Unintended trade-offs between food security and environmental sustainability: Impacts of China's dietary shift and afforestation under a stringent climate mitigation policy

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Abstract

Food, land, and climate are deeply interconnected and play a crucial role in achieving Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger), SDG 13 (climate action), and SDG 15 (life on land). However, measures designed to advance one SDG may create trade-offs or unintended consequences for others, highlighting the need to assess their broader systemic impacts. This study examines the linkages between food security, sustainable land management, and climate change within the food-land-climate nexus, focusing on China and its main food and feed trading partners. Using an integrated environmental-economic model, we assessed the impacts of four mitigation measures: a dietary shift in China (S1), a unilateral afforestation policy in China (S2), a global uniform carbon tax (S3), and a combined scenario integrating all measures (S4). We found that China's dietary shift (S1) lowered domestic GHG emissions by 2.4% but increased global GHG emissions by 4.2% due to higher dairy consumption, which contributed to deforestation in trading partners. A unilateral afforestation policy in China (S2) reduced domestic GHG emissions by 5.9%, but the expansion of food production and deforestation abroad offset 70% of mitigated GHG reductions in China. Implementing a global uniform carbon tax (S3) at \$43/tCO_2-eq to achieve a 25% global GHG reduction under the Paris Agreement raised food prices by 138%, with China's GHG emissions declining by 29%. The combined scenario (S4) resulted in the largest GHG reduction (42%) in China but at the cost of a 205% increase in food prices. This outcome was driven by deforestation in trading partners, necessitating a higher carbon tax of \$69/tCO_2-eq to meet the same GHG mitigation target. These findings underscore the urgent need for a nexus framework to balance climate mitigation, food security, and land sustainability, ensuring that policies do not create unintended trade-offs for others.

Keywords

Diet shift; Afforestation; Food security; Land-based mitigation; Climate change mitigation

1. Introduction

Food systems have placed tremendous pressure on planetary boundaries (PB, the environmental limits within which humanity can safely operate) regarding climate change, ocean acidification, biogeochemical flows (nitrogen and phosphorus), and land-use changes (M. Springmann et al., 2018). The Paris Climate Agreement seeks to restrict global warming to well below 2°C and possibly below 1.5°C above pre-industrial levels (IPCC-WGIII, 2014; UNFCC, 2015). However, achieving the 1.5°C target is considered unattainable without mitigating emissions from food systems (Clark et al., 2020). Agriculture, forestry, and other land use (AFOLU) contributed 20–25% of global greenhouse gas (GHG) emissions in 2010 (Blanco et al., 2014), making it a critical sector that must be addressed to achieve ambitious long-term climate mitigation goals. The AFOLU sector is widely regarded in the literature as having substantial emissions reduction potential with relatively cost-effective mitigation opportunities compared to other sectors (Harmsen et al., 2019; Hasegawa & Matsuoka, 2015; Popp, Lotze-Campen, & Bodirsky, 2010).

The interdependencies between food, land, and climate change have gained increasing attention, often framed as the food-land-climate nexus (Stefan Frank et al., 2021; Fujimori et al., 2022). This nexus is closely tied to achieving multiple Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger), SDG 13 (climate action), and SDG 15 (life on land) (Doelman et al., 2022; Newbold et al., 2015). However, food, land, and climate change have, in the past, often been addressed in isolation, often leading to unintended trade-offs or unforeseen consequences, where solving one problem inadvertently exacerbates another (Johnson et al., 2019; J. Liu et al., 2018). For example, land-based mitigation measures, such as large-scale afforestation, can trigger land competition between forest and food production, potentially driving up food prices and undermining food security (Doelman, Stehfest, Tabeau, & van Meijl, 2019; Peña-Lévano, Taheripour, & Tyner, 2019; van Meijl et al., 2018). Further, a carbon tax, recognised as the most efficient market-based GHG emission mitigation policy instrument (S. Frank et al., 2018), could potentially raise prices of emission-intensive food products and pose risks to food security, given that the “polluter pays principle” implies higher carbon taxes for “dirty” food producers compared to “clean” food producers (Peña-Lévano et al., 2019). Also, shifting towards less animal-based diets does not guarantee a reduction in total resource use and economy-wide emissions (Gatto, Kuiper, & van Meijl, 2023; Long, Zhu, Weikard, Oenema, & Hou, 2024; Mason-D'Croz et al., 2022). This is because the saved resources would be reallocated to other sectors across the whole economy, which may mitigate the expected environmental benefits.

A holistic nexus approach (implying systems are inextricably linked to form a complex system of interrelations) is needed to better leverage potential synergies and minimise trade-offs in the food-land-climate nexus (J. Liu et al., 2018; van Vuuren et al., 2015), yet such a framework is still lacking. Although the nexus concept has been mentioned in discussions of sustainable development for a few decades, it has only recently received significant attention from scientific and policy disciplines, especially the interactions between the domains of food, land, and climate change, which are crucial given the challenges posed by escalating food demand, limited agricultural land, and climate change. To analyse the complex linkages among food, land, and climate change, integrated nexus frameworks have been created either through the expansion of applied general equilibrium (AGE) models or the linking of partial equilibrium (PE) models, which endogenously capture interactions among different global economic sectors (Johnson et al., 2019). However, few studies have applied quantitative methods and analysed the linkages to multi-dimensional SDGs in the food-land-climate nexus on a global scale. In addition, measures aimed at achieving one or more specific SDGs may cause trade-offs or unexpected changes for other SDGs and /or for other sectors in our society. It remains unclear how solutions to one SDG affect other SDGs in the land-food-climate nexus.

