**f**) S2, (**g**) S3, and (**h**) S4 with respect to the baseline (S0). Changes in economy-wide emissions of eutrophication pollutants (Tg N-eq) in China and MTP in scenarios (**i**) S1, (**j**) S2, (**k**) S3, and (**l**) S4 with respect to the baseline (S0). Economy-wide emissions refer to total emissions of GHGs, acidification pollutants, and eutrophication pollutants from all sectors in the entire economies of China and MTP. Definitions of scenarios (S1 - Food scenario: A dietary shift in China; S2 - Land scenario: An afforestation policy in China; S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling; S4 - Combined scenarios: S1+S2+S3) are described in **Supplementary Table 1**.

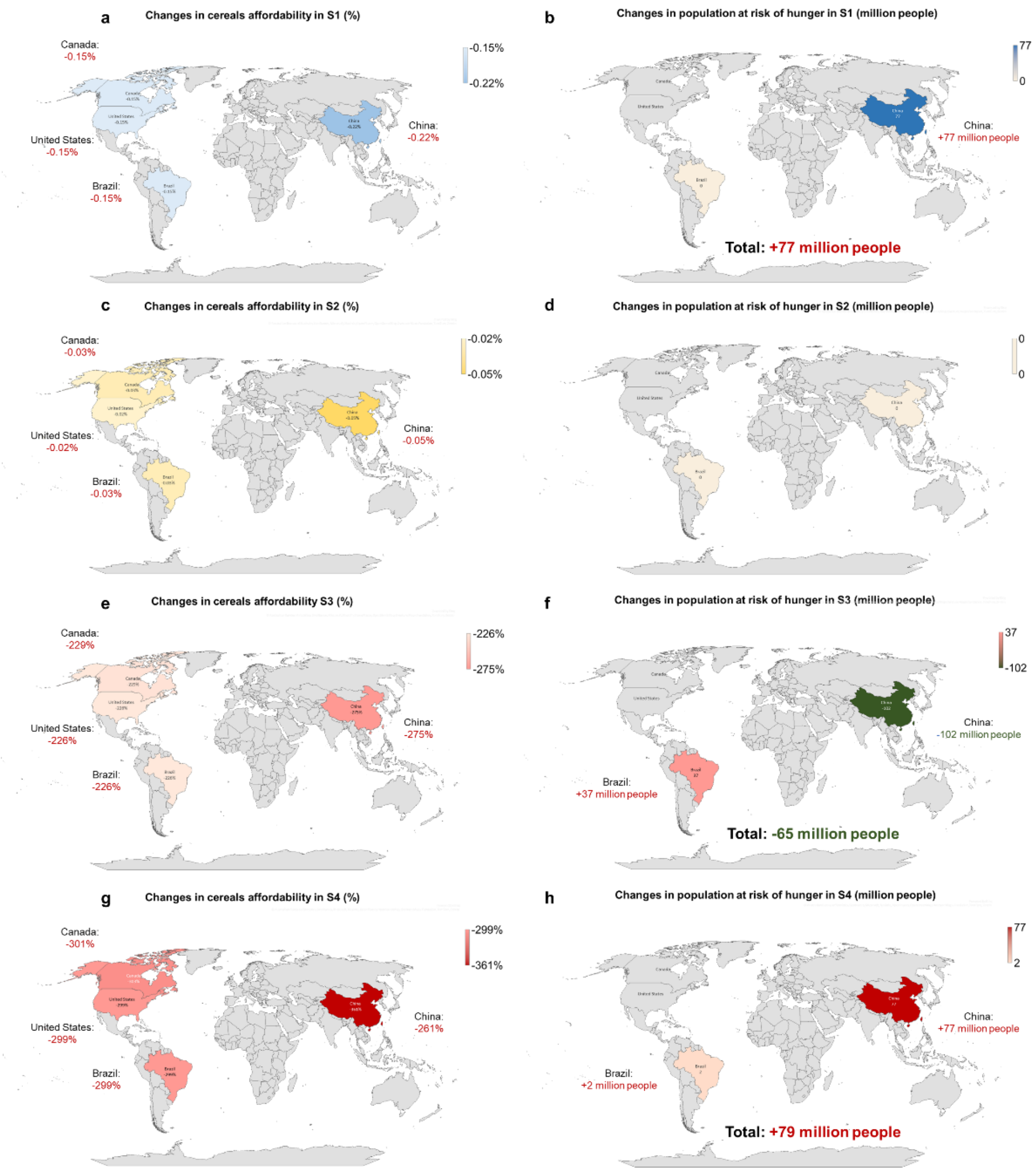

Fig. 4 | Impacts of mitigation measures on food security in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in cereals affordability (%) in China and MTP in scenarios (**a**) S1, (**c**) S2, (**e**) S3, and (**g**) S4 with respect to the baseline (S0). Changes in population at risk of hunger (million people; S0 = 140.7 million people for China; S0 = 5.3 million people for Brazil) in China and MTP in scenarios (**b**) S1, (**d**) S2, (**f**) S3, and (**h**) S4 with respect to the baseline (S0). According to the FAO approach, it is assumed that there is no risk of hunger for high-income countries; consequently, the population at risk of hunger is not applied to the United States and Canada. Definitions of scenarios (S1 - Food scenario: A dietary shift in China; S2 - Land scenario: An afforestation policy in China; S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling; S4 - Combined scenarios: S1+S2+S3) are described in **Supplementary Table 1**.

