SUPPLEMENTARY INFORMATION

How can sustainable food production and consumption in China be achieved?

Weitong Long[1,2], Xueqin Zhu[1*], Hans-Peter Weikard[1], Oene Oenema[2,3], Yong Hou[2*]

[1]Environmental Economics and Natural Resources Group, Wageningen University, Hollandseweg 1, 6706 KN Wageningen, The Netherlands

[2]State Key Laboratory of Nutrient Use and Management, College of Resources and Environmental Science, China Agricultural University, 100193 Beijing, China

[3]Wageningen Environmental Research, 6708 PB Wageningen, The Netherlands

* Corresponding author at: Wageningen University, 6706 KN Wageningen, The Netherlands; China Agricultural University, 100193, Beijing, China.

E-mail addresses: xueqin.zhu@wur.nl (X. Zhu); yonghou@cau.edu.cn (Y. Hou).

Contents

Mathematically, various ways exist to represent applied general equilibrium (AGE) models, according to Ginsburgh and Keyzer (2002). To identify the optimal solution or pathway towards greater sustainability and enable the efficient allocation of resources in the economy, we used the welfare format of the AGE models for our analysis. In the supplementary information, following the theoretical structure in Section 1, we specified the model for our study by explicitly considering producers, consumers, production goods, consumption goods, intermediate goods, and environmental quality. Subsequently, we presented the calibration of our model and the definition of scenarios. Finally, we provided supplementary figures and tables, along with the sectoral aggregation scheme, social accounting matrices, and emissions data for all the regions in our study.

1. Theoretical structure of a welfare program

In the economy, we have m consumers, n producers, l commodities, and e pollutants with local and global impacts. Representative consumers in a region are indexed as i (i=1, 2, …, m), i.e., there are m regions in our model, which sets the consumption plan to maximise their utility. Each consumer also faces a budget constraint: $px_i \leq h_i$, where p is the price vector, x_i is a vector of consumption of commodities, and h_i is the consumer's income. Each producer j (j=1, 2, …, n) is endowed with a technology (represented by a set Y_j) and chooses the feasible production plan (expressed as $y_j \in Y_j$) to maximise profit (defined as py_j, where p is the price vector). Commodities indexed as k (k=1, 2, …, l) are either used for final consumption or as intermediate inputs for production. We also include a vector of environmental quality g (g=1, 2, …, e) related to a set of local and global pollutants from the production processes in our model.

The integrated environmental-economic model enables us to capture the economic functions of the environment, i.e., the goods and services that the environment provides to economic activities (Zhu, 2004), which include emissions as joint outputs of production and amenity services in consumer utility. When extending environmental issues to general equilibrium models, the emissions can be treated either as inputs (or the use of environmental resources) for production or by-products (or joint outputs) of production. We adopt the latter option because the modelling of emissions as outputs using emission coefficients is relatively straightforward and assumes a linear relationship between emissions and production. Environmental quality will have impacts on utility because of the amenity services provided by the environment. We consider the amenity services of the environment in the utility function using environmental quality indicators. In this way, the inputs from the environmental system to the economic system (production and consumption) and the emissions of local and global pollutants from the economic system to the environmental system will change the environmental condition and provide feedback to the economic system, thus having impacts on production and consumption.

Individual utility (u_i) of consumer (region) i depends on a vector of rival goods (x_i) and environmental quality related to local and global pollutants (g_i) in region i.

Formally, social welfare (W) is defined as a weighted sum of the individual utility of all consumers as follows:

$$\mathrm{W} = \max \sum_i \alpha_i u_i(x_i, g_i) \tag{1}$$

where α_i is the Negishi weight of the representative consumer in each region i (i =1, 2, …, m).

For the welfare (Negishi) format of the AGE model, the economy maximises the social welfare function (1) under the conditions of x_i≥0, g_i≥0 all i, y_j^+≥0, y_j^-≥0 all j, y_g^+≥0 subjects to a set of constraints, including production technology of producers, balance equations of commodities and consumer budget constraints. y_j (positive y_j^+ and negative y_j^- indicates output and input, respectively) is the vector of net production of producer j without specifying regions, while y_{ij} is the vector of net production of producer j in region i. y_g^+ is the total supply of environmental quality related to local and global pollutants (see below).

Neglecting subscript i, the transformation function for the production technology of producer j for rival goods can be written:

$$F_j(y_j^+ - y_j^-) \leq 0 \tag{2}$$

where F_j is the transformation function for producer j that produces the netput $(y_j^+ - y_j^-)$.

For each commodity k (k =1, 2, …, l), we have the following balance equation:

$$\sum_i x_i \leq \sum_j (y_j^+ - y_j^-) + \sum_i \omega_i \qquad (p) \tag{3}$$

where $\sum_i x_i$ is the total consumption of commodities (including environmental quality). $\sum_j (y_j^+ - y_j^-)$ is the total net production (including environmental quality) if each producer produces only one good. $\sum_i \omega_i$ is the total initial endowments (i.e., capital, labour, land). Lagrange multiplier p is the vector of the shadow prices of commodities, including environmental quality. The shadow price p of good measures how much the welfare changes if the good increases by one more unit, i.e., the marginal value of the good. This equation states that the consumption of commodities must be smaller than or equal to its production plus its initial endowments.

The transformation function for the production technology of environmental quality related to local and global pollutants can be written as follows:

$$F_g(y_g^+ - \sum_j y_j^+) \leq 0 \tag{4}$$

where F_g is the transformation function that "produces" a certain level of environmental quality (y_g^+) related to global pollutants via an exogenous environmental process.

For the environmental quality g (g=1, 2, …, e) related to each global pollutant, we have the following balance equation:

$$g_i = y_g^+ \qquad (\phi_i) \qquad (5)$$

where Lagrange multipliers ϕ_i is the shadow price of the environmental quality related to local and global pollutants in region i, reflecting the environmental willingness to pay of consumer i to pay for improving environmental quality by one unit. Equality in equation (5) means the non-rivalry of environmental quality. Every consumer i faces the same environmental quality y_g^+; thus, each individual's consumption should be equal to the total supply of the environmental quality due to its non-rivalry.

The budget constraint for a consumer i holds so that the expenditure of the consumer must be equal to his or her income:

$$px_i + \phi_i g_i = p\omega_i + \sum_j \theta_{ij} \prod_j(p) \qquad (\lambda_i) \qquad (6)$$

where the left-hand side shows the total expenditure and the right-hand side shows the income of the consumer. px_i is the total expenditure on the consumption of good j in region i. $\phi_i g_i$ is the payment to the "environmental services" in region i for improving the environmental quality. The income of consumer i consists of the remuneration for his initial endowments (e.g., capital, labour, land) $p\omega_i$ and profits received from firms $\sum_j \theta_{ij} \prod_j(p)$. θ_{ij} is the non-negative share of consumer i in the producer j. $\sum_j \theta_{ij}$=1 because all profits are distributed. $\prod_j(p)$ is the maximal profit of producer j. λ_i is the Lagrange multiplier associated with the budget constraint of the consumer in region i.

For the Negishi weight α_i:

$$\alpha_i = \frac{1}{\lambda_i} \qquad (7)$$

where the Negishi weight α_i attributed to consumer i is the inverse of the Lagrange multiplier λ_i.

2. Numerical model

2.1 Objective function

We rewrite the objective function "social welfare (W)" as the weighted sum of the log utility (U_i) of all consumers, according to Zhu and Van Ierland (2006).

$$\mathrm{W} = \max \sum_i \alpha_i \log U_i \qquad (8)$$

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)). The Negishi weights are determined in such a way that each consumer spends exactly its total income (i.e., remuneration of initial endowments, distributed profits from producers, and payments to the 'environmental sector') on the consumption of goods and environmental quality.

2.2 Utility function

In our model, the consumer's utility depends on the consumption of two types of goods: rival goods (e.g., pork, soybean) and environmental quality as a non-rival public good (see Fig. A1.). The utility function is a two-level nested function containing the Constant Elasticity of Substitution (CES) function and Cobb-Douglas (C-D) function describing the behaviour of a representative consumer (household to maximise its utility subject to budget constraints) (Fig. A2.). At the top level, a C-D function is used to aggregate the consumption of rival goods (i.e., cereals, vegetables and fruits, soybean, other crops, pig, poultry, other animals, soy-based food, other food, non-food) and non-rival goods (i.e., GWP, AP, and EP environmental quality). The utility function of the consumer in region i is written as:

$$U_i = gg_i^{\varepsilon g_i} ga_i^{\varepsilon a_i} ge_i^{\varepsilon e_i} (\prod_s C_{i,s}^{\beta_{i,s}})^{1-\varepsilon g_i - \varepsilon a_i - \varepsilon e_i} \quad (9)$$

where consumption goods s refers to cereals, vegetables and fruits, soybean, other crops, pig, poultry, other animals, soy-based food, other food, and non-food. gg_i, ga_i, and ge_i are the GWP, AP, and EP environmental quality in region i, respectively. εg_i ($0<\varepsilon g_i<1$), εa_i ($0<\varepsilon a_i<1$), and εe_i ($0<\varepsilon e_i<1$) are the elasticity of utility concerning GWP, AP, and EP environmental quality in region i, i.e., the expenditure share of GWP, AP, and EP environmental quality in total consumption in region i, respectively, and $\varepsilon g_i + \varepsilon a_i + \varepsilon e_i < 1$. $C_{i,s}$ 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 $\sum_s \beta_{i,s} = 1$.

The consumption of a protein composite ($C_{i,psc}$) of pig and soy-based food (SBF) in China is defined in a CES function as:

$$C_{i,psc} = [\delta_{i,sbf}^{\frac{1}{\sigma}} C_{i,sbf}^{\frac{\sigma-1}{\sigma}} + (1-\delta_{i,sbf})^{\frac{1}{\sigma}} C_{i,pig}^{\frac{\sigma-1}{\sigma}}]^{\frac{\sigma}{\sigma-1}} \quad (10)$$

$$\delta_{i,sbf} = \frac{C_{i,sbf}}{C_{i,sbf}+C_{i,pig}} \quad (11)$$

where $C_{i,sbf}$ and $C_{i,pig}$ are the consumption of SBF and pig in region i, respectively. σ is the elasticity of substitution between SBF and pig. $\delta_{i,sbf}$ is the expenditure share of SBF in the protein composite of pig and SBF consumption in region i.

2.3 Production function

We present the production functions of thirteen producers, namely, cereals, vegetables and fruits, soybean, other crops, pig, poultry, other animals, compound feed, soy-based food, other food, nitrogen fertiliser, phosphorus fertiliser, and non-food.

