SUPPLEMENTARY INFORMATION

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

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Contents

Mathematically, various ways exist to represent applied general equilibrium (AGE) models, according to Ginsburgh and Keyzer [1]. To identify the optimal solution towards greater sustainability and enable the efficient allocation of resources in the economy, we use the welfare format of the AGE models for our analysis. The Supplementary Information (SI) is structured into three sections: Supplementary Methods, Supplementary Results, and Supplementary Discussion. In the Supplementary Methods, we specify the model for our study by explicitly considering producers, consumers, production goods, consumption goods, and intermediate goods. This is followed by a description of the model calibration and scenario definitions. The subsequent sections present the Supplementary Results and Supplementary Discussion. Finally, we provide supplementary figures and tables, along with the sectoral aggregation scheme, social accounting matrices, and emissions data for all the regions in our study.

Supplementary Methods

Objective function

The objective function "social welfare (W)" is the weighted sum of the log utility (U_i) of all consumers, according to Zhu and Van Ierland [2].

$$\mathrm{W} = \max \sum_i \alpha_i \log U_i \tag{1}$$

where α_i is the Negishi weight of the representative consumer in each region i (i=China and its main food and feed trading partners (MTP, including Brazil, United States, and Canada)).

Utility function

In our model, the consumer's utility depends on the consumption of rival goods. The utility function is a Cobb-Douglas (C-D) function describing the behaviour of a representative consumer (household to maximise its utility subject to budget constraints) consuming rival goods. The utility function of the consumer in region i is written as:

$$U_i = \prod_s C_{i,s}^{\beta_{i,s}} \tag{2}$$

where consumption goods s refers to cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops, monogastric livestock, ruminant livestock, processed food, and non-food. $C_{i,s}$ is the consumption of the rival good in region i. $\beta_{i,s}$ is the elasticity of utility concerning the consumption of rival good s in region i, i.e., the expenditure share of consumption good s in consumption of rival goods in region i, and $\sum_s \beta_{i,s} = 1$.

Production function

We present the production functions of eighteen producers, namely, cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops, monogastric livestock, ruminant livestock, compound feed, cereal brans, alcoholic pulps, oil cakes, processed food, nitrogen fertiliser, phosphorus fertiliser, non-food, food waste recycling service, and food waste collection service.

The production function of producer j in region i is specified as:

$$Y_{i,j} = A_{i,j}[(KL_{i,j})^{\eta_{1i,j}}(LB_{i,j})^{\eta_{2i,j}}(LD1_{i,j})^{\eta_{3i,j}}(LD2_{i,j})^{\eta_{4i,j}}(NFE_{i,j})^{\eta_{5i,,j}}(PFE_{i,j})^{\eta_{6i,j}}$$

$$(CER_{i,j})^{\eta_{7i,j}}(OSD_{i,j})^{\eta_{8i,j}}(VF_{i,j})^{\eta_{9i,j}}(RT_{i,j})^{\eta_{10i,j}}(SGR_{i,j})^{\eta_{11i,j}}(OTC_{i,j})^{\eta_{12i,j}}$$

$$(COF_{i,j})^{\eta_{13i,j}}(BRAN_{i,j})^{\eta_{14i,j}}(PULP_{i,j})^{\eta_{15i,j}}(CAKE_{i,j})^{\eta_{16i,j}}]^{1-\xi_{i,j}}$$

$$[(CERW_{i,j})^{\delta_{1i,j}}(OSDW_{i,j})^{\delta_{2i,j}}(VFW_{i,j})^{\delta_{3i,j}}(RTW_{i,j})^{\delta_{4i,j}}$$

$$(BRANW_{i,j})^{\delta_{5i,j}}(PULPW_{i,j})^{\delta_{6i,j}}(CAKEW_{i,j})^{\delta_{7i,j}}]^{\xi_{i,j}}$$

(3)

where $Y_{i,j}$ is the production of sector j in region i. $A_{i,j}$ is the technological parameter of the production of sector j in region i. $KL_{i,j}$, $LB_{i,j}$, $LD1_{i,j}$ and $LD2_{i,j}$ are capital, labour, cropland, and pastureland inputs for production of sector j in region i, respectively. $NFE_{i,j}$, $PFE_{i,j}$, $CER_{i,j}$, $OSD_{i,j}$, $VF_{i,j}$, $RT_{i,j}$, $SGR_{i,j}$, $OTC_{i,j}$, $COF_{i,j}$, $BRAN_{i,j}$, $PULP_{i,j}$, and $CAKE_{i,j}$ are nitrogen fertiliser, phosphorus fertiliser, cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops, compound feed, cereal bran, alcoholic pulp, and oil cake inputs for the production of sector j in region i, respectively. $CERW_{i,j}$, $OSDW_{i,j}$, $VFW_{i,j}$, $RTW_{i,j}$, $BRANW_{i,j}$, $PULPW_{i,j}$, and $CAKEW_{i,j}$ are discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste recycling service as feed input for the production of sector j in region i, respectively. $\xi_{i,j}$ ($0<\xi_{i,j}<1$) is the cost share of food waste for the production of sector j in region i. η_f (f=1, 2, 3, …, 16) is the cost share of each factor and intermediate input for production, and $\sum_{f=1}^{16} \eta_f = 1$. δ_f (f=1, 2, 3, …, 7) is the cost share of each food waste input for production, and $\sum_{f=1}^{7} \delta_f = 1$.

We also add several additional constraints on the production of crops (i.e., cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops), livestock (i.e., monogastric livestock, ruminant livestock), and food processing by-products (i.e., cereal brans, alcoholic pulps, oil cakes) based on the information from the social accounting matrices (SAM) (see Appendix Tables 2-3) in the base year of 2014 for China and its trading partners.

Crops can't be produced in a "factory-like" setting because the chemical processes within plants require specific nutrients that can't be substituted for one another. Different combinations of nutrients, such as nitrogen and phosphorus, lead to varying crop yields. Thus, we keep the total output of crop as a fixed ratio of nitrogen and phosphorus fertiliser inputs. In other words, the ratios of nitrogen and phosphorus fertiliser inputs for per unit of crop output remain constant across all scenarios. Since livestock productivity is directly tied to the protein and energy levels of feed, the total output of livestock is a fixed ratio of feed inputs in terms of protein and energy. When substituting primary feed (i.e., feed crops and compound feed) with food waste and food processing by-products, the protein and energy feed supplies per unit of animal output are kept constant in all scenarios. Since food processing by-products are calculated based on the consumption of food products and specific technical conversion factors, we maintain a constant ratio of by-product output to the consumption of corresponding food products across all scenarios.

The production function of food waste recycling service in region i is specified as:

$$Y_{i,wfe} = CERW_{i,oap} + OSDW_{i,oap} + VFW_{i,oap} + RTW_{i,oap} + BRANW_{i,oap} + PULPW_{i,oap} + CAKEW_{i,oap}$$

(4)

where $Y_{i,wfe}$ is the production of food waste recycling service in region i. $CERW_{i,oap}$, $OSDW_{i,oap}$, $VFW_{i,oap}$, $RTW_{i,oap}$, $BRANW_{i,oap}$, $PULPW_{i,oap}$, and $CAKEW_{i,oap}$ are discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) recycled as feed input for the production of monogastric livestock in region i, respectively.

The production function of food waste collection service in region i is specified as:

$$Y_{i,wtr} = C_{i,cerw} + C_{i,osdw} + C_{i,vfw} + C_{i,rtw} + C_{i,branw} + C_{i,pulpw} + C_{i,cakew} \tag{5}$$

where $Y_{i,wtr}$ is the production of food waste collection service in region i. $C_{i,cerw}$, $C_{i,osdw}$, $C_{i,vfw}$, $C_{i,rtw}$ $C_{i,branw}$, $C_{i,pulpw}$, and $C_{i,cakew}$ are discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) collected for landfill and incineration in region i, respectively.

When emissions are outputs of the production process, the emissions intensities of greenhouse gases (GHGs) ($\varepsilon_{gg,i,j}$, kg CO_2 equivalent USD^{-1}), acidification pollutants ($\varepsilon_{ga,i,j}$, kg NH_3 equivalent USD^{-1}), and eutrophication pollutants (EP, $\varepsilon_{ge,i,j}$, kg N equivalent USD^{-1}) from producer j in region i are calculated as:

$$\varepsilon_{gg,i,j} = \frac{EM^{+0}_{gg,i,j}}{Y^0_{i,j}} \tag{6}$$

$$\varepsilon_{ga,i,j} = \frac{EM^{+0}_{ga,i,j}}{Y^0_{i,j}} \tag{7}$$

$$\varepsilon_{ge,i,j} = \frac{EM^{+0}_{ge,i,j}}{Y^0_{i,j}} \tag{8}$$

where $EM^{+0}_{gg,i,j}$ is the emissions of GHGs gg (gg=CO_2, CH_4, and N_2O emissions) from producer j in region i in the base run. $EM^{+0}_{ga,i,j}$ is the emissions of acidification pollutants ga (ga=NH_3, NO_x, and SO_2 emissions) from producer j in region i in the base run. $EM^{+0}_{ge,i,j}$ is the emissions of eutrophication pollutants ge (ge= N and P losses) from producer j in region i in the base run. $Y^0_{i,j}$ is the production of producer j in region i in the base run.

Next, the emissions in different scenarios are calculated by multiplying the current production level by corresponding emission intensities. The total emissions of GHGs, acidification pollutants, and eutrophication pollutants from all producers in region i are calculated as follows:

$$EMG^+_{i,j} = \sum_{gg} \varepsilon_{gg,i,j} * Y_{i,j} * Eqv_{gg}$$

for emissions of GHGs gg = CO_2, CH_4, and N_2O emissions

(9)

$$EMA^+_{i,j} = \sum_{ga} \varepsilon_{ga,i,j} * Y_{i,j} * Eqv_{ga}$$

for emissions of acidification pollutants ga = NH_3, NO_x, and SO_2 emissions

(10)

$$EME^+_{i,j} = \sum_{ge} \varepsilon_{ge,i,j} * Y_{i,j} * Eqv_{ge}$$

for emissions of eutrophication pollutants ge = N and P losses

(11)

where $EMG_{i,j}^{+}$, $EMA_{i,j}^{+}$, and $EME_{i,j}^{+}$ are the total emissions of GHGs, acidification pollutants, and eutrophication pollutants from producer j in region i, respectively. Eqv_{gg}, Eqv_{ga}, and Eqv_{ge} are the GWP, AP, and EP equivalent factors based on Goedkoop, et al. [3].

Balance equations

In our applied model, we consider factor inputs (i.e., capital, labour, and land) to be mobile between different sectors but immobile between China and its trading partners. Cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops are used for direct consumption and intermediate use for monogastric livestock, ruminant livestock, compound feed, food processing by-products (i.e., cereal bran, alcoholic pulp, and oil cake), and processed food production. Food processing by-products (i.e., cereal bran, alcoholic pulp, and oil cake) and compound feed are produced for intermediate use for monogastric livestock and ruminant livestock production. Monogastric livestock, ruminant livestock, processed food, and non-food are used for direct consumption. Nitrogen fertiliser and phosphorus fertiliser are used for cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops production but not for consumption. We note C for consumption, XNET for net export (exports minus imports), and Y for production. Variables with a bar stand for exogenous ones.

International trade is modelled using the assumption of perfect substitutes between domestic and imported goods, adhering to the Heckscher-Ohlin assumption [4]. With this assumption, production will take place in countries with comparative advantages, meaning goods will be produced in the countries that can produce them most efficiently. To prevent a strong specialisation effect under free international trade, which could reduce some goods' production to zero in a certain region, we set a lower bound of 10% of the original production for each sector in our model.

The balance equations for cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops in region i are as follows:

$$C_{i,cer} + CER_{i,oap} + CER_{i,ctl} + CER_{i,cof} + CER_{i,bran} + CER_{i,pulp} + CER_{i,otf} + XNET_{i,cer} \leq Y_{i,cer} \qquad (p_{i,cer}) \tag{12}$$

$$C_{i,osd} + OSD_{i,oap} + OSD_{i,ctl} + OSD_{i,cof} + OSD_{i,cake} + OSD_{i,otf} + XNET_{i,osd} \leq Y_{i,osd} \qquad (p_{i,osd}) \tag{13}$$

$$C_{i,vf} + VF_{i,oap} + VF_{i,ctl} + VF_{i,cof} + VF_{i,otf} + XNET_{i,vf} \leq Y_{i,vf} \qquad (p_{i,vf}) \tag{14}$$

$$C_{i,rt} + RT_{i,oap} + RT_{i,ctl} + RT_{i,cof} + RT_{i,otf} + XNET_{i,rt} \leq Y_{i,rt} \qquad (p_{i,rt}) \tag{15}$$

$$C_{i,sgr} + SGR_{i,oap} + SGR_{i,ctl} + SGR_{i,cof} + SGR_{i,otf} + XNET_{i,sgr} \leq Y_{i,sgr} \quad (p_{i,sgr}) \tag{16}$$

$$C_{i,ocr} + OCR_{i,oap} + OCR_{i,ctl} + OCR_{i,cof} + OCR_{i,otf} + XNET_{i,vf} \leq Y_{i,ocr} \quad (p_{i,ocr}) \tag{17}$$

where $CER_{i,oap}$, $CER_{i,ctl}$, $CER_{i,cof}$, $CER_{i,bran}$, $CER_{i,pulp}$, and $CER_{i,otf}$ are cereals used for monogastric livestock, ruminant livestock, compound feed, cereal bran, alcoholic pulp, and processed food production in region i, respectively. $OSD_{i,oap}$, $OSD_{i,ctl}$, $OSD_{i,cof}$, $OSD_{i,bran}$, and $OSD_{i,otf}$ are cereals used for monogastric livestock, ruminant livestock, compound feed, oil cake, and processed food production in region i, respectively. $VF_{i,oap}$, $VF_{i,ctl}$, $VF_{i,cof}$, and $VF_{i,otf}$ are vegetables & fruits used for monogastric livestock, ruminant livestock, compound feed, and processed food production in region i, respectively. $RT_{i,oap}$, $RT_{i,ctl}$, $RT_{i,cof}$, and $RT_{i,otf}$ are roots & tubers used for monogastric livestock, ruminant livestock, compound feed, and processed food production in region i, respectively. $SGR_{i,oap}$, $SGR_{i,ctl}$, $SGR_{i,cof}$, and $SGR_{i,otf}$ are sugar crops used for monogastric livestock, ruminant livestock, compound feed, and processed food production in region i, respectively. $OCR_{i,oap}$, $OCR_{i,ctl}$, $OTC_{i,cof}$, and $OTC_{i,otf}$ are other non-food crops used for monogastric livestock, ruminant livestock, compound feed, and processed food production in region i, respectively. $p_{i,cer}$, $p_{i,osd}$, $p_{i,vf}$, $p_{i,rt}$, $p_{i,sgr}$, and $p_{i,ocr}$ are the shadow prices of cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops in region i, respectively.

The balance equations for food processing by-products (i.e., cereal bran, alcoholic pulp, and oil cake) in region i are as follows:

$$BRAN_{i,oap} + XNET_{i,bran} \leq Y_{i,bran} \qquad (p_{i,bran}) \tag{18}$$

$$PULP_{i,oap} + XNET_{i,pulp} \leq Y_{i,pulp} \qquad (p_{i,pulp}) \tag{19}$$

$$CAKE_{i,oap} + XNET_{i,cake} \leq Y_{i,cake} \qquad (p_{i,cake}) \tag{20}$$

where $BRAN_{i,oap}$, $PULP_{i,oap}$, and $CAKE_{i,oap}$ are cereal bran, alcoholic pulp, and oil cake used for monogastric livestock production in region i, respectively. $p_{i,bran}$, $p_{i,pulp}$, and $p_{i,cake}$ are the shadow prices of cereal bran, alcoholic pulp, and oil cake in region i.

The balance equation for compound feed in region i is as follows:

$$COF_{i,oap} + COF_{i,ctl} + XNET_{i,cof} \leq Y_{i,cof} \qquad (p_{i,cof}) \tag{21}$$

where $COF_{i,oap}$ and $COF_{i,ctl}$ are compound feed used in monogastric livestock and ruminant livestock production in region i, respectively. $p_{i,cof}$ is the shadow price of compound feed in region i.

The balance equation for monogastric livestock, ruminant livestock, processed food, and non-food in region i is as follows:

$$C_{i,j} + XNET_{i,j} \leq Y_{i,j} \qquad (p_{i,j}) \tag{22}$$

where $p_{i,j}$ is the shadow price of good j in region i.

The balance equations for nitrogen and phosphorus fertiliser in region i are as follows:

$$NFE_{i,cer} + NFE_{i,osd} + NFE_{i,vf} + NFE_{i,rt} + NFE_{i,sgr} + NFE_{i,ocr} \\ + XNET_{i,nfe} \leq Y_{i,nfe} \qquad (p_{i,nfe}) \tag{23}$$

$$PFE_{i,cer} + PFE_{i,osd} + PFE_{i,vf} + PFE_{i,rt} + PFE_{i,sgr} + PFE_{i,ocr} \\ + XNET_{i,pfe} \leq Y_{i,pfe} \qquad (p_{i,pfe}) \tag{24}$$

where $NFE_{i,cer}$, $NFE_{i,osd}$, $NFE_{i,vf}$, $NFE_{i,rt}$, $NFE_{i,sgr}$ and $NFE_{i,ocr}$ are the nitrogen fertiliser used for cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops production in region i, respectively. $PFE_{i,cer}$, $PFE_{i,osd}$, $PFE_{i,vf}$, $PFE_{i,rt}$, $PFE_{i,sgr}$ and $PFE_{i,ocr}$ are the phosphorus fertiliser used for cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops production in region i, respectively. $p_{i,nfe}$ and $p_{i,pfe}$ are the shadow prices of nitrogen fertiliser and phosphorus fertiliser in region i, respectively.

For trade balance of all goods:

$$\sum_i XNET_{i,j} = 0 \qquad (p_j) \tag{25}$$

In the applied model, we assume that factor endowments (i.e., capital, labour, cropland, and pastureland) are mobile between different sectors but immobile among the two regions. For the balance equations of production factor inputs:

$$\sum_j KL_{i,j} \leq \overline{TKL_i} \qquad (r_i) \tag{26}$$

$$\sum_j LB_{i,j} \leq \overline{TLB_i} \qquad (w_i) \tag{27}$$

$$\sum_j LD1_{i,j} \leq \overline{TLD1_i} \qquad (k1_i)$$

for sector j = cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and other non-food crops

(28)

$$\sum_j LD2_{i,j} \leq \overline{TLD2_i} \qquad (k2_i)$$

for sector j = ruminant livestock

(29)

where $\overline{TKL_i}$, $\overline{TLB_i}$, $\overline{TLD1_i}$ and $\overline{TLD2_i}$ are the factor endowments (i.e., capital, labour, cropland, pastureland) supply in region i, respectively. r_i, w_i, $k1_i$, and $k2_i$ are the shadow prices of capital, labour, cropland, and pastureland in region i, respectively.

If an emission permit system is implemented to control the total emissions of GHGs, acidification and eutrophication pollutants from all producers, then the following relationship holds:

$$\sum_j EMG^{+}_{i,j} \leq \overline{TMG^{+}_i} \qquad (p_{eg,i}) \tag{30}$$

$$\sum_j EMA^{+}_{i,j} \leq \overline{TMA^{+}_i} \qquad (p_{ea,i}) \tag{31}$$

$$\sum_j EME^{+}_{i,j} \leq \overline{TME^{+}_i} \qquad (p_{ee,i}) \tag{32}$$

where TMG^{+}_i, TMA^{+}_i, and TME^{+}_i are the total emissions of GHGs, acidification and eutrophication pollutants from all producers in region i, respectively. $\overline{TMG^{+}_i}$, $\overline{TMA^{+}_i}$, and $\overline{TME^{+}_i}$ are the permitted level of the total emissions of GHGs, acidification and eutrophication pollutants in region i, respectively. Emissions should not be above a certain level for the regeneration of the environment. For benchmarking, the permitted emission level is the total emission level in the base year. For an environmental policy study (scenarios S3-4), the permitted emission level can be an exogenous emission permit determined by the ecological limit. $p_{eg,i}$, $p_{ea,i}$, and $p_{ee,i}$ are the shadow prices of the emissions of GHGs, acidification and eutrophication pollutants in region i, respectively.

Monogastric livestock's demand for food waste recycling service must be equal to or less than the supply of food waste recycling service, then the following relationship holds:

$$CERW_{i,oap} \leq \overline{CERW_{i,oap}} \qquad (p_{i,cerw1}) \tag{33}$$

$$OSDW_{i,oap} \leq \overline{OSDW_{i,oap}} \qquad (p_{i,osdw1}) \tag{34}$$

$$VFW_{i,oap} \leq \overline{VFW_{i,oap}} \qquad (p_{i,vfw1}) \tag{35}$$
$$RTW_{i,oap} \leq \overline{RTW_{i,oap}} \qquad (p_{i,rtw1}) \tag{36}$$
$$BRANW_{i,oap} \leq \overline{BRANW_{i,oap}} \qquad (p_{i,branw1}) \tag{37}$$
$$PULPW_{i,oap} \leq \overline{PULPW_{i,oap}} \qquad (p_{i,pulpw1}) \tag{38}$$
$$CAKEW_{i,oap} \leq \overline{CAKEW_{i,oap}} \qquad (p_{i,cakew1}) \tag{39}$$

where $\overline{CERW_{i,oap}}$, $\overline{OSDW_{i,oap}}$, $\overline{VFW_{i,oap}}$, $\overline{RTW_{i,oap}}$, $\overline{BRANW_{i,oap}}$, $\overline{PULPW_{i,oap}}$, and $\overline{CAKEW_{i,oap}}$ are the supply of discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste recycling service as feed input for monogastric livestock production in region i, respectively. $p_{i,cerw1}$, $p_{i,osdw1}$, $p_{i,vfw1}$, $p_{i,rtw1}$, $p_{i,branw1}$, $p_{i,pulpw1}$, and $p_{i,cakew1}$ are the shadow prices of discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste recycling service as feed input for monogastric livestock production in region i, respectively.