This study bridges the gap by analysing the linkages between food security, sustainable land management, and climate change in the food-land-climate nexus, with a particular emphasis on China and cross-border impacts on its major food and feed trading partners, given its critical role in global markets for food and feed. A sustainable food system should be able to feed everyone on Earth while also stabilising global land use, and reducing climate change (Foley et al., 2011). To achieve that, we focused on the improvement of one or more components in the food-land-climate nexus. In this study, four scenarios were simulated: three scenarios focusing on improving one nexus component, and one combined scenario focusing on improving all nexus components. The food scenario (S1) indicates a dietary shift in China toward the EAT-Lancet diet recommendations (Willett et al., 2019), aligning with SDG 2 (zero hunger). The land scenario (S2) represents a unilateral afforestation policy based on China's National Forest Management Plan (2016– 2050) (Forest Park of National Forestry and Grassland Administration (FPNFGA), 2016), supporting SDG 15 (life on land). The climate scenario (S3) presents the implementation of a global uniform carbon tax to reduce GHG emissions, in line with the Paris Agreement (IPCC-WGIII, 2014; UNFCC, 2015) and SDG13 (climate action). The combined scenario (S4: S1+S2+S3) integrates all land, food, and climate measures. Key food security indicators (food prices, affordability, and availability) and environmental sustainability indicators (cropland use, pastureland use, nitrogen fertiliser use, phosphorus fertiliser use, emissions of GHGs, emissions of acidification poulltants, and emissions of eutrophication pollutants) were assessed for China and its major food and feed trading partners (MTP, including Brazil, the United States, and Canada).

The remaining part of the paper is structured as follows: In section 2, we present our research methods. Section 3 displays and interprets our model results for different scenarios, including food, land, and climate ones. Finally, in section 4, we conclude with discussions on the policy implications of moving towards sustainable food systems in China.

2. Materials and methods

2.1 The integrated environmental-economic model and database.

The integrated environmental-economic model based on an AGE framework has been widely used to identify the optimal solution towards greater sustainability and enable efficient allocation of resources in the economy under social welfare maximisation (Fischer et al., 2007; Greijdanus, 2013; Keyzer & Van Veen, 2005; Le Thanh, 2016; van Wesenbeeck & herok, 2006). For this study, we developed a global comparative static AGE model, a modified version of an integrated environmental-economic model, (Long et al., 2024; Zhu, 2004; Zhu & Van Ierland, 2006; Zhu & Van Ierland, 2005, 2012; Zhu, van Wesenbeeck, & van Ierland, 2006) and improved the representation of agriculture, forestry and other land use (AFOLU)-related (crop, livestock, foestry) sectors and associated non-agriculture (compound feed, food processing by-products, nitrogen and phosphorous fertiliser, and non-food) sectors. Our model distinguished four regions: China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). These 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 represents the latest available year of the Global Trade Analysis Project (GTAP) database. Our model is solved using the general algebraic modelling system (GAMS) software package (GAMS, 2022).

GTAP version 10 database (GTAP, 2014) was 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. Following Gatto, Kuiper, van Middelaar, and van Meijl (2024), we converted dollar-based quantities to physical quantities (Tg) to allow the tracing of biophysical flows through the global economy. Data on physical quantities (see Supplementary Table 2) of crop, livestock, and fertiliser production was obtained from FAO (2022). Data on the trade shares matrix was calculated from the UN Comtrade Database (2022).

2.2 Modelling land use change and forest carbon supply.

In the model, the allocation of land is determined through a constant elasticity of transformation (CET) function, which is widely used in the previous literature (A. A. Golub et al., 2013; Hertel, Lee, & Rose, 2009; Peña-Lévano et al., 2019; Taheripour, Zhao, Horridge, Farrokhi, & Tyner, 2020). 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. Physical area of cropland, pastureland, and forest land are obtained from FAO (2022). Following the GTAP land use and land cover database (Baldos, 2017; Baldos & Corong, 2020; Pena Levano, Taheripour, & Tyner, 2015), we align the land cover data in our AGE model with FAO land cover data (see Supplementary Table 3). The forestry component of the model is calibrated using outputs from the Global Timber Model (GTM) (Austin et al., 2020; Sohngen & Mendelsohn, 2007), a partial equilibrium, dynamic optimisation model representing the global forestry sector. Following Hertel et al. (2009) and A. Golub, Hertel, Lee, Rose, and Sohngen (2009), forest carbon stocks can be increased by increasing the biomass on existing forest acreage (the intensive margin) or by expanding forest land. The annual forestry carbon sequestration intensity (see Supplementary Table 11) derived from Nguyen, Hermansen, and Mogensen (2010) is distributed evenly over a depreciation period of 20 years, as suggested by IPCC (2006) and BSI (2008). Additional details were provided in Supllementary Information.

2.3 Environmental impact assessment.

Three main environmental impacts of food systems were 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 were derived from Goedkoop et al. (2009). Data on CO_2, CH_4, and N_2O emissions were obtained 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 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%) (Lamsal et al., 2011). We used the global eutrophication database of food and non-food provided by Hamilton et al. (2018) to obtain data on N and P losses to water bodies. We derived nitrogen and phosphorous fertiliser use by crop types and countries from Ludemann, Gruere, Heffer, and Dobermann (2022).

The total emissions of GHGs, acidification pollutants, and eutrophication pollutants for the food and non-food sectors in the base year were calculated first. Then, we allocated 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. Detailed information about emissions sources across sectors is provided in Appendix Table 6. 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.

2.4 Food security indicators.

The FAO (1996) 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 focused on the first two dimensions. First, food availability is defined as "calories per capita per day available for consumption". Second, the access dimension is tied to people's purchasing power, which depends on food prices, dietary habits, and income trends (Lele et al., 2016). We calculated the crop-based food price, animal-based food price, and average food price (including crop-based food and animal-based food). We then estimated changes in food affordability by subtracting changes in the average wage across the whole economy from fluctuations in cereal prices.

