Phosphorus utilization efficiency and status of phosphorus reuse in China from 1990 to 2019

Contents

Contents 1
1. Chinese phosphorus cycle model 2
2. Calculation of pollutant emissions from aquaculture. 15
3. P resource efficiency 16
4. The proportion of countries importing and exporting Chinese phosphate chemical products 18
5. Uncertainty analysis 19

1. Chinese phosphorus cycle model

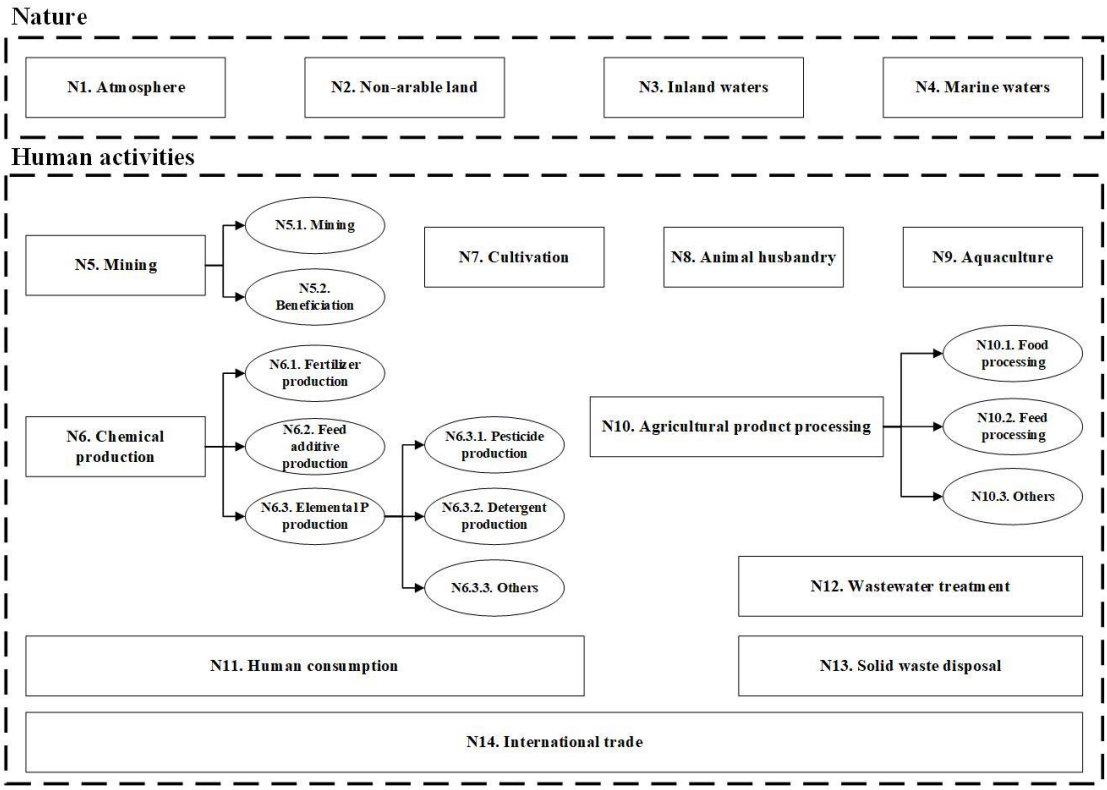

Figure S1. Chinese phosphorus cycle model framework.

This study was based on the China Phosphorus Cycle Model developed by Liu et al., (2016) which was divided into two parts: natural activities and human activities, with a total of fourteen modules. The natural cycle includes the atmosphere (N1), non-arable land (N2), inland water systems (N3), and marine systems (N4); human activities include mining (N5), chemical production (N6), cultivation (N7), animal husbandry (N8), aquaculture (N9), agricultural product processing (N10), human consumption (N11), wastewater treatment (N12), solid waste disposal (N13), and international trade (N14). The detailed contents of each module are shown in Figure S1. The model follows the law of conservation of mass and is based on the MFA method: inflow = outflow + inventory change. All phosphorus flow calculation formulas are divided into three categories: 1) the independent calculation, which is derived by multiplying activity data with relevant coefficients; 2) the non-independent calculation, which is derived by deduction of other phosphorus flow results; 3) the system balance, which is deduced by known phosphorus flow in the system. All activity data and explanations are given in Table S1, and all parameter data and explanations are given in Table S2.

1. Atmosphere

$$O_1 = O_{1-2}^{AD} + O_{1-3}^{AD} + O_{1-4}^{AD} + O_{1-7}^{AD} \quad (\text{Equation S. } 1-1.)$$

Where

$$O_{1-2}^{AD} = (D^{TA} - D^{IW} - D^{AL}) \times P_1^{AD} \quad (\text{Equation S. } 1-2.)$$

$$O_{1-3}^{AD} = D^{IW} \times P_1^{AD} \quad (\text{Equation S. } 1-3.)$$

$$O_{1-4}^{AD} = D^{MW} \times P_2^{AD} \quad (\text{Equation S. } 1-4.)$$

$$O_{1-7}^{AD} = D^{AL} \times P_1^{AD} \quad (\text{Equation S. } 1-5.)$$

2. Non-arable land

$$O_2 = O_{2-1}^{WE} + O_{2-3}^{RL} + O_{2-5}^{PO} + O_{2-2}^{WT} + O_{2-7}^{WT} + O_{2-8}^{PS} + O_{2-10}^{WD} \quad (\text{Equation S. } 2-1)$$

Where

$$O_{2-1}^{WE} = (D^{TA} - D^{IW} - D^{AL}) \times P^{WE} \quad (\text{Equation S. } 2-2)$$

$$O_{2-3}^{RL} = (D^{TA} - D^{IW} - D^{AL}) \times P^{RL} \quad (\text{Equation S. } 2-3)$$

$$O_{2-5}^{PO} = BalancingN_5 \quad (\text{Equation S. } 2-4)$$

$$O_{2-2}^{WT} = (D^{TA} - D^{IW} - D^{AL}) \times P^{WT} \quad (\text{Equation S. } 2-5)$$

$$O_{2-7}^{WT} = D^{AL} \times P^{WT} \quad (\text{Equation S. } 2-6)$$

$$O_{2-8}^{PS} = BalancingN_8(herbivores) \quad (\text{Equation S. } 2-7)$$

$$O_{2-10}^{WD} = D^{WD} \times P_1^{WD} \times P_2^{WD} \quad (\text{Equation S. } 2-8)$$

3.Inland waters

$$O_3 = O_{3-4}^{RT} + O_{3-10}^{NFW} \quad (\text{Equation S. } 3-1)$$

Where

$$O_{3-4}^{RT} = \begin{pmatrix} O_{1-3}^{AD} + O_{2-3}^{RL} + O_{5.2-3}^{WW,nt} + O_{6.1-3}^{WW,nt} + O_{6.2-3}^{WW,nt} + O_{6.3-3}^{WW,nt} + O_{6.3.1-3}^{WW,nt} \\ + O_{6.3.2-3}^{WW,nt} + O_{7-3}^{RF} + O_{7-3}^{LH} + O_{8-3}^{AE,nu} + O_{9-3}^{NL} + O_{10.1-3}^{WW,nt} + O_{11-3}^{WW,nt} + O_{12-3}^{EF} \end{pmatrix} \times P^{RT} \quad (\text{Equation S. } 3-2)$$

$$O_{3-10}^{NFW} = D^{NFW} \times P^{FW} \quad \text{(Equation S. 3 - 3)}$$

4.Marine waters

$$O_4 = O_{4-1}^{SS} + O_{4-10}^{NSW} \quad \text{(Equation S. 4 - 1)}$$

Where

$$O_{4-1}^{SS} = \frac{D^{MW}}{D^{GMW}} \times P^{SS} \quad \text{(Equation S. 4 - 2)}$$

$$O_{4-10}^{NSW} = D^{NSW} \times P^{SW} \quad \text{(Equation S. 4 - 3)}$$

5.Mining

$$O_{5.1} = O_{5.1-14}^{PR} + O_{5.1-5.2}^{PR} + O_{5.1-6}^{PR} + O_{5.1-2}^{GG} \quad \text{(Equation S. 5.1 - 1)}$$

Where

$$O_{5.1-14}^{PR} = D^{PR,ne} \times P^{PR} \quad \text{(Equation S. 5.1 - 2)}$$

$$O_{5.1-5.2}^{PR} = (D^{PR} - D^{PR,ne}) \times P^{PR} \times P^{BF} \quad \text{(Equation S. 5.1 - 3)}$$

$$O_{5.1-6}^{PR} = \left(D^{PR} - D^{PR,ne}\right) \times P^{PR} \times \left(1 - P^{BF}\right) \quad \text{(Equation S. 5.1 - 4)}$$

$$O_{5.1-2}^{GG} = D^{PR} \times P_1^{GG} \times P_2^{GG} \quad \text{(Equation S. 5.1 - 5)}$$