Consumer's demand for food waste collection service must be equal to or less than the supply of food waste collection service, then the following relationship holds:

$$C_{i,cerw} \leq \overline{C_{i,cerw}} \qquad (p_{i,cerw2}) \tag{40}$$
$$C_{i,osdw} \leq \overline{C_{i,osdw}} \qquad (p_{i,osdw2}) \tag{41}$$
$$C_{i,vfw} \leq \overline{C_{i,vfw}} \qquad (p_{i,vfw2}) \tag{42}$$
$$C_{i,rtw} \leq \overline{C_{i,rtw}} \qquad (p_{i,rtw2}) \tag{43}$$
$$C_{i,branw} \leq \overline{C_{i,branw}} \qquad (p_{i,branw2}) \tag{44}$$
$$C_{i,pulpw} \leq \overline{C_{i,pulpw}} \qquad (p_{i,pulpw2}) \tag{45}$$
$$C_{i,cakew} \leq \overline{C_{i,cakew}} \qquad (p_{i,cakew2}) \tag{46}$$

where $\overline{C_{i,cerw}}$, $\overline{C_{i,osdw}}$, $\overline{C_{i,vfw}}$, $\overline{C_{i,rtw}}$, $\overline{C_{i,branw}}$, $\overline{C_{i,pulpw}}$, and $\overline{C_{i,cakew}}$ are the supply of discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste collection service for landfill and incineration in region i, respectively. $p_{i,cerw2}$, $p_{i,osdw2}$, $p_{i,vfw2}$, $p_{i,rtw2}$, $p_{i,branw2}$, $p_{i,pulpw2}$, and $p_{i,cakew2}$ are the shadow prices of discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste collection service for landfill and incineration in region i, respectively.

Budget constraint

Since goods are tradable, the consumer has to either finance its trade deficit or invest its trade surplus. Thus, the budget constraint for consumer i holds such that total expenditure, adjusted for the trade balance, must equal be equal to the income:

$$Exp_i + \sum_j (p_j XNET_{i,j}) = h_i \tag{47}$$

where Exp_i is the total expenditure of consumer in region i. $\sum_j (p_j XNET_{i,j})$ is the trade balance in region i. A positive trade balance value indicates a trade surplus in region i, while a negative trade balance value signifies a trade deficit in region i. h_i is the income of consumer in region i.

The total expenditure of consumer in region i consists of spending income on both consumption of goods and food waste collection service:

$$Exp_i = \sum_s (p_{i,s} C_{i,s}) + p_{i,cerw2} C_{i,cerw} + p_{i,osdw2} C_{i,osdw} + p_{i,vfw2} C_{i,vfw} + p_{i,rtw2} C_{i,rtw} + p_{i,branw2} C_{i,branw} + p_{i,pulpw2} C_{i,pulpw} + p_{i,cakew2} C_{i,cakew} \quad (48)$$

where consumption goods s refers to cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops, monogastric livestock, ruminant livestock, processed food, and non-food. $\sum_s (p_{i,s} C_{i,s})$ is the total expenditure on the consumption goods in region i. $p_{i,cerw2} C_{i,cerw}$, $p_{i,osdw2} C_{i,osdw}$, $p_{i,vfw2} C_{i,vfw}$, $p_{i,rtw2} C_{i,rtw}$, $p_{i,branw2} C_{i,branw}$, $p_{i,pulpw2} C_{i,pulpw}$, and $p_{i,cakew2} C_{i,cakew}$ are the payments to the discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) sent to food waste collection service for landfill and incineration in region i, respectively. The Negishi weight (α_i) in the welfare function (equation 1) will be chosen such that the budget constraints hold for each representative consumer in region i.

Consumer's income is the sum of the remuneration of initial endowments employed in production and payments to the environmental sector. Given that food waste is either consumed by livestock as feed or consumed by consumers as a cost of collecting food waste from the municipality, we should also include income from food waste recycling service and food collection service. Thus, the consumer' s income is:

$$h_i = r_i \overline{TKL_i} + w_i \overline{TLB_i} + k1_i \overline{TLD1_i} + k2_i \overline{TLD2_i} + p_{i,cerw1} CERW_{i,oap} + p_{i,osdw1} OSDW_{i,oap} + p_{i,vfw1} VFW_{i,oap} + p_{i,rtw1} RTW_{i,oap} + p_{i,branw1} BRANW_{i,oap} + p_{i,pulpw1} PULPW_{i,oap} + p_{i,cakew1} CAKEW_{i,oap} + p_{i,cerw2} C_{i,cerw} + p_{i,osdw2} C_{i,osdw} + p_{i,vfw2} C_{i,vfw} + p_{i,rtw2} C_{i,rtw} + p_{i,branw2} C_{i,branw} + p_{i,pulpw2} C_{i,pulpw} + p_{i,cakew2} C_{i,cakew} + p_{eg,i} \overline{TMG_i^+} + p_{ea,i} \overline{TMA_i^+} + p_{ee,i} \overline{TME_i^+} \quad (49)$$

where $p_{i,cerw1} CERW_{i,oap}$, $p_{i,osdw1} OSDW_{i,oap}$, $p_{i,vfw1} VFW_{i,oap}$, $p_{i,rtw1} RTW_{i,oap}$, $p_{i,branw1} BRANW_{i,oap}$, $p_{i,pulpw1} PULPW_{i,oap}$, and $p_{i,cakew1} CAKEW_{i,oap}$ are the income from food waste recycling service in region i. $p_{i,cerw2} C_{i,cerw}$, $p_{i,osdw2} C_{i,osdw}$, $p_{i,vfw2} C_{i,vfw}$, $p_{i,rtw2} C_{i,rtw}$, $p_{i,branw2} C_{i,branw}$, $p_{i,pulpw2} C_{i,pulpw}$, and $p_{i,cakew2} C_{i,cakew}$ are the income from food waste collection service in region i. $p_{eg,i} \overline{TMG_i^+}$, $p_{ea,i} \overline{TMA_i^+}$, and $p_{ee,i} \overline{TME_i^+}$ are the income from selling emission permits of GHGs, acidification and eutrophication pollutants.

The producers' profits are specified as follows and equal zero:

$$PROF_{i,j} = p_j Y_{i,j} - r_i KL_{i,j} - w_i LB_{i,j} - k1_i LD1_{i,j} - k2_i LD2_{i,j} - p_{cer} CER_{i,j} - p_{osd} OSD_{i,j} - p_{vf} VF_{i,j} - p_{rt} RT_{i,j} - p_{sgr} SGR_{i,j} - p_{ocr} OCR_{i,j} - p_{cof} COF_{i,j} - p_{bran} BRAN_{i,j} - p_{pulp} PULP_{i,j} - p_{cake} CAKE_{i,j} - p_{nfe} NFE_{i,j} - p_{pfe} PFE_{i,j} - p_{i,cerw1} CERW_{i,oap} - p_{i,osdw1} OSDW_{i,oap} - p_{i,vfw1} VFW_{i,oap} - p_{i,rtw1} RTW_{i,oap} - p_{i,branw1} BRANW_{i,oap} - p_{i,pulpw1} PULPW_{i,oap} - p_{i,cakew1} CAKEW_{i,oap} - p_{eg,i} EMG_{i,j}^+ - p_{ea,i} EMA_{i,j}^+ - p_{ee,i} EME_{i,j}^+ \quad (50)$$

Model calibration

As in the literature on AGE models, we follow the Harberger convention [5] to calibrate the model using the base year SAMs. It means that the prices of all goods and factors are set to one, and the quantities of consumption and production goods equal the monetary value of the base year SAMs [6]. We calibrate the parameters in production and utility functions based on the cost shares of inputs in total production output and expenditure shares of consumption goods in total expenditure derived from the base year SAMs. In order to calibrate food waste-related parameters and add discarded food waste and food processing by-products (i.e., cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, roots & tubers waste, cereal bran waste, alcoholic pup waste, and oil cake waste) into the SAMs (see Appendix Tables 2-3), our model treats food waste recycling service as feed input for monogastric livestock production (see equation 3), and assumes that consumer buys food waste collection service for consumption (see equation 48).

Definition of scenarios

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. The total amount 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 Tables 4. The cost of increasing the supply of food waste recycling service is modelled as a rising percentage of the initial cost of recycling food waste and food processing by-products as feed (54 dollar ton^{-1}), while the cost of decreasing the supply of food waste collection service is modelled as a declining percentage of the initial cost of collecting food waste and food processing by-products for landfill and incineration (82 dollar ton^{-1}). Physical quantities and prices of food waste recycling and collection services in China are presented in Supplementary Tables 4-5.

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. In S1, cross-provincial transportation of food waste is not allowed, which limits the maximum utilisation rate of food waste with high moisture content to 54% in China, according to Fang, et al. [7].

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, taking into account economies of scale. In S2, cross-provincial transportation of food waste is allowed in S2. Economies of scale in food waste recycling are considered in S2, where a 1% increase in recycled waste results in only a 0.078% rise in recycling costs, indicating that increasing the amount of recycled waste might not necessarily incur additional costs, as reported by Cialani and Mortazavi [8]. This is because, initially, recycling entails high fixed costs, yet as production scales up, marginal costs decrease and then stabilise.

S3 - S1 + A modest emission mitigation target

In S3, the equations below shows that the total emissions of GHGs, acidification and eutrophication pollutants from all sectors j in the entire economies of China and MTP are no more than their baseline (S0) emission levels.

$$\sum_j EMG_{i,j}^{+} \leq \overline{TMG_i^{+}} \qquad (p_{eg,i}) \tag{51}$$

$$\sum_j EMA_{i,j}^{+} \leq \overline{TMA_i^{+}} \qquad (p_{ea,i}) \tag{52}$$

$$\sum_j EME_{i,j}^{+} \leq \overline{TME_i^{+}} \qquad (p_{ee,i}) \tag{53}$$

S4 - S1 + An ambitious emission mitigation target

In S4, the equations below shows that the total emissions of GHGs, acidification and eutrophication pollutants from all sectors j in the entire economies of China and MTP are no more than the emission thresholds set by China's and MTP's annual GHG mitigation targets under the Intended Nationally Determined Contributions (INDC) of the Paris Agreement [9], as well as China's emission reduction goals for acidification and eutrophication pollutants in line with the "14th Five-Year Plan" [10].

$$\sum_j EMG_{CN,j}^{+} \leq 0.974 * \overline{TMG_i^{+}} \qquad (p_{eg,i}) \tag{54}$$

$$\sum_j EMG_{MTP,j}^{+} \leq 0.98 * \overline{TMG_i^{+}} \qquad (p_{eg,i}) \tag{55}$$

$$\sum_j EMA_{CN,j}^{+} \leq 0.975 * \overline{TMA_i^{+}} \qquad (p_{ea,i}) \tag{56}$$

$$\sum_j EMA_{MTP,j}^{+} \leq \overline{TMA_i^{+}} \qquad (p_{ea,i}) \tag{57}$$

$$\sum_j EME_{CN,j}^{+} \leq 0.98 * \overline{TME_i^{+}} \qquad (p_{ee,i}) \tag{58}$$

$$\sum_j EME_{MTP,j}^{+} \leq \overline{TME_i^{+}} \qquad (p_{ee,i}) \tag{59}$$

Conversion of dollar-based quantities to physical quantities

GTAP version 10 database [11] is used to calibrate our AGE model and provide dollar-based quantities. We designed a sectoral aggregation scheme comprising 16 sectors (see Appendix Table 1) based on the original GTAP database to produce social accounting matrices (SAM) (see Appendix Tables 2-3) 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 [12], while physical bilateral trade quantities are obtained from FAO [13] 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 taxation purposes. We then apply the RAS approach (also referred to bi-proportional balancing) [14] 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 FAO [13]. 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. [15], 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. The physical production quantity of grass from natural grassland is derived from Miao and Zhang [16]. We only include grass from natural grassland where ruminant livestock is grazing for feed, and grass from remaining grassland is excluded. The dollar-based production quantity of grass is estimated as the value flow from the pastureland to ruminant livestock 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.

Environmental impact database

Data on CO_2, CH_4, and N_2O emissions are obtained from the Climate Analysis Indicators Tool (CAIT) [17]. GHG emissions calculations in our model follow the IPCC National GHG Emission Guidelines [18]. We derive NH_3, NO_x, and SO_2 emissions from Liu, et al. [19], Huang, et al. [20], and Dahiya, et al. [21], respectively. We consider NO_x emissions from energy use only, as agriculture's contribution to NO_x emissions is generally small ($\leqslant 2\%$) [22]. We use the global eutrophication database of food and non-food provided by Hamilton, et al. [23] 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. [24]. 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 6). Emissions of food waste recycling and collection services are obtained from Alsaleh and Aleisa [25], Hong, et al. [26], and Hong, et al. [27]. Two types of land use, i.e., cropland and pastureland, are distinguished. We update the GTAP data on crop harvested areas using the FAO [13] database. Pastureland is defined as areas where ruminant grazing occurs. We derive nitrogen and phosphorous fertiliser use by crop types and countries from Ludemann, et al. [28].

Feasibility of upcycling food waste and food processing by-products as feed

To ensure the feasibility of upcycling food waste and food processing by-products as feed, scenarios S1-S4 incorporate four key assumptions related to food waste source separation, collection, transportation, pre-treatment technologies, and consumer acceptance. First, policies on food waste source separation and collection, currently implemented mainly in major cities such as Beijing and

Shanghai [29,30], are assumed to gradually expand nationwide, accompanied by increasing awareness and participation in food waste separation among households and restaurants in China. Second, food waste collection and transportation logistics are designed to improve alongside policy developments and infrastructure expansion. With increased financial support from the Chinese government, including investments in infrastructure and technological innovations, pilot food waste collection systems already operational in over 33 cities [31] are expected to scale up nationwide, enhancing waste disposal infrastructure and ensuring sufficient capacity for efficient collection and transportation of food waste. Third, pre-treatment technologies, including sorting, shredding, thermal treatment of drying and dehydration, deodorizing, fermentation, hydrolysis, and extrusion of food waste into feed pellets [25], are considered to remove excess moisture, reduce perishability, and extend shelf life, thereby enhancing the feasibility of cross-provincial transportation of food waste. Fourth, consumer acceptance of livestock products raised on food waste-based feed may be improved over time. Extensive field-based evidence has demonstrated that properly treated food waste is safe for animals with minimal health risks [32], and targeted education programs and community outreach can help address consumer concerns about product safety and enhance acceptance of food waste-based animal feed.

Estimation of feed cost and cost savings under various scenarios

The total feed cost per unit of monogastric livestock production is calculated by dividing the total feed cost (including feed crops, compound feed, food waste, and food processing by-products) by the economic output of monogastric livestock in China. In S0, the costs of feed crops (including cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, and sugar crops), compound feed, and select food processing by-products (including distiller's grains from liquor production, brewer's grains from barley beer production, and oil cake), along with the economic output of monogastric livestock, are derived from their market prices based on the SAMs in the GTAP database. Specifically, value flows from feed crops, compound feed, and these food processing by-products to monogastric livestock, as indicated in the SAMs, represent the corresponding feed costs. The costs of additional food processing by-products (including cereal bran and distiller's grains from maize ethanol production) are determined by multiplying their physical production quantities (tons) from FAO by their corresponding prices (USD ton^{-1}), which are calculated using data from UN Comtrade Database [12]. Detailed information on the costs of feed crops, compound feed, and food processing by-products is provided in the notes under Appendix Table 1 in SI. The cost of food waste (cereal grains waste, vegetables & fruits waste, roots & tubers waste, and oilseeds & pulses waste) is estimated based on the price of food waste recycling service, which includes the cost of sorting, shredding, thermal treatment of drying and dehydration, deodorizing, fermentation, hydrolysis, and extrusion of food waste into feed pellets (see Supplementary Table 5). In S1-S4, the cost associated with the increased utilisation of food waste and food processing by-products as feed is also estimated using the price of food waste recycling service. The cost savings from increased utilisation of food waste and food processing by-products as feed are then determined by comparing the total feed cost per unit of monogastric livestock production across scenarios S1-S4 with S0.

Supplementary Results

Results related to crop production and fertiliser use

The expansion of monogastric livestock production, a relatively labour-intensive sector, increases labour demand, leading to a 0.13-0.22% rise in average wages across the Chinese economy in S1-S2 (Supplementary Fig. 5). Consequently, labour becomes comparatively more expensive than other inputs (i.e., capital, cropland, and fertilisers). Higher labour costs and reduced labour availability (Supplementary Fig. 7) incentivises crop producers to use more cropland and fertilisers to substitute labour. This leads to a 0.8-2.3% increase in total nitrogen fertiliser use and a 0.8-2.8% increase in total phosphorus fertiliser use (Supplementary Fig. 4a,b). Crop producers prioritise reducing the production of relatively labour-intensive crops; for example, roots & tubers and sugar crops decrease by 6-90% and by 15-32%, respectively (Supplementary Fig. 6). The saved cropland is reallocated to increase the production of cereal grains by 0.8-1.5%, vegetables and fruits by 1.7-2.7%, and other non-food crops by 8-18% (Supplementary Fig. 6). Notably, the production of oilseeds & pulses decreases by 1.6% with partial upcycling but increases by 95% with full upcycling. This variation occurs because oilseeds & pulses are both relatively labour-intensive and cropland-intensive compared to other crops, making their production dependent on the interplay between labour and cropland costs at different levels of upcycling.

Results related to knock-on effects beyond the agricultural sectors

We observe that the increase of 11.5-18.4 million people employed in monogastric livestock production is largely a transfer from the non-food sector (i.e., industries and services; detailed in Appendix Table 1) (Supplementary Fig. 7a,c). Output in the non-food sector declines slightly by 1.0-1.4% (Supplementary Fig. 8a,c) with an absolute loss of 28-41 billion US dollars (USD, 2014 constant price) (Supplementary Fig. 9a). In contrast, nitrogen and phosphorus fertiliser production surges by 35-36% and 20-59% (Fig. 2c), respectively, due to rising demand and decreased production costs, as the shrinking non-food sector improves the availability of inputs to fertiliser production. As a consequence, China becomes an exporter of nitrogen and phosphorus fertiliser (Fig. 2f). The absolute value of fertiliser output rises by 5.4-7.0 billion USD (Supplementary Fig. 9a), which compensates for less than one-fifth of the total output decrease of the non-food sector. The economic losses in the crop and non-food sectors are largely offset by the expansion of the monogastric livestock and fertiliser sectors (Supplementary Fig. 9a). The overall impact on China's economy is a 0.02-0.07% (0.8-2.6 billion USD) decrease in GDP (Supplementary Fig. 11) and a slight positive impact on household welfare (0.18-0.32%) (Supplementary Fig. 12).

Supplementary Discussion

Interconnection between food security and environmental sustainability

Our study highlights the need to integrate both food security and environmental sustainability into policy decisions to leverage potential win-win opportunities, especially under current challenges such as climate change and resource constraints. In essence, policymakers should pay closer attention to the interconnection between food security and environmental sustainability to better leverage potential synergies and minimise trade-offs [33]. The reduction in GHG emissions, coupled with the enhancements in food security, underscores the rationale for policymakers to promote upcycling food waste and food processing by-products as feed. This also aligns with China's recent emphasis on carbon neutrality and food security as leading priorities [34,35]. However, policymakers should remain vigilant regarding indirect effects and spillovers, particularly the unintended increases in emissions of acidification and eutrophication pollutants. We implement two emission taxes to absorb the rebound effects of upcycling food waste and food processing by-products as feed in China. Our findings show that ambitious emission taxes counteract rebound effects but lead to a 9.4% rise in food prices, thereby threatening global food security. This aligns with findings of Hasegawa, et al. [36], who revealed the risk of increased food insecurity under stringent global climate change mitigation policy. Conversely, modest emission taxes provide an opportunity to absorb the rebound effects in China and safeguard global food security. Therefore, to avoid unintended negative environmental impacts and achieve the dual dividend of environmental sustainability and food security, it is essential to carefully design and implement tailored, complementary policies rather than relying on a single, one-size-fits-all solution. In China, the responsibility for food security and environmental sustainability falls on different government agencies, highlighting the pressing need for improved coordination and consistency within the government to effectively tackle these intertwined issues [37]. In addition, a globally coordinated mitigation policy is imperative for reducing the exceedance of the planetary boundaries for emissions of GHGs, acidification pollutants, and eutrophication pollutants, as unilateral environmental policies can lead to "carbon leakage" by outsourcing the production of emission-intensive goods to countries which lack environmental regulations [38].

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. Our results indicate that the average food price, food affordability, and population at risk of hunger are more sensitive to the substitution of cropland with other inputs for crop production, whereas food availability is more sensitive to the conversion of dollar-based quantities to physical quantities. Additionally, we find that emissions of GHGs and acidification pollutants are more sensitive to the feasibility of upcycling food waste and food processing by-products as feed, while emissions of eutrophication pollutants are more sensitive to the cereal self-sufficiency target. Our model is less sensitive to cleaner crop and livestock production technology. As such, while potential data variations may moderately influence the magnitude of our results, they do not alter the overall trends of food security indicators and environmental impacts, and our main conclusions remain plausible.

1) Feasibility of upcycling food waste and food processing by-products as feed

In scenario S2, we initially analysed the impacts of fully upcycling food waste and food processing by-products as feed (100% of food waste and 100% of food processing by-products for monogastric livestock) in China. While food waste is a rich source of digestible protein and energy, several barriers limit its large-scale use in animal feed. These include the technical feasibility of converting food waste into animal feed, logistical constraints such as transportation costs and shelf life, and concerns over product safety and consumer acceptance [32]. Given these constraints, we have now analysed the impacts of upcycling 75% of food waste and 100% of food processing by-products as feed in China in S2 on agricultural production and the broader economy, with implications for global food security and environmental sustainability.