2.5 Definition of scenarios.

To estimate the impacts of mitigation measures in the food-land-climate nexus on food security and environmental sustainability, we examined five scenarios, including one baseline (S0) scenario representing the economies of China and MTP in 2014, and four scenarios of improvements in 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.

S1 - Food scenario: A dietary shift in China. Shifting to the EAT-Lancet diet has been widely recommended for its substantial health and environmental benefits (Guo et al., 2022; Marco Springmann, Godfray, Rayner, & Scarborough, 2016; Willett et al., 2019). Meat consumption in China has exceeded the recommended consumption levels reported by the EAT-Lancet diet (Willett et al., 2019). In scenario S1, we simulated an exogenous dietary shift in China toward the EAT-Lancet diet recommendations. We first estimated the gap in food consumption between current levels in China and the recommended targets in the EAT-Lancet diet. Subsequently, we adjusted China's food consumption patterns to close one-third of this gap, accounting for the unaffordability of a complete dietary shift for households. Detailed conditions for the dietary shift in China were provided in Supplementary Table 8.

S2 - Land scenario: A unilateral afforestation policy in China. Afforestation, with its potential for negative GHG emissions, is widely recognised as essential in global climate change mitigation efforts (Doelman et al., 2020). 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 simulated a unilateral afforestation policy in China based on the National Forest Management Plan (2016–2050) (Forest Park of National Forestry and Grassland Administration (FPNFGA), 2016). This plan, proposed by China's National Forestry and Grassland Administration, outlines an ambitious tree-planting program to expand forest land in China by 20% (41.6 Mha) by 2050.

S3 – Climate scenario: A global uniform carbon tax. Implementing carbon taxes is considered an effective policy instrument to identify the most cost-effective mitigation pathway for achieving the climate change mitigation target set by the Paris Agreement (Avetisyan, Golub, Hertel, Rose, & Henderson, 2011; Hasegawa et al., 2018; Jiang, Liu, & Deng, 2022). In scenario S3, we implemented a global uniform carbon tax to achieve a 25% reduction in net total GHG emissions in China and its trading partners by 2030. This aligns with the 2°C climate stabilisation target (Lee et al., 2023) outlined in the Paris Agreement (IPCC-WGIII, 2014; UNFCC, 2015), which aims to limit global warming well below 2°C above pre-industrial levels, requiring global GHG emissions to peak by 2025 and drop by 25% by 2030. This tax is applied uniformly across all economic sectors, including AFOLU and non-agricultural sectors, following the most widely adopted approach in the literature (Fujimori et al., 2022; Hasegawa et al., 2018). We selected the 2°C target instead of the 1.5°C target because Matthews and Wynes (2022) 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.

S4- Combined scenarios: S1+S2+S3. In the combined scenario S4, all measures were combined to examine their potential synergies or trade-offs in the food-land-climate nexus. This scenario incorporates a dietary shift (S1) and a unilateral afforestation policy (S2) in China, along with a global uniform carbon tax (S3).

3. Results

3.1 S1 - Food scenario: A dietary shift in China.

In the food scenario (S1), we simulated an exogenous dietary shift in China toward a less animal-based diet, closing one-third of the gap between current food consumption and the EAT-Lancet diet recommendations. This dietary shift in China requires higher consumption of oilseeds & pulses (95%), and dairy products (66%) compared to the baseline diet while requiring a lower intake of cereal grains (11%), vegetables & fruits (10%), roots & tubers (23%), sugar crops (28%), non-ruminant meat (25%), and ruminant meat (19%) (see Supplementary Table 8). As a result, food availability in China declined by 7.6%, while consumers in its main food and feed trading partners, including Brazil, the United States, and Canada, experienced a 3.7% increase in food availability (Fig. 1a). Given that China accounts for over 70% of the total population across these regions, the reduction in food availability within China outweighs the gains in its trading partners, resulting in a 4.2% decline in global average food availability (Fig. 1a). The lower total food demand in China and its trading partners decreased the average food price by 0.06% (Fig. 1e). Cereals affordability for labour force in China and its trading partners increased by 0.10-0.13% (Fig. 1i), as a result of a rise in the average wage across the economy (0.02-0.06%) and a decrease in cereals price (0.08%) (Supplementary Table 13).

The reduction in cropland use (0.01%) in China was minimal, as the decline in domestic cropland use (8.56 Mha) was almost entirely offset by an increase in net cropland exports (8.54 Mha) (Supplementary Fig. 1a). Similarly, the decrease in pastureland use (1.5%) in China was limited, as the reduction in pastureland for ruminant meat (57 Mha) was largely counterbalanced by an increased pastureland demand for dairy production (51 Mha) (Fig. 2e). With the possibility of international trade, regional food production patterns do not necessarily align with regional food consumption trends, as production is allocated to regions with comparative advantages. For instance, the increase in oilseeds & pulses consumption in China and its trading partners was largely supplied by its expanded production in the United States (68%) (Fig. 3c). Similarly, the rise in dairy consumption was primarily met by higher dairy production in China (57%) and Brazil (50%) (Fig. 3e, 3f). As a result, total cropland use decreased by 0.63% (Fig. 2a), while total pastureland use expanded by 3.2% across China and its trading partners (Fig. 2e). Globally, the 3.2% reduction in nitrogen fertiliser use and 3.3% reduction in phosphorus fertiliser use in China were offset by a 39% increase in nitrogen fertiliser use and a 45% increase in phosphorus fertiliser use in the United States (Fig. 4a, 4e). As a result, total nitrogen fertiliser use across China and its trading partners declined by 3.3%, while total phosphorus fertiliser use increased by 2.3% (Fig. 4a, 4e).