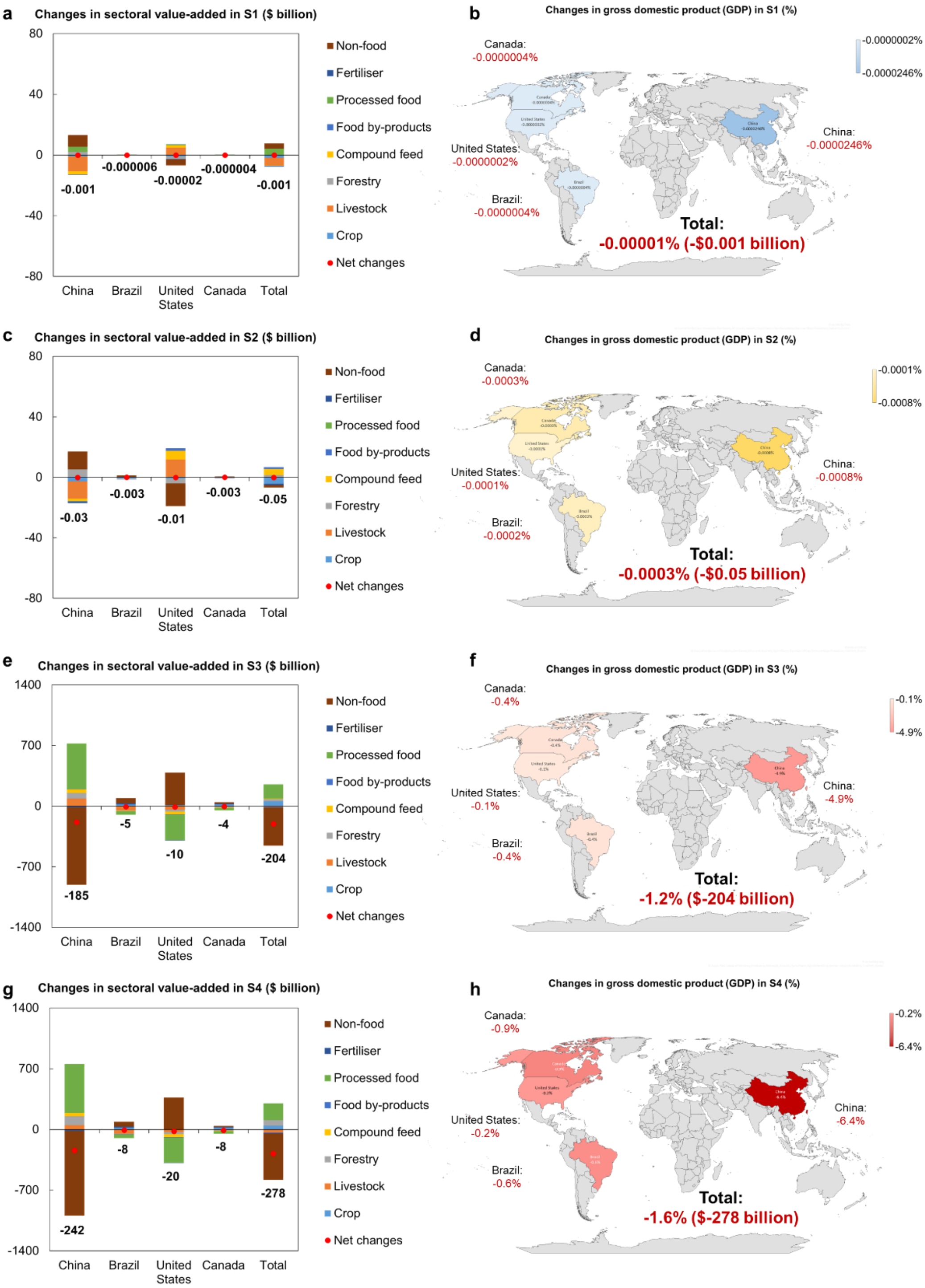

Fig. 5 | Impacts of mitigation measures on economic losses in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in sectoral vaule-added ($ billion) in China and MTP in scenarios (**a**) S1, (**c**) S2, (**e**) S3, and (**g**) S4 with respect to the baseline (S0). Changes in gross domestic product (GDP, %) in China and MTP in scenarios (**b**) S1, (**d**) S2, (**f**) S3, and (**h**) S4 with respect to the baseline (S0). GDP is calculated as the sum of sectoral vaule-added in the entire economy. Definitions of scenarios (S1 - Food scenario: A dietary shift in China; S2 - Land scenario: An afforestation policy in China; S3 - Climate scenario: A global uniform carbon tax with carbon tax revenue recycling; S4 - Combined scenarios: S1+S2+S3) are described in **Supplementary Table 1**.