We find that upcycling 75% of food waste and 100% of food processing by-products as feed in China in S2 reduces the supply of feed protein and feed energy by both 7%, and increases total feed cost (including feed crops, compound feed, food waste, and food processing by-products) per unit of monogastric livestock production by 0.4%. As a result, monogastric livestock production in China declines by 7% in S2 (Supplementary Table 11), which leads to a reduction in emissions of all pollutants from livestock production (Supplementary Fig. 17a,b,c). The contraction of monogastric livestock production, a relatively labour-intensive sector, decreases labour demand, leading to a 0.04% decrease in average wages across the Chinese economy in S2. Lower labour costs and increased labour availability increase the production of relatively labour-intensive crops in China; for example, roots & tubers and sugar crops by 83% and by 14%, respectively, in S2 (Supplementary Table 11). However, emissions of all pollutants from crop production in China decline (Supplementary Fig. 17a,b,c), as the emission reductions from decreased production of less labour-intensive crops outweigh the emission increases from the expansion of labour-intensive crops. As a result, the combined emission reductions from crop and livestock production lower total emissions of acidification and eutrophication pollutants in China in S2 by 1% and 0.5%, respectively (Supplementary Fig. 17a,b,c). Nevertheless, total emissions of GHGs in China in S2 increase by 0.4% due to more food waste in landfills and incinerators and the expansion of the non-food sector (Supplementary Table 11). In contrast, total emissions of GHGs, acidification pollutants, and eutrophication pollutants in MTP increase by 0.2%, 2.8%, and 0.8%, respectively, in S2 (Supplementary Fig. 17a,b,c), primarily driven by a 12% expansion in monogastric livestock production in MTP (Supplementary Table 11). Overall, upcycling 75% of food waste and 100% of food processing by-products as feed in China has a slight negative impact on all food security indicators in S2 (Supplementary Fig. 17d-k).

2) Conversion of dollar-based quantities to physical quantities

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. However, material intensity coefficients exhibit significant variations (Supplementary Tables 12) due to differences in commodity composition between primary and processed agricultural sectors in GTAP, as well as regional price disparities. Moreover, variations in material intensity coefficients (kg USD^{-1}) directly affect the protein and energy supply per USD for specific commodity groups across regions. Our analysis shows that monogastric and ruminant livestock provide fewer than 1200 kcal per USD, whereas commodities such as cereal grains, oilseeds & pulses, and sugar crops offer over 6000 kcal per USD (Supplementary Table 13), aligning with findings from Chepeliev [39]. Additionally, we find that food processing by-products and food waste generally supply higher protein and energy levels per USD compared to feed crops and compound feed (Supplementary Tables 14-15). Given these uncertainties, we have now analysed the impacts of ±10% variations in material intensity coefficients on agricultural production and the broader economy, with implications for global food security and environmental sustainability.

We find that a 10% reduction in material intensity coefficients leads to a 9-10% decrease in food availability in both China and MTP across all scenarios, with a comparable negative impact on the population at risk of hunger in both regions (Supplementary Fig. 18f,g,j,k). Conversely, a 10% increase in material intensity coefficients results in a 9-10% increase in food availability across all scenarios, yielding a similar positive effect on the population at risk of hunger in China and MTP (Supplementary Fig. 19f,g,j,k). The impacts of ±10% variations in material intensity coefficients on the average food price and food affordability in both China and MTP across all scenarios are minimal (Supplementary Fig. 18d,e,h,i; Supplementary Fig. 19d,e,h,i). Likewise, ±10% variations in material intensity coefficients have a minor effect on emissions of all pollutants in China and MTP across all scenarios (Supplementary Fig. 18a-c; Supplementary Fig. 19a-c).

3) Substitution of cropland with other inputs for crop production

Our model initially maintained total crop output as a fixed ratio of nitrogen and phosphorus fertiliser inputs but did not impose a fixed ratio between total crop output and cropland input. Now, we have analysed the impacts of imposing a fixed ratio between total crop output and cropland input. This constraint prevents fluctuations in crop yield per hectare and may alter agricultural production and sectors beyond agriculture across the entire economy, ultimately shaping global food security and environmental sustainability.

We find that imposing a fixed ratio between total crop output and cropland input restricts crop producers' ability to expand cropland to maintain crop output under rising labour costs and reduced labour availability in S1-S2. As a result, crop production becomes more vulnerable to these labour constraints, exacerbating feed crop shortages. Since monogastric livestock production in China relies more on feed crops than in MTP, as reflected in higher feed crop cost shares in China (Supplementary Table 16), the reduction in feed crop availability leads to a 1.7-1.9% decline in monogastric livestock production in China, while production in MTP increases by 1.1-1.6% in S1-S2 (Supplementary Table 17). Additionally, the contraction of monogastric livestock production in China frees up labour, which is reallocated to fertiliser production, leading to a 5.5-8.2% increase in nitrogen fertiliser production and a 3.8-10.1% increase in phosphorus fertiliser production in S1-S2 (Supplementary Table 17). This expansion in fertiliser supply enables greater fertiliser application in crop production, which contributes to a 0.2-3.6% increase in total crop production in China in S1-S2. The increases in crop and fertiliser production raise total emissions of GHGs in China by 0.08-0.09% in S1-S2 (Supplementary Fig. 20a). In contrast, the expansion of livestock production in MTP results in a 0.4-0.5% increase in total emissions of acidification pollutants in MTP in S1-S2 (Supplementary Fig. 20b).

Imposing a fixed ratio between total crop output and cropland input has minimal effects on food security in S1-S3 (Supplementary Fig. 20d-k) but negatively impacts S4 due to higher emission taxes required for achieving an ambitious mitigation target. This leads to a 4.6% rise in the average global food price (Supplementary Fig. 20d,h), reducing food affordability in China and MTP by 5.6% and 3.8%, respectively (Supplementary Fig. 20e,i). Furthermore, nitrogen and phosphorus fertiliser prices rise by 14% and 3%, respectively (Supplementary Table 18), which increases fertiliser costs and reduces total crop production. Consequently, food availability in China and MTP decreases by

3.1% and 2.2% (Supplementary Fig. 20g,k), respectively, which in turn increases the population at risk of hunger by 31% in China and 245% in MTP (Supplementary Fig. 20f,j) in S4.

4) Cereal self-sufficiency target

Our model initially set a 10% lower bound on original production for each sector to prevent extreme specialisation effects under free international trade, which could otherwise eliminate the production of certain goods in specific regions. Since the Chinese government's self-sufficiency ratio (SSR refers to the magnitude of production in relation to domestic use) redline [40] mandates a 95% self-sufficiency target for wheat, rice, and maize to ensure domestic food security, we have now analysed the impacts of implementing a 95% self-sufficiency requirement for cereal grains in China. This could influence trade flows, with broader implications for global food security and environmental sustainability. We examine the SSR of cereal grains in China across scenarios S0-S4 and find that only in S3 does the SSR drop below 95%, reaching 83% (Supplementary Table 11). As a result, implementing the 95% SSR constraint only affects scenario S3.

We find that implementing the 95% self-sufficiency requirement for cereal grains in China in S3 raises the SSR for cereal grains by 15% (Supplementary Table 12). This leads to higher emissions of GHGs and acidification pollutants from crop production in China (Supplementary Fig. 17a,b). However, emissions of eutrophication pollutants from crop production decline in China (Supplementary Fig. 17c), primarily due to a 63% reduction in the SSR for oilseeds & pulses (Supplementary Table 12). This occurs because cereal grains have relatively higher emission intensities of GHGs and acidification pollutants compared to oilseeds & pulses (Appendix Tables 8-9), while oilseeds & pulses have relatively higher eutrophication pollutant intensities than cereal grains (Appendix Table 10). Emissions from livestock production remain largely unchanged, as the self-sufficiency constraint has minimal impacts on livestock production. Given the increases in emissions of GHGs and acidification pollutants from crop production, reductions in emissions from non-agricultural sectors (Supplementary Fig. 17a,b) are needed to ensure that total emissions in China remain below baseline (S0) levels in S3. Consequently, China's production adjustments result in a 0.2% reduction in total emissions of GHGs and a 2.4% reduction in total emissions of eutrophication pollutants in China, while total emissions of acidification pollutants remain unchanged compared to conditions without the SSR constraint. In contrast, in MTP, China's 95% self-sufficiency requirement for cereal grains has the opposite effects compared to China. It leads to lower emissions of GHGs and acidification pollutants (Supplementary Fig. 17a,b) but higher emissions of eutrophication pollutants from crop production in MTP (Supplementary Fig. 17c). Additionally, it increases emissions of all pollutants from non-agricultural sectors (Supplementary Fig. 17a,b,c). As a result, MTP's production adjustments lead to a 0.3% reduction in total emissions of GHGs and a 1.9% reduction in total emissions of acidification pollutants in MTP. However, total emissions of eutrophication pollutants in MTP increase by 0.8% compared to conditions without the SSR constraint. Despite this increase, total emissions of eutrophication pollutants in MTP remain below baseline (S0) levels in S3. Overall, the 95% self-sufficiency requirement for cereal grains in China has a slight negative impact on food access but a minor positive effect on food availability in S3 (Supplementary Fig. 17d-k).

5) Cleaner crop and livestock production technology

We initially calculated 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}) by dividing each sector's emissions by its economic value. These dollar-based emission intensities are presented in Appendix Tables 8-10. Since China's emission intensities in crop and livestock production are generally higher than those of its trading partners due to excessive chemical fertiliser use and poor manure management, there is significant potential for improvements. To address this, China has made substantial investments in agricultural research and development (R&D) to advance cleaner production technologies and promote sustainable agricultural production, with expenditures reaching 9.8 billion USD in 2020 [41]. Now, we assume that financial support for R&D facilitates the full adoption of cleaner production technology, leading to a 25% reduction in emission intensities in China's crop and livestock production. Given the uncertainties in emission intensities and China's substantial R&D investments, we have now analysed the impacts of a 25% reduction in emission intensities of all pollutants in crop and livestock production in China on agricultural production and the broader economy, with implications for global food security and environmental sustainability.

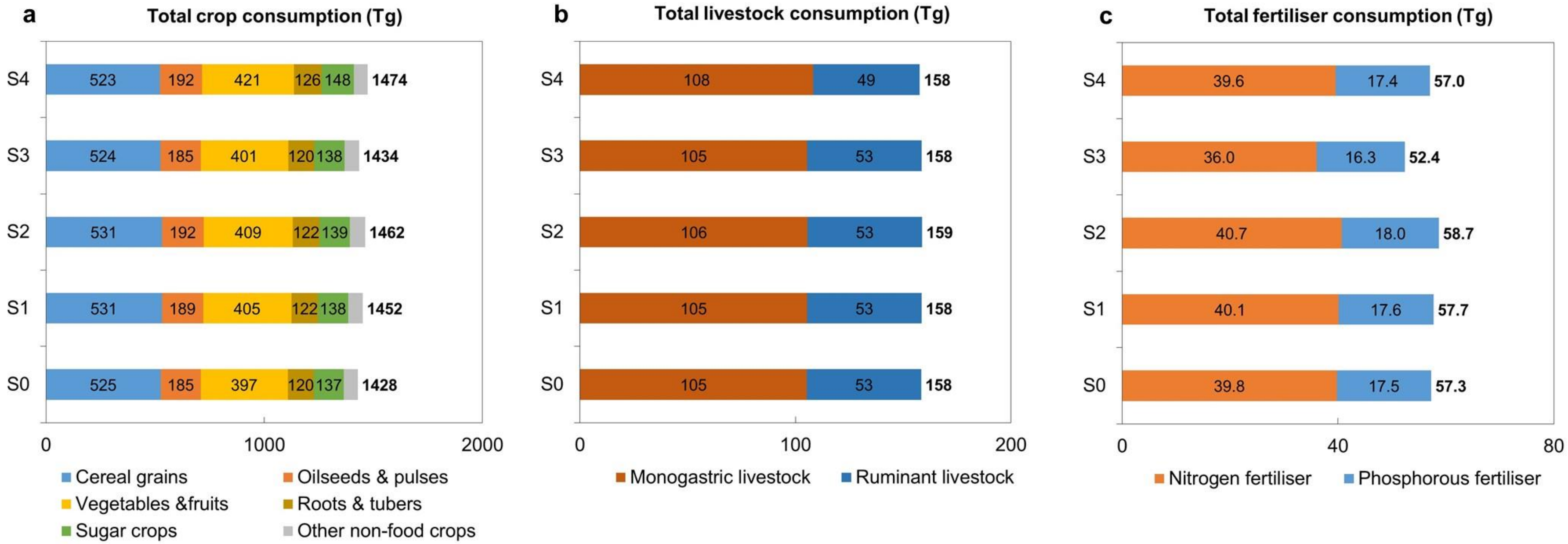
We find that a 25% reduction in the emission intensities of all pollutants in crop and livestock production in China results in a proportional decrease in the emissions of all pollutants from these sectors in S1-S2 (Supplementary Fig. 22a,b,c). Since emissions from crop and livestock production contribute more to economy-wide emissions of acidification (43%) and eutrophication (45%) pollutants than to GHG emissions (6%) in China (Supplementary Fig. 13), the 25% reduction in emission intensities results in a greater decline in Chinese economy-wide emissions of acidification (0.7-1.2%) and eutrophication (0.3-0.6%) pollutants compared to GHG emissions (0.04-0.08%) in S1-S2 (Supplementary Fig. 22a,b,c). The 25% reduction in emission intensities has minimal effects on food security in S1-S4 (Supplementary Fig. 22d-k).

Limitations and future outlook

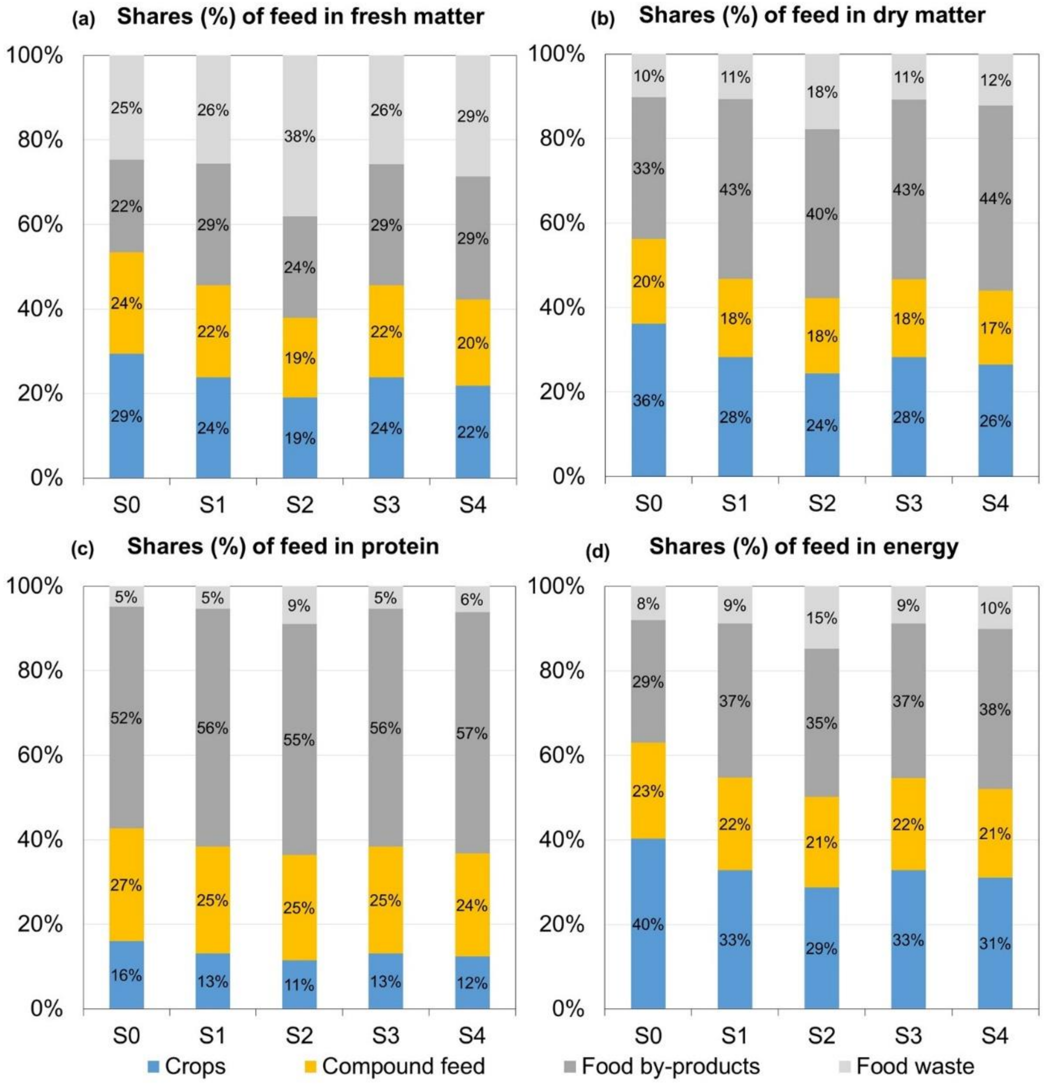
First, some specifications in our model are appropriate for illustrating possible rebound effects, but some simplifications may exaggerate trends. Our model assumes fixed budget shares for consumers, fixed cost shares for producers, full mobility of factor endowments (capital, labour, and land) across sectors, the absence of trade barriers, and the treatment of domestic and imported goods as perfect substitutes. For instance, future research necessitates introducing separate labour and capital markets for agricultural and non-agricultural sectors or allowing for land shifts within agroecological zones with similar soil, landform, and climatic features, as included in the MAGNET [42] and GTAP-AEZ [43] models to account for barriers to factor mobility. Additionally, refining the trade assumption by adopting the Armington assumption [44], which allows for imperfect substitutability between domestic and imported goods, could provide a more nuanced representation of trade. However, this approach also adds complexity, weakens the role of comparative advantage, and may overstate trade frictions. Therefore, the careful selection of the Armington elasticity, which determines the ease of substitution between domestic and imported goods, is essential. Second, our model does not account for sub-national heterogeneity, such as variations in agricultural production, feed prices, food waste treatment costs, and supply sources. Future research could enhance the model's spatial resolution to capture sub-national heterogeneity, providing more precise insights for region-specific policy design and implementation. Third, we use dollar-based shares to allocate physical material flows, which, following previous studies [39,45], does not account for variations in product quality along the global supply chain that are reflected in price discrepancies across countries and regions. However, this remains a common approach for converting dollar-based quantities to physical quantities, as no universally accepted method has yet addressed this issue. Our study serves as a step towards bridging monetary AGE models with biophysical and nutritional (e.g. protein and energy) constraints, providing a foundation for further research to further address this limitation. Fourth, this study employs a static modelling framework to isolate the impacts of upcycling food waste and food processing by-products as animal feed and implementing emission taxes under current economic conditions. This approach does not account for 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). Since these factors could reshape crop and livestock production portfolios in China and its trading partners, with broader implications for global food security and environmental sustainability, future research could incorporate dynamic modelling and extra scenario analyses to better capture these uncertainties.

Other limitations include the omission of the substitution between animal manure and chemical fertilisers, the exclusion of certain feed types, the lack of policy simulations to support food waste and by-product upcycling, potential constraints on food waste availability due to SDG 12.3 ("halving food waste"), and the absence of health impact assessments, such as diet- and weight-related risks, all of which present avenues for future research. For example, we do not explicitly examine the substitution between animal manure and chemical fertilisers, since the rebound effect of livestock production expansion in China could increase animal manure, which, if recycled onto cropland, may reduce the demand for chemical fertilisers and lower associated emissions. Although this is beyond the scope of our analysis, future research could apply the methodologies we outlined to investigate this substitution. Additionally, extending our modelling framework to include additional feed types like maize silage, alfalfa hay, and roughage-like by-products would improve the assessment of nutritional balances, particularly in the context of ruminant livestock production. Since these feeds are primarily used for ruminant livestock, which is not our main focus, this falls outside the scope of our study. Furthermore, our analysis concentrates on scenarios outlining technically and physically possible options and does not endeavour to depict policy instruments for achieving the goal of increased utilisation of food waste and food processing by-products as feed, aligning with previous literature on upcycling food waste and food processing by-products as animal feed [7,46-48]. How to design and implement policies that can achieve the goal of increased utilisation of food waste and food processing by-products as feed should be a pivotal direction for future research. Moreover, in line with SDG 12.3 ("halving food waste") [49], high priority should be placed on reducing food waste. With less food waste available for animal feed, the impacts of upcycling food waste as feed may diminish. However, we consider our estimates of the impacts of upcycling food waste as feed as conservative, as we did not factor in cross-provincial transportation of food waste with high moisture content (except in scenario S2). Last but not least, health impacts resulting from changes in food consumption, such as diet- and weight-related risks [50], could also be considered.