GHG reductions within China's food system was dominated by lower production of cereal grains (16 Tg CO_2-eq), non-ruminant meat (18 Tg CO_2-eq), and ruminant meat

(38 Tg CO_2-eq) (Supplementary Fig. 2a, 3a). However, the primary contributors to economy-wide GHG reductions in China were fertiliser production contraction (296 Tg CO_2-eq) and land-use change (101 Tg CO_2-eq) (Fig. 5a), with the latter resulting from the conversion of saved cropland and pastureland into forest land. Despite these reductions, GHG savings were partially offset by the expansion of non-food consumption (172 Tg CO_2-eq) (Fig. 5a). Beyond China, pastureland expansion (34 Mha) in Brazil occurred at the expense of cropland (3 Mha) and forestland (31 Mha) (Fig. 2i), leading to 938 Tg CO_2-eq emissions from land-use change (Fig. 2m). Overall, the total economy-wide GHG emissions across China and its trading partners increased by 4.2% (Fig. 5a). In contrast, the total economy-wide emissions of acidification and eutrophication pollutants decreased by 2.8% and 2.1%, respectively (Fig. 5e, 5i).

3.2 S2 - Land scenario: A unilateral afforestation policy in China.

In the land scenario (S2), we simulated a 20% (41.6 Mha) increase in forest land in China based on an ambitious afforestation target set by the Chinese government. This forest land expansion in China was achieved through a 0.1 Mha reduction in cropland and a 41.5 Mha reduction in pastureland (Fig. 2j), resulting in a mitigation of 700 Tg CO_2-eq GHG emissions from land-use change (Fig. 2n). This reduction exceeds the total GHG emissions from China's agricultural production, i.e., 678 Tg CO_2-eq in 2014 (see Appendix Table 7). These findings suggest that China's agricultural sector could achieve carbon neutrality by implementing a unilateral afforestation policy in China.

The reduction in agricultural land in China led to a decline in domestic food production and exports, increasing reliance on food imports and stimulating expanded food production among its trading partners. This resulted in a 0.006% increase in the average food price and a marginal decrease of 0.0-0.1% in cereals affordability for the labour force in China and its trading partners (Fig. 1f, 1j). For dairy products, China's production fell by 52% (Fig. 3e). However, Chinese consumers could meet their demand through increased dairy imports from trading partners, as the unilateral afforestation policy did not alter dietary patterns (Fig. 1b). The expansion of pastureland (3 Mha) and cropland (4 Mha) in China's trading partners came at the expense of a 7 Mha reduction in forest land (Fig. 2j). The most significant change was observed in the United States, where pastureland expanded by 52 Mha, driven by the 39% increase in dairy producton (Fig. 3g). These land cover changes led to a 496 Tg CO_2-eq increase in GHG emissions from land-use change outside China, offsetting nearly 70% of the emissions mitigated through afforestation in China (Fig. 2n). Shifts in crop portfolios led to a 1.3% increase in total nitrogen fertiliser use but a 0.1% decrease in total phosphorus fertiliser use across China and its trading partners (Fig. 4b, 4f). Overall, the total economy-wide emissions of GHGs and eutrophication pollutants across China and its trading partners declined by 1.0% each (Fig. 5b, 5j). In contrast, the total economy-wide emissions of acidification pollutants saw a slight increase of 0.05% (Fig. 5f).

3.3 S3 - Climate scenario: A global uniform carbon tax.

In the climate scenario (S3), a carbon tax of \$43/t CO_2-eq was required to achieve a 25% reduction in total GHG emissions across China and its trading partners, amounting to approximately 4923 Tg CO_2-eq from the baseline economy. This global uniform carbon tax would lead to the production of each good primarily occurring in regions with relatively lower GHG emission intensities. The largest reduction in total GHG emissions occurred in China, primarily driven by the contraction of non-food production (3685 Tg CO_2-eq), making it the biggest contributor to GHG mitigation (Fig. 5c). Forestry sequestration was the second-largest contributor to GHG mitigation (Fig. 5c), with the most significant impact in Brazil (713 Tg CO_2-eq), followed by the United States (176 Tg CO_2-eq), Canada (104 Tg CO_2-eq), and China (59 Tg CO_2-eq) (Fig. 1o). Overall, total economy-wide emissions of GHGs and acidification pollutants across China and its trading partners declined by 25% and 6%, respectively (Fig. 5c, 5g). In contrast, eutrophication pollutant emissions surged by 6% (Fig. 5k), driven by increased production of processed food, which has lower GHG emission intensity but higher eutrophication emission intensity.

The global uniform carbon tax led to a 138% increase in average food prices (Fig. 1g), with significantly higher price surges in GHG-intensive agricultural sectors, such as cereal grains (184%), dairy products (145%), and ruminant meat (219%) (Supplementary Fig. 5c). As a result, cereals affordability for the labour force in China and its trading partners decreased by 188-240% (Fig. 1k). Cereals became less affordable in China than in its trading partners, as wages declined more sharply in China (Supplementary Table 13). In addition, this global uniform carbon tax would encourage consumers in China and its trading partners to shift from “dirty” food products with higher GHG emission intensities (e.g., cereal grains, oilseeds & pulses, roots & tubers, dairy, and ruminant meat) to “clean” food products with lower GHG emission intensities (e.g., vegetables & fruits, sugar crops, and non-ruminant meat) (Fig. 1c). This dietary shift led to a 2.6% decline in global food availability (Fig. 1c). Due to their high GHG emission intensities, the prices of nitrogen and phosphorus fertilisers surged by 155% and 197%, respectively (Supplementary Fig. 5c). Consequently, total fertiliser use across China and its trading partners declined by 21% for nitrogen and 8% for phosphorus (Fig. 4c, 4g).