5.2. Beneficiation

$$O_{5.2} = O_{5.2-6}^{PR} + O_{5.2-2}^{TL} + O_{5.2-3}^{WW,nt} + O_{5.2-12}^{WW,ft} \quad \text{(Equation S. 5.2 - 1)}$$

Where

$$O_{5.2-6}^{PR} = O_{5.1-5.2}^{PR} \times P^{CR} \quad \text{(Equation S. 5.2 - 2)}$$

$$O_{5.2-3}^{WW,nt} = \frac{142}{62 \times 30\%} \times O_{5.2-6}^{PR} \times P_1^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 5.2 - 3)}$$

$$O_{5.2-12}^{WW,ft} = \frac{142}{62 \times 30\%} \times O_{5.2-6}^{PR} \times P_1^{WWG} \times P^{WW} \quad \text{(Equation S. 5.2 - 4)}$$

$$O_{5.2-2}^{TL} = BalancingN_{5.2} \quad \text{(Equation S. 5.2 - 5)}$$

6. Chemical production

6.1. Fertilizer production

$$O_{6.1} = O_{6.1-14}^{FT} + O_{6.1-7}^{FT} + O_{6.1-3}^{WW,nt} + O_{6.1-12}^{WW,ft} + O_{6.1-2}^{PG} + O_{6.1-6.3.3}^{PG} \quad \text{(Equation S. 6.1 − 1)}$$

Where

$$O_{6.1-14}^{FT} = D^{FT,ne} \times P^{FT} \times \frac{62}{142} \quad \text{(Equation S. 6.1 − 2)}$$

$$O_{6.1-7}^{FT} = D^{FT} \times \frac{62}{142} - D^{FT,ne} \times P^{FT} \times \frac{62}{142} \quad \text{(Equation S. 6.1 − 3)}$$

$$O_{6.1-3}^{WW,nt} = D^{FT} \times \frac{P^{HFT}}{P^{FT}} \times P_2^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 6.1 − 4)}$$

$$O_{6.1-12}^{WW,ft} = D^{FT} \times \frac{P^{HFT}}{P^{FT}} \times P_2^{WWG} \times P^{WW} \quad \text{(Equation S. 6.1 − 5)}$$

$$O_{6.1-2}^{PG} = D^{FT} \times \frac{P^{HFT}}{P^{FT}} \times P_1^{PG} \times P_2^{PG} \times \frac{62}{142} \times (1 - P_3^{PG}) \quad \text{(Equation S. 6.1 − 6)}$$

$$O_{6.1-6.3.3}^{PG} = D^{FT} \times \frac{P^{HFT}}{P^{FT}} \times P_1^{PG} \times P_2^{PG} \times \frac{62}{142} \times P_3^{PG} \quad \text{(Equation S. 6.1 − 7)}$$

6.2. Feed additive production

$$O_{6.2} = O_{6.2-14}^{FA} + O_{6.2-10.2}^{FA} + O_{6.2-3}^{WW,nt} + O_{6.2-12}^{WW,ft} + O_{6.2-2}^{SW} \quad \text{(Equation S. 6.2 − 1)}$$

Where

$$O_{6.2-14}^{FA} = D^{FA,ne} \times P^{FA} \quad \text{(Equation S. 6.2 − 2)}$$

$$O_{6.2-10.2}^{FA} = (D^{FA} - D^{FA,ne}) \times P^{FA} \quad \text{(Equation S. 6.2 − 3)}$$

$$O_{6.2-3}^{WW,nt} = D^{FA} \times P_3^{WWG} \times P^{FAWW} \times \frac{62}{142} \times (1 - P^{WW}) \quad \text{(Equation S. 6.2 − 4)}$$

$$O_{6.2-12}^{WW,ft} = D^{FA} \times P_3^{WWG} \times P^{FAWW} \times \frac{62}{142} \times P^{WW} \quad \text{(Equation S. 6.2 − 5)}$$

$$O_{6.2-2}^{SW} = D^{FA} \times P^{SWG} \times P^{FASW} \times \frac{62}{142} \quad \text{(Equation S. 6.2 − 6)}$$

6.3. Elemental P production

$$O_{6.3} = O_{6.3-14}^{EP} + O_{6.3-6.3.1}^{EP} + O_{6.3-6.3.2}^{EP} + O_{6.3-6.3.3}^{EP} + O_{6.3-3}^{WW,nt} + O_{6.3-12}^{WW,ft} + O_{6.3-6.3.3}^{FP} + O_{6.3-6.3.3}^{SL} + O_{6.3-2}^{SL} \quad \text{(Equation S. 6.3 − 1)}$$

Where

$$O_{6.3-14}^{EP} = D^{EP,ne} \quad \text{(Equation S. 6.3 − 2)}$$

$$O_{6.3-6.3.1}^{EP} = BalancingN_{6.3.1} \quad \text{(Equation S. 6.3 − 3)}$$

$$O_{6.3-6.3.2}^{EP} = BalancingN_{6.3.2} \quad \text{(Equation S. 6.3 − 4)}$$

$$O_{6.3-6.3.3}^{EP} = D^{EP} - O_{6.3-14}^{EP} - O_{6.3-6.3.1}^{EP} - O_{6.3-6.3.2}^{EP} \quad \text{(Equation S. 6.3 − 5)}$$

$$O_{6.3-3}^{WW,nt} = D^{EP} \times P_4^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 6.3 − 6)}$$

$$O_{6.3-12}^{WW,ft} = D^{EP} \times P_4^{WWG} \times P^{WW} \quad \text{(Equation S. 6.3 − 7)}$$

$$O_{6.3-6.3.3}^{FP} = D^{EP} \times P_1^{FP} \times P_2^{FP} \quad \text{(Equation S. 6.3 − 8)}$$

$$O_{6.3-6.3.3}^{SL} = D^{EP} \times P_1^{SL} \times P_2^{SL} \times \frac{62}{142} \times P_3^{SL} \quad \text{(Equation S. 6.3 − 9)}$$

$$O_{6.3-2}^{SL} = D^{EP} \times P_1^{SL} \times P_2^{SL} \times \frac{62}{142} \times (1 - P_3^{SL}) \quad \text{(Equation S. 6.3 − 10)}$$

6.3.1. Pesticide production

$$O_{6.3.1} = O_{6.3.1-14}^{OP} + O_{6.3.1-7}^{OP} + O_{6.3.1-3}^{WW,nt} + O_{6.3.1-12}^{WW,ft} \quad \text{(Equation S. 6.3.1 − 1)}$$

Where

$$O_{6.3.1-14}^{OP} = D^{P,ne} \times P_1^{OP} \times P_2^{OP} \quad \text{(Equation S. 6.3.1 − 2)}$$

$$O_{6.3.1-7}^{OP} = (D^{P} - D^{P,ne}) \times P_1^{OP} \times P_2^{OP} \quad \text{(Equation S. 6.3.1 − 3)}$$

$$O_{6.3.1-3}^{WW,nt} = D^{P} \times P_1^{OP} \times P_5^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 6.3.1 − 4)}$$

$$O_{6.3.1-12}^{WW,ft} = D^{P} \times P_1^{OP} \times P_5^{WWG} \times P^{WW} \quad \text{(Equation S. 6.3.1 − 5)}$$

6.3.2. Detergent production

$$O_{6.3.2} = O_{6.3.2-14}^{DG} + O_{6.3.2-11}^{DG} + O_{6.3.2-3}^{WW,nt} + O_{6.3.2-12}^{WW,ft} \quad \text{(Equation S. 6.3.2 − 1)}$$

Where

$$O_{6.3.2-14}^{DG} = D^{DG,ne} \times P_1^{DG} \times P_2^{DG} + D^{DG,ne} \times (1 - P_1^{DG}) \times P_3^{DG} \quad \text{(Equation S. 6.3.2 − 1)}$$

$$O_{6.3.2-11}^{DG} = (D^{DG} - D^{DG,ne}) \times P_1^{DG} \times P_2^{DG} + (D^{DG} - D^{DG,ne}) \times (1 - P_1^{DG}) \times P_3^{DG} \quad \text{(Equation S. 6.3.2 − 1)}$$

$$O_{6.3.2-3}^{WW,nt} = D^{DG} \times P_6^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 6.3.2 − 1)}$$

$$O_{6.3.2-12}^{WW,ft} = D^{DG} \times P_6^{WWG} \times P^{WW} \quad \text{(Equation S. 6.3.2 − 1)}$$

7.Cultivation

$$0_7 = 0_{7-14}^{RC} + 0_{7-7}^{RC,sd} + 0_{7-10}^{RC} + 0_{7-7}^{CS,ru} + 0_{7-10}^{CS,fd} + 0_{7-11}^{CS,fl} + 0_{7-2}^{CS,nu} + 0_{7-1}^{WE} + 0_{7-3}^{RF} + 0_{7-3}^{LH} + \Delta S_7^{SD} \quad \text{(Equation S. 7 − 1)}$$