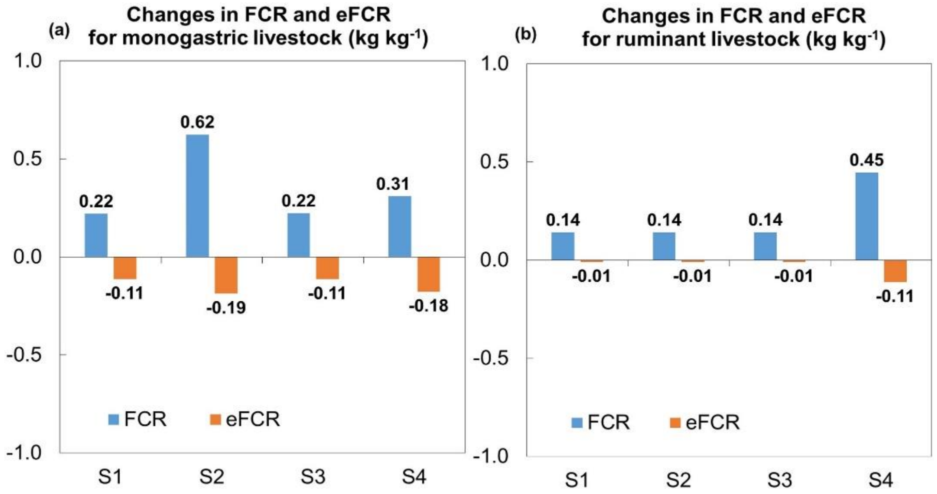
Supplementary Figures



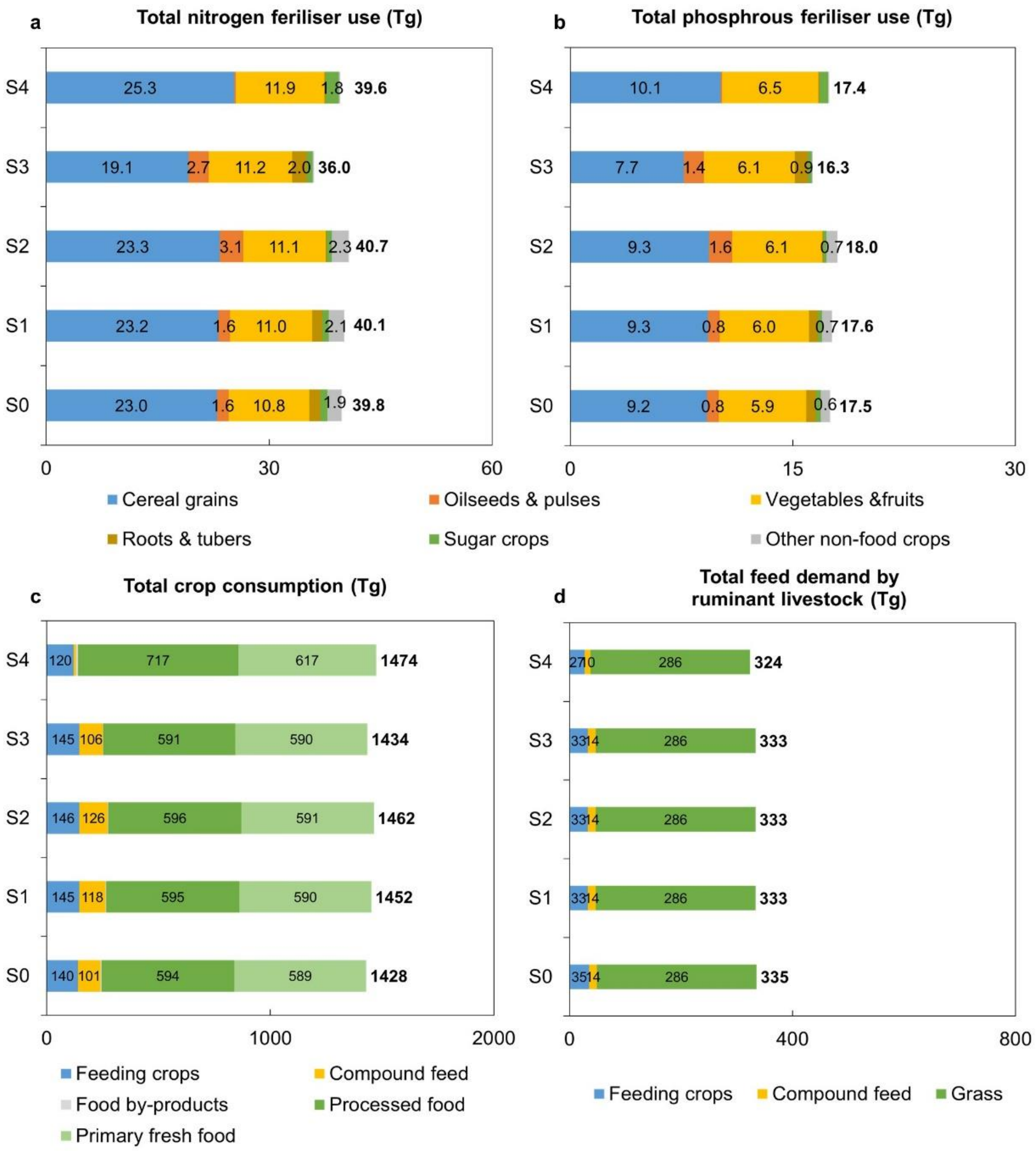
Supplementary Fig. 1 | Total (a) crop, (b) livestock, and (c) fertiliser consumption (Tg) in scenarios. Total crop consumption exclude food waste and food processing by-products used by "food waste recycling service" and "food waste collection service" sectors (see Supplementary Table 4 for detailed data). 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).



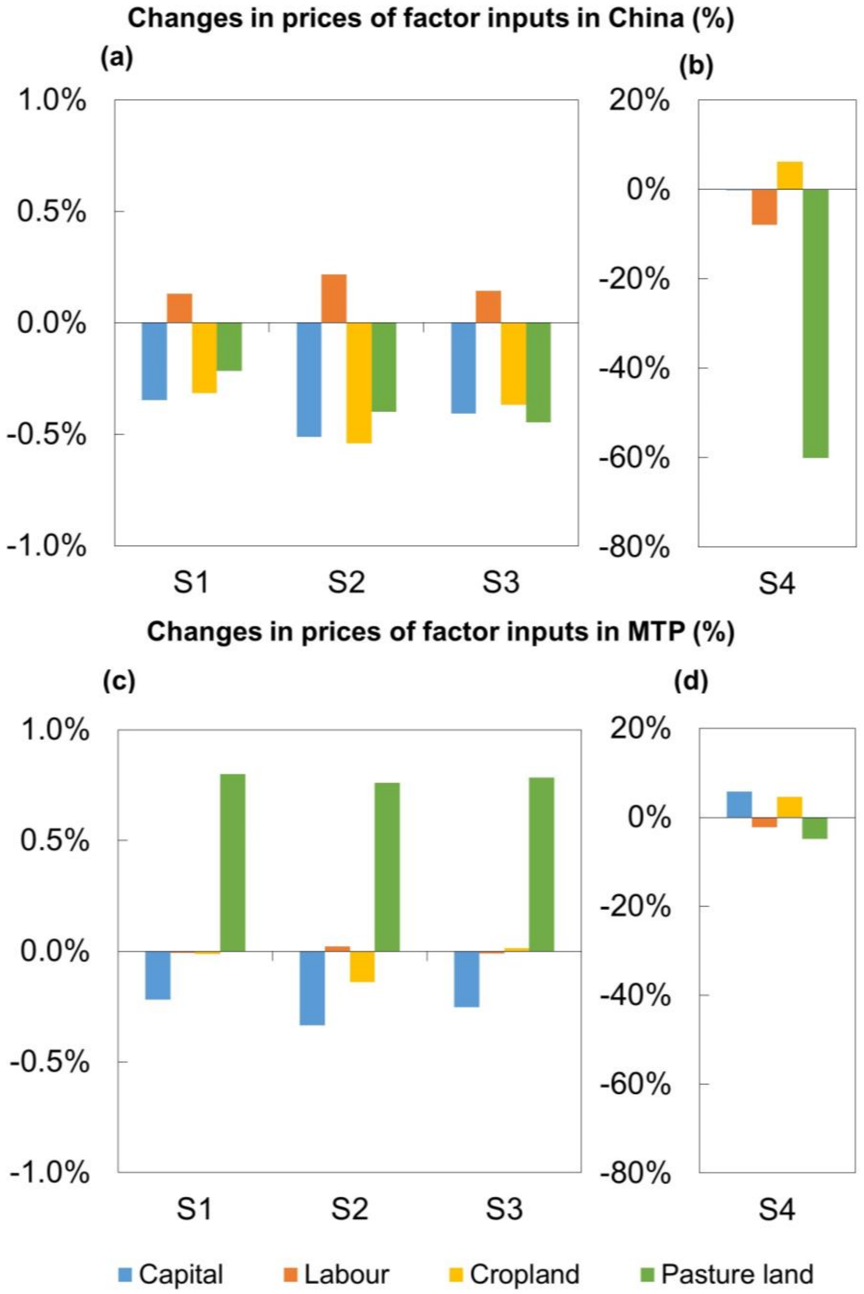
Supplementary Fig. 2 | Shares (%) of each type of feed within the total feed use for monogastric livestock production, categorized by (a) fresh matter, (b) dry matter, (c) protein, and (d) energy in China in scenarios.



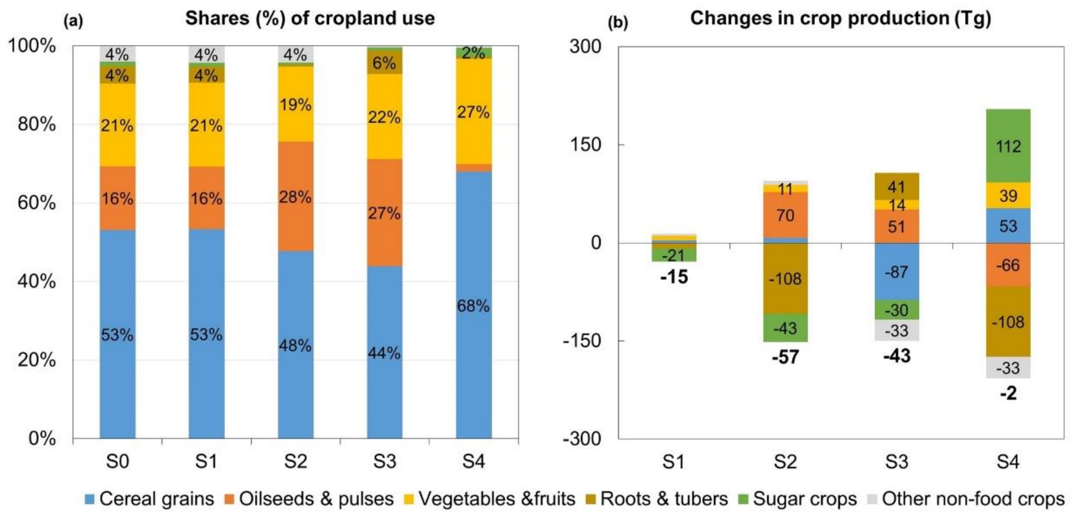
Supplementary Fig. 3 | Changes in FCR (kg kg^{-1}) and eFCR (kg kg^{-1}) for (a) monogastric livestock and (b) ruminant livestock production in China in scenarios with respect to the baseline (S0).



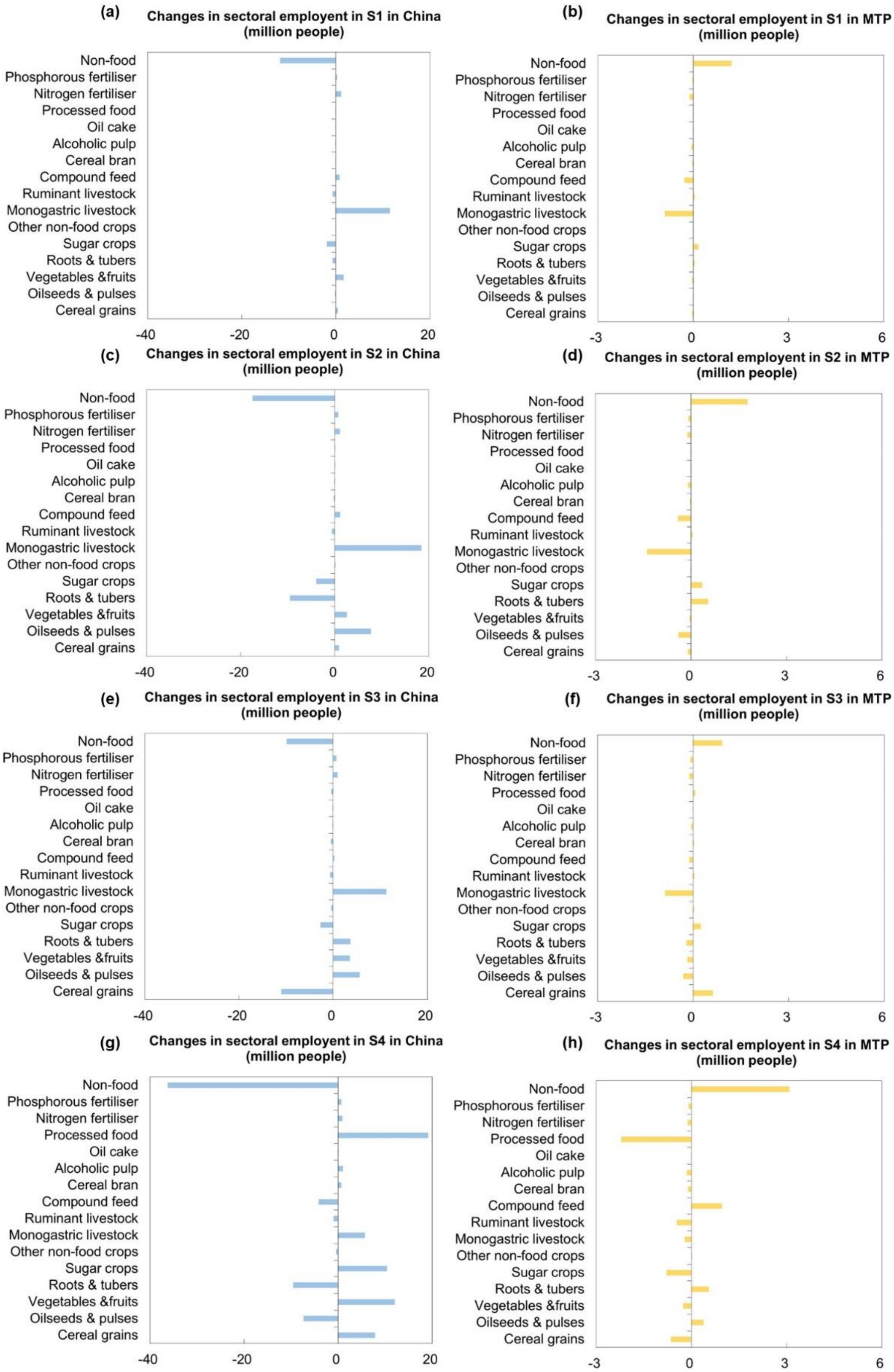
Supplementary Fig. 4 | Total (a) nitrogen fertiliser use (Tg), (b) phosphorous fertiliser use (Tg), (c) crop consumption (Tg), and (d) feed demand by ruminant livestock (Tg) in scenarios.



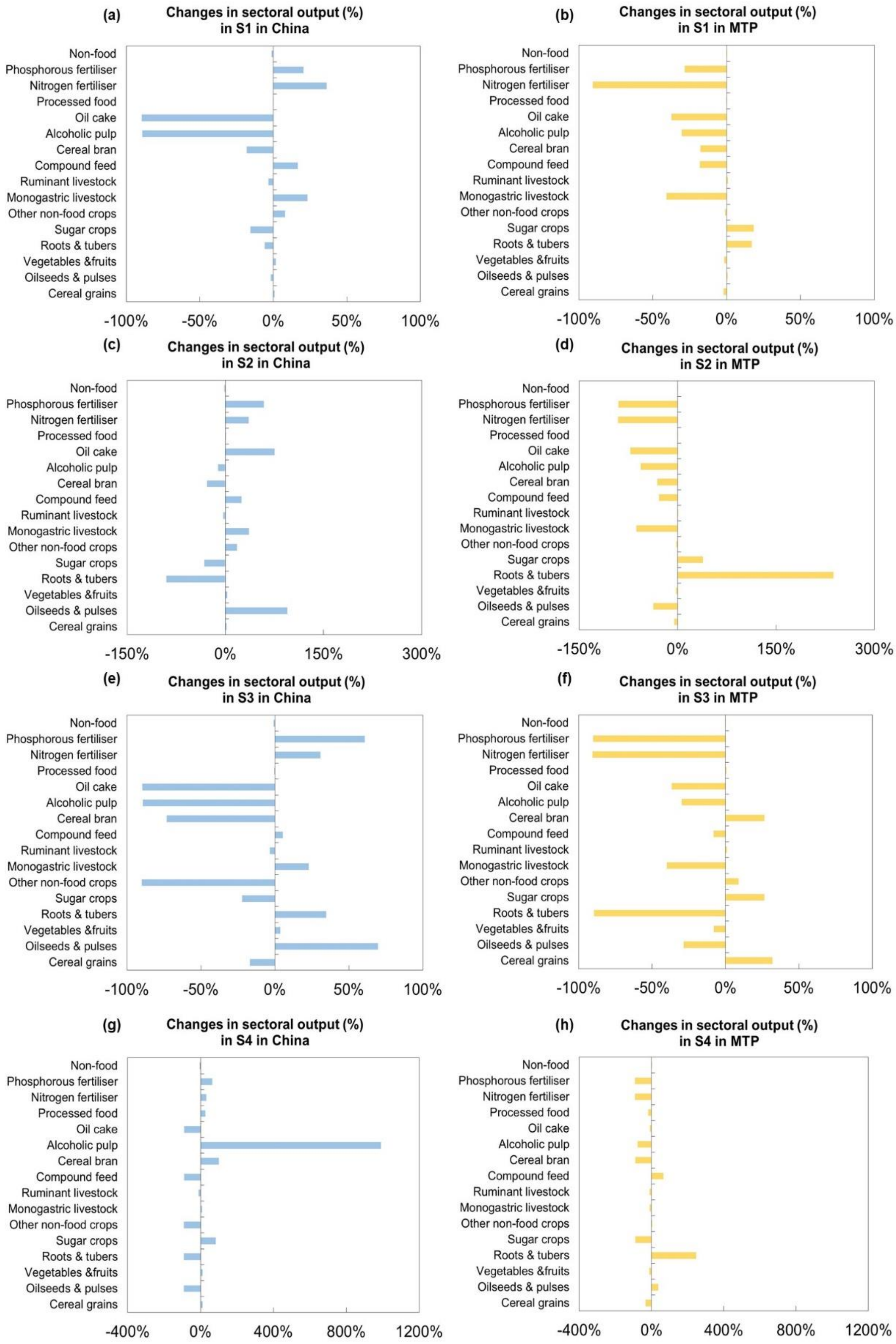
Supplementary Fig. 5 | Changes (%) in prices of factor inputs in China in scenarios (a) S1-3 and (b) S4 with respect to the baseline (S0). Changes (%) in prices of factor inputs in MTP in scenarios (c) S1-3 and (d) S4 with respect to the baseline (S0).



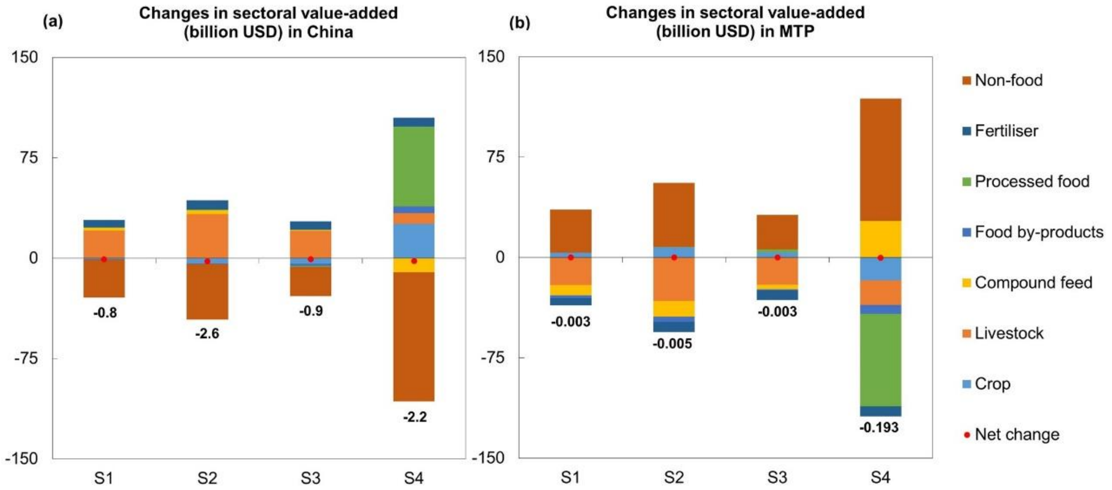
Supplementary Fig. 6 | (a) Shares (%) of each type of crop within the total cropland use in China in scenarios. (b) Changes (Tg) in crop production in China in scenarios with respect to the baseline (S0).



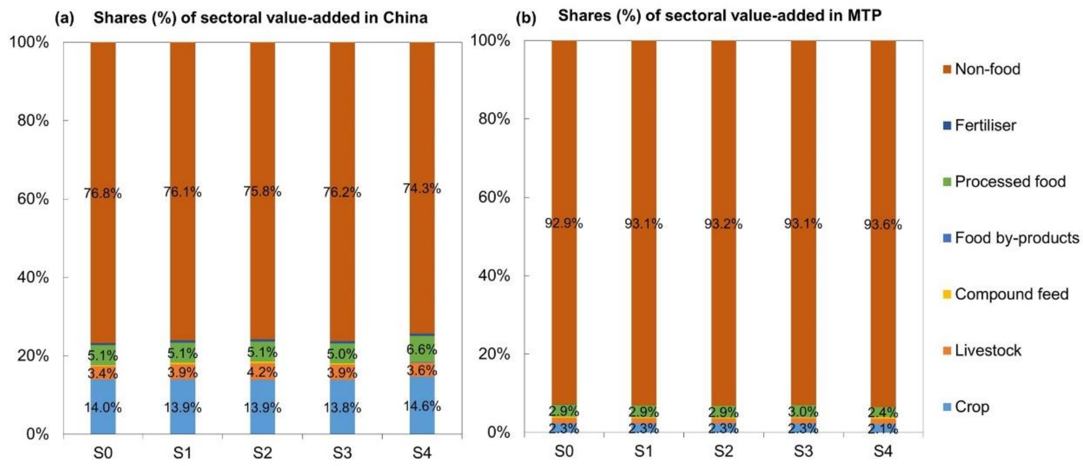
Supplementary Fig. 7 | Changes (million people) in sectoral employment in China in scenarios (a) S1, (c) S2, (e) S3, and (g) S4 with respect to the baseline (S0). Changes (million people) in sectoral employment in MTP in scenarios (b) S1, (d) S2, (f) S3, and (h) S4 with respect to the baseline (S0).