3.4 S4 - Combined scenarios: S1+S2+S3.

In the combined scenario (S4), China's dietary shift (S1) and afforestation policy (S2) were integrated with the global uniform carbon tax (S3) to achieve a 25% reduction in total GHG emissions across China and its trading partners. Among all scenarios, S4 resulted in the largest economy-wide GHG reduction in China, with GHG emissions decreasing by 42%, compared to 2.4% in S1, 5.9% in S2, and 29% in S3 (Table 1; Fig. 5a-d). However, the additional GHG reduction in China came at the cost of heightened food security risks. This was because the combination caused deforestation in its trading partners, leading to an increase in global GHG emissions. Consequently, a higher carbon tax of $69/t CO_2-eq was needed to achieve the same GHG mitigation target. As a result, these combined measures drove up average food prices by 205% and reduced cereals affordability for the labour force in China and its trading partners by 280-343% (Fig. 1h, 1i).

4. Concluding remarks

This paper has attempted to analyse the linkages between food security, sustainable land management, and climate change in the food-land-climate nexus, with a particular emphasis on China. Particularly, we examined the impacts of different measures of achieving lower emissions, including a dietary shift in China (S1), a unilateral afforestation policy in China (S2), a global uniform carbon tax (S3), and a combined scenario integrating all measures (S4). Our results indicate interesting results for achieving sustainable food systems and land management under climate change.

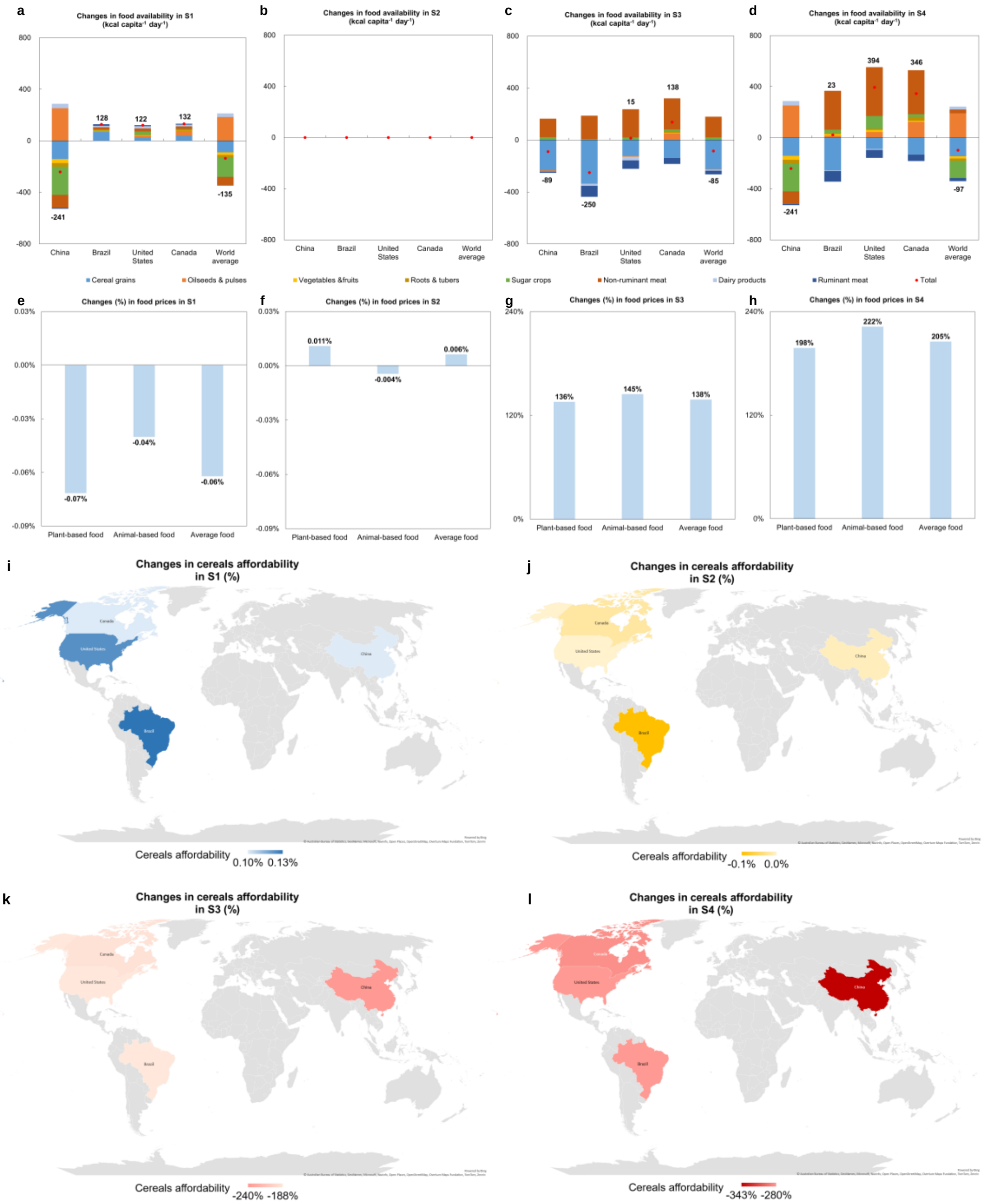

Fig. 1 | Impacts of mitigation measures on food security indicators in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in food availability (kcal capita^{-1} day^{-1}) in China and MTP in scenarios (**a**) S1, (**b**) S2, (**c**) S3, and (**d**) S4 with respect to the baseline (S0). Changes in crop-based food price, animal-based food price, and average food price (including crop-based food and animal-based food) in China and MTP in scenarios (**e**) S1, (**f**) S2, (**g**) S3, and (**h**) S4 with respect to the baseline (S0). Changes in cereals affordability for labour force in China and MTP in scenarios (**i**) S1, (**j**) S2, (**k**) S3, and (**l**) S4 with respect to the baseline (S0).

