Rebound effects may undermine benefits of upcycling food waste and food processing by-products as animal feed in China

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Abstract

Upcycling food waste and food processing by-products as animal feed could reduce livestock-related emissions, but rebound effects, where lower feed costs lead to livestock expansion, may diminish these benefits. Using an integrated environmental-economic model, we assess the impacts of this upcycling in China's monogastric livestock production. We find that the upcycling increases monogastric livestock production by 23-36% and raises total acidification emissions in China by 2.5-4.0%, while domestically total greenhouse gas emissions decrease by 0.5-1.4% through less waste sent to landfills and incinerators and non-food contraction. This upcycling enhances food security and has significant knock-on effects beyond the agricultural sectors, thereby influencing sectoral employment, gross domestic product, and household welfare. While emission taxes could absorb the rebound effects on emissions, they may also negatively impact food security and shift emissions abroad, depending on tax levels. Our study, thus, supports policy design aimed at achieving environmental sustainability and food security.

Keywords

circular food system; food waste; food security; environmental impacts; environmental-economic modelling; rebound effects.

Main

Animal-sourced food (ASF), such as meat, milk, and eggs, is the main contributor to the environmental impacts of food systems, including global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) [1]. The global demand for ASF, driven by population growth and increased prosperity and urbanisation, is expected to double by 2050, especially in emerging economies [2,3]. This surge in livestock production has exacerbated food-feed competition and contributed to the exceedance of the planetary boundaries (PBs) for emissions of greenhouse gases (GHGs), acidification pollutants, and eutrophication pollutants [4]. Currently, livestock production uses 70% of global agricultural [5] and contributes 13-18% of anthropogenic GHG emissions [6], 40% of the ammonia (NH_3) and nitrous oxide (N_2O) emissions [7], and around 24% of nitrogen (N) and 55% of phosphorus (P) losses to water bodies [8]. Without addressing emissions from livestock, achieving climate targets and reducing emissions of acidification and eutrophication pollutants will remain challenging.

Globally, the estimated share of food produced for human consumption that is lost or wasted increased from one-third (1.3 billion tons per year) in 2011 [9] to 40% (2.5 billion tons per year) by 2021 [10]. This rise reflects a more comprehensive assessment that includes previously excluded on-farm losses and updated data across the entire supply chain. A large proportion of food waste ends up in landfills or incinerators, exacerbating GHG emissions and climate change [11]. Upcycling food waste and food processing by-products (also called "low-opportunity-cost feed products (LCFs)"), as animal feed presents a circular strategy to recycle nutrients that would otherwise be lost, mitigate land pressure, alleviate food-feed competition, and reduce emissions from food systems and waste disposal [12-14]. The upcycling prioritises land for food rather than feed production and supports food supply without expanding land use, thereby enhancing food security, reducing emissions [12-14], and contributing to Sustainable Development Goals (SDGs), including SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 13 (climate action), and SDG 15 (life on land) [15].

Despite recognition of its environmental benefits, knowledge gaps remain regarding the rebound effects associated with upcycling food waste and food processing by-products as animal feed. First, previous linear optimisation studies [12-14] may have overestimated the environmental benefits by neglecting "rebound effects" [16], where lower feed costs lead to livestock production expansion, potentially diminishing environmental benefits. While "rebound effects" have been extensively studied in energy systems [17,18], their implications in food systems remain underexplored. Some studies have explored the rebound effects of dietary shifts [19] and halving food loss and waste [20], but the rebound effects of upcycling remain largely unquantified. Second, strategies to absorb these rebound effects have not yet been explored. Implementing synergistic emission taxes that encompass emissions of GHGs and pollutants leading to acidification and eutrophication is considered an effective policy instrument to identify the most economically cost-effective mitigation pathway for achieving given mitigation targets [21-23]. Such emission taxes can reduce production in emission-intensive sectors (e.g., livestock) and promote producers and consumers to transition from emission-intensive goods to cleaner alternatives. Thus, a coordinated strategy that integrates upcycling with emission taxes is essential to help absorb the rebound effects. However, unilateral carbon taxes may lead to "carbon leakage", as emission-intensive production may shift to regions with weaker carbon regulations, thereby reducing policy effectiveness [24,25]. This highlights the need for internationally coordinated action, such as the recent net-zero commitments under the Paris Agreement [26]. Moreover, an integrated tax plan for taxes on emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), and sulphur dioxide (SO_2) from energy use in China can reduce socioeconomic and welfare costs by 50% compared to independent plans [23]. This underscores the importance of combining carbon and other environmental taxes to achieve a win-win situation for the economy and environment.

This study focuses on China, the world's largest livestock producer, responsible for 46% of global pork, 34% of eggs, and 13% of poultry production in 2018 [3]. Moreover, around 27% of food produced for human consumption is lost or wasted in China [27], implying an opportunity for large-scale upcycling. In addition, the Chinese government has proposed to lower the agricultural product processing loss to below 3% by 2035 [28] and to substitute human-edible feed ingredients (e.g., soybeans, maize) in animal feed with food waste and food processing by-products [29]. Evidently, before this action plan is widely implemented in China, there is a great need to better understand potential rebound effects that may influence the expected benefits of upcycling.

To address these gaps, we use an integrated environmental-economic applied general equilibrium (AGE) modelling approach to assess the impacts of the environmental and economic impacts of upcycling food waste and food processing by-products as feed in China's monogastric livestock production, capturing both domestic effects in China and cross-border impacts on its main food and feed trading partners (MTP, including Brazil, the United States, and Canada) through bilateral trade. We also explore how implementing regional uniform emission taxes on economy-wide emissions (i.e., total emissions from all sectors in the entire economy) of GHGs (including CO_2, methane (CH_4), and N_2O), acidification pollutants (including NH_3, NO_x, and SO_2), and eutrophication pollutants (including N and P losses to water bodies) in China and MTP could absorb the rebound effects of this upcycling while safeguarding food security. We examine five scenarios: (i) the baseline (S0) scenario represents the economic and environmental conditions of all sectors (including agriculture, industries, and services) in the entire economies of China and MTP in 2014; (ii) scenario S1 involves partially upcycling (54% of food waste and 100% of food processing by-products used as feed); (iii) scenario S2 involves fully upcycling (100% of food waste and 100% of food processing by-products used as feed); (iv) scenario S3 combines S1 with modest emission taxes to ensure that economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants in China and MTP do not exceed their baseline (S0) levels; (v) scenario 4 combines S1 with ambitious emission taxes to meet China's and the MTP's annual economy-wide GHG mitigation targets under the Intended Nationally Determined Contributions (INDC) of the Paris Agreement [26], as well as China's emission reduction goals for economy-wide emissions of acidification and eutrophication pollutants in line with the "14th Five-Year Plan" [30]. In S1, cross-provincial transportation of high-moisture food waste is not allowed, limiting its utilisation to 54% in China according to Fang, et al. [13], whereas it is allowed in S2. We consider food waste (cereal grains waste, vegetables & fruits waste, roots & tubers waste, and oilseeds & pulses waste) during distribution, retailing, and consumption (both households and out-of-home), as well as food processing by-products (cereal bran, alcoholic pulp, and oil cakes). Total protein and energy supplies per unit of animal output are kept constant in all scenarios. Detailed scenario assumptions and sensitivity analyses are provided in Supplementary Information (SI).