Where

$$0_{7-14}^{RC} = \mathrm{D}^{RC,ne} \times \mathrm{P}^{RC} \quad \text{(Equation S. 7 − 2)}$$

$$0_{7-7}^{RC,sd} = \mathrm{D}^{SA} \times \mathrm{P}^{SD} \times \mathrm{P}^{RC} \quad \text{(Equation S. 7 − 3)}$$

$$0_{7-10}^{RC} = \mathrm{D}^{RC} \times \mathrm{P}^{RC} - D^{SA} \times \mathrm{P}^{SD} \times \mathrm{P}^{RC} - D^{RC,ne} \times \mathrm{P}^{RC} \quad \text{(Equation S. 7 − 4)}$$

$$0_{7-7}^{CS,ru} = \mathrm{D}^{RC} \times P_1^{CS} \times P_2^{CS} \times P_3^{CS} \quad \text{(Equation S. 7 − 5)}$$

$$0_{7-10}^{CS,fd} = \mathrm{D}^{RC} \times P_1^{CS} \times P_2^{CS} \times P_4^{CS} \quad \text{(Equation S. 7 − 6)}$$

$$0_{7-11}^{CS,fl} = \mathrm{D}^{RC} \times P_1^{CS} \times P_2^{CS} \times P_5^{CS} \quad \text{(Equation S. 7 − 7)}$$

$$0_{7-2}^{CS,nu} = \mathrm{D}^{RC} \times P_1^{CS} \times P_2^{CS} \times P_6^{CS} \quad \text{(Equation S. 7 − 8)}$$

$$0_{7-1}^{WE} = \mathrm{D}^{AL} \times \mathrm{P}^{WE} \quad \text{(Equation S. 7 − 9)}$$

$$0_{7-3}^{RF} = \mathrm{D}^{AL} \times \mathrm{P}^{RF} \quad \text{(Equation S. 7 − 10)}$$

$$0_{7-3}^{LH} = \mathrm{D}^{AL} \times \mathrm{P}^{LH} \quad \text{(Equation S. 7 − 11)}$$

$$\Delta S_7^{SD} = BalancingN_7 \quad \text{(Equation S. 7 − 12)}$$

8.Animal husbandry

$$0_8 = 0_{8-14}^{LA} + 0_{8-10}^{LA} + 0_{8-10}^{DE} + 0_{8-7}^{AE,ru} + 0_{8-3}^{AE,nu} + 0_{8-2}^{AE,nu} + \Delta S_8^{LA} \quad \text{(Equation S. 8 − 1)}$$

Where

$$0_{8-14}^{LA} = \mathrm{D}^{LA,ne} \times \mathrm{P}^{LA} \quad \text{(Equation S. 8 − 2)}$$

$$0_{8-10}^{LA} = (\mathrm{D}^{LA} - \mathrm{D}^{LA,ne}) \times \mathrm{P}^{LA} \quad \text{(Equation S. 8 − 3)}$$

$$0_{8-10}^{DE} = \mathrm{D}^{DR} \times \mathrm{P}^{DR} + D^{EG} \times \mathrm{P}^{EG} \quad \text{(Equation S. 8 − 4)}$$

$$0_{8-7}^{AE,ru} = \mathrm{D}^{DLA} \times P_1^{AE} \times P_2^{AE} \quad \text{(Equation S. 8 − 5)}$$

$$0_{8-3}^{AE,nu} = \mathrm{D}^{DLA} \times P_1^{AE} \times P_3^{AE} \quad \text{(Equation S. 8 − 6)}$$

$$0_{8-2}^{AE,nu} = \mathrm{D}^{DLA} \times P_1^{AE} \times P_4^{AE} \quad \text{(Equation S. 8 − 7)}$$

$$\Delta S_8^{LA} = \Delta \mathrm{D}^{LA} \times \mathrm{P}^{LA} \quad \text{(Equation S. 8 − 8)}$$

9.Aquaculture

$$O_9 = O_{9-14}^{CW} + O_{9-10}^{CW} + O_{9-3}^{NL} + O_{9-4}^{NL} \quad \text{(Equation S. 9 − 1)}$$

Where

$$O_{9-14}^{CW} = D^{CW,ne} \times P^{FW} \quad \text{(Equation S. 9 − 2)}$$

$$O_{9-10}^{CW} = D^{CFW} \times P^{FW} + D^{CSW} \times P^{SW} - D^{CW,ne} \times P^{FW} \quad \text{(Equation S. 9 − 3)}$$

O_{9-3}^{NL} = Refer to Part Two: Calculation of pollutant emissions from aquaculture (Equation S. 9 − 4)

O_{9-4}^{NL} = Refer to Part Two: Calculation of pollutant emissions from aquaculture (Equation S. 9 − 5)

10.Agricultural product processing

10.1. Food processing

$$O_{10.1} = O_{10.1-14}^{PF} + O_{10.1-11}^{PF} + O_{10.1-10.2}^{PF} + O_{10.1-7}^{BP} + O_{10.1-10.2}^{BP} + O_{10.1-10.3}^{BP} + O_{10.1-3}^{WW,nt} + O_{10.1-12}^{WW,ft} + O_{10.1-13}^{SW} \quad \text{(Equation S. 10.1 − 1)}$$

Where

$$O_{10.1-14}^{PF} = (D^{RI,ne} + D^{FL,ne}) \times P^{RC} + D^{PO,ne} \times P_1^{PO} + D^{SU,ne} \times P^{SU} + D^{MT,ne} \times P_1^{MT} + D^{DR,ne} \times P^{DR} + D^{EG,ne} \times P^{EG} \quad \text{(Equation S. 10.1 − 2)}$$

$$O_{10.1-11}^{PF} = O_{10.1-11}^{PF,grains} + O_{10.1-11}^{PF,oil} + O_{10.1-11}^{PF,oil\ crops} + O_{10.1-11}^{PF,sugar} + O_{10.1-11}^{PF,meat} + O_{10.1-11}^{PF,dairy\ and\ egg} + O_{10.1-11}^{PF,other} \quad \text{(Equation S. 10.1 − 3)}$$

$$O_{10.1-11}^{PF,grains} = O_{7-10}^{RC,rice} \times P_1^{RI} + O_{7-10}^{RC,wheat} \times P_1^{WH} + O_{7-10}^{RC,maize} + O_{7-10}^{RC,millet} + O_{7-10}^{RC,sorghum} + O_{7-10}^{RC,tubers} + O_{7-10}^{RC,beans} \times (1 - P_2^{PO}) - (D^{RI,ne} + D^{FL,ne}) \times P^{RC} - O_{10.1-10.2}^{PF,grains} \quad \text{(Equation S. 10 − 4)}$$

$$O_{10.1-11}^{PF,oil} = \frac{O_{7-10}^{RC,oil\ crops}}{P^{RC}} \times P_1^{PO} \times P_2^{PO} \times P_3^{PO} - D^{PO,ne} \times P_1^{PO} \quad \text{(Equation S. 10.1 − 5)}$$

$$O_{10.1-11}^{PF,oil\ crops} = O_{7-10}^{RC,oil\ crops} \times (1 - P_2^{PO}) \quad \text{(Equation S. 10.1 − 6)}$$

$$O_{10.1-11}^{PF,sugar} = (D^{SU} - D^{SU,ne}) \times P^{SU} \quad \text{(Equation S. 10.1 − 7)}$$

$$O_{10.1-11}^{PF,meat} = D^{MT} \times (1 - P_2^{MT}) \times P_1^{MT} - D^{MT,ne} \times P_1^{MT} \quad \text{(Equation S. 10.1 − 8)}$$

$$O_{10.1-11}^{PF,dairy\ and\ egg} = O_{8-10}^{DE} - D^{DE,ne} \times P^{DR} - D^{EG,ne} \times P^{EG} \quad \text{(Equation S. 10.1 − 9)}$$

$$O_{10.1-11}^{PF,other} = O_{7-10}^{RC,vegetable} + O_{3-10}^{NFW} + O_{4-10}^{NSW} + O_{9-10}^{CW} \quad \text{(Equation S. 10.1 − 10)}$$

$$O_{10.1-10.2}^{PF,grains} = BalancingN_{10.2} \quad \text{(Equation S. 10.1 − 11)}$$

$$O_{10.1-7}^{BP} = O_{7-10}^{RC,rice} \times P_2^{RI} \quad \text{(Equation S. 10.1 − 12)}$$

$$O_{10.1-10.2}^{BP} = O_{10.1-10.2}^{BP,rice\ bran} + O_{10.1-10.2}^{BP,wheat\ bran} + O_{10.1-10.2}^{BP,oil\ meal} + O_{10.1-10.2}^{BP,bone} \quad \text{(Equation S. 10.1 − 13)}$$