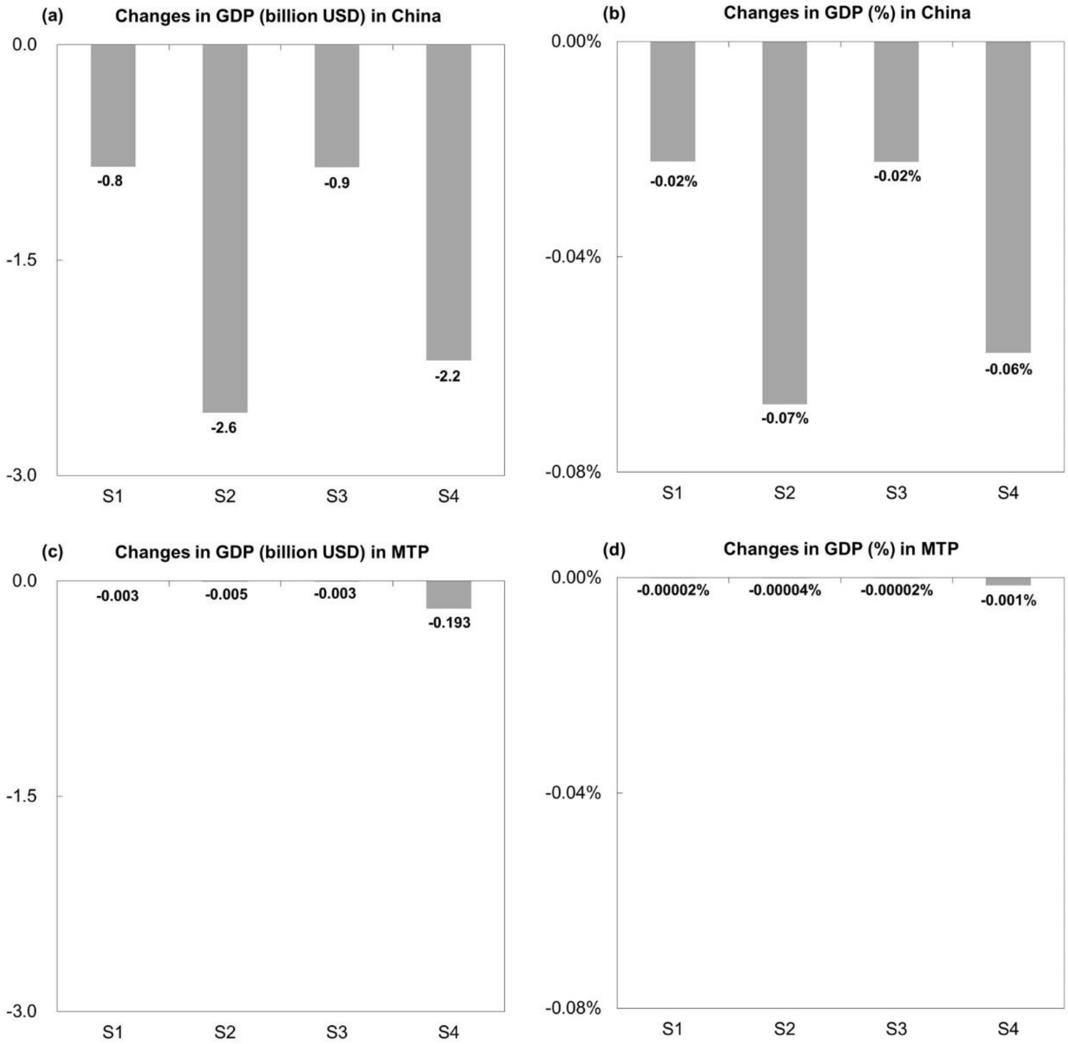
Supplementary Fig. 8 | Changes (%) in sectoral output (i.e., the value of production) in China in scenarios (a) S1, (c) S2, (e) S3, and (g) S4 with respect to the baseline (S0). Changes (%) in sectoral output (i.e., the value of production) in MTP in scenarios (b) S1, (d) S2, (f) S3, and (h) S4 with respect to the baseline (S0).



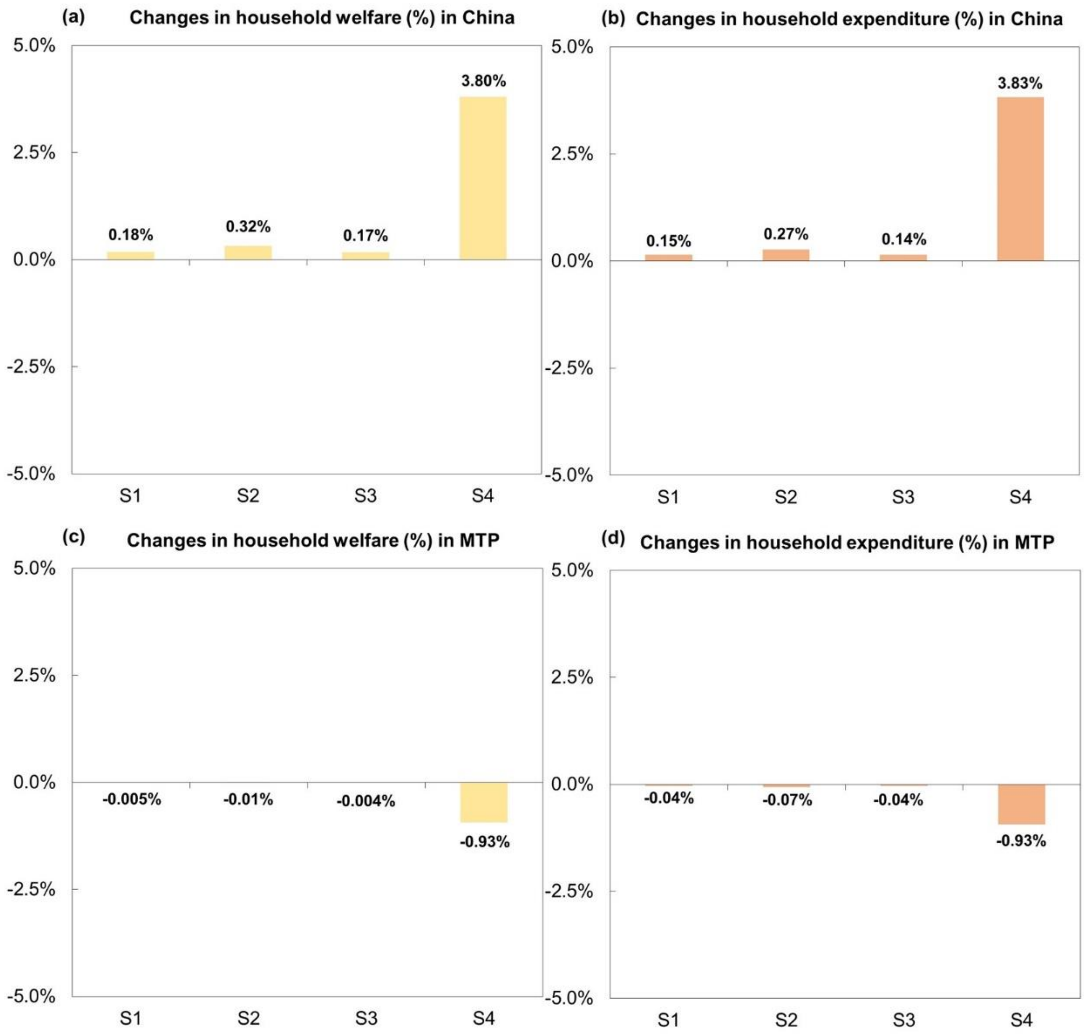
Supplementary Fig. 9 | Changes (billion USD) in sectoral value-added (a) in China and (b) MTP in scenarios with respect to the baseline (S0).



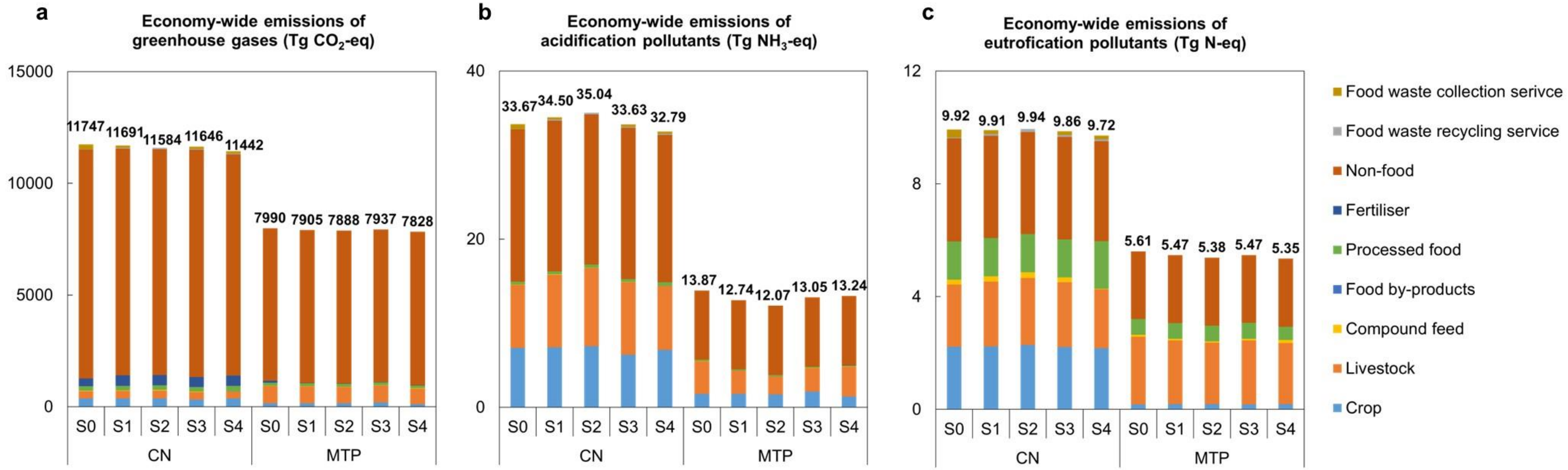
Supplementary Fig. 10 | Shares (%) of sectoral value-added in (a) China and (b) MTP in scenarios.



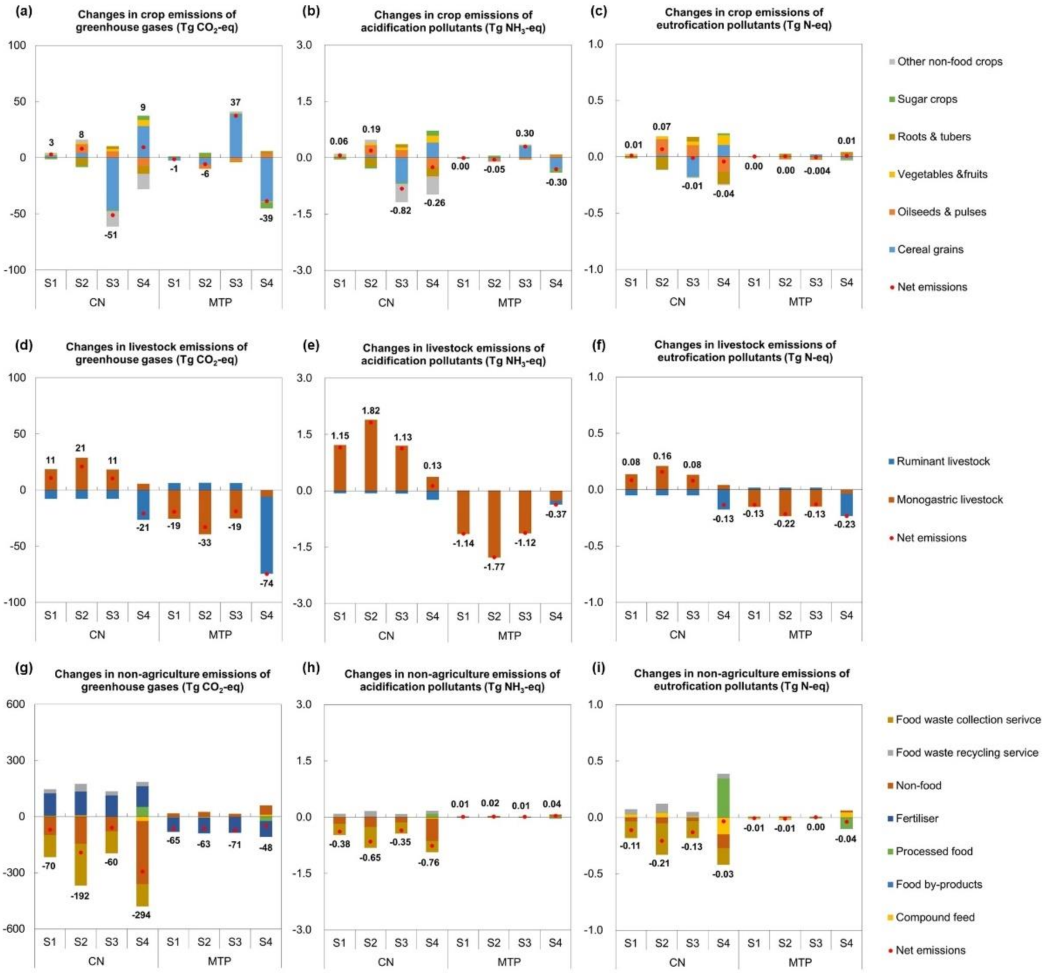
Supplementary Fig. 11 | (a) Absolute changes (billion USD) and (b) relative changes (%) in gross domestic product (GDP) in China in scenarios with respect to the baseline (S0). (c) Absolute changes (billion USD) and (d) relative changes (%) in gross domestic product (GDP) in MTP in scenarios with respect to the baseline (S0).



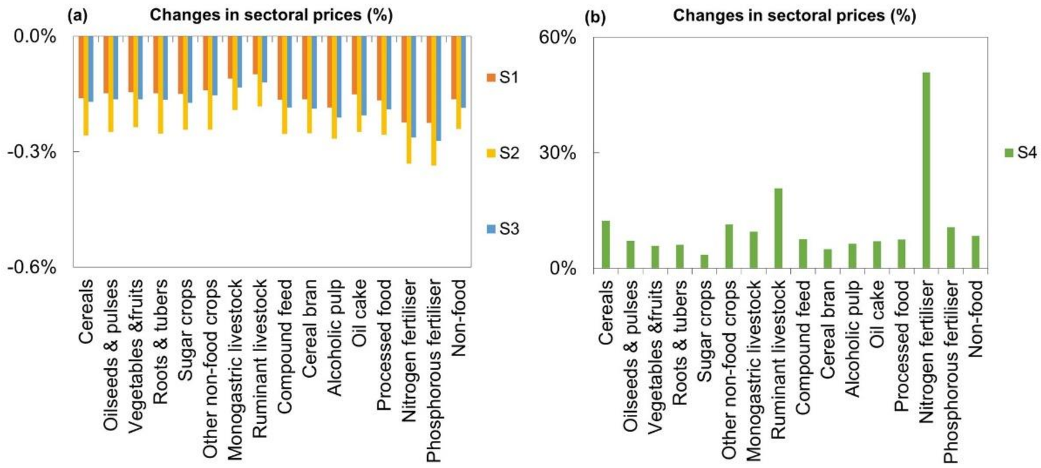
Supplementary Fig. 12 | Changes (%) in (a) household welfare and (b) household expenditure in China in scenarios with respect to the baseline (S0). Changes (%) in (c) household welfare and (d) household expenditure in MTP in scenarios with respect to the baseline (S0).



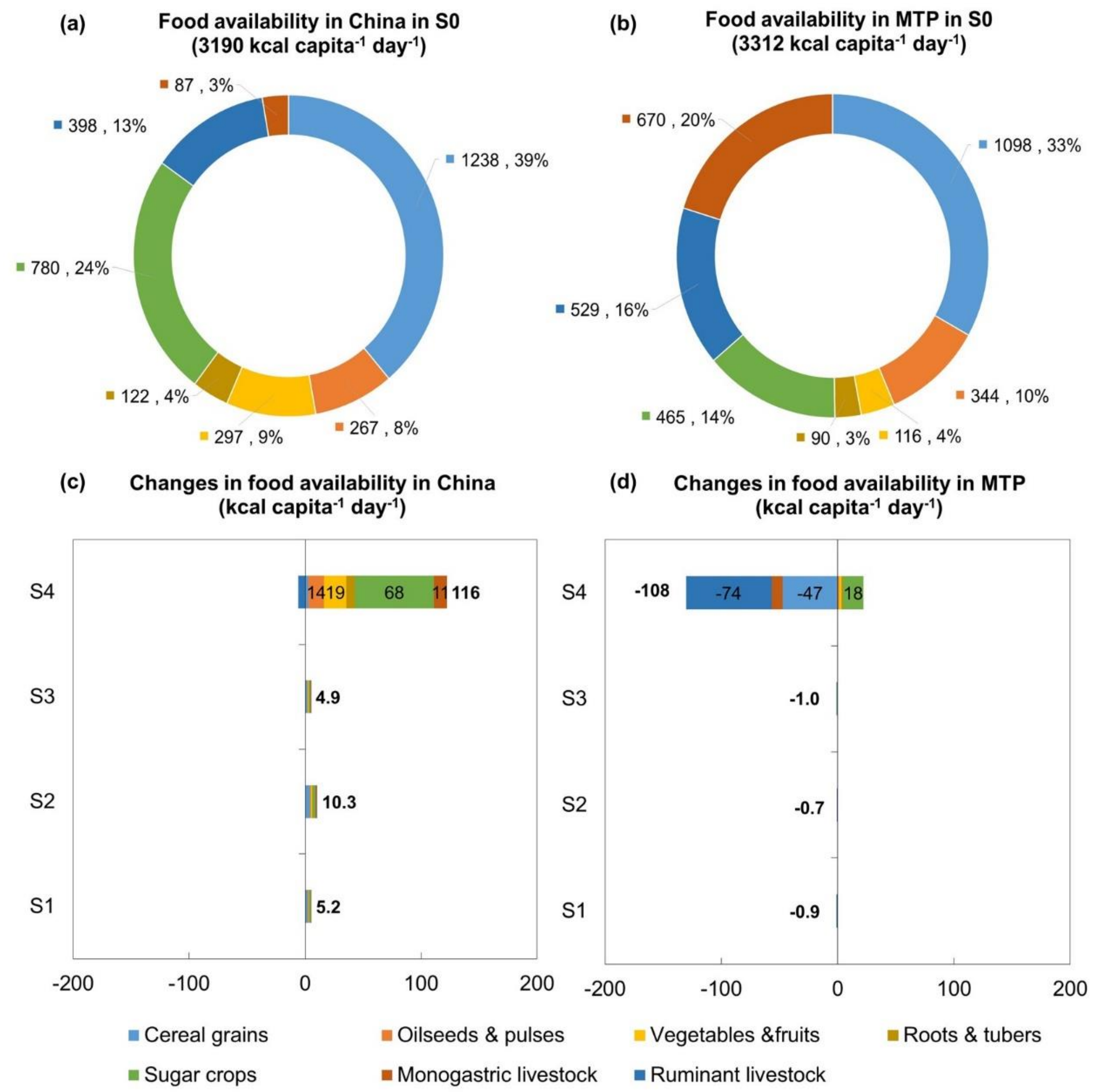
Supplementary Fig. 13 | (a) Economy-wide emissions of greenhouse gases (Tg CO2-eq), (b) acidification pollutants (Tg NH3-eq), and (c) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios.



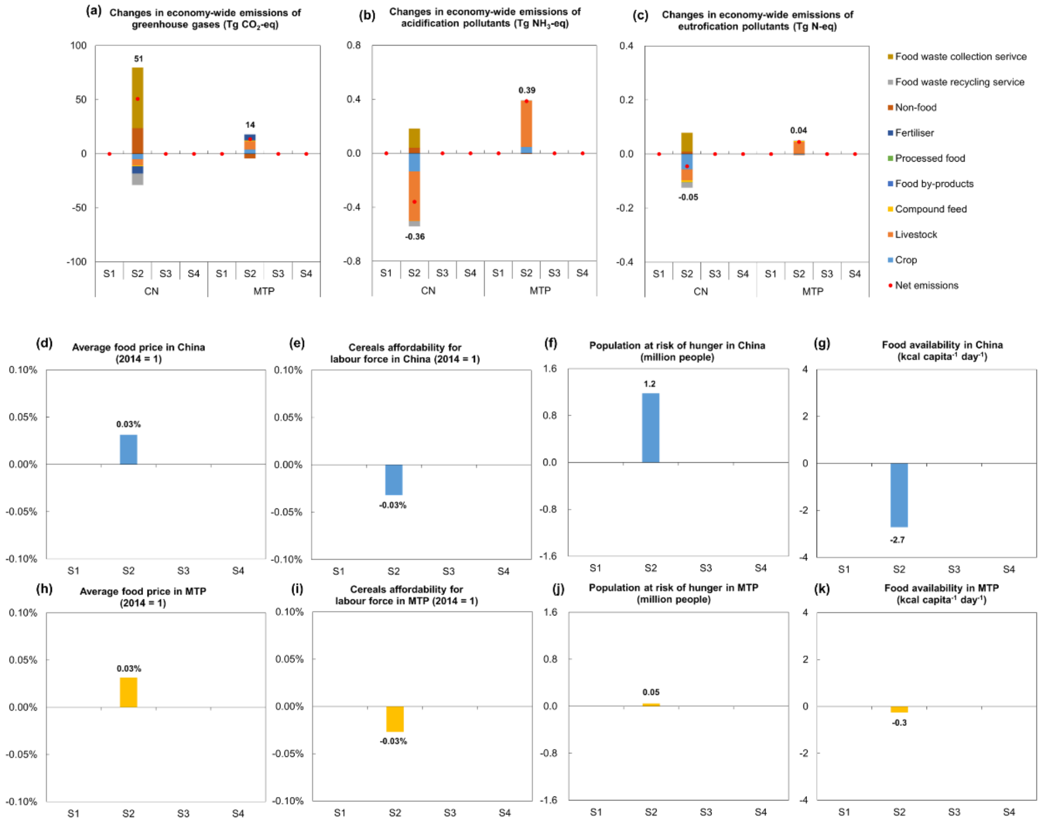
Supplementary Fig. 14 | Changes in crop emissions of (a) greenhouse gases (Tg CO_2-eq), (b) acidification pollutants (Tg NH_3-eq), and (c) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0). Changes in livestock emissions of (d) greenhouse gases (Tg CO_2-eq), (e) acidification pollutants (Tg NH_3-eq), and (f) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0). Changes in non-agriculture emissions of (g) greenhouse gases (Tg CO_2-eq), (h) acidification pollutants (Tg NH_3-eq), and (i) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0).