Results

Overview of current utilisation of food waste and food processing by-products.

In 2014, China produced about 104 Tg (1 Tg = 10^6 tons) of monogastric livestock products (pork: 57 Tg; poultry meat: 18 Tg; egg: 29 Tg) and 53 Tg of ruminant livestock products (milk: 42 Tg; beef: 6 Tg; lamb: 4 Tg) [3]. We estimate that 226 Tg food waste (equivalent to 54 Tg in dry matter; 7 Tg in crude protein; 690 billion MJ in energy) and 155 Tg food processing by-products (equivalent to 139 Tg in dry matter; 49 Tg in crude protein; 1907 billion MJ in energy) were available in China in 2014, but only 39% of the food waste and 51% of the food processing by-products were recycled as feed for monogastric livestock production, with the remainder disposed in landfills and incinerators (Supplementary Tables 3-4). Food waste remains underutilised as feed in China due to the early-stage development of recycling infrastructure and the livestock sector's reliance on concentrated feed [2]. Although many by-products (e.g., unprocessed oil cakes) are protein-rich, they contain anti-nutritional factors that hinder nutrient absorption. Fermentation can mitigate these effects and enhance digestibility [31], but its limited adoption leads to large volumes of by-products being discarded in landfills or incinerators.

Rebound effects of livestock production expansion.

Unlike previous studies that considered upcycling as costless [12-14], we assume that increasing costs of upcycling are born by monogastric livestock producers, and consumers benefit from decreasing costs associated with less waste sent to landfills and incinerators. We find that upcycling in scenarios S1 and S2 increases the share of food waste and food processing by-products used as feed within the total feed use in dry matter from 43% in S0 to 53-58% in S1 and S2 (Supplementary Fig. 2b). Upcycling increases the supply of feed protein by 27-40% and feed energy by 26-39%, and reduces total feed cost per unit of monogastric livestock production by 2.1-3.0%. Consequently, the upcycling expands monogastric livestock production by 23-36% in S1 and S2 (Fig. 2b). This expansion improves China's comparative advantage in monogastric livestock trade in the global market, transforming it from a net importer (importing 1% of output in S0) to a net exporter (exporting 18-25% of output in S1 and S2) (Fig. 2e) while displacing production in its trading partners, which declines by 41-63% (Supplementary Fig. 8b,d). As a result, total monogastric livestock production across China and its trading partners increases slightly (0.08-0.18%), leading to a minute decline (0.11-0.19%) in the global monogastric livestock price (Supplementary Fig. 15). Ruminant livestock production decreases by 3% as the expansion of monogastric livestock reduced the availability of feed crops and compound feed to ruminant livestock (Fig. 2b). To meet domestic demand, ruminant livestock imports rises from 1% of output in the baseline (S0) to 4% (Fig. 2e).

Expanded monogastric livestock production raises the demand for primary feed (i.e., feed crops and compound feed), which surprisingly outweighs the reduction in primary feed use by substituting it with food waste and food processing by-products. The overall feed demand for both monogastric and ruminant livestock increases by 17-34% due to a 33-67% rise in feed demand in fresh form for monogastric livestock (Fig. 3b). The upcycling increases the feed conversion ratio (FCR, the ratio of fresh feed inputs to live weight gain) for monogastric livestock by 0.22-0.62 kg kg^{-1}, but decreases the edible feed conversion ratio (eFCR, the amount of human-edible feedstuffs, i.e., feed crops and compound feed, used for per unit of live weight gain) by 0.11-0.19 kg kg^{-1}, indicating its reduced reliance on human-edible feedstuffs (Supplementary Fig. 3a). Since feed crops and compound feed account for only 12% of ruminant feed (compared to 88% from grass, see Supplementary Fig. 4d), upcycling has a minor impact on ruminant production and its FCR and eFCR (Supplementary Fig. 3b). The growing demand for crops used as animal feed increases reliance on crop imports, with the import share rising from 11% in the baseline (S0) to 15-19% (Fig. 2d), considering that the total crop production declines by 1.2-4.4% (Fig. 2a). Despite the decline in crop production, the cultivated crop area expands by 0.6-13% (Fig. 3a), driven by higher labour costs (Supplementary Fig. 5) and reduced labour availability (Supplementary Fig. 7), which incentivise crop producers to substitute labour with increased cropland use. Adjustments in crop and livestock production also have knock-on effects beyond the agricultural sectors in the broader economy, thereby influencing sectoral employment, gross domestic product (GDP), and household welfare (a measure of economic well-being in US dollars). Upcycling shifts labour from the non-food sector to monogastric livestock and fertiliser production, with economic losses in crop and non-food sectors largely offset by expansions in these sectors (Supplementary Fig. 9a), resulting in a slight GDP decline (0.02–0.07%) (Supplementary Fig. 11) and improved household welfare (0.18–0.32%)

(Supplementary Fig. 12). Detailed impacts on crop production and fertiliser use, as well as knock-on effects beyond the agricultural sectors, are presented in Supplementary Results.

Asymmetric impacts of upcycling food waste and food processing by-products on food security and environment sustainability.

We find that the 23-36% expansion in monogastric livestock production in S1 and S2, along with its knock-on effects beyond the agricultural sectors, increase Chinese economy-wide emissions of acidification pollutants by 2.5-4.0% (Fig. 4b) and eutrophication pollutants by ±0.2% (Fig. 4c). In contrast, the 0.5-1.4% decrease in economy-wide GHG emissions in China is caused by less waste sent to landfills and incinerators and non-food contraction (Fig. 4a). Economy-wide emissions in MTP are reduced by 1.1-1.3% for GHGs, by 8-13% for acidification pollutants, and by 2.5-4.0% for eutrophication pollutants. These environmental benefits for MTP arise from a reduction in their domestic livestock and fertiliser production as China shifts from a net importer to an exporter of livestock products and fertilisers (Fig. 2e,f).

For assessing food security, we use four indicators covering two dimensions: two indicators for food availability, i.e., dietary energy availability and the population at risk of hunger; two indicators for food access, i.e., cereals affordability for labour force and the average food price. Population at risk of hunger is estimated by multiplying the prevalence of undernourishment (PoU), determined primarily by dietary energy availability from our model, by the total population. Cereals affordability for labour force is estimated by subtracting changes in the average wage across the entire economy from fluctuations in cereal prices. Our findings suggest that upcycling, accompanied by resource reallocation across the entire economy, enhances food security in China without compromising that of its trading partners. In addition, the reduced cost of food waste disposal enables consumers in China to allocate more of their income to food consumption. Since the cost of food waste disposal is relatively small in the baseline (S0), the resulting improvements in most food security indicators are modest. Globally, the average food price declines by 0.1-0.2% (Fig. 5a,e). In China, dietary energy availability increases by 0.2-0.3%, and the population at risk of hunger decreases by 1.6-3.2% (Fig. 5c,d). Cereals affordability for labour force increases by 0.3-0.5% (Fig.