$$O_{10.1-10.2}^{BP,rice\ bran} = O_{7-10}^{RC,rice} \times P_3^{RI} \quad \text{(Equation S. 10.1 − 14)}$$

$$O_{10.1-10.2}^{BP,wheat\ bran} = O_{7-10}^{RC,wheat} \times (1 - P_1^{WH}) \quad \text{(Equation S. 10.1 − 15)}$$

$$O_{10.1-10.2}^{BP,oil\ meal} = O_{7-10}^{RC,oil\ crops} \times P_2^{PO} - \frac{O_{7-10}^{RC,oil\ crops}}{P^{RC}} \times P_1^{PO} \times P_2^{PO} \times P_3^{PO} - \frac{O_{7-10}^{RC,oil\ crops}}{P^{RC}} \times P_2^{PO} \times P_7^{WWG} \quad \text{(Equation S. 10.1 − 16)}$$

$$O_{10.1-10.2}^{BP,bone} = O_{8-10}^{LA} \times P_3^{MT} - D^{MT} \times (1 - P_2^{MT}) \times P_1^{MT} \quad \text{(Equation S. 10.1 − 17)}$$

$$O_{10.1-10.3}^{BP} = O_{7-10}^{RC,sugarcane} + O_{7-10}^{RC,sugar\ beet} - D^{SU} \times P^{SU} \quad \text{(Equation S. 10.1 − 18)}$$

$$O_{10.1-3}^{WW,nt} = O_{10.1-3}^{WW,oil} + O_{10.1-3}^{WW,meat} \quad \text{(Equation S. 10.1 − 19)}$$

$$O_{10.1-3}^{WW,oil} = \frac{O_{7-10}^{RC,oil\ crops}}{P^{RC}} \times P_2^{PO} \times P_7^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 10.1 − 20)}$$

$$O_{10.1-3}^{WW,meat} = (D^{LA} - D^{LA,ne}) \times P_8^{WWG} \times (1 - P^{WW}) \quad \text{(Equation S. 10.1 − 21)}$$

$$O_{10.1-12}^{WW,ft} = O_{10.1-12}^{WW,oil} + O_{10.1-12}^{WW,meat} \quad \text{(Equation S. 10.1 − 22)}$$

$$O_{10.1-12}^{WW,oil} = \frac{O_{7-10}^{RC,oil\ crops}}{P^{RC}} \times P_2^{PO} \times P_7^{WWG} \times P^{WW} \quad \text{(Equation S. 10.1 − 23)}$$

$$O_{10.1-12}^{WW,meat} = (D^{LA} - D^{LA,ne}) \times P_8^{WWG} \times P^{WW} \quad \text{(Equation S. 10.1 − 24)}$$

$$O_{10.1-13}^{SW} = O_{8-10}^{LA} \times (1 - P_3^{MT}) - (D^{LA} - D^{LA,ne}) \times P_8^{WWG} \quad \text{(Equation S. 10.1 − 25)}$$

10.2. Feed processing

$$O_{10.2} = O_{10.2-14}^{AF} + O_{10.2-9}^{AF} + O_{10.2-8}^{AF} \quad \text{(Equation S. 10.2 − 1)}$$

Where

$$O_{10.2-14}^{AF} = D^{AF,ne} \times P^{AF} \quad \text{(Equation S. 10.2 − 2)}$$

$$O_{10.2-9}^{AF} = D^{CFW} \times P_1^{FF} \times P_2^{FF} + D^{CSW} \times P_1^{SF} \times P_2^{SF} \quad \text{(Equation S. 10.2 − 3)}$$

$$O_{10.2-8}^{AF} = BalancingN_8(excluding\ herbivores) \quad \text{(Equation S. 10.2 − 4)}$$

10.3. Others

$$O_{10.3} = O_{10.3-11}^{NF} \quad \text{(Equation S. 10.3 − 1)}$$

Where

$$O_{10.3-11}^{NF} = O_{7-10}^{RC,cotton\ fiber} + O_{7-10}^{RC,bast} + O_{7-10}^{RC,tobacco} + O_{2-10}^{WD} + O_{10.1-10.3}^{BP} \quad \text{(Equation S. 10.3 − 2)}$$

11. Human consumption

$$O_{11} = O_{11-7}^{HE} + O_{11-2}^{HE} + O_{11-3}^{HE} + O_{11-12}^{HE} + O_{11-2}^{SW} + O_{11-13}^{SW} + O_{11-3}^{WW,nt} + O_{11-12}^{WW,ft} + \Delta S_{11}^{HM} \quad \text{(Equation S. 11 − 1)}$$

Where

$$\mathrm{O}_{11-7}^{HE} = \mathrm{D}^{UHM} \times P_1^{UHE} \times P_2^{UHE} + D^{RHM} \times P_1^{RHE} \times P_2^{RHE} \quad \text{(Equation S. 11 − 2)}$$

$$\mathrm{O}_{11-2}^{HE} = \mathrm{D}^{RHM} \times P_1^{RHE} \times (1 - P_2^{RHE}) \quad \text{(Equation S. 11 − 3)}$$

$$\mathrm{O}_{11-3}^{HE} = \mathrm{D}^{UHM} \times P_1^{UHE} \times (1 - P_2^{UHE}) \times P_3^{UHE} \quad \text{(Equation S. 11 − 4)}$$

$$\mathrm{O}_{11-12}^{HE} = \mathrm{D}^{UHM} \times P_1^{UHE} \times (1 - P_2^{UHE}) \times (1 - P_3^{UHE}) \quad \text{(Equation S. 11 − 5)}$$

$$\mathrm{O}_{11-2}^{SW} = \mathrm{D}^{RHM} \times P_1^{RSW} \times P_2^{RSW} \quad \text{(Equation S. 11 − 6)}$$

$$\mathrm{O}_{11-13}^{SW} = \mathrm{D}^{USW} \times P^{USW} \quad \text{(Equation S. 11 − 7)}$$

$$\mathrm{O}_{11-3}^{WW,nt} = O_{11-3}^{UWW,nt} + O_{11-3}^{RWW,nt} \quad \text{(Equation S. 11 − 8)}$$

$$\mathrm{O}_{11-3}^{UWW,nt} = \mathrm{D}^{DW} \times \frac{\mathrm{D}^{UHM}}{(\mathrm{D}^{UHM} + \mathrm{D}^{RHM})} \times P_9^{WWG} \times P_1^{UWW} \times (1 - P_2^{UWW}) \quad \text{(Equation S. 11 − 9)}$$

$$\mathrm{O}_{11-3}^{RWW,nt} = \mathrm{D}^{DW} \times \frac{\mathrm{D}^{RHM}}{(\mathrm{D}^{UHM} + \mathrm{D}^{RHM})} \times P_9^{WWG} \times P^{RWW} \quad \text{(Equation S. 11 − 10)}$$

$$\mathrm{O}_{11-12}^{WW,ft} = \mathrm{D}^{DW} \times \frac{\mathrm{D}^{UHM}}{(\mathrm{D}^{UHM} + \mathrm{D}^{RHM})} \times P_9^{WWG} \times P_1^{UWW} \times P_2^{UWW} \quad \text{(Equation S. 11 − 11)}$$

$$\Delta\mathrm{S}_{11}^{HM} = (\Delta\mathrm{D}^{UHM} \times \Delta D^{RHM}) \times P^{HM} \quad \text{(Equation S. 11 − 12)}$$

12. Wastewater treatment

$$O_{12} = O_{12-3}^{EF} + O_{12-7}^{SL} + O_{12-13}^{SL} \quad \text{(Equation S. 12 − 1)}$$