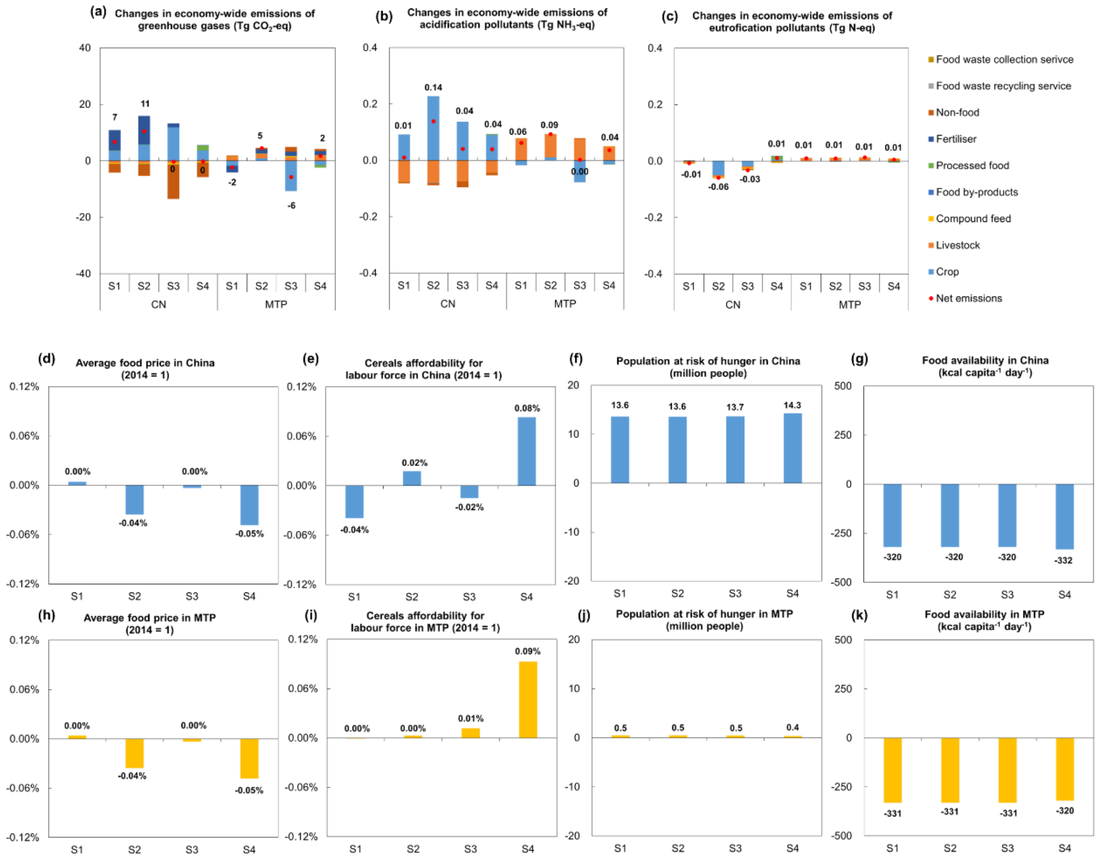
Supplementary Fig. 15 | Changes (%) in sectoral prices in scenarios (a) S1-S3 and (b) S4 with respect to the baseline (S0).



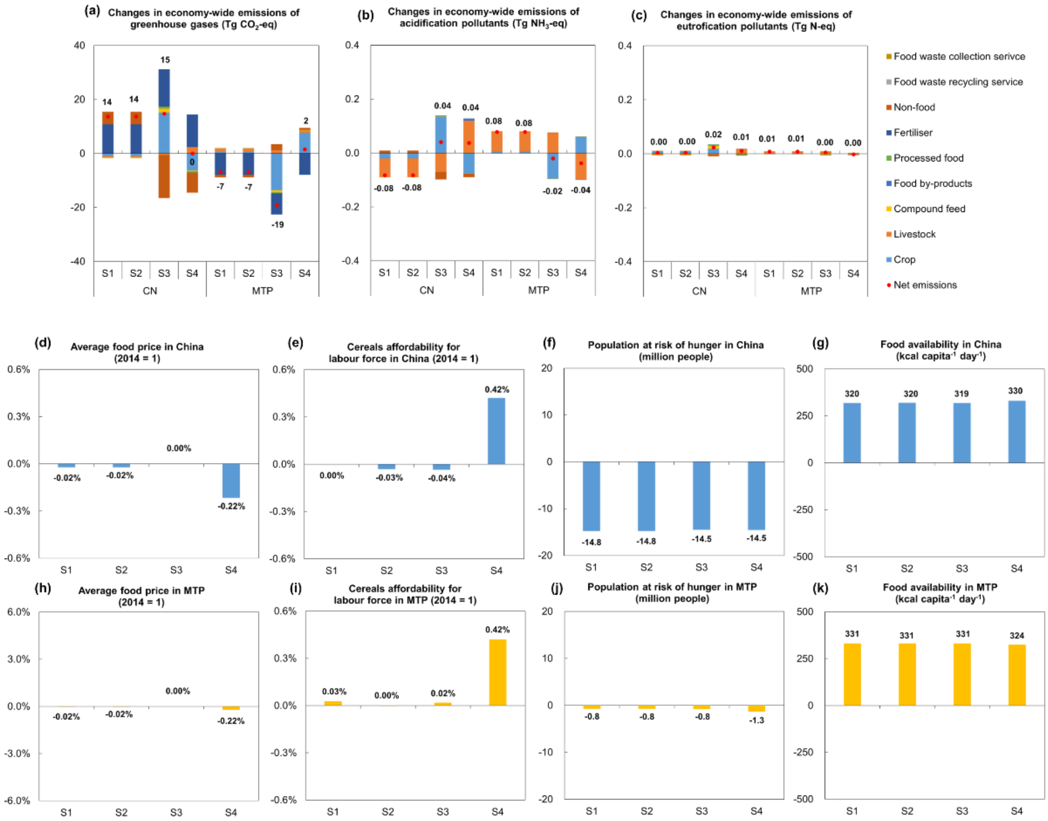
Supplementary Fig. 16 | Composition of food availability (%; kcal capita^{-1} day^{-1}) in (a) China and (b) MTP in the baseline (S0). Changes in food availability (kcal capita^{-1} day^{-1}) in (c) China and (d) MTP in scenarios with respect to the baseline (S0).



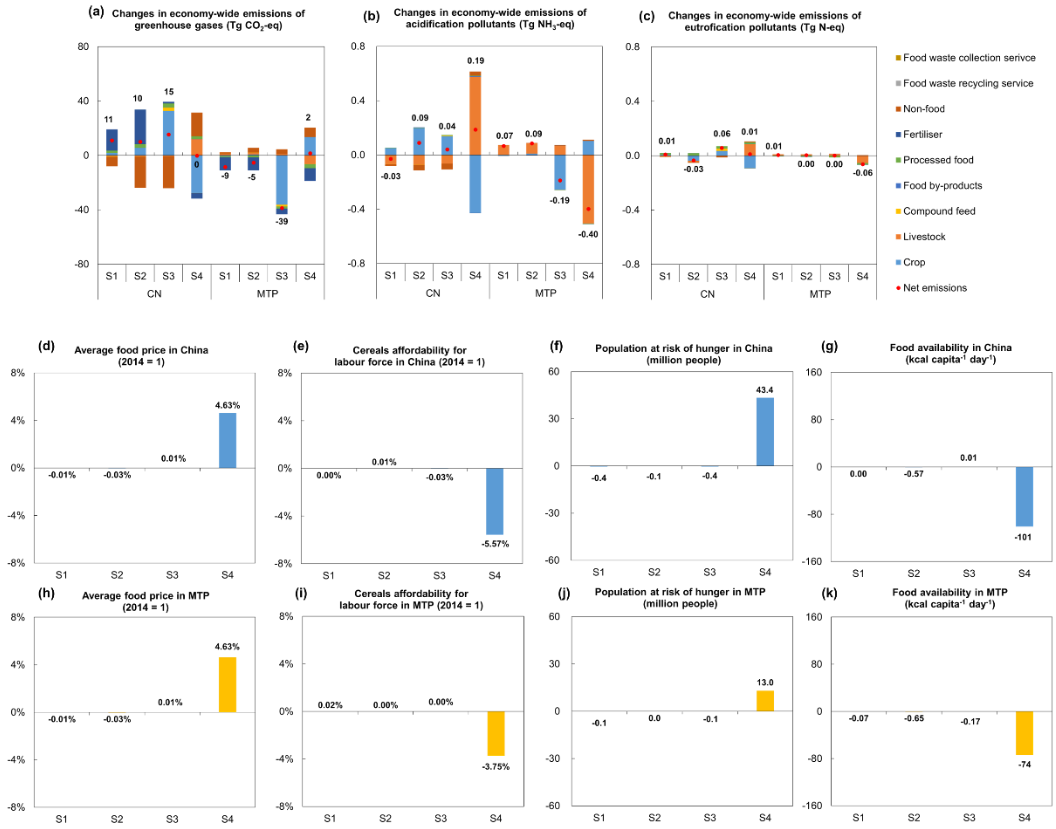
Supplementary Fig. 17 | Changes in (a) economy-wide emissions of greenhouse gases (Tg CO_2-eq), (b) acidification pollutants (Tg NH_3-eq), and (c) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0) under upcycling 75% of food waste and 100% of food processing by-products as feed. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under upcycling 75% of food waste and 100% of food processing by-products as feed. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under upcycling 75% of food waste and 100% of food processing by-products as feed.



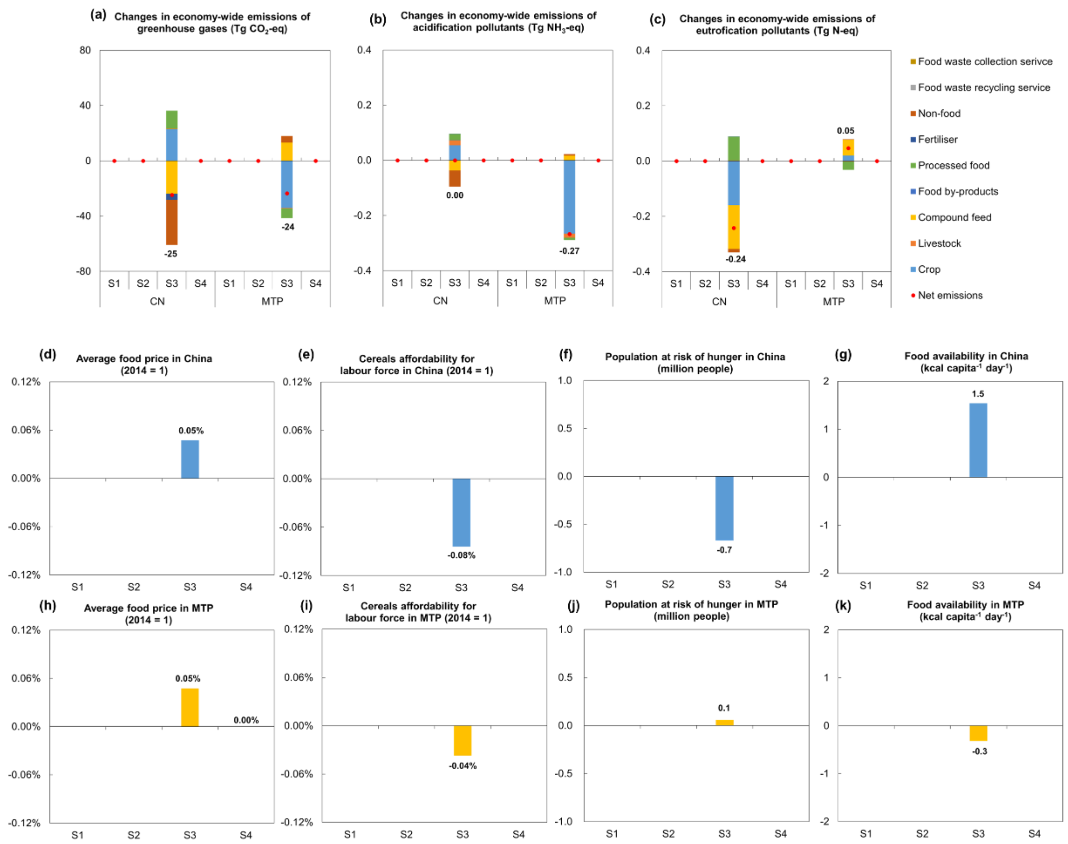
Supplementary Fig. 18 | Changes in (a) economy-wide emissions of greenhouse gases (Tg CO_2-eq), (b) acidification pollutants (Tg NH_3-eq), and (c) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0) under a 10% decrease in material intensity coefficients. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under a 10% decrease in material intensity coefficients. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under a 10% decrease in material intensity coefficients.



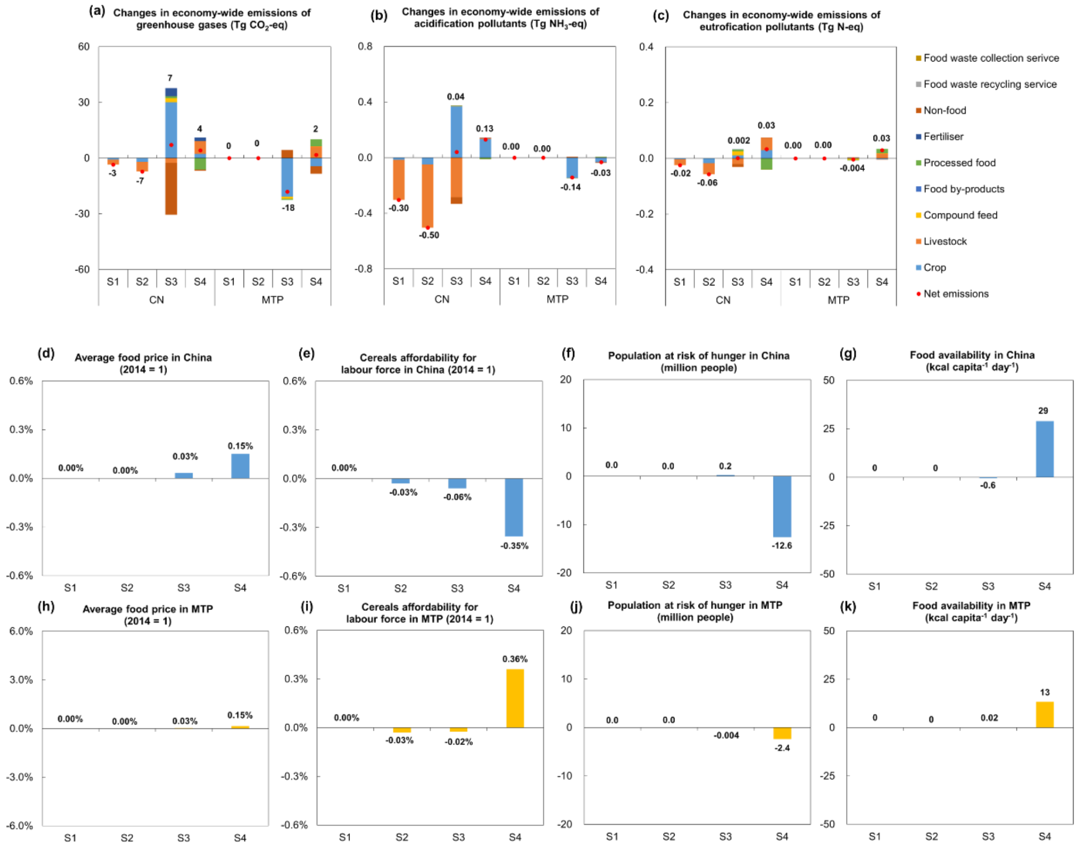
Supplementary Fig. 19 | Changes in (a) economy-wide emissions of greenhouse gases (Tg CO_2-eq), (b) acidification pollutants (Tg NH_3-eq), and (c) eutrophication pollutants (Tg N-eq) in China and MTP in scenarios with respect to the baseline (S0) under a 10% increase in material intensity coefficients. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under a 10% increase in material intensity coefficients. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under a 10% increase in material intensity coefficients.



Supplementary Fig. 20 | Changes in (a) economy-wide emissions of greenhouse gases (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) under a fixed ratio between total crop output and cropland input. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under a fixed ratio between total crop output and cropland input. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under a fixed ratio between total crop output and cropland input.



Supplementary Fig. 21 | Changes in (a) economy-wide emissions of greenhouse gases (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) under a 95% self-sufficiency requirement for cereal grains in China. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under a 95% self-sufficiency requirement for cereal grains in China. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under a 95% self-sufficiency requirement for cereal grains in China.



Supplementary Fig. 22 | Changes in (a) economy-wide emissions of greenhouse gases (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) under a 25% reduction in emission intensities of all pollutants in crop and livestock production in China. Changes in (d) average food price (including primary food products and processed food), (e) cereals affordability for labour force, (f) population at risk of hunger (million people), and (g) food availability (kcal capita^{-1} day^{-1}) in China in scenarios with respect to the baseline (S0) under a 25% reduction in emission intensities of all pollutants in crop and livestock production in China. Changes in (h) average food price (including primary food products and processed food), (i) cereals affordability for labour force, (j) population at risk of hunger (million people), and (k) food availability (kcal capita^{-1} day^{-1}) in MTP in scenarios with respect to the baseline (S0) under a 25% reduction in emission intensities of all pollutants in crop and livestock production in China.

Supplementary Tables

Supplementary Table 1 | Summary of key assumptions used in scenario narratives and compensatory measures in China.

Scenarios [a]	Used as animal feed in its total supply [b]	Emission mitigation target
S0: Baseline	Food waste: 39% By-products: 51%	No
S1: Partial use of food waste and food processing by-products as feed [c]	Food waste: 54% By-products: 100%	No
S2: Full use of food waste and food processing by-products as feed [c]	Food waste: 100% By-products: 100%	No
S3: S1 + A modest emission mitigation target [d]	Food waste: 54% By-products: 100%	Implementing regional uniform emission taxes to control total emissions of greenhouse gases, acidification pollutants, and eutrophication pollutants from all sectors in the entire economies of China and MTP no more than their baseline (S0) levels.
S4: S1 + An ambitious emission mitigation target [d]	Food waste: 54% By-products: 100%	Implementing regional uniform emission taxes to reduce total emissions of greenhouse gases by 2.6% in China and 2.0% in MTP in line with their annual mitigation target of Intended Nationally Determined Contributions (INDC) under the Paris Agreement [9]. Implementing regional uniform emission taxes to reduce total emissions of acidification and eutrophication pollutants in China by 2.5% and 2.0%, respectively, according to the annual mitigation target set by China's "14th Five-Year Plan" [10]. Implementing regional uniform emission taxes to control total emissions of acidification and eutrophication pollutants in MTP no more than the baseline (S0) level.

[a] 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.
[b] In S1, cross-provincial transportation of food waste with high moisture content is not allowed, which limits the maximum utilisation rate of food waste to 54% in China, according to Fang, et al. [7], whereas it is allowed in S2.
[c] The cost of increasing the supply of food waste recycling service is modelled as a rising percentage of the initial cost of recycling food waste and food processing by-products as feed (54 dollar ton^{-1}), while the cost of decreasing the supply of food waste collection service is modelled as a declining percentage of the initial cost of collecting food waste and food processing by-products for landfill and incineration (82 dollar ton^{-1}). Economies of scale in food waste recycling were considered in S2, where a 1% increase in recycled waste results in only a 0.078% rise in recycling costs, indicating that increasing the amount of recycled waste might not necessarily incur additional costs, as reported by Cialani and Mortazavi [8]. This is because, initially, recycling entails high fixed costs, yet as production scales up, marginal costs decrease and then stabilise. The utilisation 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 Tables 3. Physical quantities and prices of food waste recycling and collection services in China are presented in Supplementary Tables 4-5.
[d] The main environmental problem associated with food systems depends on emissions from economic activities. Therefore, the introduction of economy-wide emission taxes could motivate producers and consumers to shift from emission-intensive activities, commodities, and technologies to cleaner alternatives. These policies aim to reduce emissions by pricing environmental emissions. Shadow prices of emissions, derived from the marginal value of the emission balance equations, ensure that total emissions from all producers across the entire economy remain below a specified emission threshold. For a given emission mitigation target for each type of pollutant, the AGE model can endogenously calculate the shadow prices of emissions of various pollutants.

Supplementary Table 2 | Physical production quantities (Tg) in in primary equivalents for each product in China (CN) and its main food and feed trading partners (MTP) in S0.

	CN	MTP
Cereal grains [a]	521.33	595.93
Oilseeds & pulses [a]	74.04	255.65
Vegetables & fruits [a]	397.23	116.39
Roots & tubers [a]	119.82	54.76
Sugar crops [a]	133.61	792.67
Other non-food crops [a]	36.48	23.24
Monogastric livestock [a]	103.15	59.11
Ruminant livestock [a]	52.53	160.49
Compound feed [b]	102.60	103.00
Cereal bran [c]	11.37	12.01
Alcoholic pulp [c]	3.41	76.09
Oil cake [c]	58.06	84.37
Processed food [d]	593.20	580.80
Nitrogen fertiliser [a]	39.60	13.65
Phosphorous fertiliser [a]	17.43	8.96
Grass [e]	286.22	0.00

[a] Physical production quantities of cereal grains, oilseeds & pulses, vegetables & fruits, roots & tubers, sugar crops, other non-food crops, monogastric livestock, ruminant livestock, nitrogen fertiliser, and phosphorous fertiliser are obtained from FAO [13]. Here, physical production quantities of cereal grains waste, oilseeds & pulses waste, vegetables & fruits waste, and roots & tubers waste are excluded and presented in Supplementary Table 4.
[b] The physical production quantity of compound feed is calculated according to the weighted averages of crops included in the compound feed at the regional level.
[c] Physical production quantities of cereal bran, alcoholic pulp, and oil cake are estimated from the consumption of corresponding food products and specific technical conversion factors [51]. Here, physical production quantities of discard biomass of cereal bran, alcoholic pulp, and oil cake are excluded and presented in Supplementary Table 4.
[d] The physical production quantity of processed food is calculated according to the weighted averages of crops included in the processed food at the regional level.
[e] The physical production quantity of grass from natural grassland is derived from Miao and Zhang [16]. Here, grass refers to grass from natural grassland where ruminant livestock is grazing for feed, and grass from remaining grassland is excluded. We do not present grass production data in MTP due to data unavailability.