Our model treats manure as input in the production of crops for fertility, and animals require manure generation permits for animal production. Manure permits are attributed, and as a result, users must pay for the manure. Thus, manure is viewed as the input for the production process. The production function of producer j (including crops and animals) in region i is specified as:

$$Y_{i,j} = A_{i,j} {MN_{i,j}}^{\xi_{i,j}} [(KL_{i,j})^{\eta_{1i,j}} (LB_{i,j})^{\eta_{2i,j}} (LD_{i,j})^{\eta_{3i,j}} (NFE_{i,j})^{\eta_{4i,,j}} (PFE_{i,j})^{\eta_{5i,j}} (CER_{i,j})^{\eta_{6i,j}} (VF_{i,j})^{\eta_{7i,j}} (SOY_{i,j})^{\eta_{8i,j}} (OTC_{i,j})^{\eta_{9i,j}} (COF_{i,j})^{\eta_{10i,j}}]^{1-\xi_{i,j}} \quad (12)$$

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. $MN_{i,j}$ is the manure input for the production of sector j (here j= cereals, vegetables and fruits, soybean, other crops, pig, poultry, other animals) in region i. $KL_{i,j}$, $LB_{i,j}$, and $LD_{i,j}$ are capital, labour, and land inputs for production j in region i, respectively. $NFE_{i,j}$, $PFE_{i,j}$, $CER_{i,j}$, $VF_{i,j}$, $SOY_{i,j}$, $OTC_{i,j}$, and $COF_{i,j}$ are nitrogen fertiliser, phosphorus fertiliser, cereals, vegetables and fruits, soybean, other crops, and compound feed inputs for the production of sector j in region i, respectively. $\xi_{i,j}$ ($0<\xi_{i,j}<1$) is the cost share of the manure for the production of sector j in region i. η_f (f=1, 2, 3, …, 10) is the cost share of each input for production, and $\sum_{f=1}^{10} \eta_f = 1$.

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

$$\varepsilon_{gg,i,j} = \frac{EM^{+0}_{gg,i,j}}{Y^0_{i,j}} \quad (13)$$

$$\varepsilon_{ga,i,j} = \frac{EM^{+0}_{ga,i,j}}{Y^0_{i,j}} \quad (14)$$

$$\varepsilon_{ge,i,j} = \frac{EM^{+0}_{ge,i,j}}{Y^0_{i,j}} \quad (15)$$

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= NH_3 emissions, and 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 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 (16)

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

for emissions of acidification pollutants ga =NH_3, NO_x, and SO_2 emissions (17)

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

for emissions of eutrophication pollutants ge = N and P losses (18)

where $EMG^{+}_{i,j}$, $EMA^{+}_{i,j}$, and $EME^{+}_{i,j}$ are the total emissions of GHGs, acidification 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 (see Table A1).

Similarly, the manure coefficient ($\varepsilon_{i,mn}$, kg manure kg^{-1} animal) in region i is calculated as:

$$\varepsilon_{i,mn} = \frac{Y^0_{i.mn}}{(Y^0_{i,pig}+Y^0_{i,pou}+Y^0_{i,ota})} \quad (19)$$

where $Y^0_{i.mn}$ is manure production in region i in the base run. $Y^0_{i,j}$ are the production of pig, poultry, and other animals in region i in the base run, respectively.

Next, the manure production in different scenarios is calculated by multiplying the current animal production by the manure coefficient. The manure production in region i is calculated as:

$$Y_{i,mn} = \varepsilon_{i,mn} * (Y_{i,pig} + Y_{i,pou} + Y_{i,ota}) \quad (20)$$

where $Y_{i,mn}$ is the manure production in region i, which depends on the production of pig, poultry, and other animals.

2.4 Environmental quality

Environmental quality is "supplied" by the environment and determined by the emissions of pollutants from all producers across the whole economy. We consider three types of environmental quality indicators related to three types of pollutants that would affect consumer utility.

In order to measure the relative change in environmental quality under different scenarios, we follow Zhu and Van Ierland (2005) to specify the environmental quality indicators related to GWP, AP, and EP ($y_{gg}^{+},\ y_{ga}^{+},\ y_{ge}^{+}$) as:

$$y_{gg,i}^{+} = 100 * \frac{2*TMG_i^{+0} - TMG_i^{+}}{TMG_i^{+0}} \tag{21}$$

$$y_{ga,i}^{+} = 100 * \frac{2*TMA_i^{+0} - TMA_i^{+}}{TMA_i^{+0}} \tag{22}$$

$$y_{ge,i}^{+} = 100 * \frac{2*TME_i^{+0} - TME_i^{+}}{TME_i^{+0}} \tag{23}$$

where TMG_i^{+0}, TMA_i^{+0}, and TME_i^{+0} are the total emissions of GHGs, acidification and eutrophication pollutants in the base run in region i. TMG_i^{+}, TMA_i^{+}, and TME_i^{+} is the total emissions of GHGs, acidification and eutrophication pollutants after the scenarios in region i. In the base run, $TMG_i^{+} = TMG_i^{+0}$, $TMA_i^{+} = TMA_i^{+0}$, and $TME_i^{+} = TME_i^{+0}$. Thus, $y_{gg,i}^{+} = 100$, $y_{ga,i}^{+} = 100$, and $y_{ge,i}^{+} = 100$. If the score is higher than 100 in a scenario analysis, the environmental quality has been improved. If the score is lower than 100 in the scenario analysis, the environmental quality is worse than before.

2.5 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 MTP. Cereals, vegetables & fruits, and other crops are used for direct consumption and intermediate use for pig, poultry, other animals, compound feed, and other food production. Soybean is produced for direct consumption and intermediate use for pig, poultry, other animals, compound feed, and SBF production. Compound feed is produced for intermediate use for pig, poultry, and other animals production. Pig, poultry, other animals, SBF, other food, and non-food are used for direct consumption. Nitrogen fertiliser and phosphorus fertiliser are used for cereals, vegetables and fruits, soybean, and other 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 (Deardorff, 1982). 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 cereals, vegetables & fruits, and other crops in region i are as follows:

$$C_{i,cer} + CER_{i,pig} + CER_{i,pou} + CER_{i,ota} + CER_{i,cof} + CER_{i,otf} + XNET_{i,cer} \leq Y_{i,cer} \qquad (p_{i,cer}) \tag{24}$$

$$C_{i,vf} + VF_{i,pig} + VF_{i,pou} + VF_{i,ota} + VF_{i,cof} + VF_{i,otf} + XNET_{i,vf} \leq Y_{i,vf} \qquad (p_{i,vf}) \tag{25}$$

$$C_{i,otc} + OTC_{i,pig} + OTC_{i,pou} + OTC_{i,ota} + OTC_{i,cof} + OTC_{i,otf} + XNET_{i,otc} \leq Y_{i,otc} \qquad (p_{i,otc}) \tag{26}$$

where $CER_{i,pig}$, $CER_{i,pou}$, $CER_{i,ota}$, $CER_{i,cof}$, and $CER_{i,otf}$ are cereals used for pig, poultry, other animals, compound feed, and other food production in region i, respectively. $VF_{i,pig}$, $VF_{i,pou}$, $VF_{i,ota}$, $VF_{i,cof}$, and $VF_{i,otf}$ are vegetables &fruits used for pig, poultry, other animals, compound feed, and other food production in region i, respectively. $OTC_{i,pig}$, $OTC_{i,pou}$, $OTC_{i,ota}$, $OTC_{i,cof}$, and $OTC_{i,otf}$ are other crops used for pig, poultry, other animals, compound feed, and other food production in region i, respectively. $p_{i,cer}$, $p_{i,vf}$, and $p_{i,otc}$ are the shadow prices of cereals, vegetables & fruits, and other crops in region i, respectively.

The balance equation for soybean in region i is as follows:

$$C_{i,soy} + SOY_{i,pig} + SOY_{i,pou} + SOY_{i,ota} + SOY_{i,cof} + SOY_{i,sbf} + XNET_{i,soy} \leq Y_{i,soy} \qquad (p_{i,soy}) \tag{27}$$

where $SOY_{i,pig}$, $SOY_{i,pou}$, $SOY_{i,ota}$, $SOY_{i,cof}$, and $SOY_{i,sbf}$ are soybean used for pig, poultry, other animals, compound feed, and SBF production in region i, respectively. $p_{i,soy}$ is the shadow price of soybean in region i.

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

$$COF_{i,pig} + COF_{i,pou} + COF_{i,ota} + XNET_{i,cof} \leq Y_{i,cof} \qquad (p_{i,cof}) \tag{28}$$

where $COF_{i,pig}$, $COF_{i,pou}$, and $COF_{i,ota}$ are compound feed used for pig, poultry, other animals production in region i, respectively. $p_{i,cof}$ is the shadow price of compound feed in region i.

The balance equation for pig, poultry, other animals, SBF, other food, and non-food in region i is as follows:

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

for goods j = pig, poultry, other animals, SBF, other food, and non-food (29)

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

The balance equation for nitrogen fertiliser and phosphorus fertiliser in region i is as follows:

$$NFE_{i,cer} + NFE_{i,vf} + NFE_{i,soy} + NFE_{i,otc} + XNET_{i,nfe} \leq Y_{i,nfe} \qquad (p_{i,nfe}) \qquad (30)$$

$$PFE_{i,cer} + PFE_{i,vf} + PFE_{i,soy} + PFE_{i,otc} + XNET_{i,pfe} \leq Y_{i,pfe} \qquad (p_{i,pfe}) \qquad (31)$$

where $NFE_{i,cer}$, $NFE_{i,vf}$, $NFE_{i,soy}$ and $NFE_{i,otc}$ are the nitrogen fertiliser used for cereals, vegetables and fruits, soybean, and other crops production in region i, respectively. $PFE_{i,cer}$, $PFE_{i,vf}$, $PFE_{i,soy}$ and $PFE_{i,otc}$ are the phosphorus fertiliser used for cereals, vegetables and fruits, soybean, and other crops production in region i, respectively. $p_{i,nfe}$ and $p_{i,pfe}$ are the shadow prices of nitrogen and phosphorus fertiliser in region i, respectively.

Manure is either used for cereals, vegetables and fruits, soybean, and other crops production or leakage to the environment from pig, poultry, and other animals production. The balance equation for manure in region i is as follows:

$$MN_{i,cer} + MN_{i,vf} + MN_{i,soy} + MN_{i,otc} + MN_{i,pig} + MN_{i,pou} + MN_{i,ota} = Y_{i,mn} \qquad (p_{i,mn}) \qquad (32)$$

where $MN_{i,cer}$, $MN_{i,vf}$, $MN_{i,soy}$, and $MN_{i,otc}$ are the manure used for cereals, vegetables and fruits, soybean, and other crops production in region i, respectively. $MN_{i,pig}$, $MN_{i,pou}$, and $MN_{i,ota}$ are the manure leakage to the environment from pig, poultry, and other animals production in region i, respectively. $p_{i,mn}$ is the shadow price of manure in region i.