Where

$$\mathrm{O}_{12-3}^{EF} = O_{5.2-12}^{WW,ft} \times \frac{P_1^{WWD}}{P_1^{WWG}} + O_{6.1-12}^{WW,ft} \times \frac{P_2^{WWD}}{P_2^{WWG}} + O_{6.2-12}^{WW,ft} \times \frac{P_3^{WWD}}{P^{FAWW}} + O_{6.3-12}^{WW,ft} \times \frac{P_4^{WWD}}{P_4^{WWG}} + O_{6.3.1-12}^{WW,ft} \times \frac{P_5^{WWD}}{P_5^{WWG}} + O_{6.3.2-12}^{WW,ft} \times \frac{P_6^{WWD}}{P_6^{WWG}} + O_{10.1-12}^{WW,oil} \times \frac{P_7^{WWD}}{P_7^{WWG}} + O_{10.1-12}^{WW,meat} \times \frac{P_8^{WWD}}{P_8^{WWG}} + O_{11-12}^{WW,ft} \times (1 - P_1^{WWT}) \quad \text{(Equation S. 12 − 2)}$$

$$\mathrm{O}_{12-7}^{SL} = O_{11-12}^{WW,ft} \times P_1^{WWT} \times P_2^{WWT} \quad \text{(Equation S. 12 − 3)}$$

$$O_{12-13}^{SL} = O_{5.2-12}^{WW,ft} \times \left(1 - \frac{P_1^{WWD}}{P_1^{WWG}}\right) + O_{6.1-12}^{WW,ft} \times \left(1 - \frac{P_2^{WWD}}{P_2^{WWG}}\right) + O_{6.2-12}^{WW,ft} \times \left(1 - \frac{P_3^{WWD}}{P^{FAWW}}\right)$$
$$+O_{6.3-12}^{WW,ft} \times \left(1 - \frac{P_4^{WWD}}{P_4^{WWG}}\right) + O_{6.3.1-12}^{WW,ft} \times \left(1 - \frac{P_5^{WWD}}{P_5^{WWG}}\right) + O_{6.3.2-12}^{WW,ft} \times \left(1 - \frac{P_6^{WWD}}{P_6^{WWG}}\right)$$
$$+O_{10.1-12}^{WW,oil} \times \left(1 - \frac{P_7^{WWD}}{P_7^{WWG}}\right) + O_{10.1-12}^{WW,meat} \times \left(1 - \frac{P_8^{WWD}}{P_8^{WWG}}\right) + O_{11-12}^{WW,ft} \times P_1^{WWT}$$
$$\times (1 - P_2^{WWT}) \quad \text{(Equation S. 12 − 4)}$$

13. Solid waste disposal

$$O_{13} = O_{13-2}^{SW,sp} + O_{13-2}^{SW,ld} + O_{13-2}^{SW,in} + O_{13-7}^{SW,cp} \quad \text{(Equation S. 13 − 1)}$$

Where

$$O_{13-2}^{SW,sp} = (O_{10.1-13}^{SW} + O_{11-13}^{SW} + O_{12-13}^{SL}) \times (1 - P_1^{SWD}) \quad \text{(Equation S. 13 − 2)}$$

$$O_{13-2}^{SW,ld} = (O_{10.1-13}^{SW} + O_{11-13}^{SW} + O_{12-13}^{SL}) \times P_1^{SWD} \times P_2^{SWD} \quad \text{(Equation S. 13 − 3)}$$

$$O_{13-2}^{SW,in} = (O_{10.1-13}^{SW} + O_{11-13}^{SW} + O_{12-13}^{SL}) \times P_1^{SWD} \times P_3^{SWD} \quad \text{(Equation S. 13 − 4)}$$

$$O_{13-7}^{SW,cp} = (O_{10.1-13}^{SW} + O_{11-13}^{SW} + O_{12-13}^{SL}) \times P_1^{SWD} \times P_4^{SWD} \quad \text{(Equation S. 13 − 5)}$$

Table S1. Activity Data

ID	Units	Description	Source
DTA	Mha	Total land area of China	NBSC,2013-2020
DIW	Mha	Area of Chinese inland waters	NBSC,2013-2020
DMW1	Mha	Arear of Chinese marine waters(the east China sea & South China sea)	NBSC,2013-2020
DMW2	Mha	Arear of Chinese marine waters(Yellow sea & Bohai sea)	NBSC,2013-2020
DAL	Mha	The annual area of Chinese arable land	NBSC,2013-2020
DWD	Mm^3	The annual wood production	NBSC,2013-2020
DRT	Mm^3	The annual sea outflow of China	MWRP,2013-2020
DNFW	Kt	The annual production of naturally grown freshwater products	NBSC,2013-2020
DAFW	Kt	The annual production of artificially cultured freshwater products	NBSC,2013-2020
DFW1	Kt	Fish	NBSC,2013-2020
DFW2	Kt	Shrimp and crab	NBSC,2013-2020
DFW3	Kt	Shellfish	NBSC,2013-2020
DFW4	Kt	Others	NBSC,2013-2020
DGMW	Mha	The area of global marine waters	NBSC,2013-2020
DNSW	Kt	The annual production of naturally grown seawater products	NBSC,2013-2020
DASW	Kt	The annual production of artificially cultured seawater products	NBSC,2013-2020
DSW1	Kt	Fish	NBSC,2013-2020
DSW2	Kt	Shrimp and crab	NBSC,2013-2020
DSW3	Kt	Shellfish	NBSC,2013-2020
DSW4	Kt	Algae	NBSC,2013-2020
DSW5	Kt	Others	NBSC,2013-2020
DPRNE	Kt	The annual net export of raw phosphate rocks	UN Comtrade ,2013-2020
DPR	Kt	The annual production of raw phosphate rocks(containing 30% P_2O_5)	DIS,2013-2020
DFTNE4	Kt	The annual net export of fertilizers (HS 310310)	UN Comtrade,2013-2020
DFTNE5	Kt	-HS 310390	UN Comtrade,2013-2020
DFTNE6	Kt	-HS 310520	UN Comtrade,2013-2020
DFTNE7	Kt	-HS 310530	UN Comtrade,2013-2020
DFTNE8	Kt	-HS 310540	UN Comtrade,2013-2020
DFTNE9	Kt	-HS 310551	UN Comtrade,2013-2020
DFTNE10	Kt	-HS 310559	UN Comtrade,2013-2020
DFTNE11	Kt	-HS 310560	UN Comtrade,2013-2020
DFT	Kt	The annual production of fertilizers (expressed with 100% P_2O_5)	DIS,2013-2020
DFANE	Kt	The annual net export of feed additives (HS 283525)	UN Comtrade,2013-2020
DFA	Kt	The annual production of feed additives	CPCIF,2013-2020
DEPNE	Kt	The annual net export of elemental P	UN Comtrade,2013-2020
DEP	Kt	The annual production of elemental P	CPCIF,2013-2020
DPNE	Kt	The annual net export of pesticides	CPCIF,2013-2020
DP	Kt	The annual production of pesticides	DIS,2013-2020
DDGNE1	Kt	The annual net export of soap and detergents (HS 3402)	UN Comtrade,2013-2020