Supplementary Table 3 | Utilisation rates (%) of food waste and food processing by-products in the baseline (S0) for China.

	Used as feed (%)	Discarded biomass (%) [c]
Cereals waste	39% [a]	Landfill (40%) & incineration (21%)
Vegetables & fruits waste	39% [a]	Landfill (40%) & incineration (21%)
Roots & tubers waste	39% [a]	Landfill (40%) & incineration (21%)
Oil seeds & pulses waste	39% [a]	Landfill (40%) & incineration (21%)
Cereal bran	36% [b]	Landfill (42%) & incineration (22%)
Alcoholic pulp	16% [b]	Landfill (55%) & incineration (29%)
Oil cake	72% [b]	Landfill (18%) & incineration (10%)

[a] In China, quantitative empirical data on food waste recycled as feed for monogastric livestock is not available. We infer that the practices of feeding food waste to monogastric livestock in Japan and South Korea are rather similar to those in China, following Fang, et al. [7]. Thus, we assume that a similar proportion (39%, the mean of values in Japan and South Korea [52]) of food waste is being used as feed in China in 2014 in S0.

[b] The utilisation rates of food processing by-products recycled as feed in China in 2014 in S0 are based on Fang, et al. [7].

[c] Excluding the portion of food waste and food processing by-products recycled as feed, 66% of the remaining amounts in China in 2014 are sent to landfills, while 34% are incinerated, according to Kaza, et al. [53] and Bhada-Tata and Hoornweg [54].

Supplementary Table 4 | Physical quantities (Tg) of food waste and food processing by-products and their utilisation in China in S0.

	Total in fresh form (Tg)	Total in dry matter (Tg)	Total in crude protein (Tg)	Total in energy (billion MJ)	Physical quantity in fresh form (Tg)		
					Used as feed [a]	Discarded biomass [b]	Net export [c]
Total food waste	**226**	**54**	**7**	**690**	**88**	**138**	**-**
1) Cereal grains waste [b]	36.09	31.40	3.14	447	14.08	22.02	-
2) Vegetables & fruits waste [b]	175.01	17.50	2.98	183	67.76	107.25	-
3) Roots & tubers waste [b]	13.32	3.46	0.28	42	5.20	8.13	-
4) Oilseeds & pulses waste [b]	1.28	1.19	0.18	18	0.50	0.78	-
Total food processing by-products	**155**	**139**	**49**	**1907**	**78**	**85**	**-8**
1) Cereal bran [c]	31.05	27.63	4.42	338	11.08	19.97	-0.004
2) Alcoholic pulp [c]	42.07	34.20	9.23	439	6.66	38.94	-3.53
3) Oil cake [c]	81.98	76.91	35.38	1130	59.80	26.59	-4.41
Total	**381**	**192**	**56**	**2597**	**166**	**223**	**-8**

[a] The amount of food waste used as feed corresponds to the quantity directed to the “food waste recycling service” sector. The amount of food processing by-products used as feed are not directed to the “food waste recycling service” sector; instead, these by-products with economically values are purchased directly by livestock producers in the feed market. When upcycling the discarded biomass of food waste and food processing by-products, these biomass are directed to the “food waste recycling service” sector.

[b] Discarded biomass of food waste and food processing by-products refers to the quantity collected for landfill and incineration, meaning the amount directed to the “food waste collection service” sector.

[c] Since food waste is considered a local resource within China, there is no net export of food waste. Negative net export values indicate that China imports food processing products from its trading partners, while positive net export values indicate that China exports these products to its trading partners. For each food processing by-product, the sum of physical quantities used as feed, discarded biomass, and net export equals its total production in fresh form.

Supplementary Table 5 | Prices of food waste recycling service and food waste collection service in China. [a]

	Food waste treatment	Price [b] (dollar ton^{-1})	Weighted price [c] (dollar ton^{-1})
Food waste recycling service	Recycling waste as feed	54	54
Food waste collection service	Collection	40	82
	Landfill	31	
	Incineration	64	

[a] Food waste recycling service refers to recycling food waste as feed for monogastric livestock production, and food waste collection service means collecting food waste for landfill and incineration.

[b] The process of recycling food waste and food processing by-products as animal feed involves sorting, shredding, thermal treatment of drying and dehydration, deodorizing, fermentation, hydrolysis, and extrusion of food waste into feed pellets, as outlined by Alsaleh and Aleisa [25]. The collection includes pick up, transfer, and transport to the final disposal site for food waste. By multiplying the quantity of food waste with the price of food waste treatment, we can calculate the value of food waste generation. The prices of food waste recycling and collection services are obtained from Alsaleh and Aleisa [25], Kaza, et al. [53] and Bhada-Tata and Hoornweg [54]. Since the value of food waste generation needs to be taken from the “wtr” demand of consumers and monogastric producers, we further check whether or not the value of food waste generation is more than 80% of the initial demand of “wtr”. If it is higher than 80% of the “wtr” demand, the economic value of food waste generation is scaled down.

[c] The weighted price of food waste collection service = collection price (40 $/t) + 66%*landfill price (31$/t)+34%*incineration price (64$/t)=82$/t.

Supplementary Table 6 | The economic and mass allocation of food processing main and by-products. [a]

	Main and by-products	By-product group	Economic share (%)	Mass share (%)
Cereal flour production [a]	Cereal flour	-	93%	86%
	Cereal bran	Cereal bran	7%	14%
Maize ethanol production	Maize ethanol	-	83%	49%
	Distiller’s grain from maize ethanol	Alcoholic pulp	17%	51%
Barley beer production	Barley beer	-	98%	82%
	Brewer’s grain from barley beer	Alcoholic pulp	2%	18%
Liquor production	Liquor	-	97%	25%
	Distiller’s grain from liquor	Alcoholic pulp	3%	75%
Vegetable oil production	Soybean oil	-	44%	23%
	Soybean oil cake	Oil cake	56%	77%
	Other oil	-	66%	43%
	Other oil cake	Oil cake	34%	57%

[a] Data source: Haque, et al. [55], Mackenzie, et al. [24], Nyhan, et al. [56], and Pourmehdi and Kheiralipour [57]

Supplementary Table 7 | Estimated mean dry matter (DM, %), crude protein (CP, %), and energy (MJ kg DM^{-}) contents of feed sub-groups in China (CN) and its main food and feed trading partners (MTP). [a]

	Dry matter (DM, %)		Crude protein (CP, %)		Energy (MJ kg DM^{-1})	
	CN	MTP	CN	MTP	CN	MTP
Cereal grains	89	89	11	10	18.25	18.82
Oilseeds & pulses	74	86	22	32	19.72	19.78
Vegetables & fruits	10	10	19	19	13.80	13.80
Roots & tubers	29	29	5	5	21.54	21.54
Sugar crops	69	69	16	16	19.68	19.68
Compound feed	48	70	34	23	18.61	19.36
Cereal bran	89	89	16	16	12.24	12.24
Alcoholic pulp	75	75	27	27	12.84	12.84
Oil cake	89	89	46	47	14.69	14.94
Cereal grains waste [b]	87	-	10	-	14.25	-
Vegetables & fruits waste [b]	10	-	17	-	10.45	-
Roots & tubers waste [b]	26	-	8	-	12.15	-
Oilseeds & pulses waste [b]	94	-	15	-	14.70	-
Cereal bran waste [b]	89	-	16	-	12.24	-
Alcoholic pulp waste [b]	75	-	27	-	12.84	-
Oil cake waste [b]	89	-	46	-	14.69	-
Grass	27	27	12	12	11.20	11.20

[a] The values are weighted averages of feed types included in the groups at the regional level. Data are sourced from the NUFER database [58], MITERRA-EUROPE database [59], NRC [60], NRC [61], NRC [62], NRC [63], and China Feed–database Information Network Centre ((http://www.chinafeeddata.org.cn/).

[b] It is hard to find empirical data about the nutrients of specific kinds of food waste; thus, following Fang, et al. [7], we use the nutrient contents of the original food types to calculate the weighted average nutrient content of food waste. This is unlike many other studies, which combine all food waste into one waste stream.

Supplementary Table 8 | Estimated mean energy (kcal kg^{-1}) contents of food sub-groups in China (CN) and its main food and feed trading partners (MTP). [a]

	Cereal grains	Oilseeds & pulses	Vegetables & fruits	Roots & tubers	Sugar crops	Monogastric livestock	Ruminant livestock
CN	3496	8136	372	780	3871	1910	831
MTP	3496	8247	485	780	3871	2017	857

[a] The values are weighted averages of food types included in the groups at the regional level. Data are sourced from Willett, et al. [64].

Supplementary Table 9 | China's domestic use and trade shares (%) of food and feed products with its main food and feed trading partners (MTP) and the rest of the world (RoW) in 2014. [a]

	Domestic use in China	Net export from Brazil [b]	Net export from the United States [b]	Net export from Canada [b]	Net export from RoW [b]
Cereal grains	101.28%	-0.001%	-0.07%	-0.43%	-0.78%
Vegetables & fruits [c]	100.13%	0.02%	-0.04%	-0.01%	-0.10%
Roots & tubers [c]	100.13%	0.02%	-0.04%	-0.01%	-0.10%
Oilseeds & pulses	159.89%	-25.12%	-4.26%	-22.98%	-7.53%
Sugar crops	101.10%	-0.99%	0.003%	-0.08%	-0.03%
Other non-food crops	106.74%	-0.52%	0.04%	-2.15%	-4.10%
Monogastric livestock	101.02%	-0.16%	-0.16%	-0.50%	-0.20%
Ruminant livestock	104.11%	0.03%	-0.04%	-0.23%	-3.88%
Oil cake [d]	105.85%	-0.39%	-0.38%	-0.13%	-4.94%
Compound feed [e]	96.77%	0.05%	0.08%	0.61%	2.48%
Cereal bran [e]	96.77%	0.05%	0.08%	0.61%	2.48%
Distiller's grains from maize ethanol production [e]	96.77%	0.05%	0.08%	0.61%	2.48%
Processed food [e]	96.77%	0.05%	0.08%	0.61%	2.48%
Distiller's grains from liquor production [f]					
Brewer's grains from barley beer production [f]	101.29%	-0.13%	0.00%	-0.56%	-0.59%
Total	102.04%	-0.69%	-0.15%	-0.71%	-0.50%

[a] Data source: Calculated based on the GTAP database [11]. Detailed sectoral information in the GTAP database is provided in Appendix Table 1. [b] Negative net export values indicate that China imports crop and livestock products from a specific country, while positive net export values indicate that China exports these products to a specific country. For each product, the sum of domestic use and net export shares equals one. [c] Since roots & tubers are split from the "Vegetables& fruits (v_f)" sector, their domestic use and trade shares are assumed to align with those of the "(v_f)" sector. [d] Since oil cake is split from the "Vegetable oils and fats (vol)" sector, its domestic use and trade shares are assumed to align with those of the "(vol)" sector. [e] Since compound feed, cereal bran, distiller's grains from maize ethanol production, and processed food are split from the "Food products nec (ofd)" sector, their domestic use and trade shares are assumed to align with those of the "(ofd)" sector. [f] Since distiller's grains from liquor production and brewer's grains from barley beer production are split from the "Beverages and Tobacco products (b_t)" sector, their domestic use and trade shares are assumed to align with those of the "(b_t)" sector.

Supplementary Table 10 | Monogastric livestock production (Tg) of China, its main food and feed trading partners (MTP), and the rest of the world (RoW), along with their percentage shares (%) of global production in 2014. [a]

	Pig meat [b]	Poultry meat [b]	Egg [b]	Total [b]
China	56.71 (49.23%)	17.50 (15.73%)	28.94 (27.61%)	103.15 (31.14%)
Brazil	3.19 (2.77%)	12.98 (11.67%)	2.48 (2.36%)	18.65 (5.63%)
United States	10.37 (9.00%)	20.40 (18.33%)	5.97 (5.70%)	36.74 (11.09%)
Canada	1.96 (1.70%)	1.28 (1.15%)	0.47 (0.45%)	3.71 (1.12%)
RoW	42.96 (37.29%)	59.11 (53.12%)	66.94 (63.87%)	169.01 (51.02%)
Total	115.19 (100.00%)	111.27 (100.00%)	104.80 (100.00%)	331.27 (100.00%)

[a] Data source: Derived from the FAO database [13].

[b] The numbers outside the brackets represent the physical quantities of monogastric livestock, while those inside the brackets indicate the percentage share of each country's monogastric livestock production of global production.

Supplementary Table 11 | Changes (%) in sectoral output (i.e., the value of production) in scenarios with respect to the baseline (S0) in China (CN) and its main food and feed trading partners (MTP) in 2014 under upcycling 75% of food waste and 100% of food processing by-products as feed. [a]

		cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf
S1	CN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	MTP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S2	CN	-0.73	-98.47	-0.49	83.34	13.93	-9.73	-6.95	0.00	-4.03	2.87	38.37	-97.70	-0.02	0.82	-37.70	0.23
	MTP	2.39	38.29	0.35	-217.43	-16.76	0.86	12.07	-0.02	5.18	9.06	8.51	19.53	-0.05	0.00	60.99	-0.06
S3	CN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	MTP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S4	CN	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	MTP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a] cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food.

Supplementary Table 12 | Material intensity coefficients (kg USD^{-1}) of each commodity in China (CN) and its main food and feed trading partners (MTP) in 2014. [a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	wfe	wtr
CN	2.71	3.20	1.47	4.24	4.14	18.58	0.59	0.83	1.89	3.35	8.48	283.22	1.37	3.11	3.83	18.52	12.20
MTP	6.24	4.31	1.11	4.99	28.94	1.11	0.18	0.22	1.66	2.86	14.18	35.11	1.13	2.93	0.98	-	-

[a] Data source: Calculated by our study. cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. wfe=food waste recycling service. wtr=food waste collection service.

Supplementary Table 13 | Energy intensity coefficients (kcal USD^{-1}) of food sub-groups in China (CN) and its main food and feed trading partners (MTP) in 2014. [a]

	Cereal grains	Oilseeds & pulses	Vegetables & fruits	Roots & tubers	Sugar crops	Monogastric livestock	Ruminant livestock
CN	10108	26511	1030	4041	16041	1135	692
MTP	14231	38183	492	3642	6237	1163	672

[a] Data source: Calculated by our study.

Supplementary Table 14 | Energy intensity coefficients (MJ USD^{-1}) of feed sub-groups in China (CN) and its main food and feed trading partners (MTP) in 2014. [a]

		CN	MTP
Cereal grains		0.26	0.56
Oilseeds & pulses		0.52	1.19
Vegetables & fruits		0.03	0.02
Roots & tubers		0.06	0.07
Sugar crops		0.46	3.19
Compound feed		0.31	0.27
Cereal bran		0.48	0.41
Alcoholic pulp		1.72	2.87
Oil cake		115.95	14.69
Food waste recycling service	Cereal grains waste	1.61	-
	Oilseeds & pulses waste	2.61	-
	Vegetables & fruits waste	0.31	-
	Roots & tubers waste	0.39	-
	Cereal bran waste	2.64	-
	Alcoholic pulp waste	3.75	-
	Oil cake waste	7.58	-
Food waste collection service	Cereal grains waste	1.06	-
	Oilseeds & pulses waste	1.72	-
	Vegetables & fruits waste	0.21	-
	Roots & tubers waste	0.25	-
	Cereal bran waste	1.74	-
	Alcoholic pulp waste	2.47	-
	Oil cake waste	4.99	-

[a] Data source: Calculated by our study.

Supplementary Table 15 | Protein intensity coefficients (kg USD^{-1}) of feed sub-groups in China (CN) and its main food and feed trading partners (MTP) in 2014. [a]

		CN	MTP
Cereal grains		43.94	104.51
Oilseeds & pulses		46.67	73.28
Vegetables & fruits		2.03	1.53
Roots & tubers		26.49	31.20
Sugar crops		56.25	392.96
Compound feed		16.91	22.54
Cereal bran		36.45	31.13
Alcoholic pulp		81.69	136.58
Oil cake		3702.84	466.85
Food waste recycling service	Cereal grains waste	229.58	-
	Oilseeds & pulses waste	255.89	-
	Vegetables & fruits waste	19.35	-
	Roots & tubers waste	58.50	-
	Cereal bran waste	201.73	-
	Alcoholic pulp waste	178.33	-
	Oil cake waste	242.11	-
Food waste collection service	Cereal grains waste	151.19	-
	Oilseeds & pulses waste	168.51	-
	Vegetables & fruits waste	12.74	-
	Roots & tubers waste	38.52	-
	Cereal bran waste	132.85	-
	Alcoholic pulp waste	117.44	-
	Oil cake waste	159.44	-

[a] Data source: Calculated by our study.

Supplementary Table 16 | Cost shares (%) of inputs in China's and its main food and feed trading partners' (MTP) monogastric livestock production functions. [a]

	China [b]	MTP [b]
Cost shares of cereal grains input	15.82	3.75
Cost shares of oilseeds &pulses input	0.54	0.07
Cost shares of vegetables & fruits input	3.08	0.35
Cost shares of roots & tubers input	0.32	0.04
Cost shares of sugar crops input	0.10	0.06
Cost shares of other non-food crops input	0.36	0.13
Cost shares of compound feed input	24.83	29.75
Cost shares of cereal bran input	1.82	4.18
Cost shares of alcoholic pulp input	0.43	4.92
Cost shares of oil cake input	0.12	2.36
Cost shares of cereal grains waste input	0.96	-
Cost shares of vegetables & fruits waste input	4.65	-
Cost shares of roots & tubers waste input	0.36	-
Cost shares of oilseeds &pulses waste input	0.03	-
Cost shares of LAB input	33.70	35.00
Cost shares of CAP input	12.87	19.40
Total	100.00	100.00

[a] Calculated according to SAMs in the Appendix Tables 2-3.

[b] Note: Only ruminant livestock directly use land, while monogastric livestock does not, as its feed is produced using land elsewhere in the system. With intensification, monogastric livestock production increasingly occurs in facilities resembling manufacturing rather than land-based sectors. Therefore, we exclude direct land competition for monogastric livestock production. However, there is indirect competition, as higher monogastric livestock production increases feed demand, driving up land use for feed. This competition is captured through intermediate demand equations for feed in monogastric livestock production. Consequently, following Golub, et al. [65], we exclude land rents from the cost structure of monogastric livestock production.

Supplementary Table 17 | Changes (%) in sectoral output (i.e., the value of production) in scenarios with respect to the baseline (S0) in China (CN) and its main food and feed trading partners (MTP) in 2014 under a fixed ratio between total crop output and cropland input. [a]

		cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf
S1	CN	0.22	3.15	0.22	-2.11	-0.53	1.70	-1.68	0.20	-1.44	1.51	2.34	0.91	0.86	5.47	3.82	-0.07
	MTP	-0.28	-0.77	-0.19	4.63	2.42	-0.74	1.56	-0.06	1.08	0.03	0.64	1.13	-0.71	-0.92	-3.56	0.01
S2	CN	-0.06	-77.48	0.35	57.83	12.22	25.20	-1.92	0.19	-1.02	10.28	7.99	70.61	1.32	8.17	10.13	-0.22
	MTP	0.57	31.33	-0.27	-154.80	-12.59	-4.81	1.11	-0.06	0.50	-6.79	1.15	-3.65	-1.11	-0.92	-0.36	0.05
S3	CN	17.73	-54.52	-1.65	-38.77	0.40	-3.32	-1.60	0.20	9.61	57.03	2.35	0.91	1.41	4.19	-39.98	-0.23
	MTP	-34.04	23.36	6.20	102.13	1.88	4.76	1.44	-0.06	-8.49	-44.01	0.53	1.01	-1.17	-0.92	55.48	0.05
S4	CN	-6.65	0.75	-3.18	-0.02	-14.64	-3.33	10.04	1.49	-0.04	-6.54	234.08	808.98	1.01	-0.52	-0.91	0.17
	MTP	11.70	-7.33	-3.43	-24.37	0.57	0.98	-18.70	0.72	0.20	-0.05	-12.87	-81.47	-2.25	-0.92	-0.36	0.10

[a] cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food.

Supplementary Table 18 | Changes (%) in sectoral prices in scenarios with respect to the baseline (S0) in 2014 under a fixed ratio between total crop output and cropland input. [a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf
S1	-0.01	-0.02	-0.01	-0.01	-0.01	-0.03	-0.04	0.00	0.00	-0.01	0.01	-0.06	0.00	0.02	0.02	0.01
S2	-0.02	-0.03	-0.02	-0.01	-0.02	-0.03	-0.07	-0.03	-0.02	-0.04	-0.03	-0.07	-0.02	-0.03	-0.04	-0.02
S3	0.01	0.00	0.01	0.01	0.02	-0.01	-0.01	0.02	0.02	0.02	0.04	0.00	0.03	0.05	0.06	0.04
S4	5.55	6.01	5.98	5.96	6.80	6.12	1.86	0.75	3.02	2.30	-2.30	5.30	2.62	14.19	3.24	1.62

[a] cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food.

Supplementary Table 19 | Sectoral self-sufficiency ratios (SSR, %) in scenarios S0-S4 in China in 2014. [a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf
S0	98.96	39.89	99.95	100.21	98.36	57.29	98.87	99.14	101.63	99.97	46.98	92.64	100.16	97.42	98.28	113.75
S1	98.71	38.36	99.91	93.15	82.58	58.36	121.67	95.91	100.33	73.94	4.83	18.97	100.17	131.75	117.44	112.46
S2	99.48	74.68	99.88	9.81	66.02	61.49	134.00	95.77	99.69	64.32	39.41	261.21	100.12	128.91	151.77	111.78
S3	82.63	67.50	102.74	134.27	76.57	5.49%	121.28	95.88	90.81	24.33	4.85	19.13	99.55	140.62	169.32	112.71
S4	109.59	3.87	103.60	9.68	166.75	5.77	103.03	94.89	10.81	208.98	567.39	27.50	120.07	127.49	161.02	105.89

[a] cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food.