5b), as a result of a rise in the average wage across the Chinese economy (0.13-0.22%) (Supplementary Fig. 5) and a decrease in cereals price (0.16-0.26%) (Supplementary Fig. 15).

Absorbing rebound effects through emission taxes.

The modest mitigation target of S3 absorbs the rebound effects estimated for S1 in China (Fig. 4) and safeguards global food security. Changes in food security indicators under S3 are nearly identical to those in S1 (Fig. 5). This is due to the relatively low tax rates on emissions of acidification pollutants (3 \$ ton^{-1} NH_3-eq) in China. The reduction in emissions of all pollutants in S3 is mainly attributed to a decrease in total crop production compared to S1 (Fig. 2a; Fig 4; Supplementary Fig. 14a,b,c). Monogastric and ruminant livestock production decreases slightly by 0.40% and 0.03%, respectively, in S3 compared to S1 (Fig. 2b). The reduction in total feed cost per unit of monogastric livestock production in S3 remains virtually unchanged from S1. Phosphorus fertiliser production increases by 40% while nitrogen fertiliser production decreases by 6% compared to S1 (Fig. 2c). As a result, emissions increase in MTP compared to S1 (Fig. 4) due to a shift of emission-intensive production from China to MTP. Nonetheless, emissions of all pollutants in MTP still remain below baseline (S0) levels.

The ambitious mitigation target of S4 counteracts the rebound effects estimated for S1 further and achieves a further emission reduction but poses a risk to food security, as the average global food price increases by 9.4% (Fig. 5a,e) and cereals affordability for labour force decreases by 20.2% in China (Fig. 5b) and by 14.5% in MTP (Fig. 5f). The negative impact on food security in China and MTP is a result of the relatively high tax rates on emissions in both regions (5 \$ ton^{-1} CO_2-eq , 788 \$ ton^{-1} NH_3-eq, and 6969 \$ ton^{-1} N-eq in China; 2.5 \$ ton^{-1} CO_2-eq in MTP). Emission taxes on acidification and eutrophication pollutants are significantly higher than those on GHGs because their lower emission levels compared to GHGs (see Appendix Tables 5-7) required higher tax rates to achieve the same mitigation target. Food availability in MTP decreases by 3.3%, while it increases by 3.6% in China (Fig. 5d,h), primarily driven by two factors in the latter case. First, ambitious emission taxes reduce emission-intensive livestock production (Fig. 2b), thereby freeing up feed crops for human consumption (Supplementary Fig. 4c). Second, consumers shift from animal-based food to more energy-dense plant-based food (Supplementary Table 8), which are less emission-intensive and thus cheaper. Consequently, the population at risk of hunger in MTP increases by 346% but declines in China by 36% (Fig. 5 c,g). The 2.6% and 2.5% reduction in economy-wide emissions of GHGs and acidification pollutants in China in S4 are largely driven by the non-food contraction compared to S1 (Fig. 4a,b). The 2.0% reduction in economy-wide emissions of eutrophication pollutants (Fig. 4c) in China is primarily driven by 16% less monogastric livestock production and a 7% decline in ruminant livestock production in S4 compared to S1 (Fig. 2b; Supplementary Fig. 14f). The total feed cost per unit of monogastric livestock production in S4 decreases by an additional 2.3% compared to S1, driven by a shift in feed composition from human-edible feedstuffs (i.e., feed crops and compound feed) to less expensive food waste and food processing by-products. This transition is reflected in a further 0.07 kg kg^{-1} reduction in eFCR for monogastric livestock (Supplementary Fig. 3a). For MTP, the 2.0% reduction in economy-wide GHG emissions can largely be attributed to reductions in total crop and livestock production (Fig. 4a). Meanwhile, economy-wide emissions of acidification and eutrophication pollutants decrease both by 5% in MTP (Fig. 4b,c).

Discussion

Upcycling food waste and food processing by-products as animal feed.

The primary challenges in upcycling food waste and processing by-products as animal feed are concerns over food and feed safety and potential animal health risks. For example, European Union (EU) legislation prohibits food waste in animal feed due to disease transmission concerns [32]. In contrast, it is more prevalent in Asian countries such as China, South Korea, and Japan, driven by growing demand for animal-sourced food, resource constraints that prioritise food production over feed, and the preference for low-cost alternative feeds among small-scale farms [11]. Extensive field-based evidence has demonstrated that properly treated food waste poses minimal health risks to animals [33]. Thermal treatments (e.g., heating, drying, and dehydration) are widely used to reduce pathogen transmission risks and ensure food and feed safety [11]. While upcycling food waste as feed has been shown not to affect livestock productivity [11], its adoption depends on demonstrating economic competitiveness relative to conventional feed [33]. Large-scale upcycling necessitates investments and policies to support infrastructure for collecting, sanitising, and distributing discarded food waste and food processing by-products to livestock producers [13]. In China, achieving near-full upcycling appears feasible due to recent expansion in the food waste treatment industries [34], strengthened municipal solid waste separation and collection policies [35], and supportive government initiatives, such as the 2025 pilot program in 20 cities to promote feed production from food waste [36]. Moreover, the proximity of industrial livestock farms to municipal waste processors further enhances this feasibility [34].

Rebound effects of upcycling food waste and food processing by-products as animal feed.

Our findings are particularly informative for policymakers focusing on reducing the environmental impact of food systems and enhancing food security, as we unveil the asymmetric impacts of upcycling on food security and environment sustainability. A decreased eFCR for monogastric livestock reflects reduced reliance on human-edible feedstuffs per unit of production. While these benefits align with prior findings, our study additionally identifies the rebound effects overlooked in previous linear optimisation studies [12-14]. We find that partially or fully upcycling, intended to reduce livestock demand for human-edible feedstuffs and lower emissions, can backfire: a 2.1-3.0% reduction in feed costs drives a 23-36% expansion in monogastric livestock production, ultimately increasing emissions. This livestock expansion is consistent with Tong, et al. [37], who estimated that upcycling food waste as feed could increase pork production in China by 14-29%, even when costs and prices remain constant. Additionally, this expansion, along with its knock-on effects beyond the agricultural sectors, increases economy-wide emissions of acidification and eutrophication pollutants in China by 2.5-4.0% and by ±0.2%, respectively, in S1 and S2. In contrast, the 0.5-1.4% decrease in economy-wide GHG emissions in China is caused by less waste sent to landfills and incinerators and non-food contraction. China's trading partners obtain environmental benefits through reduced domestic livestock and fertiliser production, as China becomes a net exporter of both. This upcycling, accompanied by resource reallocation across the entire economy, enhances food security in China without compromising that of its trading partners. Our estimation of the rebound effects aligns with Wang, et al. [38], who found that accelerated investments in technology and infrastructure, which boot crop yield in China, not only increase GHG emissions from agriculture, forestry, and other land-use sectors due to expanded crop production for export but also improve domestic food security by lowering food prices. Our results also echo Hegwood, et al. [20], who argued that rebound effects could offset more than half of avoided food loss and waste, thereby reducing environmental benefits while enhancing food security. While ambitious emission taxes counteract rebound effects, they increase food prices by 9.4%, posing risks to global food security. This aligns with Hasegawa, et al. [21], who revealed food insecurity risk under stringent climate policies. Conversely, modest emission taxes provide an opportunity to absorb the rebound effects and safeguard global food security. Our analysis highlights that while upcycling enhances food security, it may also lead to unintended environmental consequences, underscoring the need to integrate food security and environmental sustainability into policy design to leverage potential win-win opportunities. Detailed discussion on the interconnection between food security and environmental sustainability is provided in the Supplementary Discussion.