For trade balance of all goods:

$$\sum_i XNET_{i,j} = 0 \qquad (p_j) \qquad (33)$$

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

$$\sum_j KL_{i,j} \leq \overline{KL_i} \qquad (r_i) \qquad (34)$$

$$\sum_j LB_{i,j} \leq \overline{LB_i} \qquad (w_i) \tag{35}$$

$$\sum_j LD_{i,j} \leq \overline{LD_i} \qquad (k_i) \tag{36}$$

where $\overline{KL_i}$, $\overline{LB_i}$ and $\overline{LD_i}$ are the factor endowments (i.e., capital, labour, land) supply in region i, respectively. r_i, w_i, and k_i are the shadow prices of capital, labour, and land in region i, respectively.

For the environmental quality indicators related to GWP, AP, and EP in region i, consumer demand should be equal to supply as well, that is:

$$gg_i = y^+_{gg,i} \qquad (\phi_{gg,i}) \tag{37}$$

$$ga_i = y^+_{ga,i} \qquad (\phi_{ga,i}) \tag{38}$$

$$ge_i = y^+_{ge,i} \qquad (\phi_{ge,i}) \tag{39}$$

where $\phi_{gg,i}$, $\phi_{ga,i}$, and $\phi_{ge,i}$ are the shadow prices of the environmental quality indicators related to GWP, AP, and EP in region i, respectively, reflecting the willingness of consumer i to pay for improving the environmental quality indicators related to GWP, AP, and EP by one unit. That is, no free-riding occurs for the use of non-rival environmental quality. Equality means the non-rivalry of environmental quality. Non-rivalry indicates individuals suffering from bad environmental quality would not reduce the possibility of others suffering. Every consumer i faces the same environmental quality; thus, each individual's consumption should be equal to the total supply of the environmental quality due to its non-rivalry.

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

$$\sum_j EMG^+_{i,j} \leq \overline{TMG^+_i} \qquad (p_{eg,i}) \tag{40}$$

$$\sum_j EMA^+_{i,j} \leq \overline{TMA^+_i} \qquad (p_{ea,i}) \tag{41}$$

$$\sum_j EME^+_{i,j} \leq \overline{TME^+_i} \qquad (p_{ee,i}) \tag{42}$$

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 (Scenarios S5) study, 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.

2.6 Budget constraint

The budget constraint for a consumer i holds such that the expenditure must be equal to the income:

$$\sum_s \left(p_{i,s} C_{i,s}\right) + \phi_{gg,i} gg_i + \phi_{ga,i} ga_i + \phi_{ge,i} ge_i = h_i \tag{43}$$

where consumption goods s refers to cereals, vegetables and fruits, soybean, other crops, pig, poultry, other animals, soy-based food, other food, and non-food. $\sum_s \left(p_{i,s} C_{i,s}\right)$ is the total expenditure on the consumption goods in region i. $\phi_{gg,i} gg_i$, $\phi_{ga,i} ga_i$, and $\phi_{ge,i} ge_i$ are the payments to the "environmental sector" for improving the environmental quality indicators related to GWP, AP, and EP in region i, respectively. h_i is the income in region i. The Negishi weight (α_i) in the welfare function (equation 8) 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. Since manure is viewed as the input for the production process, we should also include income from manure use and leakage. Since goods are tradable, the consumer's income should exclude the export part. Thus, the consumer's income is:

$$h_i = r_i \overline{KL_i} + w_i \overline{LB_i} + k_i \overline{LD_i} - \sum_j (p_j XNET_{i,j}) + \phi_{gg,i} gg_i + \phi_{ga,i} ga_i + \phi_{ge,i} ge_i + \\ + p_{i,mn} Y_{i,mn} + p_{eg,i} \overline{TMG_i^+} + p_{ea,i} \overline{TMA_i^+} + p_{ee,i} \overline{TME_i^+} \tag{44}$$

where $\sum_j (p_j XNET_{i,j})$ is the income from exports. $p_{i,mn} Y_{i,mn}$ is the income from manure use and leakage. $p_{eg,i} \overline{TMG_i^+}$, $p_{ea,i} \overline{TMA_i^+}$, 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:

$$PROF_{i,j} = p_j Y_{i,j} - r_i KL_{i,j} - w_i LB_{i,j} - k_i LD_{i,j} - p_{cer} CER_{i,j} - p_{vf} VF_{i,j} - \\ p_{soy} SOY_{i,j} - p_{otc} OTC_{i,j} - p_{cof} COF_{i,j} - p_{nfe} NFE_{i,j} - p_{pfe} PFE_{i,j} - p_{i,mn} MN_{i,j} - \\ p_{eg,i} EMG_{i,j}^+ - p_{ea,i} EMA_{i,j}^+ - p_{ee,i} EME_{i,j}^+ \tag{45}$$

3. Model calibration

As in the literature on AGE models, we followed the Harberger convention (McLure Jr, 1975) 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 (Shoven & Whalley, 1992). 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. In order to calibrate manure-related parameters and add manure into the SAMs (see Table B2-3), our model treats manure as input in the production of crops for fertility, and animals require manure generation permits for animal production (see equation 12).

4. Definition of scenarios

4.1 S0 - Baseline

Environmental concerns were not considered in S0 because the original SAMs derived from the GTAP database do not contain expenditures on environmental concerns. Thus, the utility elasticicities (i.e., willingness to pay for environmental quality) of environmental quality indicators related to GWP (εg_i), AP (εa_i), and EP (εe_i) were 0% in China and MTP. The substitution elasticity between soybean-based food (SBF) and pig (i.e., the ease of substituting pork with SBF for consumption) was 0.5. The expenditure shares of SBF in pork-SBF protein composite consumption were 25% and 82% in China and MTP, respectively, as calculated based on the SAMs (see Appendix Table B2 & B3).

4.2 S1 - Differences in environmental concerns of consumers

In S1, we assumed that consumers in China were willing to pay 1% and those in MTP 2% of their total budget for improving environmental quality. Consumers in both regions were assumed to be willing to pay for improving environmental quality indicators related to GWP, AP, and EP equally as they attach equal importance to these types of environmental quality.

4.3 S2 - Dietary structure change

In S2, the expenditure share of SBF ($\delta_{i,sbf}$) in pork-SBF protein composite consumption increased from 25% to 50% in China, and that share in MTP remained unchanged.

4.4 S3 - Cleaner cereals production technology

In S3, a new parameter (τ) was introduced to simulate the degree of replacement of China's cereals production technology by MTP's technology. Parameter τ was the ratio of production inputs replaced by the new MTP technology. Here, we assumed a 50% partial technology replacement, which means τ=0.5, i.e., 50% of inputs for

China's cereals production was used for producing cereals with MTP's new technology. In this case, we used two production functions for the old and new technologies.

The constraints below indicated the level of intermediate and factor inputs available for each China's cereals production function. Factor and intermediate input constraints are:

$$KL1_{CN,cer} = (1-\tau)KL_{CN,cer} \quad (46)$$

$$LB1_{CN,cer} = (1-\tau)LB_{CN,cer} \quad (47)$$

$$LD1_{CN,cer} = (1-\tau)LD_{CN,cer} \quad (48)$$

$$NFE1_{CN,cer} = (1-\tau)NFE_{CN,cer} \quad (49)$$

$$PFE1_{CN,cer} = (1-\tau)PFE_{CN,cer} \quad (50)$$

$$KL2_{CN,cer} = \tau * KL_{CN,cer} \quad (51)$$

$$LB2_{CN,cer} = \tau * LB_{CN,cer} \quad (52)$$

$$LD2_{CN,cer} = \tau * LD_{CN,cer} \quad (53)$$

$$NFE2_{CN,cer} = \tau * NFE_{CN,cer} \quad (54)$$

$$PFE2_{CN,cer} = \tau * PFE_{CN,cer} \quad (55)$$

The old cereals production function is:

$$Y1_{CN,cer} = A_{CN,cer} MN1_{CN,cer}{}^{\xi_{CN,cer}} [(KL1_{CN,cer})^{\eta_{1CN,cer}} (LB1_{CN,cer})^{\eta_{2CN,cer}} (LD1_{CN,cer})^{\eta_{3CN,cer}} (NFE1_{CN,cer})^{\eta_{4CN,cer}} (PFE1_{CN,cer})^{\eta_{5CN,cer}}]^{1-\xi_{CN,cer}} \quad (56)$$

where $MN1_{CN,cer}$, $KL1_{CN,cer}$, $LB1_{CN,cer}$, $LD1_{CN,cer}$, $NFE1_{CN,cer}$ and $PFE1_{CN,cer}$, are manure, capital, labour, land, nitrogen fertiliser, and phosphorus fertiliser inputs for cereals production in China using the old cereals production function, respectively.

The new production function using MTP's cereals production technology is:

$$Y2_{CN,cer} = A_{MTP,cer} MN2_{CN,cer}{}^{\xi_{MTP,cer}} [(KL2_{CN,cer})^{\eta_{1MTP,cer}} (LB2_{CN,cer})^{\eta_{2MTP,cer}} (LD2_{CN,cer})^{\eta_{3MTP,cer}} (NFE2_{CN,cer})^{\eta_{4MTP,cer}} (PFE2_{CN,cer})^{\eta_{5MTP,cer}}]^{1-\xi_{MTP,cer}} \quad (57)$$

where $MN2_{CN,cer}$, $KL2_{CN,cer}$, $LB2_{CN,cer}$, $LD2_{CN,cer}$, $NFE2_{CN,cer}$ and $PFE2_{CN,cer}$, are manure, capital, labour, land, nitrogen fertiliser, and phosphorus fertiliser inputs for cereals production in China using the new cereals production function, respectively.