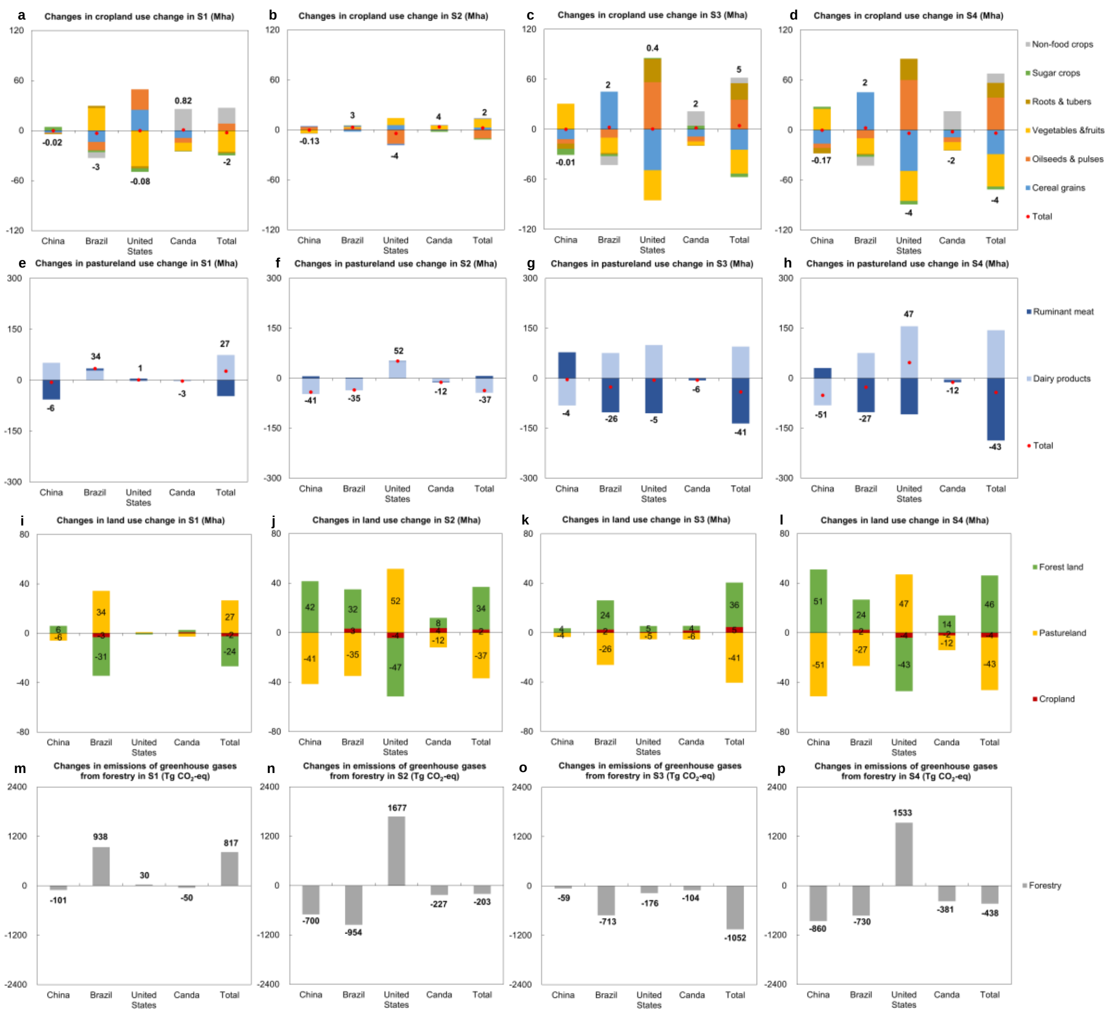

Fig. 2 | Impacts of mitigation measures on land use change and related greenhouse gases emissions in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in cropland use (Mha) in China and MTP in scenarios (**a**) S1, (**b**) S2, (**c**) S3, and (**d**) S4 with respect to the baseline (S0). Changes in pastureland use (Mha) in China and MTP in scenarios (**e**) S1, (**f**) S2, (**g**) S3, and (**h**) S4 with respect to the baseline (S0). Changes in total land use (Mha) in China and MTP in scenarios (**i**) S1, (**j**) S2, (**k**) S3, and (**l**) S4 with respect to the baseline (S0). Changes in greenhouse gases emissions from forestry (Tg CO$_2$-eq) in China and MTP in scenarios (**m**) S1, (**n**) S2, (**o**) S3, and (**p**) S4 with respect to the baseline (S0).