Despite its integrated approach, this study has some limitations that necessitate some follow-up. First, model simplifications, such as fixed budget shares for consumers, fixed cost shares for producers, and the absence of trade barriers, may exaggerate trends but are appropriate for illustrating rebound effects. Second, our model overlooks sub-national heterogeneity, and future research could address this by improving spatial resolution to provide region-specific policy insights. Third, we use dollar-based shares to allocate physical material flows without accounting for variations in product quality along the global supply chain, which may introduce conversion uncertainties. While this remains a common approach [19,39], it also highlights the need for further research to address this limitation. Fourth, 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, COVID-19) that may reshape agri-food systems. Future work could address these gaps through dynamic modelling and extra scenario analyses . To account for uncertainty, we conducted sensitivity analyses on five key factors: (1) feasibility of upcycling food waste and food processing by-products as feed; (2) conversion of dollar-based quantities to physical quantities; (3) substitution of cropland with other inputs for crop production; (4) cereal self-sufficiency target; (5) cleaner crop and livestock production technology. While potential data variations may moderately influence the magnitude of our results, they do not alter the overall trends, and our main conclusions remain plausible. Further details on these limitations and uncertainties are detailed in the Supplementary Discussion. Overall, our integrated environmental-economic framework supports policy design aimed at achieving the dual dividend of environmental sustainability and food security. Our analysis holds significant policy implications not only for China, a key global market for food and feed, but also serves as a blueprint for other emerging economies seeking to balance these dual priorities.

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, [24] and enhanced sectoral representation for agricultural (6 crop types and 2 livestock categories) and non-agricultural (compound feed, food processing by-products, processed food, fertilisers, food waste treatment, and non-food) sectors (see Fig. 1). While the static model limits its applicability to short-term policy analysis, prior studies have shown that it minimises assumptions and uncertainties about future conditions on population and economic growth [22]. This allows us to isolate the impact of upcycling food waste and food processing by-products as animal feed and implementing emission taxes under current economic conditions.

AGE models grounded in microeconomic theory represent the entire economy by integrating consumer demand, producer decisions, and market clearing into a unified framework. Consumers maximise utility by allocating income across goods and services within budget constraints, given prices and initial endowments. Producers maximise profits by selecting optimal input combinations based on production technology and given prices under perfect competition, following a zero-profit condition. This condition means that output values match input costs, preventing excess profits in constant returns to scale firms, as new firms increase supply, lower prices, and drive profits to zero, while firms incurring losses will exit the market, maintaining market equilibrium. The market clearance condition states that a market is in equilibrium when total supply equals total demand. In line with this principle, the economy reaches equilibrium when total supply matches total demand across all markets, with relative prices adjusting until consumers and producers can meet their effective demand and supply. Total supply consists of domestic production and imports, while total demand includes intermediate use by firms, household consumption, and exports. The resulting equilibrium prices ensure that all markets are cleared. For international trade, our AGE model adopted the Heckscher-Ohlin (H-O) trade assumption, treating domestic and imported goods as perfect substitutes. Under this assumption, production occurs in countries with comparative advantages, meaning goods are produced where they can be most efficiently produced. Detailed specifications of our AGE model can be found in the Supplementary Information (SI).

Our model distinguishes two regions: China and its main food and feed trading partners (MTP, including Brazil, the United States, and Canada). We select 2014 as the reference year, as it is the latest available year in the Global Trade Analysis Project (GTAP) database [40] at the time of our research. Our model is solved using the general algebraic modelling system (GAMS) software package [41]. We exclude the rest of the world (RoW) because, according to GTAP [40] trade flow data, MTP accounts for over 75% of China's total food and feed trade value in 2014, while China's trade share with RoW is smaller at 25%. Detailed information on China's domestic use and trade shares of food and feed products with MTP and RoW is provided in Supplementary Table 9. We observe that China maintains nearly 99% self-sufficiency in monogastric livestock production, with imports accounting for only 1% (0.8% from MTP and 0.2% from RoW; see Supplementary Table 9). Furthermore, monogastric livestock production in China and MTP together represents approximately 50% of global production (Supplementary Table 10).Thus, China's domestic food production plays a primary role in shaping its trade balance with MTP. Our two-region framework effectively captures the most significant trade flows influencing China's food system, while simplifying the model calculations.

Modelling circularity in livestock production requires a detailed representation of biophysical flows to consider nutritional balances and livestock feeding requirements due to increased utilisation of food waste and food processing by-products as feed for monogastric livestock production. Following Gatto, et al. [19] and Chepeliev [39], we convert dollar-based quantities (million USD) to physical quantities (Tg; 1 Tg = 10^6 tons) to allow the tracing of biophysical flows through the global economy. A detailed conversion process is described in the Supplementary Methods. Livestock categories are aggregated into monogastric livestock (including pigs, broilers, and laying hens) and ruminant livestock (including dairy cattle, other cattle, and sheep & goats). Furthermore, the inclusion of animal-specific dietary constraints in our model allows us to calculate the nutritional balance (crude protein and digestible energy), feed conversion ratios (FCR, the ratio of fresh feed inputs to live weight gain), and edible feed conversion ratio (eFCR, the amount of human-edible feedstuffs, i.e., feed crops and compound feed, used for per unit of live weight gain) for each livestock sector. First, we estimate the physical quantities of feed protein (Tg) and energy (billion MJ) required to produce the physical output of each livestock sector (Tg) in the reference year based on the FAO-FBS data and nutritional (i.e., protein and energy) contents of feed sub-groups (see Supplementary Table 7). Then, we obtain the initial composition of total feed (including feed crops, compound feed, food waste, food processing by-products, and grass) supplied to each livestock sector in the reference year. When substituting primary feed (i.e., feed crops and compound feed) in animal diets with food waste and food processing by-products, the total protein and total energy supplies per unit of animal output are kept constant in all scenarios. Our FCRs for ruminant livestock are slightly different from FCRs in the literature, as we do not fully account for maize silage, alfalfa hay, and roughage-like by-products, but this bias does not affect the impacts of upcycling food waste and food processing by-products for monogastric livestock production. Further model details, nutritional balance, and detailed composition of animals' diets are available in the SI.