Total China's cereals production:

$$Y_{CN,cer} = Y1_{CN,cer} + Y2_{CN,cer} \quad (58)$$

Emissions from China's cereals production are from two parts:

$$EMG1^{+}_{CN,cer} = \sum_{gg} \varepsilon_{gg,CN,cer} * Y1_{CN,cer} * Eqv_{gg}$$

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

(59)

$$EMA1^{+}_{CN,cer} = \sum_{ga} \varepsilon_{ga,CN,cer} * Y1_{CN,cer} * Eqv_{ga}$$

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

(60)

$$EME1^{+}_{CN,cer} = \sum_{ge} \varepsilon_{ge,CN,cer} * Y1_{CN,cer} * Eqv_{ge}$$

for emissions of eutrophication pollutants ge = N and P losses

(61)

$$EMG2^{+}_{CN,cer} = \sum_{gg} \varepsilon_{gg,MTP,cer} * Y2_{CN,cer} * Eqv_{gg}$$

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

(62)

$$EMA2^{+}_{CN,cer} = \sum_{ga} \varepsilon_{ga,MTP,cer} * Y2_{CN,cer} * Eqv_{ga}$$

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

(63)

$$EME2^{+}_{CN,cer} = \sum_{ge} \varepsilon_{ge,MTP,cer} * Y2_{CN,cer} * Eqv_{ge}$$

for emissions of eutrophication pollutants ge = N and P losses

(64)

Total emissions from China's cereals production:

$$EMG^{+}_{CN,cer} = EMG1^{+}_{CN,cer} + EMG2^{+}_{CN,cer} \quad (65)$$

$$EMA^{+}_{CN,cer} = EMGA1^{+}_{CN,cer} + EMGA2^{+}_{CN,cer} \quad (66)$$

$$EMA^{+}_{CN,cer} = EMGA1^{+}_{CN,cer} + EMGA2^{+}_{CN,cer} \quad (67)$$

4.5 S5 - Unilateral environmental policy

In S5, the equations below showed that the total emissions of GHGs, acidification and eutrophication pollutants from all sectors j in China were 3% less than in S1.

$$\sum_{j} EMG^{+}_{i,j} \leq 0.97 * \overline{TMG^{+}_{i}} \qquad (p_{eg,i}) \quad (68)$$

$$\sum_{j} EMA^{+}_{i,j} \leq 0.97 * \overline{TMA^{+}_{i}} \qquad (p_{ea,i}) \quad (69)$$

$$\sum_{j} EME^{+}_{i,j} \leq 0.97 * \overline{TME^{+}_{i}} \qquad (p_{ee,i}) \quad (70)$$

Appendix A. Supplementary figures and tables

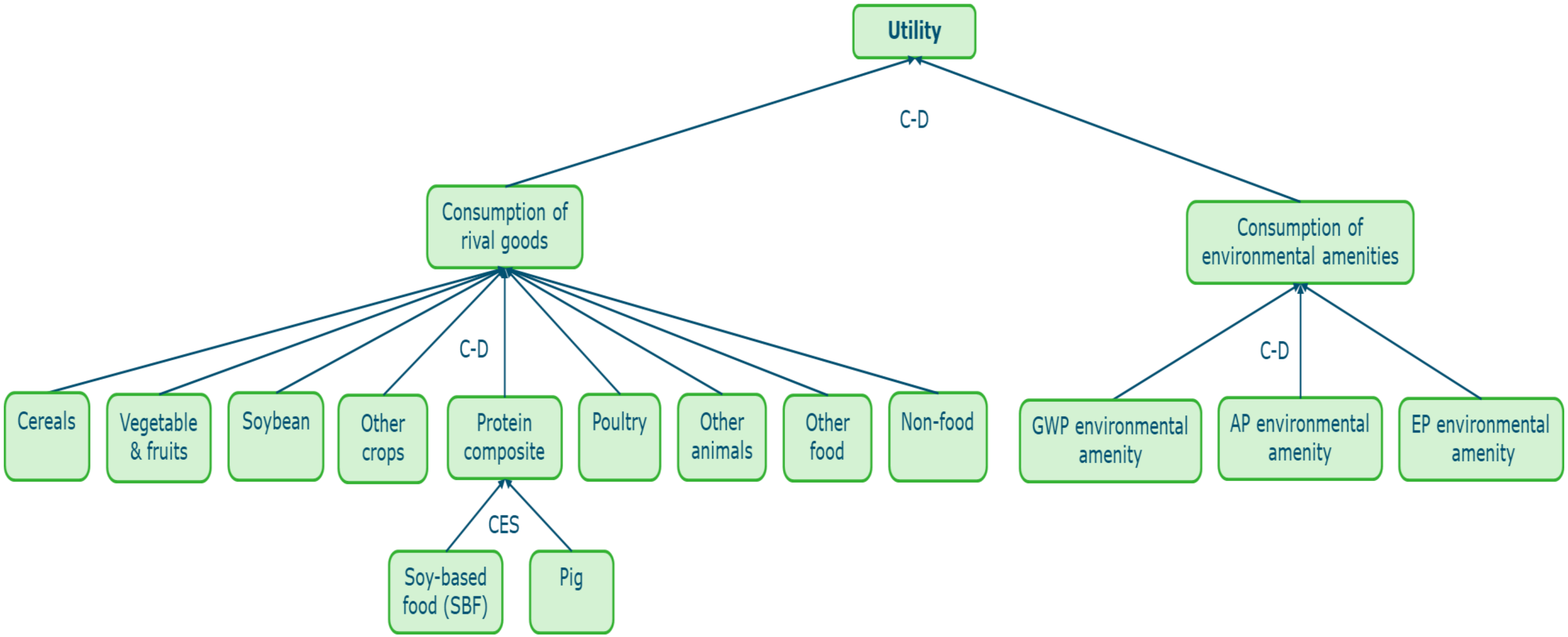

Fig. A1. The nested utility function of consumption. C-D = Cobb-Douglas. CES = Constant Elasticity of Substitution. GWP = global warming potential. AP = acidification potential. EP = eutrophication potential.

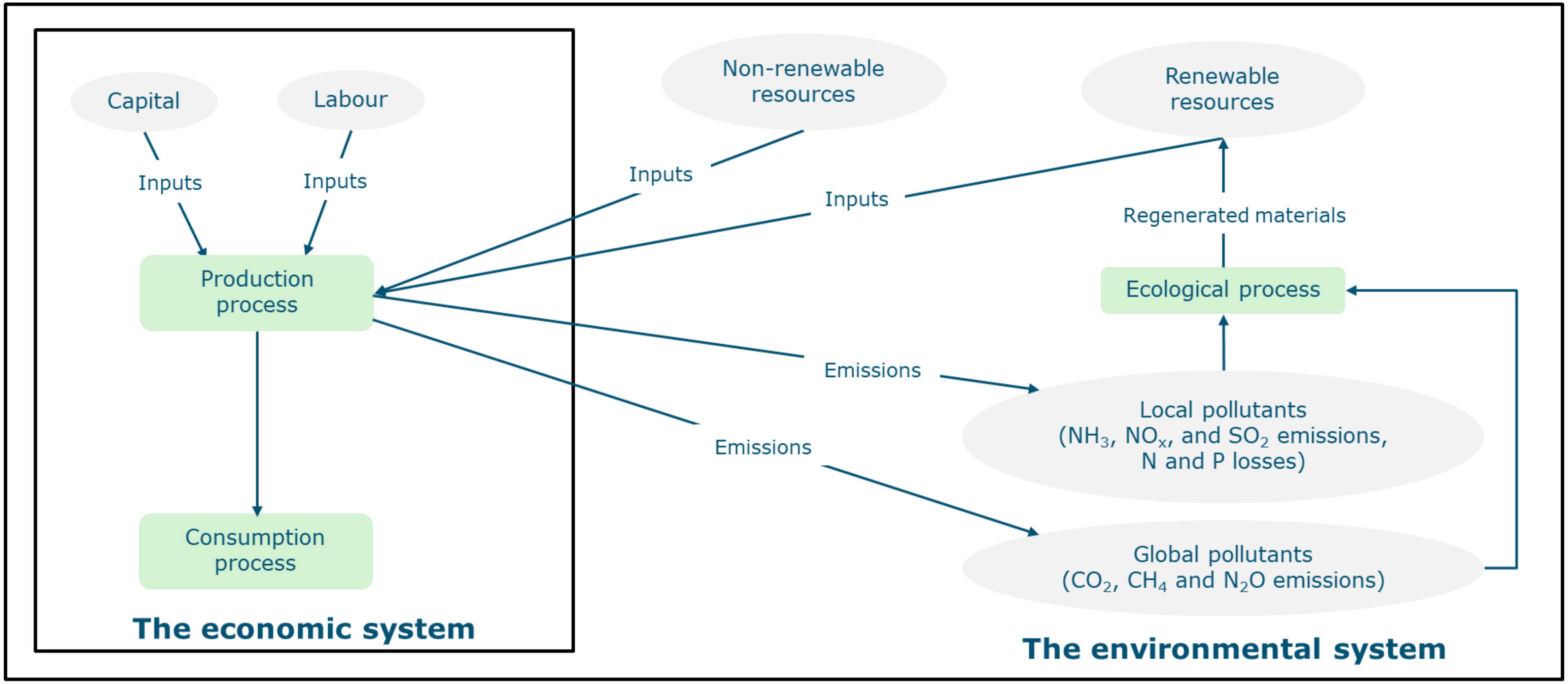

Fig. A2. Interactions between the economic system and the environmental system. The processes are indicated as squares, the stocks as circles and the flows as arrows. Source: Adapted on Van Ierland (1993). CO_2 = carbon dioxide. CH_4 = methane. N_2O = nitrous oxide. NH_3 = ammonia. NO_x = nitrogen oxides. SO_2 = sulphur dioxide. N = nitrogen. P = phosphorus.

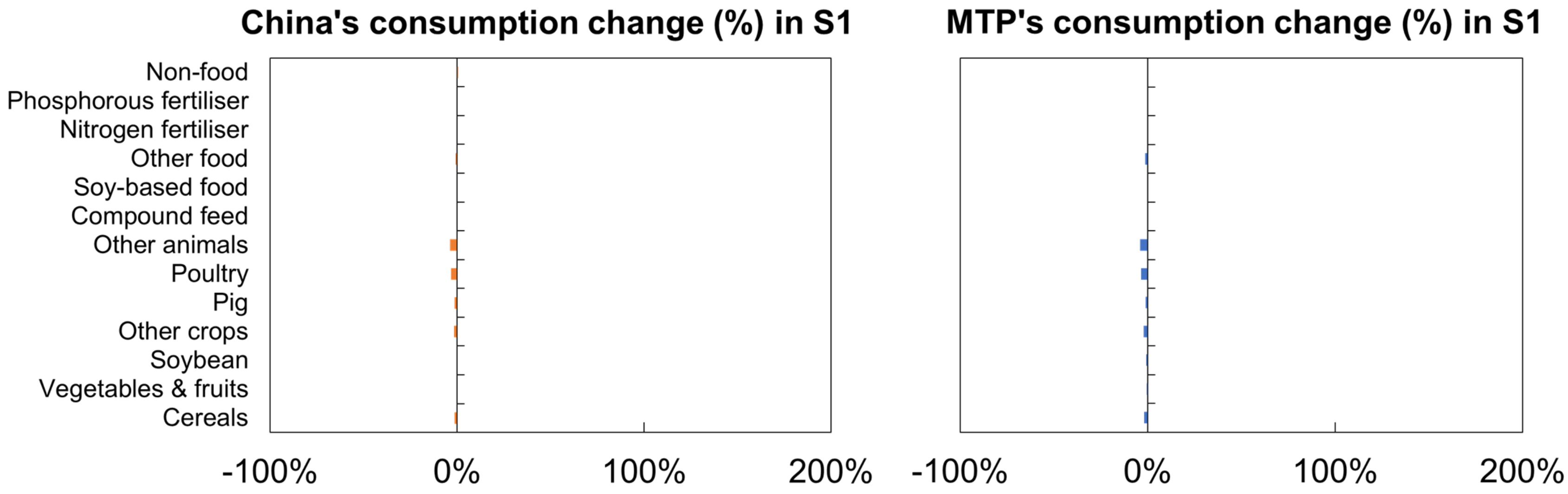

Fig. A3. Changes in consumption of goods in China and its main trading partners (MTP) when there are differences in environmental concerns of consumers (S1). Changes are relative to S0, in %.