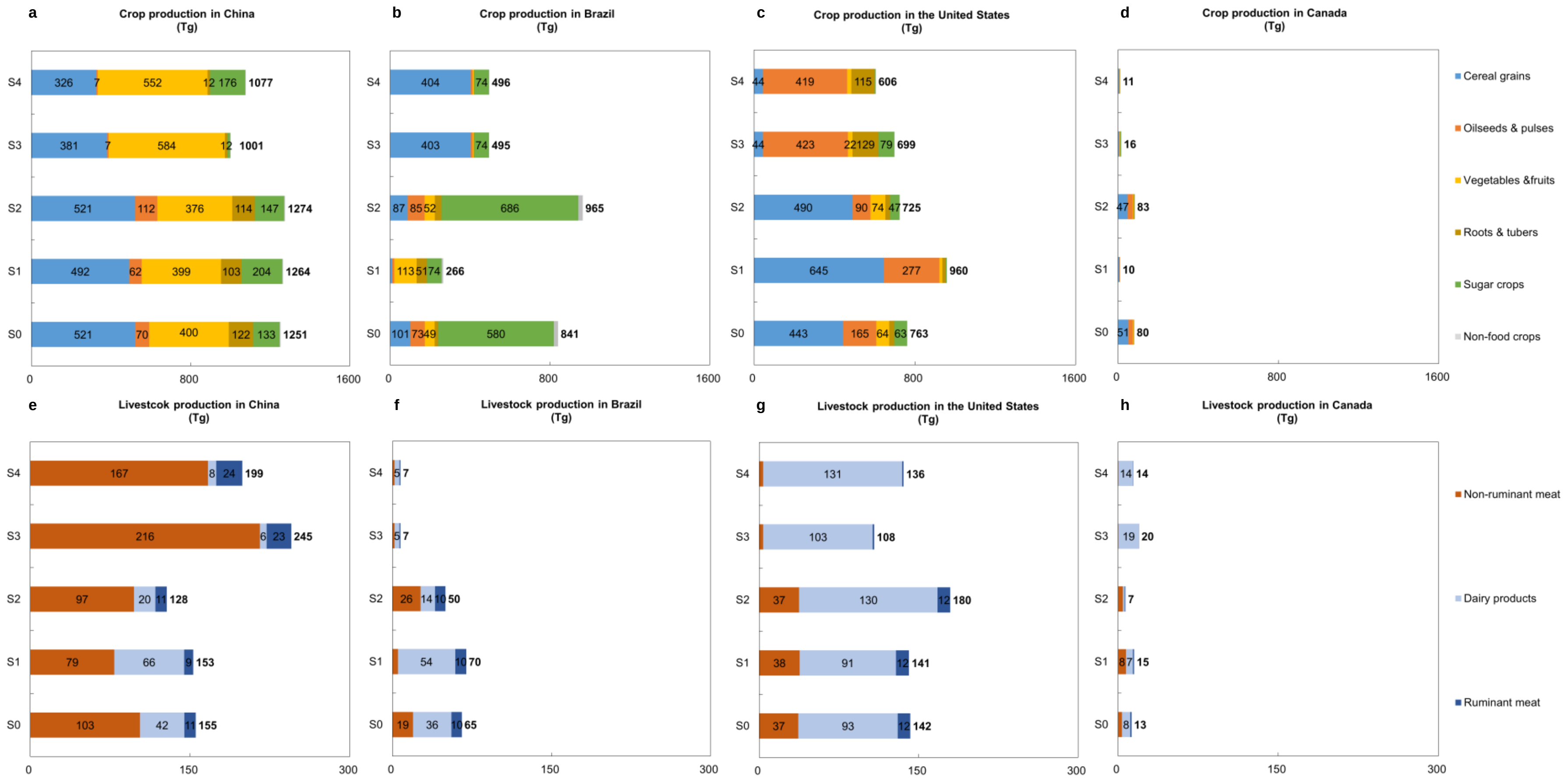

Fig. 3 | Impacts of mitigation measures on crop production and livestock production in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Crop production (Tg) in (**a**) China, (**b**) Brazil, (**c**) the United States, and (**d**) Canada in scenarios S0-S4. Livestock production (Tg) in (**e**) China, (**f**) Brazil, (**g**) the United States, and (**h**) Canada in scenarios S0-S4.