Modelling amounts and impacts of food waste and food processing by-products.

In this study, we consider food waste and food processing by-products. Food waste is considered a local resource within China, while food processing by-products can be traded between China and MTP. We focus on food intended for human consumption that is wasted during distribution, retailing, and consumption (both households and out-of-home), as it has a high potential for upcycling as animal feed. In contrast, food loss, which occurs earlier in the supply chain, is often driven by poor infrastructure and is not easily prevented or repurposed for feed use [13]; therefore, it is excluded from our analysis. Additionally, we only consider plant-sourced food waste because animal-sourced food waste may pose a risk of pathogen transfer, including foot-and-mouth and classical swine fever [42]. Food waste is quantified separately for each type of food product by multiplying primary food products after processing by China-specific food waste fractions [27] following the FAO methodology [43]. Four types of food waste are distinguished, including cereal grains waste, vegetables & fruits waste, roots & tubers waste, and oilseeds & pulses waste. Food processing by-products refer to by-products produced during the food processing stage, including 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). Food processing by-products are estimated by multiplying the production quantities of primary food products by FAO technical conversion factors for various by-products [44]. The total amounts of food waste and food processing by-products and their current use as animal feed and discarded biomass (i.e., landfill and incineration) for China in S0 are presented in Supplementary Table 4.

Our model incorporates two food waste treatment sectors, i.e., "food waste collection service" and "food waste recycling service" (Figure 1). The food waste recycling service sector recycles food waste and food processing by-products as feed for monogastric livestock production. The food waste collection service sector collects food waste and food processing by-products for landfill and incineration. Waste collection, treatment and disposal activities were included in the "Waste and water (wtr)" sector in the GTAP database. Food waste generation is added as a margin commodity, similar to how GTAP treated transport costs following Peterson [45]. Thus, the consumer price of food includes both the market price of food and the cost of collecting food waste and food processing by-products. Consumers spend their income on both consumption of goods and food waste collection service, but they derive utility solely from the consumption of goods. In terms of recycling food waste and food processing by-products as feed, monogastric livestock producer bears the associated cost. By multiplying the quantities of food waste with the unit costs of food waste treatment, we can calculate the economic value of food waste generation. Physical quantities and prices of food waste recycling and collection services in China are presented in Supplementary Tables 4-5.

Environmental impact assessment.

Economy-wide emissions considered in our study are limited to the production-related stages from all sectors in the entire economies of China and MTP, excluding land use change and household consumption. Specifically, emissions from both agricultural (6 crop types and 2 livestock categories) and non-agricultural (compound feed, food processing by-products, processed food, fertilisers, food waste treatment, and non-food) production are quantified. In line with other studies [46], land use is considered to be constant here, allowing to focus on changes in total emissions from all sectors in the entire economy without addressing the impacts of context-specific land use change. Detailed information about emission sources across sectors is provided in Appendix Table 4.

Three main environmental impacts 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 to water bodies; converted to N equivalents). The conversion factors for GWP, AP, and EP are derived from Goedkoop, et al. [47]. Detailed information on the data sources for the three environmental impacts, land use, and fertiliser use, is provided in the Supplementary Methods. The total emissions of GHGs, acidification pollutants, and eutrophication pollutants from all sectors in the entire economy 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 dollar-based emission intensities of GHGs (ton CO_2 equivalents million USD^{-1}), acidification pollutants (ton NH_3 equivalents million USD^{-1}), and eutrophication pollutants (ton N equivalents million USD^{-1}) are presented in Appendix Tables 5-10.

Food security indicators.

The FAO [48] 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. First, 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 [49]. In essence, the population at risk of hunger is determined by multiplying the prevalence of undernourishment (PoU) by the total population. 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. Second, 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, including one baseline (S0) scenario representing the economic and environmental conditions of all sectors (including agriculture, industries, and services) in the entire economies of China and MTP in 2014, two scenarios involving upcycling food waste and food processing by-products as animal feed, and two scenarios combining upcycling with emission mitigation measures. We implement regional uniform emission taxes on economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants in China and MTP under the partial use of food waste and food processing by-products as animal feed (scenario S1), considering the perishability and collection challenges of food waste, as well as the reduced availability of food waste for feed according to SDG 12.3 ("halving food waste") [15]. The latter four scenarios are compared to the 2014 baseline (S0) scenario. The scenarios are further described below and in Supplementary Table 1. To ensure the feasibility of upcycling, scenarios S1-S4 incorporate four key assumptions related to food waste source separation, collection, transportation, pre-treatment technologies, and consumer acceptance, which are detailed in the Supplementary Methods. We also provide comprehensive information in the Supplementary Methods on the estimation of feed cost and cost savings from increased utilisation of food waste and food processing by-products as feed under various scenarios.

S1 - Partial use of food waste and food processing by-products as feed. Scenario S1 analyses the impacts of partially upcycling food waste and food processing by-products (54% of food waste and 100% of food processing by-products) as feed for monogastric livestock production in China. Cross-provincial transportation of food waste is not allowed in S1, which limits the maximum utilisation rate of food waste with high moisture content to 54% in China, according to Fang, et al. [13].

S2 - Full use of food waste and food processing by-products as feed. Scenario S2 analyses the impacts of fully upcycling food waste and food processing by-products (100% of food waste and 100% of food processing by-products) as feed for monogastric livestock production in China. Cross-provincial transportation of food waste is allowed in S2 because we consider that new technology would become available for processing food waste with high moisture content. Economies of scale in food waste recycling are considered in S2; a 1% increase in recycled waste results in only a 0.078% rise in recycling costs [50]. Thus, as production scales up, marginal costs decrease and then stabilise.

S3 - S1 + A modest emission mitigation target. We implement regional uniform emission taxes to achieve a modest emission mitigation target, assuming that economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants in China and MTP do not exceed their baseline (S0) levels. For a given emission mitigation target for each type of pollutant, the AGE model can endogenously determine the emission taxes for various pollutants (expressed in \$ per ton of CO_2 equivalents, \$ per ton of NH_3 equivalents, and \$ per ton of N equivalents). This approach is commonly used in the literature [21,23] and allows to identify the most economically cost-effective mitigation pathway for achieving given emission mitigation targets.

S4 - S1 + An ambitious emission mitigation target. We implement regional uniform emission taxes to achieve an ambitious emission mitigation target, assuming that economy-wide emissions of GHGs, acidification pollutants, and eutrophication pollutants in China and MTP remain within the emission thresholds set by China's and the MTP's annual GHG mitigation targets under the Intended Nationally Determined Contributions (INDC) of the Paris Agreement [26], as well as China's emission reduction goals for acidification and eutrophication pollutants in line with the "14th Five-Year Plan" [30].

Sensitivity analysis.