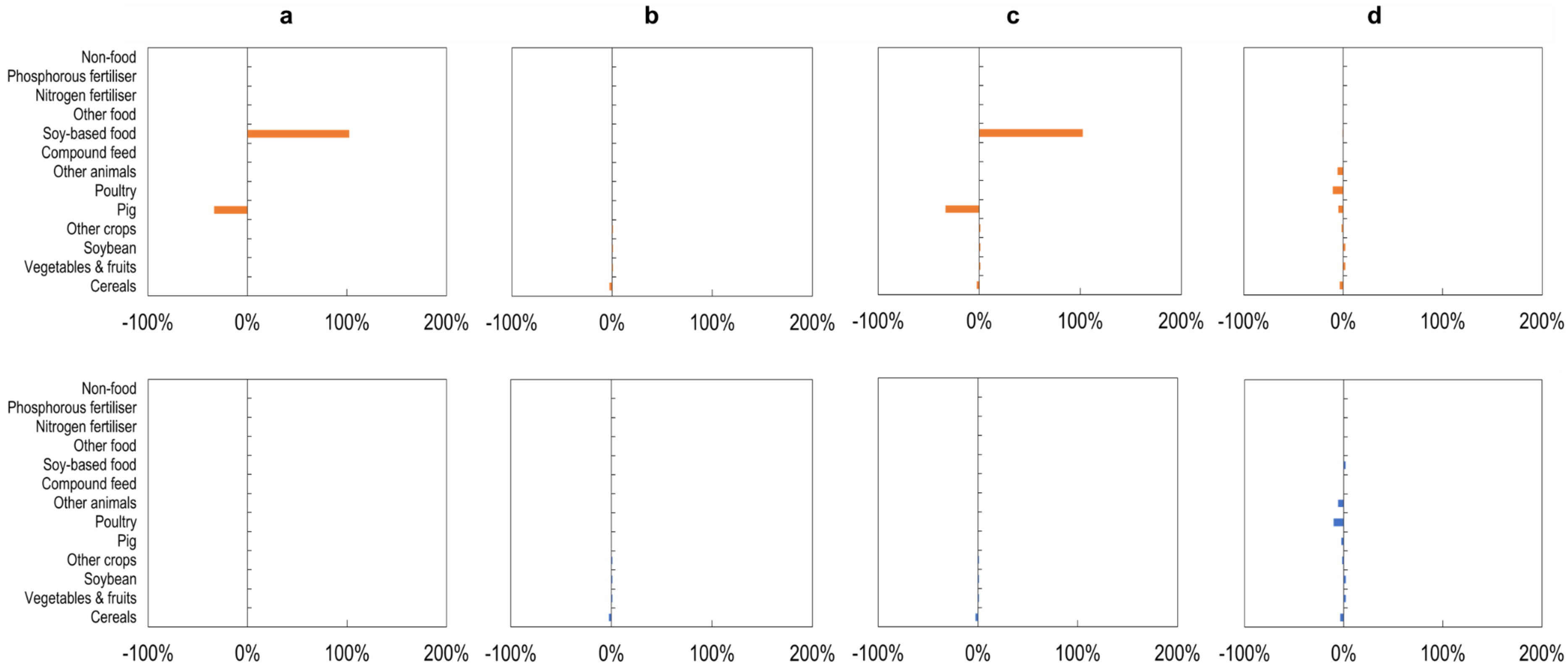

Fig. A4. Changes in consumption of goods in China (upper panels) and its main food and feed trading partners (MTP, lower panels) under scenarios of (a) dietary structure change (S2), (b) cleaner cereals production technology (S3), (c) the combination of dietary structure change and cleaner cereals production technology (S4), and (d) unilateral environmental policy (S5). Changes are relative to S1, in %.

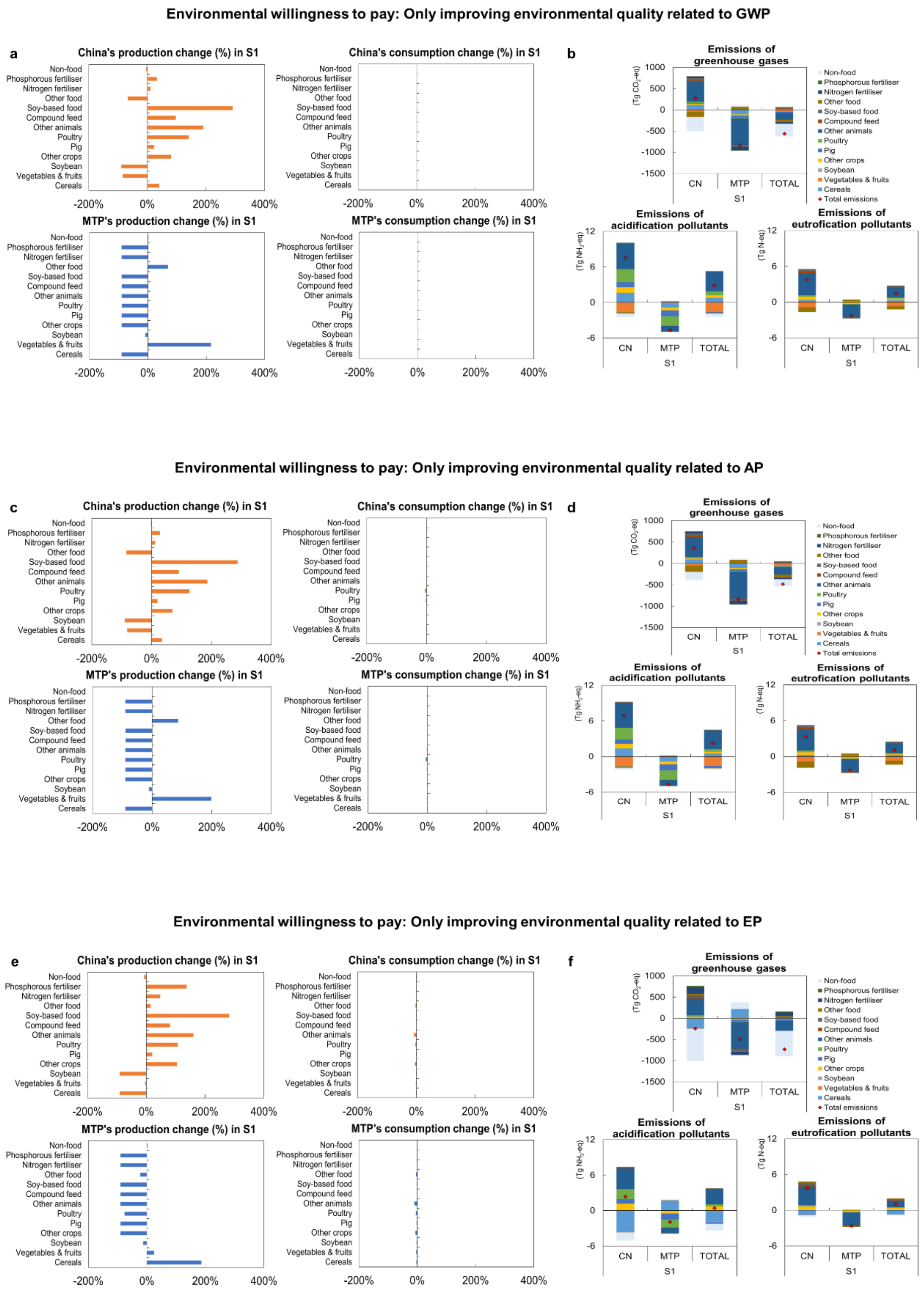

Fig. A5. Changes in (a, c, e) production (%) and consumption (%) of goods, (b, d, f) and emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) in China (CN) and its food and feed trading partners (MTP) when consumers are only willing to pay for improving one type of environmental quality for scenario S1. Changes are relative to S0.

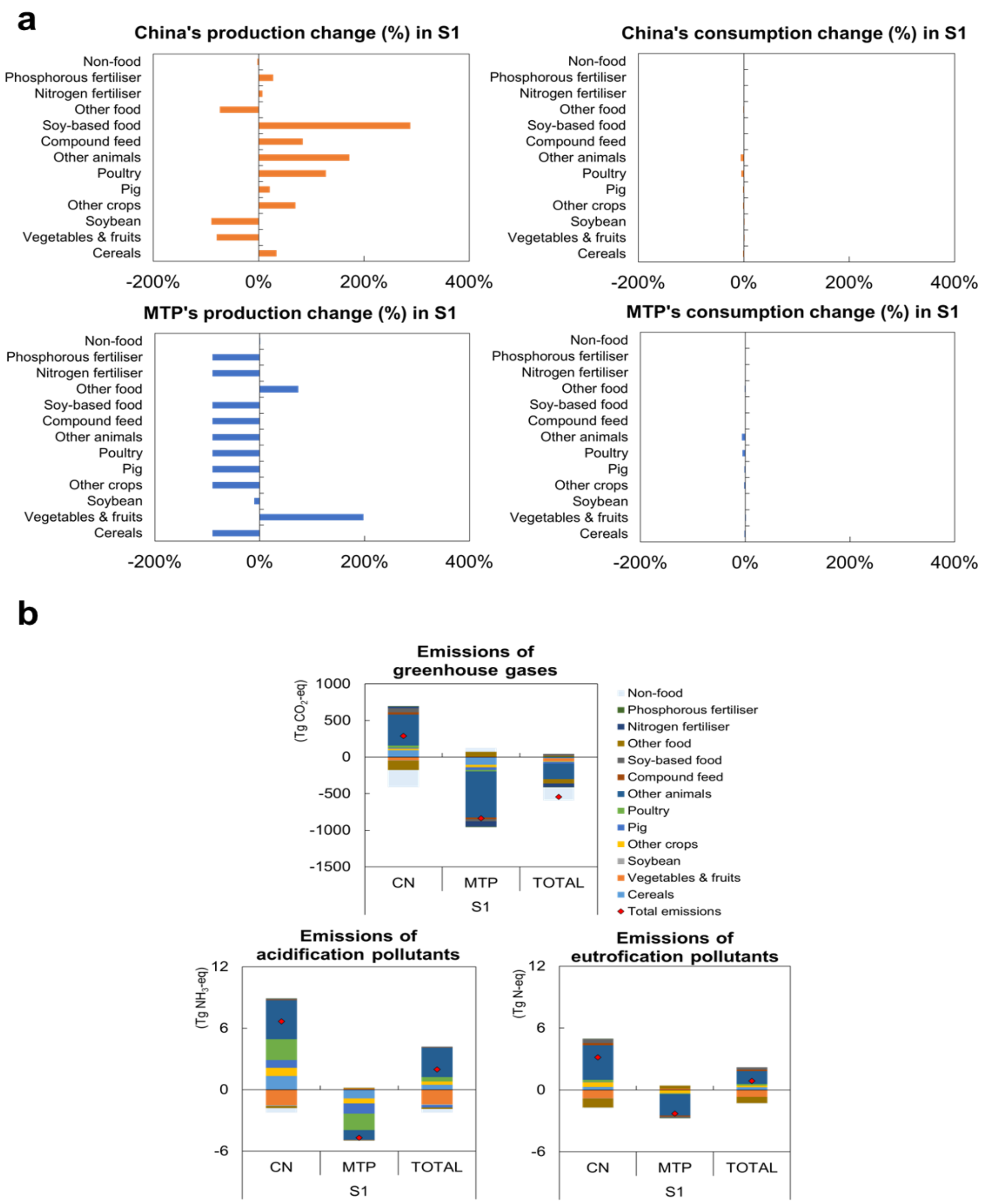

Fig. A6. Changes in (a) production (%) and consumption (%) of goods, (b) and emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) in China (CN) and its food and feed trading partners (MTP) under equal environmental willingness to pay in both regions for scenario S1. Changes are relative to S0.