DDGNE2	Kt	-HS 3401	UN Comtrade,2013-2020
DDG1	Kt	The annual production of detergents	NBSC,2013-2020
DDG2	Kt	-Soap	CNLIC,2013-2020
DRCNE1	Kt	The annual net export of raw crops (HS 100610)	UN Comtrade,2013-2020
DRCNE2	Kt	-HS 1001	UN Comtrade,2013-2020
DRCNE3	Kt	-HS 1005	UN Comtrade,2013-2020
DRCNE5	Kt	-HS 1007	UN Comtrade,2013-2020
DRCNE6	Kt	-HS 1003+1008	UN Comtrade,2013-2020
DRCNE7	Kt	-HS 1201	UN Comtrade,2013-2020
DRCNE8	Kt	-HS 0701+0714	UN Comtrade,2013-2020
DRCNE9	Kt	-HS 5201	UN Comtrade,2013-2020
DRCNE11	Kt	-HS 1202	UN Comtrade,2013-2020
DRCNE12	Kt	-HS 1205	UN Comtrade,2013-2020
DRCNE13	Kt	-HS 1207	UN Comtrade,2013-2020
DRCNE16	Kt	-HS 5303+5302	UN Comtrade,2013-2020
DRCNE17	Kt	-HS 121293	UN Comtrade,2013-2020
DRCNE18	Kt	-HS 121291	UN Comtrade,2013-2020
DRCNE19	Kt	-HS 2401	UN Comtrade,2013-2020
DRCNE20	Kt	-HS 0703+0702+0704+0705+0706+0707+0708+0709+0710+0711+0712+0713	UN Comtrade,2013-2020
DRC1	Kt	The annual production of raw crops(rice)	FAO,2013-2020
DRC2	Kt	-Wheat	FAO,2013-2020
DRC3	Kt	-Maize	FAO,2013-2020
DRC4	Kt	-Millet	FAO,2013-2020
DRC5	Kt	-Sorghum	FAO,2013-2020
DRC6	Kt	-Other grains	FAO,2013-2020
DRC7	Kt	-Beans	FAO,2013-2020
DRC8	Kt	-Tubers	FAO,2013-2020
DRC9	Kt	-Cotton fiber	FAO,2013-2020
DRC10	Kt	-Cotton seed	FAO,2013-2020
DRC11	Kt	-Peanut	FAO,2013-2020
DRC12	Kt	-Rape seed	FAO,2013-2020
DRC13	Kt	-Sesame	FAO,2013-2020
DRC14	Kt	-Sunflower	FAO,2013-2020
DRC15	Kt	-Other oilcrops	FAO,2013-2020
DRC16	Kt	-Bast fibers	FAO,2013-2020
DRC17	Kt	-Sugarcane	FAO,2013-2020
DRC18	Kt	-Sugar beet	FAO,2013-2020
DRC19	Kt	-Tobacco	FAO,2013-2020
DRC20	Kt	-Vegetable	FAO,2013-2020
DSA1	Kha	The annual sown areas of crops (rice)	FAO,2013-2020
DSA2	Kha	-Wheat	FAO,2013-2020
DSA3	Kha	-Maize	FAO,2013-2020
DSA4	Kha	-Millet	FAO,2013-2020
DSA5	Kha	-Sorghum	FAO,2013-2020
DSA6	Kha	-Other grains	FAO,2013-2020
DSA7	Kha	-Beans	FAO,2013-2020
DSA8	Kha	-Tubers	FAO,2013-2020
DSA9	Kha	-Cotton fiber	FAO,2013-2020
DSA10	Kha	-Cotton seed	FAO,2013-2020
DSA11	Kha	-Peanut	FAO,2013-2020
DSA12	Kha	-Rape seed	FAO,2013-2020
DLANE1	Kcap	The annual net export of live animals (HS 0103 Swine)	UN Comtrade,2013-2020
DLANE2	Kcap	-HS 0102 live cattle	UN Comtrade,2013-2020
DLANE3	Kcap	-HS 0104 live goat	UN Comtrade,2013-2020
DLANE4	Kcap	-HS 0105 live poultry	UN Comtrade,2013-2020
DLANE5	Kcap	-HS 0101live house, donkey, mule	UN Comtrade,2013-2020
DLA1	Kcap	The annual number of live animals to be slaughtered (pig)	NBSC,2013-2020
DLA2	Kcap	-Cattle	MARP,2013-2020
DLA3	Kcap	-Sheep	MARP,2013-2020
DLA4	Kcap	-poultry	MARP,2013-2020
DLA5	Kcap	-horse	MARP,2013-2020
DLA6	Kcap	-donkey/ass	MARP,2013-2020
DLA7	Kcap	-camel	MARP,2013-2020
DLA8	Kcap	-mule	MARP,2013-2020
DLA9	Kcap	-rabbit	MARP,2013-2020
DEG	Kt	The annual production of egg products	NBSC,2013-2020
DDR	Kt	The annual production of dairy products	NBSC,2013-2020
DDLA1	Kcap	The average dail breeding number of animals, calculated by considering the breeding cycle s of different animals (pig)	MARP,2013-2020
DDLA2	Kcap	-Cattle	MARP,2013-2020
DDLA3	Kcap	-Sheep	MARP,2013-2020
DDLA4	Kcap	-Poultry	MARP,2013-2020
DDLA5	Kcap	-Horse	MARP,2013-2020
DDLA6	Kcap	-Donkey/ass	MARP,2013-2020
DDLA7	Kcap	-Camel	MARP,2013-2020
DDLA8	Kcap	-Mule	MARP,2013-2020
DDLA9	Kcap	-Rabbit	MARP,2013-2020
DEDLA1	Kcap	The interannual change of stocks of live animals(pig)	MARP,2013-2020
DEDLA2	Kcap	-Cattle	MARP,2013-2020

DEDLA3	Kcap	-Sheep	MARP,2013-2020
DEDLA4	Kcap	-Poultry	MARP,2013-2020
DEDLA5	Kcap	-Horse	MARP,2013-2020
DEDLA6	Kcap	-Donkey	MARP,2013-2020
DEDLA7	Kcap	-Camel	MARP,2013-2020
DEDLA8	Kcap	-Mule	MARP,2013-2020
DEDLA9	Kcap	-Rabbit	MARP,2013-2020
DRINE	Kt	The annual net export of husked/milled rice(HS 100620+10030+100640)	UN Comtrade,2013-2020
DFLNE1	Kt	The annual export of flour(HS 1101+1102+1103+1104+1107+1108+1109)	UN Comtrade,2013-2020
DFLNE2	Kt	-HS 1105+1106	UN Comtrade,2013-2020
DPONE1	Kt	The annual net export of plant oil (HS 1507)	UN Comtrade,2013-2020
DPONE2	Kt	-HS 1508	UN Comtrade,2013-2020
DPONE3	Kt	-HS 1514	UN Comtrade,2013-2020
DPONE4	Kt	-HS 1511+1509	UN Comtrade,2013-2020
DSUNE	Kt	The annual net export of sugar (HS 1701+1702+1703)	UN Comtrade,2013-2020
DMTNE1	Kt	The annual net export of meat (HS 203 pork)	UN Comtrade,2013-2020
DMTNE2	Kt	-HS 201+202 beef	UN Comtrade,2013-2020
DMTNE3	Kt	-HS 0204 mutton	UN Comtrade,2013-2020
DMTNE4	Kt	-HS 207 Poultry	UN Comtrade,2013-2020
DMTNE5	Kt	-HS 0205+0208 others	UN Comtrade,2013-2020
DEGNE	Kt	The annual net export of egg	UN Comtrade,2013-2020
DDRNE	Kt	The annual net export of dairy	UN Comtrade,2013-2020
DSU	Kt	The annual production of sugar	NBSC,2013-2020
DMT1	Kt	The annual production of meat containing bones(pork)	NBSC,2013-2020
DMT2	Kt	-Beef	NBSC,2013-2020
DMT3	Kt	-Mutton	NBSC,2013-2020
DMT4	Kt	-Poultry	MARP,2013-2020
DMT5	Kt	-Others	MARP,2013-2020
DAFNE	Kt	The annual net export of animal feeds	UN Comtrade,2013-2020
DUHM	Mcap	The number of urban population	NBSC,2013-2020
DRHM	Mcap	The number of rural population	NBSC,2013-2020
DDW	Mm^3	The annual volume of domestic water use	NBSC,2013-2020
DUSW	Mt	The annual collected weight of urban solid waste	NBSC,2013-2020
DEDHM	Mcap	The interannual change of stocks of total population	NBSC,2013-2020

Table S2. Parameter data

			*
ID	Units	Description	Source
PAD1	kg/(ha*yr)	P deposition rate on inland	*
PAD2	kg/(ha*yr)	P deposition rate on marine waters	*
PWE	kg/(ha*yr)	the annual P loss rate by wind erosion	*
PRL	kg/(ha*yr)	the annual P leaching and runoff rate from non-arable land	*
PWT	kg/(ha*yr)	the annual P weathering rate	*
PWD1	kg/m^3	the average wood density	*
PWD2	%	the average P content in wood	*
PRT	%	the proportion of P contained in rivers into oceans to the total P inputs into inland waters	*
PFW	%	the P contents in freshwater products	*
PSS	Kt	the global P load in sea spray	*
PSW	%	the P contents in seawater products	*
PPR	%	the average P content in raw phosphate rocks	Zhang et al., 2020
PBF	%	The beneficiation proportion of raw phosphate rocks	*
PGG1	%	the gangue generation coefficient from mining	SCP,2018
PGG2	%	the average P content in gangues	*
PCR	%	the concentrate recovery rate of beneficiation	*
PWWG1	%	P generation coefficient in wastewater from beneficiation	SCP,2018
PWW	%	the treatment proportion of industrial wastewater	*
PFT	%	the P2O5 content in fertilizers	*
PHFT	%	the share of high-concentration P fertilizers	*
PWWG2	%	the P generation coefficient in wastewater from fertilizer production	SCP,2018
PPG1	%	the phosphogypsum generation coefficient in the production of highconcentration P fertilizers	SCP,2018
PPG2	%	the P2O5 content in phosphogypsum	*
PPG3	%	the utilization rate of phosphogypsum	J. Jiang et al., 2021
PFA	%	the P content in feed additives	Standardization Administration of P.R.China, 2017
PWWG3	M^3 /t	the wastewater generation coefficient of feed additive production	SCP,2018
PFAWW	%	the P2O5 content in untreated wastewater from feed additive production	*
PSWG	%	the solid waste generation coefficient of feed additive production	SCP,2018
PFASW	%	the P2O5 content in solid waste from feed additive production	*
PFP1	%	the ferrophosphorus generation coefficient of elemental P production	SCP,2018
PFP2	%	the P content in ferrophosphorus	*
PSL1	%	the slag generation coefficient of element P production	SCP,2018
PSL2	%	the P2O5 content in slags	*
PSL3	%	the utilization rate of slags	*
PWWG4	%	the P generation coefficient in wastewater from elemental P production	*
POP1	%	the share of organophosphorus pesticides	Liu et al., 2020