To evaluate the robustness of our results and assess the relative importance of key input parameters, we conducted a series of sensitivity analyses and decomposed uncertainties into five major sources: (1) feasibility of upcycling food waste and food processing by-products as feed; (2) conversion of dollar-based quantities to physical quantities; (3) substitution of cropland with other inputs for crop production; (4) cereal self-sufficiency target; (5) cleaner crop and livestock production technology. We employed the one-at-a-time method to assess the sensitivity of food security indicators and environmental impacts to variations in these uncertainty sources. This approach, widely used in marginal impact analysis, isolates the effect of a single input variable while keeping all others constant. The larger the ratio of relative output change to relative input change, the greater the sensitivity of the results to that parameter. Further details on the series of sensitivity analyses are provided in Supplementary Discussion.

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 agricultural (6 crop types and 2 livestock categories) and non-agricultural (compound feed, food processing by-products, processed food, fertilisers, food waste treatment, 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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Author contributions

W.L., X.Z., H.P.W., and Y.H. designed the research. W.L. and X.Z. 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., H.P.W., O.O., and Y.H. 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 Supplementary Information (SI).

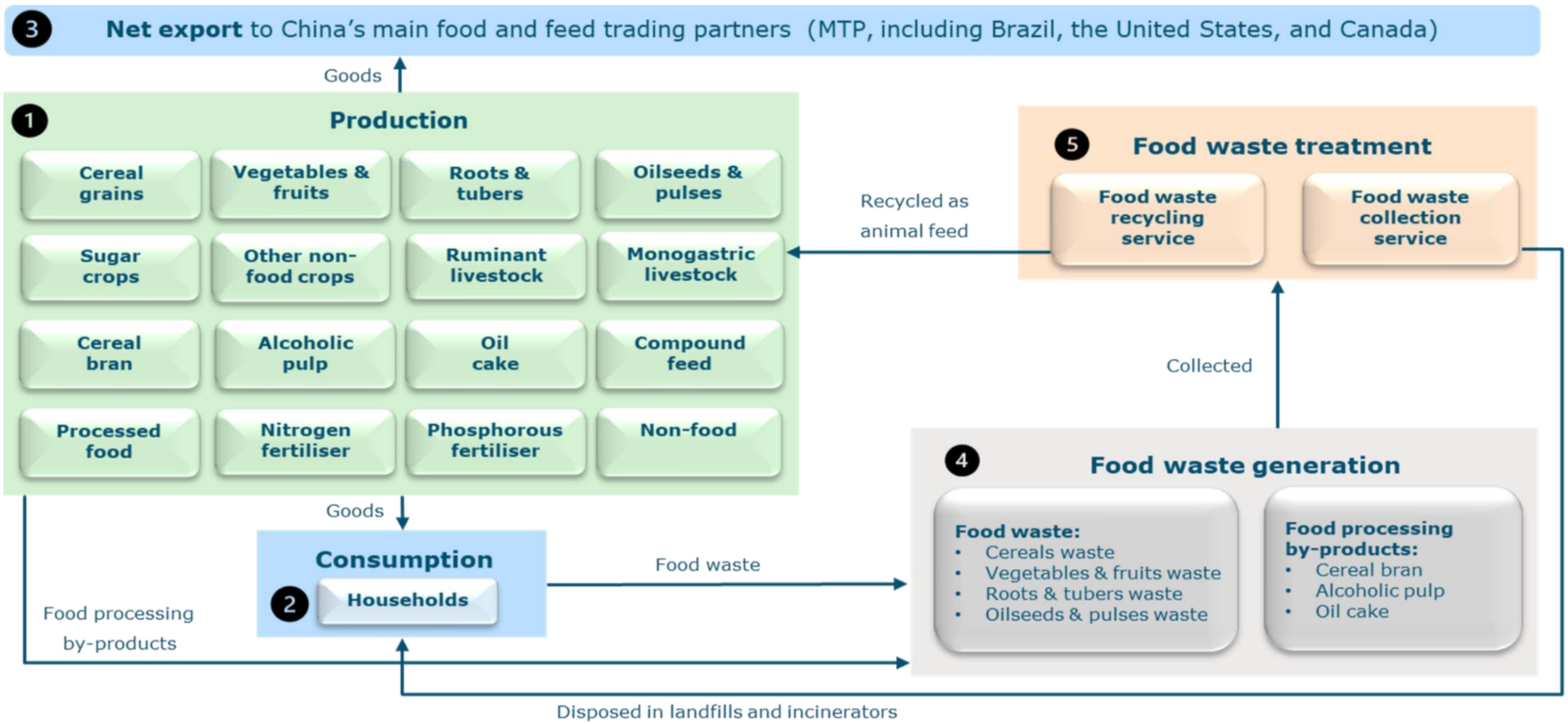

Fig. 1 | Representation of the economy in China in the applied general equilibrium (AGE) framework with food waste and food processing by-products. The framework includes four parts: (1) Production; (2) Consumption; (3) Net export; (4) Food waste generation; (5) Food waste treatment. The generated food waste and food processing by-products are sent either to the "food waste recycling service" sector or the "food waste collection service" sector. The food waste recycling service sector recycles food waste and food processing by-products as feed for monogastric livestock production. The food waste collection service sector collects food waste and food processing by-products for landfill and incineration. The consumer price of food includes both the market price of food and the cost of collecting food waste and food processing by-products. The monogastric livestock producer bears the cost of recycling food waste and food processing by-products as feed. Detailed information is presented in Methods and Supplementary Information.