Supplementary Table 20 | Changes (%) in sectoral self-sufficiency ratios (SSR) in scenarios with respect to the baseline (S0) in China in 2014 under a 95% self-sufficiency requirement for cereal grain in China. [a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf
S1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S3	14.99	-63.11	12.80	-120.86	93.93	2.17	0.27	-0.02	-82.07	67.24	183.40	130.55	6.31	-3.79	6.16	-0.41
S4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

[a] cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food.

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Appendix Tables

Appendix Table 1 | Sectoral aggregation scheme.

Aggregated sectors	GTAP original sectors
Cereal grains	“Paddy rice (pdr)”, “Processed rice (pcr)”, “Wheat (wht)”, and “Cereals grains nec (gro)” sectors
Oilseeds & pulses	“Oil seeds (osd)” sector, and pulses split from the original “Vegetables& fruits (v_f)” sector
Vegetables & fruits	“Vegetables, fruits, nuts (v_f)” sector after splitting out pulses, and roots & tubers
Roots & tubers	Split from the original “Vegetables& fruits (v_f)” sector
Sugar crops	“Sugar cane & Sugar beet (c_b)” and Sugar (sgr)” sectors
Other non-food crops	“Plant-based fibers (pfb)”, and “Crops nec (ocr)” sectors
Monogastric livestock	“Animal products nec (oap)” and “Meat products nec (omt)” sectors
Ruminant livestock	“Cattle, sheep, goats, horses (ctl)”, “Meat: cattle, sheep, goats, horses (cmt)”, “Raw milk (rmk)”, “Wool, silk-worm cocoons (wol)”, and “Dairy products (mil)” sectors
Compound feed [a]	Split from the original “Food products nec (ofd)” sector
Cereal bran [a]	Split from the original “Food products nec (ofd)” sector
Alcoholic pulp [a]	Distiller’s grains from maize ethanol production split from the original “Food products nec (ofd)” sector; Distiller’s grains from liquor production and brewer’s grains from barley beer production split from the original “Beverages and Tobacco products (b_t)” sector
Oil cake [a]	Split from the original “Vegetable oils and fats (vol)” sector
Processed food [a]	“Food products nec (ofd)” sector after splitting out splitting out compound feed, cereal bran, and distiller’s grains from maize ethanol production; “Beverages and Tobacco products (b_t)” sector after splitting out distiller’s grains from liquor production and brewer’s grains from barley beer production; Vegetable oils and fats (vol)” sector after splitting out oil cake
Nitrogen fertiliser [b]	Split from the original “Manufacture of chemicals and chemical products (chm)” sector
Phosphorous fertiliser [b]	Split from the original “Manufacture of chemicals and chemical products (chm)” sector
Food waste recycling service [c]	Split from the original “Waste and water (wtr)” sector

Aggregated sectors	GTAP original sectors
Food waste collection service [c]	Split from the original "Waste and water (wtr)" sector
Non-food	"Manufacture of chemicals and chemical products (chm)" sector after splitting out nitrogen fertiliser and phosphorous fertiliser; "Waste and water (wtr)" sector after splitting out food waste recycling service and food waste collection service; "Forestry (frs)", "Fishing (fsh)", "Coal (coa)", "Oil (oil)", "Gas (gas)", "Minerals nec (oxt)", "Petroleum, coal products (p_c)", "Electricity (ely)", "Gas manufacture, distribution (gdt)", "Textiles （tex)", "Wearing apparel (wap)", "Leather products (lea)", "Wood products (lum)", "Paper products, publishing (ppp)", "Manufacture of pharmaceuticals, medicinal chemical and botanical products (bph)", "Manufacture of rubber and plastics products (rpp)", "Mineral products nec (nmm)", "Ferrous metal (i_s)", "Metal nec (nfm)", "Metal products (fmp)", Electronic equipment (ele)", "Manufacture of electrical equipment (eeq)", "Manufacture of machinery and equipment n.e.c. (ome)", "Motor vehicles and parts (mvh)", "Transport equipment nec (otn)", "Manufactures nec (omf)", "Construction (cns)", "Wholesale and retail trade; repair of motor vehicles and motorcycles (trd)", "Accommodation, Food and service activities (afs)", "Land transport and transport via pipelines (otp)", "Warehousing and support activities (whs)", "Sea transport (wtp)", "Air transport （atp)", "Communication (cmn)", "Financial services nec (ofi)", "Insurance (ins)", "Real estate activities (rsa)", "Other Business Services nec (obs)", "Recreation & other services (ros)", "Other Services (Government) (osg)", "Education (edu)", "Human health and social work (hht)", "Dwellings: ownership of dwellings (imputed rents of houses occupied by owners) (dwe)" sectors

[a] The value flow from the "Food products nec (ofd)" sector to monogastric and ruminant livestock in the original GTAP database after splitting out the economic values of cereal bran and distiller's grains from maize ethanol production is assumed to be compound feed. Cereal bran and distiller's grains from maize ethanol production are split from the "Food products nec (ofd)" sector based on their shares of economic values in the "Food products nec (ofd)" sector. Economic values of cereal bran and distiller's grains from maize ethanol production are determined by multiplying their region-specific physical production quantities (tons) by the corresponding regional prices (USD ton^{-1}). These prices are determined by dividing the export trade value (USD) by the export trade weight (tons) at the regional level, using data from the UN Comtrade Database [12]. The value flow from the "Beverages and Tobacco products (b_t)" sector to monogastric livestock in the original GTAP database are assumed to be distiller's grains from liquor production and brewer's grains from barley beer production. The value flow from the "Vegetable oils and fats (vol)" sector to monogastric livestock in the original GTAP database is assumed to be oil cake.

[b] The nitrogen and phosphorus fertilisers are taken from the original "Manufacture of chemicals and chemical products" sector following the method of Sturm [66] and Bartelings, et al. [67].

[c] Food waste recycling and collection services are split from the "Waste and water (wtr)" sector in the original GTAP database according to the shares of economic values of food waste recycling and collection services in the total economic value of "Waste and water (wtr)" sector. Economic values of food waste recycling and collection services are calculated by multiplying the physical quantities (tons, see Supplementary Table 4) and the corresponding prices (USD ton^{-1}, see Supplementary

Table 5). Since the value of food waste generation needs to be taken from the “wtr” demand of consumers and monogastric producers, we further check whether or not the value of food waste generation is more than 80% of the initial demand of “wtr”. If it is higher than 80% of the “wtr” demand, the economic value of food waste generation is scaled down.

Appendix Table 2 | The social accounting matrix in the base year of 2014 for China (million USD).[a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf	CONS	XNET	TOT
cer	0	0	0	0	0	0	29229	9055	11363	1372	67	0	81831	0	0	0	61825	-2016	192727
osd	0	0	0	0	0	0	1002	230	8312	0	0	182	42993	0	0	0	5092	-34661	23150
vf	0	0	0	0	0	0	5685	1495	18959	0	0	0	98059	0	0	0	145756	-139	269815
rt	0	0	0	0	0	0	595	157	1986	0	0	0	10270	0	0	0	15265	-15	28259
sgr	0	0	0	0	0	0	192	515	1280	0	0	0	6619	0	0	0	24553	-903	32256
ocr	0	0	0	0	0	0	664	262	197	0	0	0	1021	0	0	0	1282	-1465	1963
oap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	176874	-3205	173669
ctl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	63546	-484	63062
cof	0	0	0	0	0	0	45882	7458	0	0	0	0	0	0	0	0	0	854	54194
bran	0	0	0	0	0	0	3371	0	0	0	0	0	0	0	0	0	0	27	3398
pulp	0	0	0	0	0	0	800	0	0	0	0	0	0	0	0	0	0	-398	402
cake	0	0	0	0	0	0	215	0	0	0	0	0	0	0	0	0	0	-10	205
otf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	432109	714	432823
nfe	7396	521	3479	471	313	621	0	0	0	0	0	0	0	0	0	0	0	-78	12721
pfe	2412	211	1542	169	83	163	0	0	0	0	0	0	0	0	0	0	0	-28	4551
nf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2563284	354672	2917956
LAD1	53323	7694	80962	8445	9849	396	0	0	0	0	0	0	0	0	0	0	-160670	0	0
LAD2	0	0	0	0	0	0	0	10240	0	0	0	0	0	0	0	0	-10240	0	0
LAB	94995	11819	148120	15450	17556	631	62255	24592	6707	959	155	8	89845	4413	1579	1542959	-2022044	0	0
CAP	34602	2905	35711	3725	4455	151	23777	9057	5390	1067	180	15	102185	8308	2972	1374997	-1609499	0	0
TRA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	312868	-312868	0
TOT	192727	23150	269815	28259	32256	1963	173669	63062	54194	3398	402	205	432823	12721	4551	2917956	0	0	4211152
cerw	0	0	0	0	0	0	754	0	0	0	0	0	0	0	0	0	1808		
vfw	0	0	0	0	0	0	3631	0	0	0	0	0	0	0	0	0	8806		

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf	CONS	XNET	TOT
rtw	0	0	0	0	0	0	278	0	0	0	0	0	0	0	0	0	667		
osdw	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	0	64		
branw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1639		
pulpw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3197		
cakew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2184		

[a] Data source: GTAP [11]. cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food. CONS=consumption. XNET=net export. TOT=total. LAD1=cropland. LAD2=pastureland. LAB=labour. CAP=capital. TRA=trade. cerw=cereal grains waste. osdw= oilseeds & pulses waste. vfw=vegetables & fruits waste. rtw= roots & tubers waste. branw=cereal bran waste. pulpw=alcoholic pulp waste. cakew=oil cake waste.

Appendix Table 3 | The social accounting matrix in the base year of 2014 for China's main food and feed trading partners (MTP) (million USD).[a]

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf	CONS	XNET	TOT
cer	0	0	0	0	0	0	3794	34288	4450	1023	414	0	32927	0	0	0	16597	2016	95511
osd	0	0	0	0	0	0	69	301	3307	0	0	2009	17059	0	0	0	1938	34661	59344
vf	0	0	0	0	0	0	354	1110	8351	0	0	0	43966	0	0	0	50755	139	104675
rt	0	0	0	0	0	0	37	116	875	0	0	0	4605	0	0	0	5316	15	10963
sgr	0	0	0	0	0	0	58	1037	1598	0	0	0	7759	0	0	0	16038	903	27392
ocr	0	0	0	0	0	0	130	413	943	0	0	0	4929	0	0	0	13124	1465	21003
oap	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	97851	3205	101056
ctl	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	214439	484	214923
cof	0	0	0	0	0	0	30067	32726	0	0	0	0	0	0	0	0	0	-854	61939
bran	0	0	0	0	0	0	4229	0	0	0	0	0	0	0	0	0	0	-27	4203
pulp	0	0	0	0	0	0	4967	0	0	0	0	0	0	0	0	0	0	398	5365
cake	0	0	0	0	0	0	2383	0	0	0	0	0	0	0	0	0	0	10	2393
otf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	514821	-714	514107
nfe	2528	940	131	38	255	685	0	0	0	0	0	0	0	0	0	0	0	78	4655
pfe	1547	1164	87	47	92	231	0	0	0	0	0	0	0	0	0	0	0	28	3195
nf	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13050326	-354672	12695654
LAD1	22886	13940	25013	2605	2260	5474	0	0	0	0	0	0	0	0	0	0	-72178	0	0
LAD2	0	0	0	0	0	0	0	15132	0	0	0	0	0	0	0	0	-15132	0	0
LAB	31115	17269	34446	3585	14182	5957	35369	71060	23869	1730	2795	231	203920	2038	1461	8550058	-8999086	0	0
CAP	37435	26030	44998	4688	10603	8655	19600	58739	18547	1450	2155	153	198941	2618	1734	4145596	-4581943	0	0
TRA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-312868	312868	0
TOT	95511	59344	104675	10963	27392	21003	101056	214923	61939	4203	5365	2393	514107	4655	3195	12695654	0	0	13926377
cerw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
vfw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

	cer	osd	vf	rt	sgr	ocr	oap	ctl	cof	bran	pulp	cake	otf	nfe	pfe	nf	CONS	XNET	TOT
rtw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
osdw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
branw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
pulpw	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
cakew	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		

[a] Data source: GTAP [11]. cer=cereal grains. osd=oilseeds & pulses. vf=vegetables & fruits. rt= roots & tubers. sgr=sugar crops. ocr=other non-food crops. oap=monogastric livestock. ctl=ruminant livestock. cof=compound feed. bran=cereal bran. pulp=alcoholic pulp. cake=oil cake. otf=processed food. nfe=nitrogen fertiliser. pfe=phosphorous fertiliser. nf=non-food. CONS=consumption. XNET=net export. TOT=total. LAD1=cropland. LAD2=pastureland. LAB=labour. CAP=capital. TRA=trade. cerw=cereal grains waste. osdw= oilseeds & pulses waste. vfw=vegetables & fruits waste. rtw= roots & tubers waste. branw=cereal bran waste. pulpw=alcoholic pulp waste. cakew=oil cake waste.

Appendix Table 4 | Emission sources of greenhouse gases, acidification pollutants, and eutrophication pollutants across various sectors of the model. [a]

Sectors	Emissions of greenhouse gases (Tg CO_2 equivalents)	Emissions of acidification pollutants (Tg NH_3 equivalents)	Eutrophication pollutants (Tg N equivalents)
Crop	• Rice methane (CH_4) • Synthetic fertiliser and manure application (N_2O)	• Synthetic fertiliser and manure application (NH_3)	• Synthetic fertiliser and manure application (N and P losses)
Livestock	• Enteric fermentation (CH_4) • Manure management (CH_4 and N_2O) • Manure grassland (N_2O)	• Manure management (NH_3) • Manure grassland (NH_3)	• Manure management (N and P losses) • Manure grassland (N and P losses)
Non-agriculture [b]	• Energy use (CO_2, CH_4, and N_2O)	• Energy use (NH_3, NO_x and SO_2)	• Energy use (N and P losses)

[a] Emissions from the production of N and P fertilisers are attributed to the respective fertiliser sector, while emissions from the application of these fertilisers are assigned to the crop sectors to prevent double counting. Data on N and P fertiliser use by crop types and countries are derived from Ludemann, et al. [28]. Manure data by animals are derived from FAO [13]. Allocation of manure for each crop is assumed to be consistent with the allocation of N fertiliser for each crop.

[b] Emission sources in non-agricultural sectors arise from energy use in sectors including compound feed, food processing by-products, processed food, fertilisers, food waste treatment, and non-food sectors.

Appendix Table 5 | Total emissions of greenhouse gases (Tg CO_2 equivalents) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN		MTP	
	Total	Total (%)	Total	Total (%)
Cereal grains	276.61	2.35	118.98	1.49
Oilseeds & pulses	8.33	0.07	9.88	0.12
Vegetables &fruits	54.88	0.04	3.34	0.08
Roots &tubers	7.46	0.47	0.82	0.04
Sugar crops	4.58	0.06	6.33	0.01
Other non-food crops	15.55	0.13	20.73	0.26
Monogastric livestock	79.37	0.68	63.77	0.80
Ruminant livestock	245.04	2.09	700.30	8.77
Compound feed	25.39	0.22	16.03	0.20
Cereal bran	0.00752	0.00006	0.00288	0.00004
Alcoholic pulp	0.0001148	0.0000010	0.0000318	0.0000004
Oil cake	0.01580	0.00013	0.01422	0.00018
Processed food	204.54	1.74	130.82	1.64
Nitrogen fertiliser	324.09	2.76	80.29	1.01
Phosphorus fertiliser	24.53	0.21	9.06	0.11
Non-food	10238.21	87.16	6825.11	85.47
Food waste recycling service	16.37	0.14	0.00	0.00
Food waste collection service	221.98	1.89	0.00	0.00
Total	11747	100.00	7985	100.00

[a] Data source: Climate Analysis Indicators Tool (CAIT) [17]. Greenhouse gas (GHG) emissions in our model follow the IPCC National GHG Emission Guidelines [18], excluding GHG emissions related to land use. Emissions of food processing by-products (i.e., cereal bran, alcoholic pulp, oil cake) are derived from Mackenzie, et al. [24]. Emissions of food waste recycling and collection services are obtained from Alsaleh and Aleisa [25], Hong, et al. [26], and Hong, et al. [27].

Appendix Table 6 | Total emissions of acidification pollutants (Tg NH_3 equivalents) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN		MTP	
	Total	Total (%)	Total	Total (%)
Cereal grains	3.94	11.71	0.94	6.77
Oilseeds & pulses	0.29	0.86	0.15	1.08
Vegetables & fruits	1.89	0.47	0.05	0.62
Roots & tubers	0.26	5.63	0.01	0.38
Sugar crops	0.16	0.77	0.09	0.10
Other non-food crops	0.54	1.60	0.34	2.47
Monogastric livestock	5.22	15.53	2.88	20.70
Ruminant livestock	2.21	6.58	1.05	7.56
Compound feed	0.04	0.13	0.02	0.13
Cereal bran	0.000328	0.0010	0.000126	0.0009
Alcoholic pulp	0.00000067	0.0000020	0.00000019	0.0000013
Oil cake	0.00080	0.0024	0.00073	0.0052
Processed food	0.35	1.05	0.16	1.11
Nitrogen fertiliser	0.0009	0.003	0.0035	0.025
Phosphorus fertiliser	0.0007	0.002	0.0029	0.021
Non-food	18.10	53.83	8.21	59.03
Food waste recycling service	0.06	0.18	0.00	0.00
Food waste collection service	0.56	1.66	0.00	0.00
Total	33.61	100.00	13.92	100.00

[a] Data source: Liu, et al. [19], Huang, et al. [20], and Dahiya, et al. [21]. Emissions of food processing by-products (i.e., cereal bran, alcoholic pulp, oil cake) are derived from Mackenzie, et al. [24]. Emissions of food waste recycling and collection services are obtained from Alsaleh and Aleisa [25], Hong, et al. [26], and Hong, et al. [27]

Appendix Table 7 | Total emissions of eutrophication pollutants (Tg N equivalents) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN		MTP	
	Total	Total (%)	Total	Total (%)
Cereal grains	1.04	10.47	0.06	1.15
Oilseeds & pulses	0.15	1.48	0.05	0.93
Vegetables & fruits	0.88	0.20	0.04	0.12
Roots & tubers	0.12	8.84	0.01	0.69
Sugar crops	0.02	1.20	0.01	0.21
Other non-food crops	0.01	0.11	0.01	0.24
Monogastric livestock	0.58	5.89	0.38	6.79
Ruminant livestock	1.63	16.46	2.02	35.96
Compound feed	0.17	1.70	0.07	1.21
Cereal bran	0.0000147	0.0001	0.0000056	0.0001
Alcoholic pulp	0.00000029	0.0000030	0.00000008	0.0000015
Oil cake	0.000037	0.0004	0.000034	0.0006
Processed food	1.35	13.66	0.56	9.95
Nitrogen fertiliser	0.0002	0.002	0.0007	0.012
Phosphorus fertiliser	0.0002	0.002	0.0009	0.015
Non-food	3.66	36.88	2.40	42.71
Food waste recycling service	0.0303	0.31	0.0000	0.00
Food waste collection service	0.2790	2.81	0.0000	0.00
Total	9.92	100.00	5.61	100.00

[a] Data source: Hamilton, et al. [23]. Emissions of food processing by-products (i.e., cereal bran, alcoholic pulp, oil cake) are derived from Mackenzie, et al. [24]. Emissions of food waste recycling and collection services are obtained from Alsaleh and Aleisa [25], Hong, et al. [26], and Hong, et al. [27]

Appendix Table 8 | Emission intensities of greenhouse gases (ton CO_2 equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereal grains	1435	1246
Oilseeds & pulses	360	166
Vegetables &fruits	203	32
Roots &tubers	264	75
Sugar crops	142	231
Other non-food crops	7922	987
Monogastric livestock	457	631
Ruminant livestock	3886	3258
Compound feed	469	259
Cereal bran	2.2	0.7
Alcoholic pulp	0.3	0.01
Oil cake	77	6
Processed food	473	254
Nitrogen fertiliser	25477	17248
Phosphorus fertiliser	5390	2836
Non-food	3509	538
Food waste recycling service	3490	0
Food waste collection service	12087	0

[a] Data source: Calculated by our study.

Appendix Table 9 | Emission intensities of acidification pollutants (ton NH_3 equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereal grains	20.44	9.84
Oilseeds & pulses	12.53	2.53
Vegetables & fruits	7.00	0.48
Roots & tubers	9.20	0.91
Sugar crops	4.96	3.29
Other non-food crops	275.09	16.19
Monogastric livestock	30.06	28.50
Ruminant livestock	35.04	4.89
Compound feed	0.74	0.32
Cereal bran	0.10	0.03
Alcoholic pulp	0.002	0.00004
Oil cake	3.90	0.31
Processed food	0.81	0.31
Nitrogen fertiliser	0.07	0.75
Phosphorus fertiliser	0.15	0.91
Non-food	6.20	0.65
Food waste recycling service	12.79	0.00
Food waste collection service	30.49	0.00

[a] Data source: Calculated by our study.

Appendix Table 10 | Emission intensities of eutrophication pollutants (ton N equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereal grains	5.40	0.63
Oilseeds & pulses	6.48	0.84
Vegetables & fruits	3.26	0.38
Roots & tubers	4.25	0.91
Sugar crops	0.62	0.37
Other non-food crops	5.09	0.48
Monogastric livestock	3.34	3.76
Ruminant livestock	25.85	9.40
Compound feed	3.14	1.13
Cereal bran	0.004	0.001
Alcoholic pulp	0.001	0.00001
Oil cake	0.18	0.01
Processed food	3.12	1.09
Nitrogen fertiliser	0.02	0.15
Phosphorus fertiliser	0.04	0.28
Non-food	1.25	0.19
Food waste recycling service	6.46	0.00
Food waste collection service	15.19	0.00

[a] Data source: Calculated by our study.