POP2	%	the P content in organophosphorus pesticides	*
PWWG5	%	the P generation coefficient in wastewater from pesticide production	SCP,2018
PDG1	%	the share of P-free detergents	*
PDG2	%	the P content in P-free detergents	*
PDG3	%	the P content in P-containing detergents	*
PWWG6	%	the P generation coefficient in wastewater from soap and synthetic detergent production	SCP,2018
PRC	%	the P contents in crop products	*
PSD1	t/ha	the use intensity of crop seeds(rice)	NDRC,2013-2020
PSD2	t/ha	the use intensity of crop seeds(wheat)	NDRC,2013-2020
PSD3	t/ha	the use intensity of crop seeds(maize)	NDRC,2013-2020
PSD4	t/ha	the use intensity of crop seeds(millet)	NDRC,2013-2020
PSD5	t/ha	the use intensity of crop seeds(sorghum)	NDRC,2013-2020
PSD7	t/ha	the use intensity of crop seeds(beans)	NDRC,2013-2020
PSD9	t/ha	the use intensity of crop seeds(cotton)	NDRC,2013-2020
PSD11	t/ha	the use intensity of crop seeds(peanut)	NDRC,2013-2020
PSD12	t/ha	the use intensity of crop seeds(rapeseed)	NDRC,2013-2020
PCS1	%	the ratio of straw to grain	*
PCS2	%	the P contents in crop straws	*
PCS3	%	the proportion of straws returned to cropland	Jiang, 2017,2018
PCS4	%	the proportion of straws used as feeds	Jiang, 2017,2018
PCS5	%	the proportion of straws used as fuels	Jiang, 2017,2018
PCS6	%	the proportion of unutilized straws	Jiang, 2017,2018
PRF	Kg/ha	the P runoff coefficient in cropland	*
PLH	Kg/ha	the P leaching coefficient in cropland	*
PLA	t/cap	the P content in live animals	*
PDR	%	the P content in dairy products	*
PEG	%	the P content in egg products	*
PAE1	g/(cap*day)	the P excreta coefficient of live animals	Shi et al., 2021
PAE2	%	the proportion of animal excreta used to cropland	Shi et al., 2021
PAE3	%	the proportion of animal excreta to inland waters	*
PAE4	%	the proportion of animal excreta to non-arable land	*
PFF1	%	the feed requirement for freshwater aquaculture	*
PFF2	%	the P content in freshwater feeds	*
PSF1	%	the feed requirement for seawater aquaculture	*
PSF2	%	the P content in seawater feeds	*
PPO1	%	the P content in plant oil	*
PPO2	%	the proportion of oil crops used for oil production	*
PPO3	%	the yield rate of plant oil	*
PSU	%	the P content in sugar	*
PMT1	%	the P content in meat	*
PMT2	%	the proportion of bones in slaughtered animals	*
PMT3	%	the slaughtering rate of animals	*
PRI1	%	the proportion of milled rice produced from raw rice	*
PRI2	%	the proportion of rice chaff/hull produced from raw rice	*
PRI3	%	the proportion of rice bran produced from raw rice	*
PWH1	%	the proportion of flour produced from wheat	*
PPO3	%	the yield rate of plant oil	*
PPO2	%	the proportion of oil crops used for oil production	*
PMT2	%	the proportion of bones in slaughtered animals	*
PWWG7	%	the P generation coefficient in wastewater from oil production	SCP,2018
PWWG8	t/cap	the P generation coefficient in wastewater from slaughtering	SCP,2018
PAF	%	the P content in industrial feeds	*
PUHE1	Kg/cap	the P generation coefficient in human excreta from urban households	*
PRHE1	Kg/cap	the P generation coefficient in human excreta from rural households	*
PUHE2	%	the proportion of urban excreta returned to cropland	*
PRHE2	%	the proportion of rural excreta returned to cropland	*
PUHE3	%	the runoff rate of unutilized urban excreta	*
PRSW2	g/kg	the P content in rural solid wastes	*
PWWG9	%	the wastewater generation rate of domestic water use	*
PUWW1	Mg/L	the P concentration in untreated urban wastewater (without excreta)	*
PRWW	Mg/l	the P concentration in untreated rural wastewater (without excreta)	*
PUWW2	%	the treatment rate of urban domestic wastewater	Ministry of Housing and Urban-Rural Development,2013-2020
PUSW	g/kg	the P content in urban solid waste	*
PRSW1	t/cap	the solid waste generation coefficient of rural human consumption	*
PRSW2	g/kg	the P content in rural solid wastes	*
PHM	Kg/cap	the average P content in adults	*
PWWD1	%	the P discharge coefficient in beneficiation wastewater	SCP,2018
PWWD2	%	the P discharge coefficient in fertilizer wastewater	SCP,2018
PWWD3	%	the P content in treated feed additive wastewater	SCP,2018
PWWD4	%	the P discharge coefficient in elemental P wastewater	SCP,2018
PWWD5	%	the P discharge coefficient in pesticide wastewater	SCP,2018
PWWD6	%	the P discharge coefficient in soap and detergent wastewater	SCP,2018
PWWD7	%	the P discharge coefficient in oil wastewater	SCP,2018
PWWD8	t/cap	the P discharge coefficient in slaughtering wastewater	SCP,2018
PWWT1	%	the P elimination rate of urban municipal wastewater treatment plant	*
PWWT2	%	the proportion of sludge returned to cropland	*
PSWD1	%	the non-hazardous treatment rate of solid waste	NBSC,2013-2020

PSWD2	%	the landfill proportion in non-hazardous treatment of solid wastes	NBSC,2013-2020
PSWD3	%	the incineration proportion in non-hazardous treatment of solid waste	NBSC,2013-2020
PSWD4	%	the compost proportion in non-hazardous treatment of solid waste	NBSC,2013-2020

* a represents coefficients from Liu et al (2016). without modification.

2. Calculation of pollutant emissions from aquaculture.

Aquaculture module phosphorus discharge A separate optimization was performed for the aquaculture module(Liu et al., 2016), resulting in a different result for aquaculture inflows to freshwater and seawater. The optimization information for this part was mainly derived from the Generation and emission coefficient manual of industrial pollution sources for the Chinese Pollution Source Census. The phosphorus is discharged into the water bodies from the aquaculture information of each province. The incorporation of pollution discharge coefficients, derived from the Handbook of Pollution Emission Coefficients of Aquaculture in China (SCC, 2007), was pivotal in capturing the regional variability of aquaculture operations across different provinces in China. At the same time, based on the aquaculture data for China's provinces in the Fishery Statistics Yearbook, the P flowing into freshwater and seawater in the model was recalculated. This method was adopted by Chinese Academy of Fishery Sciences to calculate the pollution emission coefficients of aquaculture in various provinces, which accounts for the methods the types and methods of aquaculture cultured in each province. The present study limited its analysis to data generated subsequent to the publication of the 2007 edition of the Handbook of Pollution Emission Coefficients, with subsequent calculations utilizing data from the 2018 edition of the Handbook for the years 2018 and 2019.

Chinese aquaculture industry phosphorus pollutant emissions (Equation. a)

$$\sum Pollutant\ discharge_{y,j} \quad \text{(Equation S. } a\text{)}$$

$$PD_{y,j} = PC_{y,i,j} \times IBA_{y,j} \quad \text{(Equation S. } b\text{)}$$

$$IBA_{y,j} = PRO_{y,j} - AF_{y,j} \quad \text{(Equation S. } c\text{)}$$

Where y denotes the region, and in this study, we considered 31 provinces, municipalities, and autonomous regions in mainland China. i is the mean value of the emission coefficient of farming species. Freshwater

farming includes a pond, factory, net tank, and fen farming. Marine aquaculture includes pond culture, factory farming, net tank culture, raft culture, and beach culture. Considering the data availability for each culture species in each region, we choose the mean value of each geographical region. *j* is time. In the study, the phosphorus emission information of freshwater aquaculture and marine aquaculture in each region was calculated, which correspondingly represented the phosphorus flowing into freshwater and the phosphorus flowing into seawater; PC is the pollution coefficient; IBA is the units increased in breed aquatics; PRO is the production output; AF is the amount of fingerling;