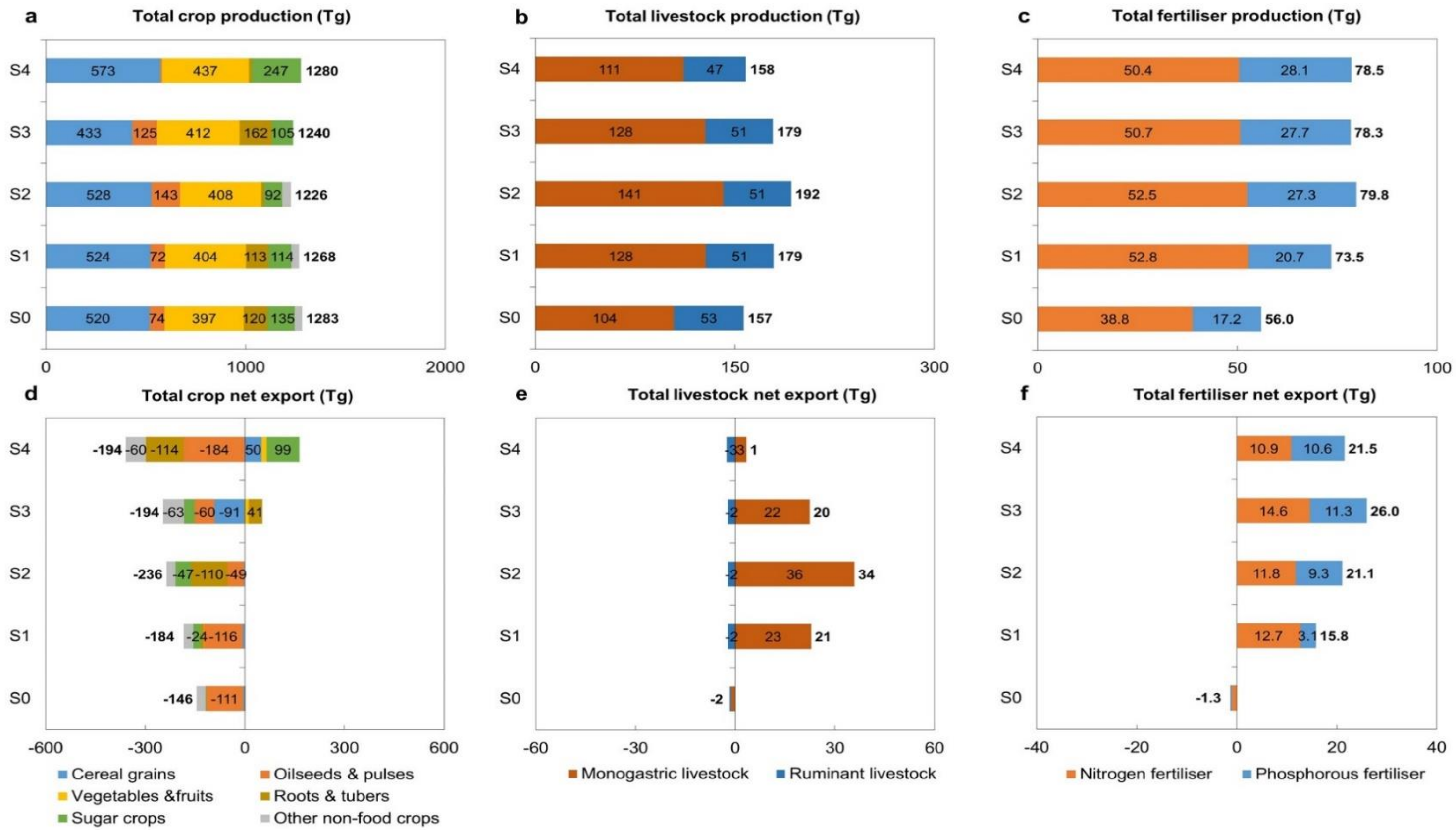

Fig. 2 | Impacts of upcycling food waste and food processing by-products as feed in China's monogastric livestock sector on domestic production and net export of total crop, livestock, and fertiliser. Total (**a**) crop, (**b**) livestock, and (**c**) fertiliser production (Tg) in scenarios. Total (**d**) crop, (**e**) livestock, and (**f**) fertiliser net export (Tg) in scenarios. Total crop production exclude food waste and food processing by-products used by "food waste recycling service" and "food waste collection service" sectors (see Supplementary Table 4 for detailed data). Definitions of scenarios (S1 - 'Partial use of food waste and food processing by-products as feed'; S2 - 'Full use of food waste and food processing by-products as feed'; S3 - 'S1 + A modest emission mitigation target'; S4 - 'S1 + An ambitious emission mitigation target') are described in Supplementary Table 1.

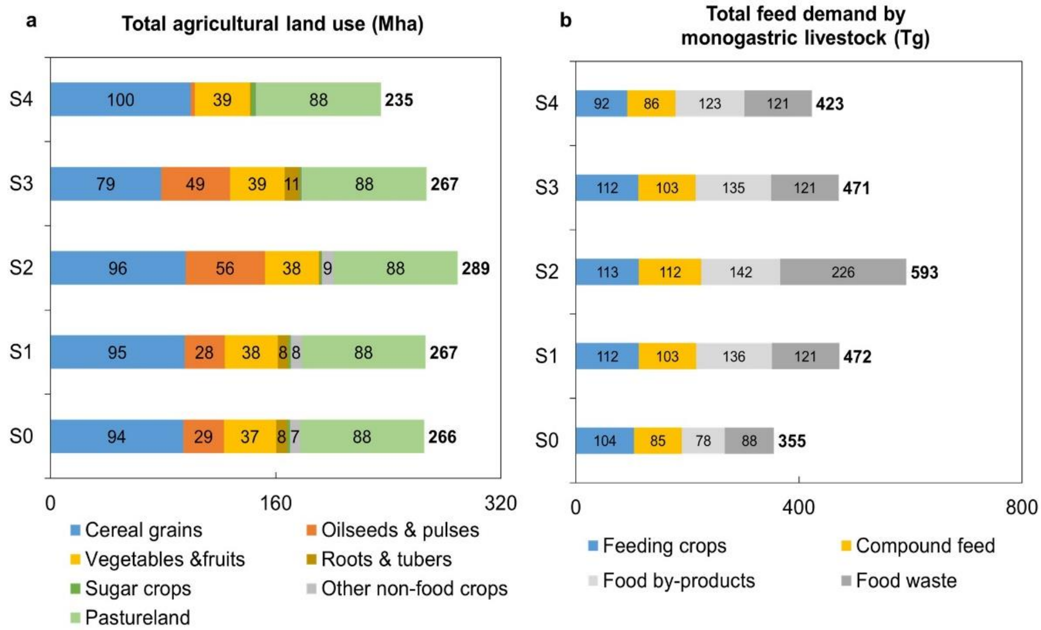

Fig. 3 | Impacts of upcycling food waste and food processing by-products as feed in China's monogastric livestock sector on domestic total agricultural land use and feed demand. (**a**) Total agricultural land use (crop harvested area and pastureland) (Mha) and (**b**) feed demand by monogastric livestock (Tg) in scenarios. Definitions of scenarios (S1 - 'Partial use of food waste and food processing by-products as feed'; S2 - 'Full use of food waste and food processing by-products as feed'; S3 - 'S1 + A modest emission mitigation target'; S4 - 'S1 + An ambitious emission mitigation target') are described in Supplementary Table 1.