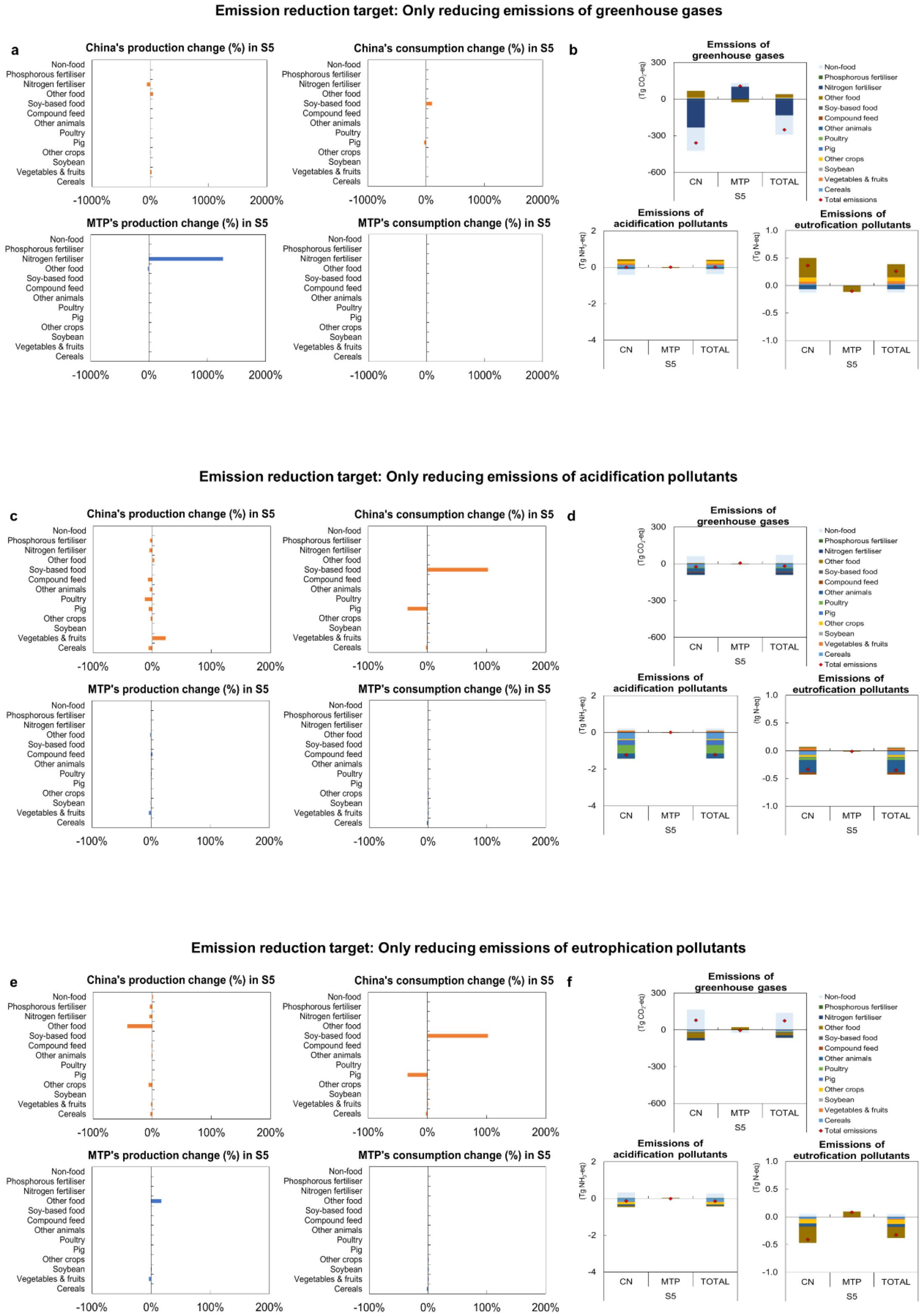

Fig. A7. Changes in (a, c, e) production (%) and consumption (%) of goods, (b, d, f) and emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) in China (CN) and its main food and feed trading partners (MTP) when setting an emission reduction target only for one type of emissions for scenario S5. Changes are relative to S1.

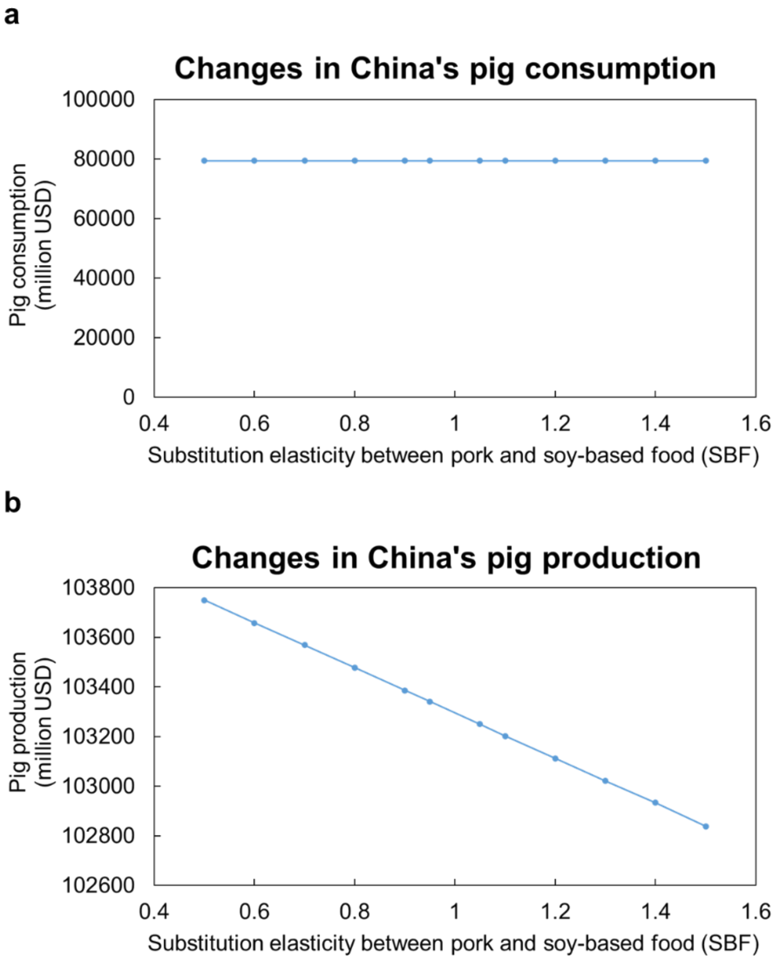

Fig. A8. Changes in China's pig (a) consumption (million USD) and (b) production (million USD) under different values of substitution elasticity between pork and soy-based food (SBF) for scenario S2. Changes are relative to S1.

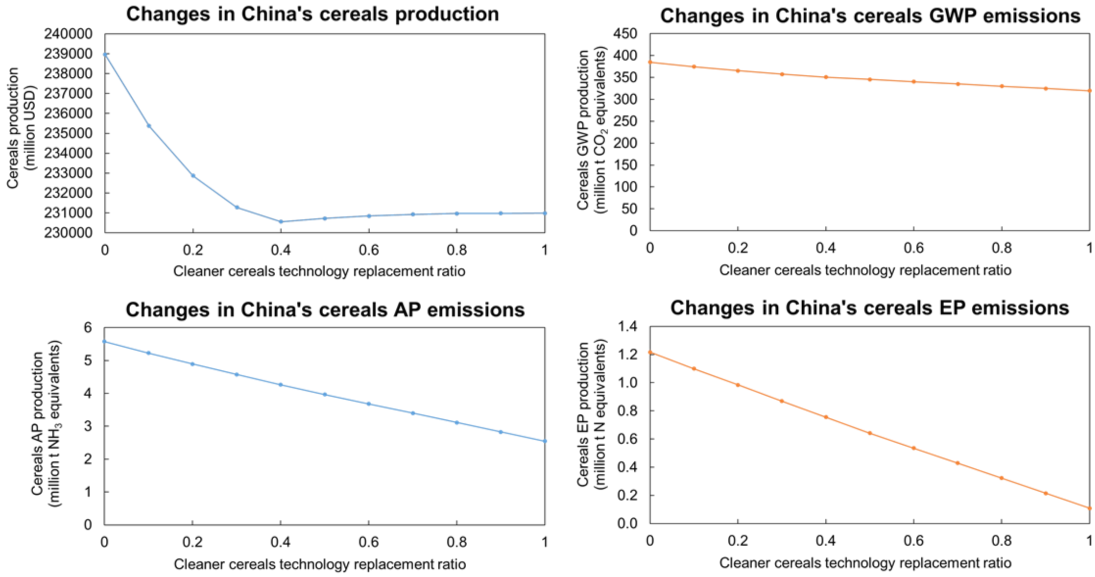

Fig. A9. Changes in China's cereals (a) production (million USD), (b) and emissions of greenhouse gases (Tg CO_2 equivalents), acidification pollutants (Tg NH_3 equivalents), and eutrophication pollutants (Tg N equivalents) under different values of technology replacement ratio for scenario S3. Changes are relative to S1.