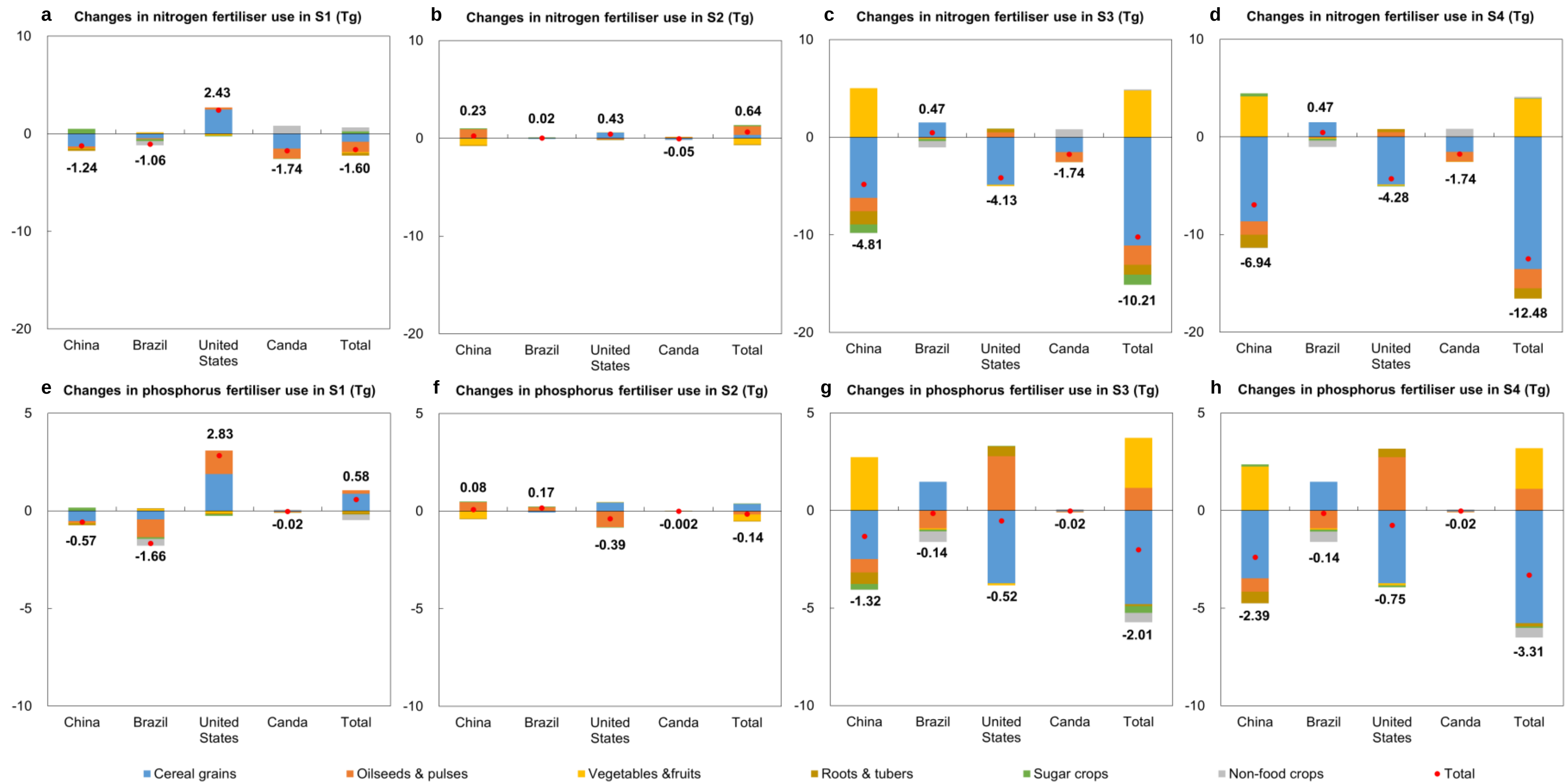

Fig. 4 | Impacts of mitigation measures on nitrogen fertiliser use and phosphorus fertliser use in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in nitrogen fertiliser use (Tg) in China and MTP in scenarios (**a**) S1, (**b**) S2, (**c**) S3, and (**d**) S4 with respect to the baseline (S0). Changes in phosphorus fertliser use (Tg) in China and MTP in scenarios (**e**) S1, (**f**) S2, (**g**) S3, and (**h**) S4 with respect to the baseline (S0).

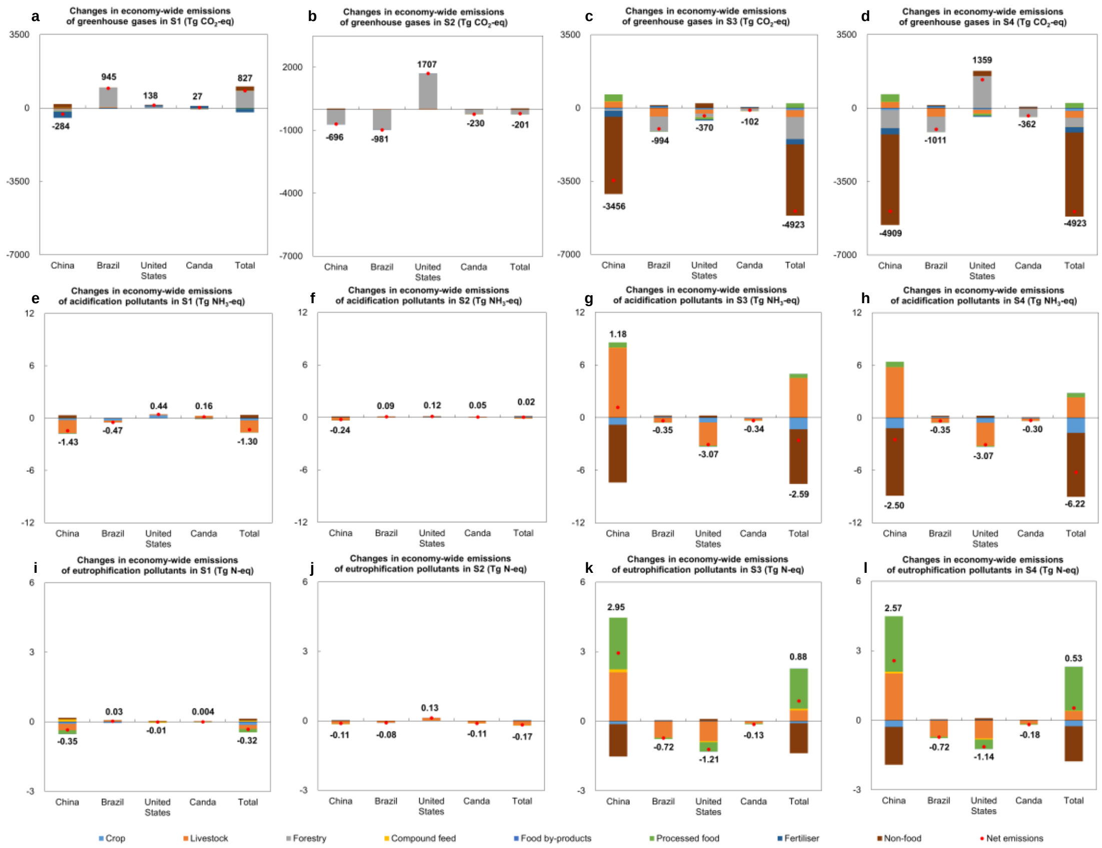

Fig. 5 | Impacts of mitigation measures on economy-wide emissions in China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). Changes in economy-wide emissions of greenhouse gases (Tg CO_2-eq) in China and MTP in scenarios (**a**) S1, (**b**) S2, (**c**) S3, and (**d**) S4 with respect to the baseline (S0). Changes in economy-wide 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 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).

Table 1. Trade-offs and synergies in the food-land-climate nexus.

Scenarios	SDG 2 (zero hunger)	SDG 15 (Life on land)	SDG 13 (climate action)
S1: Food scenario	Average food price: -0.06%	• Afforestation in China: +6 Mha • Deforestation in trading partners: -30 Mha	• China's GHG emissions: -2.4% • Global GHG emissions: +4.2%
S2: Land scenario	Average food price: +0.006%	• Afforestation in China: +42 Mha • Deforestation in trading partners: -7Mha	• China's GHG emissions: -5.9% • Global GHG emission: -1.0%
S3: Climate scenario	Average food price: +138%	• Afforestation in China: +4 Mha • Afforestation in trading partners: +33 Mha	• China's GHG emissions: -29% • Global GHG emission: -25%
S4: Combined scenario	Average food price: +205%	• Afforestation in China: +51 Mha • Afforestation in trading partners: -5 Mha	• China's GHG emissions: -42% • Global GHG emission: -25%

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