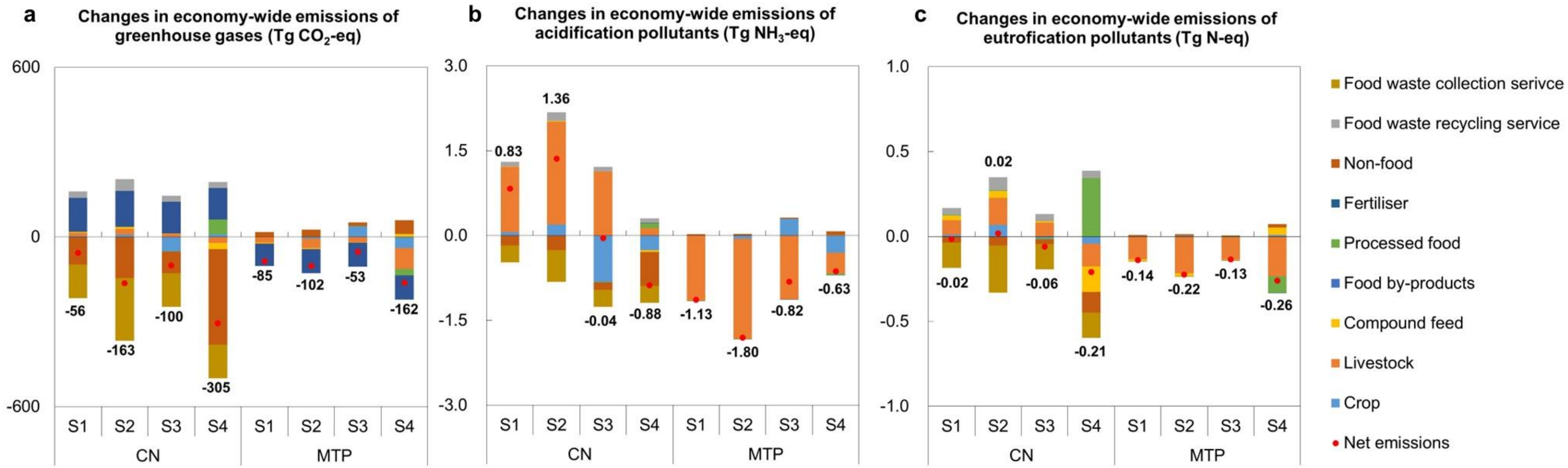

Fig. 4 | Impacts of upcycling food waste and food processing by-products as feed in China's monogastric livestock sector on economy-wide emissions in China (CN) and China's main food and feed trading partners (MTP). Changes in (**a**) economy-wide emissions of greenhouse gases (GHGs) (Tg CO_2-eq), (**b**) acidification pollutants (Tg NH_3-eq), and (**c**) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios 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. MTP includes Brazil, the United States, and Canada. Definitions of scenarios (S1 - 'Partial use of food waste and food processing by-products as feed'; S2 - 'Full use of food waste and food processing by-products as feed'; S3 - 'S1 + A modest emission mitigation target'; S4 - 'S1 + An ambitious emission mitigation target') are described in Supplementary Table 1.

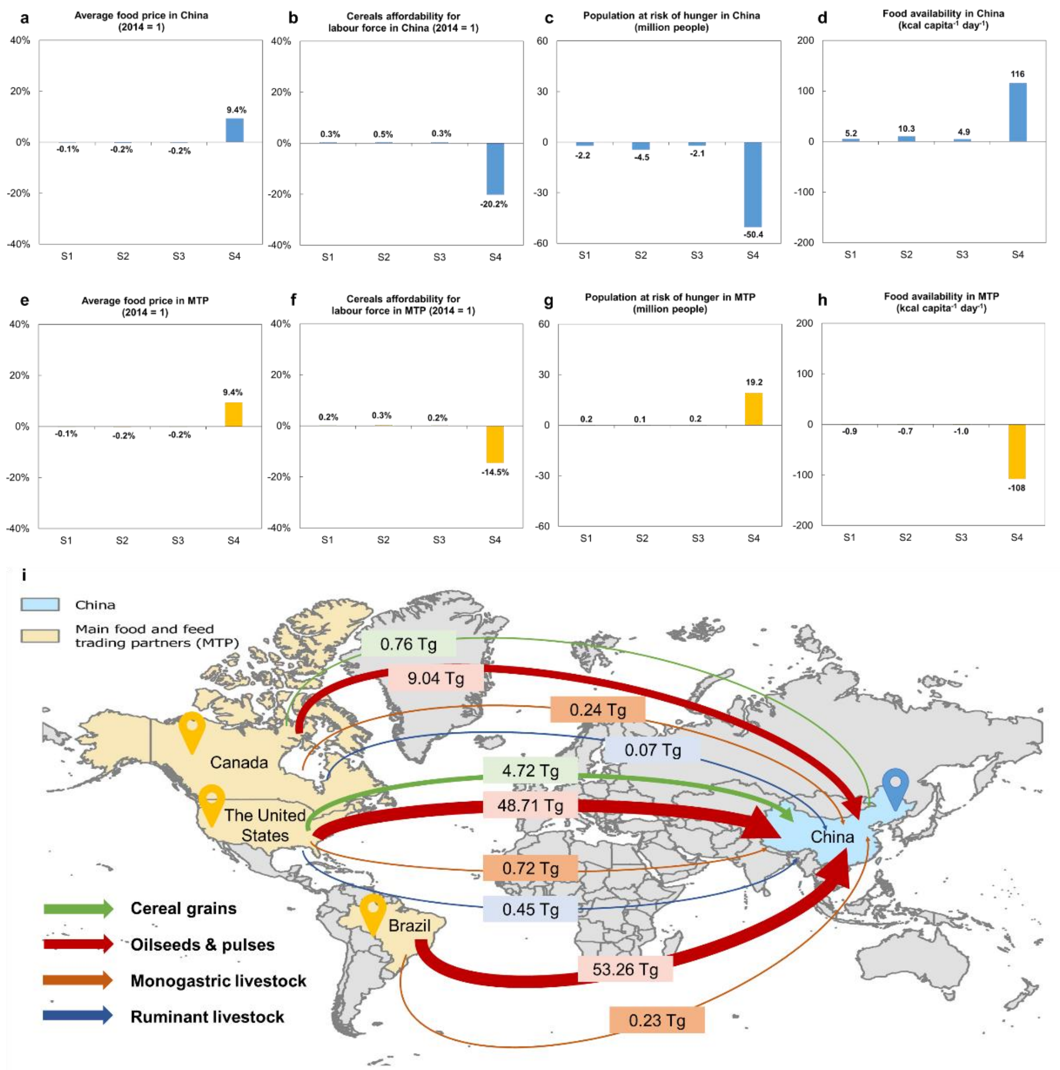

Fig. 5 | Impacts of upcycling food waste and food processing by-products as feed in monogastric livestock sector on food security indicators in China (CN) and China's main food and feed trading partners (MTP). Changes in (**a**) average food price (including primary food products and processed food), (**b**) cereals affordability for labour force, (**c**) population at risk of hunger (million people; S0 = 140.7 million people), and (**d**) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0). Changes in (**e**) average food price (including primary food products and processed food), (**f**) cereals affordability for labour force, (**g**) population at risk of hunger (million people; S0 = 5.3 million people), and (**d**) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0). (**i**) Net imports (Tg) of main food and feed products from MTP to China in the baseline (S0). MTP includes Brazil, the United States, and Canada. 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 - 'Partial use of food waste and food processing by-products as feed'; S2 - 'Full use of food waste and food processing by-products as feed'; S3 - 'S1 + A modest emission mitigation target'; S4 - 'S1 + An ambitious emission mitigation target') are described in Supplementary Table 1. Credit: World Countries base map, Esri (https://hub.arcgis.com/datasets/esri::world-countries/about).