Table A1. Conversion factors for global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP).[a]

GWP conversion factors	
1 kg carbon dioxide (CO_2)	1 kg CO_2 equivalents
1 kg methane (CH_4)	25 kg CO_2 equivalents
1 kg nitrous oxide (N_2O)	298 kg CO_2 equivalents
AP conversion factors	
1 kg ammonia (NH_3)	1 kg NH_3 equivalents
1 kg nitrogen oxides (NO_x)	0.37 kg NH_3 equivalents
1 kg sulphur dioxide (SO_2)	0.53 kg NH_3 equivalents
EP conversion factors	
1 kg nitrogen (N)	1 kg N equivalents
1 kg phosphorus (P)	7.28 kg N equivalents

[a] Data source: Goedkoop et al. (2009).

Table A2. A description overview of the scenarios.

Scenarios	Environmental concerns	Expenditure share of SBF in pork-SBF composite	Cereals production technology	Emission bound
S0: Baseline	0% for China, 0% for MTP	25% for China, 82% for MTP	-	-
S1: Differences in environmental concerns of consumers	1% for China, 2% for MTP	25% for China, 82% for MTP	-	-
S2: Dietary structure change	1% for China, 2% for MTP	50% for China, 82% for MTP	-	-
S3: Cleaner cereals production technology	1% for China, 2% for MTP	25% for China, 82% for MTP	50% of China's cereals production technology replaced with MTP's cleaner cereals production technology	-
S4: Combination of dietary structure change and cleaner cereals production technology	1% for China, 2% for MTP	50% for China, 82% for MTP	50% of China's cereals production technology replaced with MTP's cleaner cereals production technology	-
S5: Unilateral environmental policy	1% for China, 2% for MTP	25% for China, 82% for MTP	-	A 3% reduction in total emissions of GHGs, acidification and eutrophication pollutants in China

Table A3. Parameters in China's and its main food and feed trading partners' (MTP) cereals production functions.[a]

	China	MTP
$A_{i,cer}$ (technological parameter)	3.36	3.70
$\xi_{i,man}$ (cost share of manure input)	0.02%	0.04%
$\eta_{1,i,cer}$ (cost share of capital input)	17.81%	38.06%
$\eta_{2,i,cer}$ (cost share of labour input)	48.89%	31.65%
$\eta_{3,i,cer}$ (cost share of land input)	27.44%	23.19%
$\eta_{4,i,cer}$ (cost share of nitrogen fertiliser input)	4.42%	4.30%
$\eta_{5,i,cer}$ (cost share of phosphorus fertiliser input)	1.44%	2.81%

[a] Calculated according to social accounting matrices (SAMs, see Appendix Table B2 & B3).

Table A4. A description overview of the sensitivity analysis.

S1: Differences in environmental concerns of consumers (Environmental concerns)	
Current	1% for China (1%/3 for GWP, 1%/3 for AP, 1%/3 for EP), 2% for MTP (2%/3 for GWP, 2%/3 for AP, 2%/3 for EP)
Sensitivity analysis I	1% for China (1% for GWP, 0% for AP, 0% for EP; 0% for GWP, 1% for AP, 0% for EP; 0% for GWP, 0% for AP, 1% for EP), 2% for MTP (2% for GWP, 0% for AP, 0% for EP; 0% for GWP, 2% for AP, 0% for EP; 0% for GWP, 0% for AP, 2% for EP)
Sensitivity analysis II	2% for China (2%/3 for GWP, 2%/3 for AP, 2%/3 for EP), 2% for MTP (2%/3 for GWP, 2%/3 for AP, 2%/3 for EP)
S5: Unilateral environmental policy (Emission reduction target)	
Current	A 3% reduction in emissions of GHGs, acidification pollutants, and eutrophication pollutants in China
Sensitivity analysis III	A 3% reduction only in emissions of GHGs, acidification pollutants, or eutrophication pollutants separately in China
S2: Dietary structure change (Expenditure share of SBF in pork-SBF composite and substitution elasticity between pork and SBF)	
Current	50% for China, 82% for MTP; 0.5
Sensitivity analysis IV	50% for China, 82% for MTP; a range of values from 0.5 to 1.5
S3: Cleaner cereals production technology (Replacement ratio of cleaner MTP technology)	
Current	50% of China’s cereals production technology replaced with MTP’s cleaner cereals production technology
Sensitivity analysis V	A range of values from 0 to 1

Table A5. Environmental quality indicators related to global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) in China (CN) and its main food and feed trading partners (MTP) when consumers are willing to pay for improving only one type of environmental quality separately in both regions for scenario S1.

		GWP	AP	EP
Scenario 1(S1)	CN	98	79	62
	MTP	110	134	143
Only improving environmental quality related to GWP	CN	98	78	62
	MTP	111	134	141
Only improving environmental quality related to AP	CN	97	79	67
	MTP	111	134	140
Only improving environmental quality related to EP	CN	102	93	63
	MTP	106	114	147

Table A6. Environmental quality indicators related to global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) in China (CN) and its main food and feed trading partners (MTP) under the equal environmental willingness to pay in both regions for scenario S1.

		GWP	AP	EP
Scenario 1(S1)	CN	98	79	62
	MTP	110	134	143
Equal environmental willingness to pay	CN	98	80	68
	MTP	110	134	141

Table A7. Environmental quality indicators related to global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP) in China (CN) and its main food and feed trading partners (MTP) when setting an emission reduction target only for one type of emission separately in China for scenario S5.

		GWP	AP	EP
Scenario 5(S5)	CN	101	83	66
	MTP	109	134	143
Only reducing emissions of greenhouse gases	CN	101	79	58
	MTP	109	134	144
Only reducing emissions of acidification pollutants	CN	98	83	66
	MTP	110	134	143
Only reducing emissions of eutrophication pollutants	CN	98	79	66
	MTP	110	134	141

Appendix B. Sectoral aggregation scheme, social accounting matrices and emissions for all regions

Table B1. Sectoral aggregation scheme.[a]

Aggregated sectors	GTAP original sectors
Cereals	"Paddy rice (pdr)", "Processed rice (pcr)", "Wheat (wht)", and "Cereals grains nec (gro)" sectors
Vegetables & fruits	"Vegetables, fruits, nuts (v_f)" sector
Soybean	Split from "Oil Seeds (osd)" sector
Other crops	"Oil Seeds (osd)" sector after splitting out soybean; "Sugar cane, sugar beet (c_b)", "Plant-based fibers (pfb)", and "Crops nec (ocr)" sectors
Pig	Split from the original "Animal products nec (oap)" and "Meat products nec (omt)" sectors
Poultry	Split from the original "Animal products nec (oap)" and "Meat products nec (omt)" sectors
Other animals	"Animal products nec (oap)" and "Meat products nec (omt)" sectors after splitting out pig and poultry; "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	Split from the original "Food products nec (ofd)" sector
Soy-based food	Split from the original "Food products nec (ofd)" sector
Other food	"Food products nec (ofd)" after splitting out compound feed and soy-based food; "Vegetable oils and fats (vol)", "Sugar (sgr)", and "Beverages and Tobacco products (b_t)" sectors
Nitrogen fertiliser	Split from the original "Manufacture of chemicals and chemical products (chm)" sector
Phosphorous fertiliser	Split from the original "Manufacture of chemicals and chemical products (chm)" sector

Aggregated sectors	GTAP original sectors
Non-food	“Manufacture of chemicals and chemical products (chm)” sector after splitting out nitrogen fertiliser and phosphorous fertiliser; “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)”, “Water (wtr)”, “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 new sectors were compound feed, soy-based food (SBF), nitrogen fertiliser, and phosphorus fertiliser. The compound feed and SBF were split from the “Food products nec (ofd)” sector in the original GTAP database. The substance flow from “Food products nec (ofd)” to pig, poultry, and other animals was compound feed, and the substance flow from soybean to “Food products nec (ofd)” was SBF. The nitrogen and phosphorus fertilisers were taken from the original 'Manufacture of chemicals and chemical products' sector following the method of Sturm (2011) and Bartelings, Kavallari, van Meijl, and Von Lampe (2016). The manure data was derived from FAO (2022). The manure price was derived from the N and P contents of manure, the price of N in urea with 46% N, and the price of P in di-ammonium phosphate (DAP) with 46% P_2O_5 (note, urea and DAP are common N and P fertilisers).

Table B2. The social accounting matrix in the base year of 2014 for China (million $).[a]

	CER	VF	SOY	OTC	PIG	POU	OTA	COF	SBF	OTF	NFE	PFE	NF	CONS	XNET	TOT
CER	0	0	0	0	19072	5147	17048	10596	0	57131	0	0	0	61825	-2016	168804
VF	0	0	0	0	4223	1140	3496	19716	0	106297	0	0	0	165944	-158	300658
SOY	0	0	0	0	69	19	53	1323	7132	0	0	0	0	22	-4519	4099
OTC	0	0	0	0	974	263	899	12033	0	64875	0	0	0	22851	-31592	70303
PIG	0	0	0	0	0	0	0	0	0	0	0	0	0	120537	-2184	118352
POU	0	0	0	0	0	0	0	0	0	0	0	0	0	32527	-589	31938
OTA	0	0	0	0	0	0	0	0	0	0	0	0	0	118902	-1483	117419
COF	0	0	0	0	35906	9689	24012	0	0	0	0	0	0	0	38	69646
SBF	0	0	0	0	0	0	0	0	0	0	0	0	0	39647	25	39672
OTF	0	0	0	0	0	0	0	0	0	0	0	0	0	335613	212	335825
NFE	7462	3529	166	2142	0	0	0	0	0	0	0	0	0	0	-77	13221
PFER	2433	1565	101	624	0	0	0	0	0	0	0	0	0	0	-27	4695
NF	0	0	0	0	0	0	0	0	0	0	0	0	0	2530838	354668	2885506
LAD	46324	90371	1407	23058	13447	3629	16728	0	0	0	0	0	0	-194964	0	0
LAB	82526	165332	1941	35671	32317	8721	40183	12087	15140	50026	4586	1629	1530615	-1980774	0	0
CAP	30060	39861	484	8808	12343	3331	15000	13891	17400	57496	8635	3066	1354891	-1565265	0	0
TRA	0	0	0	0	0	0	0	0	0	0	0	0	0	312298	-312298	0
TOT	168804	300658	4099	70303	118352	31938	117419	69646	39672	335825	13221	4695	2885506	0	0	4160138
MAN	41	20	1.0	12	21	28	142	0	0	0	0	0	0			264

[a] Data source: GTAP (2014). CER=cereals. VF=vegetables & fruits. SOY=soybean. OTC=other crops. PIG=pig. POU=poultry. OTA=other animals. COF=compound feed. SBF=soy-based food. OTF=other food. NFE=nitrogen fertiliser. PFE=phosphorous fertiliser. NF=non-food. CONS=consumption. XNET=net export. TOT=total. LAD=land. LAB=labour. CAP=capital. TRA=trade. MAN=manure.

Table B3. The social accounting matrix in the base year of 2014 for China's main food and feed trading partners (MTP) (million $).[a]

	CER	VF	SOY	OTC	PIG	POU	OTA	COF	SBF	OTF	NFE	PFE	NF	CONS	XNET	TOT
CER	0	0	0	0	1159	2262	35268	4360	0	23594	0	0	0	16597	2016	85256
VF	0	0	0	0	115	284	1514	7258	0	39656	0	0	0	57785	158	106770
SOY	0	0	0	0	13	28	219	4994	27159	0	0	0	0	137	4519	37070
OTC	0	0	0	0	59	88	608	5177	0	28754	0	0	0	13361	31592	79639
PIG	0	0	0	0	0	0	0	0	0	0	0	0	0	27627	2184	29811
POU	0	0	0	0	0	0	0	0	0	0	0	0	0	49389	589	49978
OTA	0	0	0	0	0	0	0	0	0	0	0	0	0	247878	1483	249361
COF	0	0	0	0	13740	21849	51327	0	0	0	0	0	0	0	-38	86878
SBF	0	0	0	0	0	0	0	0	0	0	0	0	0	127149	-25	127124
OTF	0	0	0	0	0	0	0	0	0	0	0	0	0	328815	-212	328603
NFE	3665	164	225	2481	0	0	0	0	0	0	0	0	0	0	77	6612
PFER	2392	107	1451	582	0	0	0	0	0	0	0	0	0	0	27	4559
NF	0	0	0	0	0	0	0	0	0	0	0	0	0	12881812	-354668	12527144
LAD	19769	26073	9137	17903	1639	2877	16832	0	0	0	0	0	0	-94229	0	0
LAB	26982	35565	10881	21351	8712	14351	80106	34118	52243	124333	3117	2182	8465675	-8879616	0	0
CAP	32448	44860	15375	37322	4372	8239	63488	30972	47721	112267	3495	2377	4061470	-4464407	0	0
TRA	0	0	0	0	0	0	0	0	0	0	0	0	0	-312298	312298	0
TOT	85256	106770	37070	79639	29811	49978	249361	86878	127124	328603	6612	4559	12527144	0	0	13718804
MAN	33	1.5	3.4	21	15	21	213	0	0	0	0	0	0			309

[a] Data source: GTAP (2014). CER=cereals. VF=vegetables & fruits. SOY=soybean. OTC=other crops. PIG=pig. POU=poultry. OTA=other animals. COF=compound feed. SBF=soy-based food. OTF=other food. NFE=nitrogen fertiliser. PFE=phosphorous fertiliser. NF=non-food. CONS=consumption. XNET=net export. TOT=total. LAD=land. LAB=labour. CAP=capital. TRA=trade. MAN=manure.

Table B4. 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 (%)
Cereals	272	2.32	118	1.48
Vegetables & fruits	57	0.49	3	0.04
Soybean	3	0.02	4	0.05
Other crops	35	0.30	34	0.43
Pig	56	0.48	44	0.55
Poultry	23	0.20	20	0.25
Other animals	245	2.09	700	8.77
Compound feed	36	0.31	24	0.30
Soy-based food	20	0.17	35	0.44
Other food	173	1.48	88	1.10
Nitrogen fertiliser	324	2.76	80	1.01
Phosphorous fertiliser	25	0.21	9	0.11
Non-food	10477	89.19	6825	85.47
TOTAL	11747	100.00	7985	100.00

[a] Data source: Climate Analysis Indicators Tool (CAIT) (2014). Emissions related to N fertiliser production were allocated to the N fertiliser sector, while emissions related to N fertiliser application were distributed to the crop sectors. The data on N and P fertiliser use by crop types and countries were derived from Ludemann, Gruere, Heffer, and Dobermann (2022). Manure data by animals can be derived from FAO (2022). The allocation of manure for each crop is assumed to be consistent with the allocation of N fertiliser for each crop. We allocated the emissions in the base year by the economic values of the sectors when sector-level emission data were unavailable.

Table B5. 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 (%)
Cereals	3.94	11.71	0.94	6.77
Vegetables & fruits	1.89	5.63	0.05	0.38
Soybean	0.09	0.28	0.06	0.40
Other crops	1.14	3.41	0.54	3.86
Pig	3.63	10.79	1.11	7.99
Poultry	1.59	4.74	1.77	12.71
Other animals	2.21	6.58	1.05	7.56
Compound feed	0.06	0.19	0.03	0.20
Soy-based food	0.04	0.11	0.04	0.30
Other food	0.30	0.89	0.11	0.76
Nitrogen fertiliser	0.0009	0.003	0.0034	0.025
Phosphorous fertiliser	0.0007	0.002	0.0029	0.021
Non-food	18.71	55.67	8.21	59.03
TOTAL	33.61	100.00	13.92	100.00

[a] Data source: Liu et al. (2022), Huang et al. (2017), and Dahiya et al. (2020).

Table B6. 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 (%)
Cereals	0.86	8.71	0.04	0.73
Vegetables & fruits	1.00	10.08	0.07	1.21
Soybean	0.02	0.19	0.01	0.26
Other crops	0.65	6.54	0.32	5.78
Pig	0.10	1.02	0.02	0.34
Poultry	0.17	1.72	0.06	1.12
Other animals	1.94	19.60	2.32	41.30
Compound feed	0.25	2.53	0.11	1.94
Soy-based food	0.14	1.44	0.16	2.87
Other food	1.21	12.19	0.40	7.20
Nitrogen fertiliser	0.0002	0.002	0.0007	0.012
Phosphorous fertiliser	0.0002	0.002	0.0009	0.015
Non-food	3.57	35.96	2.09	37.21
TOTAL	**9.92**	100.00	**5.61**	100.00

[a] Data source: Hamilton et al. (2018).

Table B7. Emission intensities of greenhouse gases (t CO_2 equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereals	1614	1386
Vegetables & fruits	191	33
Soybean	674	106
Other crops	496	433
Pig	472	1473
Poultry	733	397
Other animals	2084	2806
Compound feed	517	274
Soy-based food	517	278
Other food	517	267
Nitrogen fertiliser	24513	12143
Phosphorous fertiliser	5223	1987
Non-food	3631	545

[a] Data source: Calculated by our study.

Table B8. Emission intensities of acidification pollutants (t NH_3 equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereals	23.3	11.1
Vegetables & fruits	6.3	0.5
Soybean	23.1	1.5
Other crops	16.3	6.7
Pig	30.6	37.3
Poultry	49.8	35.4
Other animals	18.8	4.2
Compound feed	0.9	0.3
Soy-based food	0.9	0.3
Other food	0.9	0.3
Nitrogen fertiliser	0.1	0.5
Phosphorous fertiliser	0.1	0.6
Non-food	6.5	0.7

[a] Data source: Calculated by our study.

Table B9. Emission intensities of eutrophication pollutants (t N equivalents million USD^{-1}) in China (CN) and its main food and feed trading partners (MTP).[a]

	CN	MTP
Cereals	5.12	0.48
Vegetables & fruits	3.32	0.64
Soybean	4.66	0.40
Other crops	9.23	4.07
Pig	0.85	0.64
Poultry	5.34	1.26
Other animals	16.53	9.29
Compound feed	3.60	1.26
Soy-based food	3.60	1.27
Other food	3.60	1.23
Nitrogen fertiliser	0.02	0.10
Phosphorous fertiliser	0.05	0.19
Non-food	1.24	0.17

[a] Data source: Calculated by our study.

References

Bartelings, H., Kavallari, A., van Meijl, H., & Von Lampe, M. (2016). *Estimating the impact of fertilizer support policies: A CGE approach*. Paper presented at the 19th Annual Conference on Global Economic Analysis.

Climate Analysis Indicators Tool (CAIT). (2014). Retrieved from https://www.climatewatchdata.org/?source=cait

Dahiya, S., Anhäuser, A., Farrow, A., Thieriot, H., Kumar, A., & Myllyvirta, L. (2020). Ranking the World's Sulfur Dioxide (SO2) Hotspots: 2019–2020. *Delhi Center for Research on Energy and Clean Air-Greenpeace India: Chennai, India, 48*.

Deardorff, A. V. (1982). The general validity of the Heckscher-Ohlin theorem. *The American Economic Review, 72*(4), 683-694.

FAO. (2022). Retrieved from http://www.fao.org/faostat/en/#data

Ginsburgh, V., & Keyzer, M. A. (2002). *The Structure of Applied General Equilibrium Models*. Cambridge, MA: The MIT Press.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Van Zelm, R. (2009). *ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level*. Retrieved from

GTAP. (2014). GTAP version 10 Database. Retrieved from http://www.gtap.agecon.purdue.edu/

Hamilton, H. A., Ivanova, D., Stadler, K., Merciai, S., Schmidt, J., Van Zelm, R., . . . Wood, R. (2018). Trade and the role of non-food commodities for global eutrophication. *Nature Sustainability, 1*(6), 314-321.

Huang, T., Zhu, X., Zhong, Q., Yun, X., Meng, W., Li, B., . . . Tao, S. (2017). Spatial and Temporal Trends in Global Emissions of Nitrogen Oxides from 1960 to 2014. *Environmental Science & Technology, 51*(14), 7992-8000. doi:10.1021/acs.est.7b02235

Liu, L., Xu, W., Lu, X., Zhong, B., Guo, Y., Lu, X., . . . Vitousek, P. (2022). Exploring global changes in agricultural ammonia emissions and their contribution to nitrogen deposition since 1980. *Proceedings of the National Academy of Sciences, 119*(14), e2121998119. doi:doi:10.1073/pnas.2121998119

Ludemann, C. I., Gruere, A., Heffer, P., & Dobermann, A. (2022). Global data on fertilizer use by crop and by country. *Scientific data, 9*(1), 501. doi:10.1038/s41597-022-01592-z

McLure Jr, C. E. (1975). General equilibrium incidence analysis: The Harberger model after ten years. *Journal of Public Economics, 4*(2), 125-161.

Shoven, J. B., & Whalley, J. (1992). *Applying general equilibrium*: Cambridge university press.

Sturm, V. (2011). *Taking into account the emissions from the production and use of mineral fertilizers by imposing a 'carbon tax'*. Paper presented at the 14th Annual Conference on Global Economic Analysis.

Van Ierland, E. C. (1993). *Macroeconomic analysis of environmental policy.* (Ph.D. Thesis). Wageningen University & Research,

Zhu, X. (2004). *Environmental-Economic Modelling of Novel Protein Foods: A General Equilibrium Approach.* (Ph.D. thesis). Wageningen University,

Zhu, X., & Van Ierland, E. (2006). The enlargement of the European Union: Effects on trade and emissions of greenhouse gases. *Ecological Economics, 57*(1), 1-14. doi:https://dx.doi.org/10.1016/j.ecolecon.2005.03.030

Zhu, X., & Van Ierland, E. C. (2005). A model for consumers' preferences for Novel Protein Foods and environmental quality. *Economic Modelling, 22*(4), 720-744.