3. P resource efficiency

Table S3. PUE of agriculture

Subsystem	Output (P)	Input (P)	Year	References	PUE
P rock mining	PR production (31% -P_2O_5)	World PR mine production	1961; 2013	(Chen & Graedel, 2016)	40.4; 44.8
Chemical manufacturing	Exported P rock + chemical fertilizer P rock	Imported P rock + mined P rock	1980-2012	(Wu et al., 2015)	86-88
	Chemical products (fertilizer + detergent + pesticide)	P minerals	1978-2012	(S. Jiang & Yuan, 2015)	98-94
	P-acid + elemental P + P fertilizer + detergents + feed additives + other uses	P rock	1961; 2013	(Chen & Graedel, 2016)	95.4; 86.3
Crop cultivation	Harvested grains + feed straw + industrial raw materials composed of straw	Chemical fertilizer applied to field + livestock excrement applied to fields + local pesticide applied + imported pesticide and chemical fertilizer + atmospheric deposition +irrigation + seeds + excrement from rural residents applied to fields	1980-2012	(Wu et al., 2015)	39-41
	Primary crop products (rice + wheat + rapeseed)	Fertilizer + manure + straw	1978-2012	(S. Jiang & Yuan, 2015)	54-32
	Crop + crop residue	Chemical fertilizer + domestic livestock manure + large-scale livestock manure + rural residents' manure + straw	2015	(Wu et al., 2020)	5.2
	Crop	Fertilizer + manure	1961-2019	(Zou et al., 2022)	80-50
	Crop + crop residues + grass + runoff + erosion + losses from leaching	Fertilizer + manure + recycled crop residues + recycled human excrement + atmospheric deposition + seeds	1961; 2013	(Chen & Graedel, 2016)	33.6; 40.6
	Crop + export of crop + straw	Atmospheric deposition + weathering + fertilizer + pesticides + sludge + compost	1990-2019	This study	62-71
Crop-pasture	Crop + plant + crop export + pasture grazing + harvested pasture + other	Mineral fertilizer + livestock manure + organic fertilizer + recycled biosolids + atmospheric deposition + seeds + others	2005-2020	(Chowdhury and Zhang, 2021)	51-85
Aquaculture	Cultured aquatic products + export of cultured aquatic products	Feed	1990-2019	This study	8-9
Agricultural product processing	Export from crop processing + grain food consumed by rural residents + grain food consumed by urban residents + residues/by-products used as fodder + residues/by-products used in other forms	Harvested grains	1980-2012	(Wu et al., 2015)	96-97
	Crop and animal foods (manufactured rice + flour + slaughtered animal)	Fertilizer + seed + pesticide + human manure + atmosphere deposition + feed imported + fodder + food residue	1978-2012	(S. Jiang & Yuan, 2015)	34-18
	Crop + meat + eggs + milk + fish + by-products to food	Fertilizer + human waste + deposition (wet & dry) + seed + fixation + irrigation + straw + crop by -products + animal by-products + kitchen residues + other feed	2013	(Wang et al., 2018)	24
	Food + non-food + export of food +	Cultured aquatic products + livestock	1990-	This study	92-94

	Export of non-food + feed + export of feed	breeding + crop + straw + feed additives + wood + natural aquatic products	2019		
Livestock breeding	Livestock excrement applied to fields + livestock products consumed by rural residents + livestock products consumed by urban residents + livestock products exported	Feed straw + residues/by-products used as fodder + livestock bred + kitchen waste + feed from processing industry	1980-2012	(Wu et al., 2015)	60-39
	Pig + bovine + sheep	Feed + fodder + straw	1978-2012	(S. Jiang & Yuan, 2015)	12-22
	Livestock products + export of live animals/products	Pasture grazing + crop + pasture harvest + feed + feed additives + live animals + others	2005-2020	(Biswas Chowdhury & Zhang, 2021)	2-34
	Eggs + dairy + export of eggs + export of dairy + livestock products + export of livestock products	Feed + pasture	1990-2019	This study	14-22
Rural consumption	Excrement from rural residents applied to fields + kitchen waste	Grain food consumed by rural residents + livestock products consumed by rural residents + imports for rural consumption + rural consumption of other goods	1980-2012	(Wu et al., 2015)	50-32
Urban consumption	Urban municipal wastes discharged to waste treatment	Grain food consumed by urban residents + livestock products consumed by urban residents + imports for urban consumption + urban consumption of other goods	1980-2012	(Wu et al., 2015)	4.46-40.4
Societal consumption	Human excretion + other human waste	Food	1961; 2013	(Chen & Graedel, 2016)	44.9; 46.7

Table S4. Precycling rate

Subsystem	Definition
Straws as fertilizers	The proportion of straw used as fertilizer to total wasted straw
All human activities	The proportion of phosphorus recycling to total wasted phosphorus used in human activities
Agricultural planting Livestock poultry & aquaculture	The proportion of recycled phosphorus to the total inflow of phosphorus in each subsystem

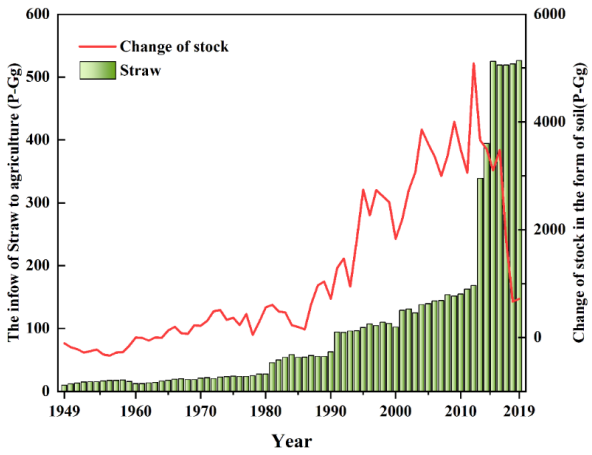

Figure S2. China agricultural straw mulching and inventory, 1949-2019.

4. The proportion of countries importing and exporting Chinese phosphate chemical products

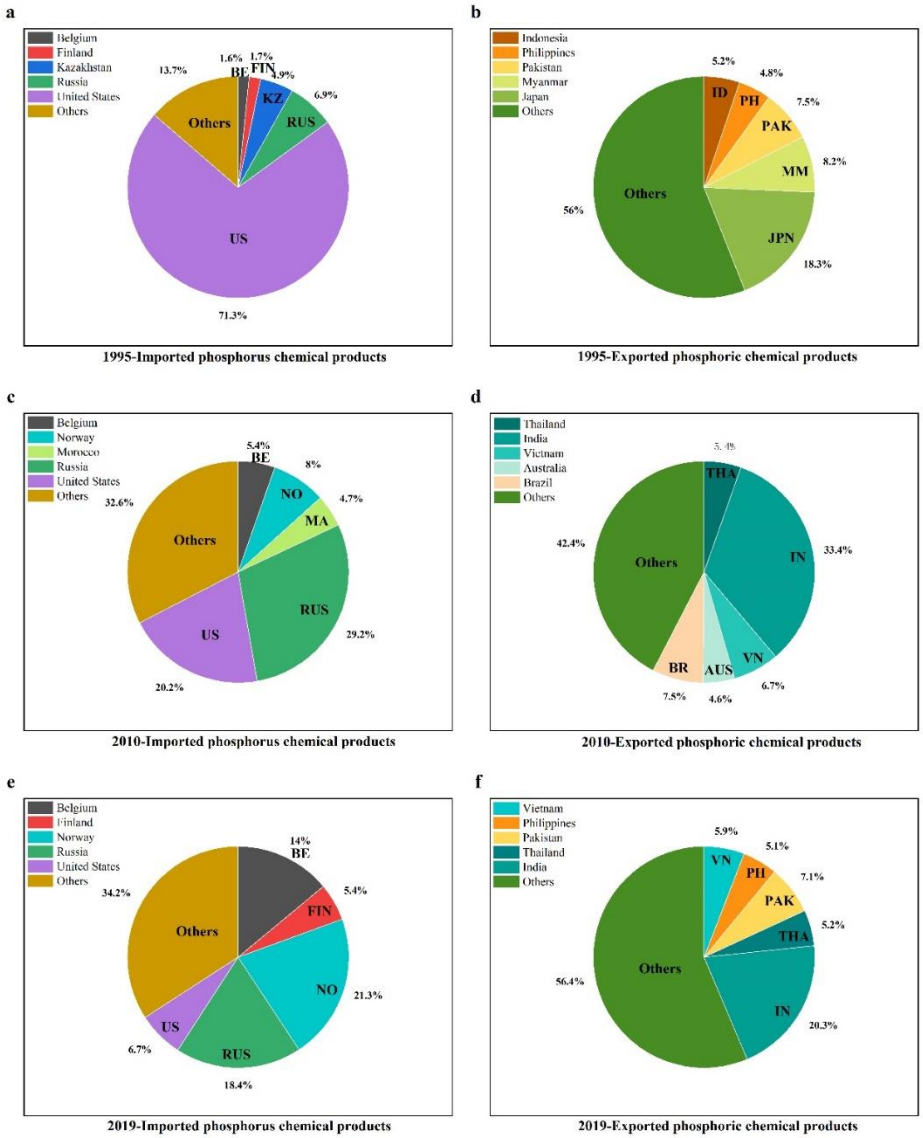

Figure S3. The proportion of countries importing and exporting Chinese phosphate chemical products. (a) Imported phosphorus chemical products in 1995; (b) Exported phosphorus chemical products in 1995; (c) Imported phosphorus chemical products in 1995; (d) Exported phosphorus chemical products in 2010; (e) Imported phosphorus chemical products in 1995; (f) Exported phosphorus chemical products in 2019.

5. Uncertainty analysis

For this study, the probability distributions of 102 phosphorus flows were calculated using Monte Carlo simulations, while the uncertainties of the activity data and parameter data and the final results were compared separately. The figure above indicates the results of the uncertainty analysis for the key phosphorus flows. In general, there exists an uncertainty objectively, but the overall results have little impact on our main study results.

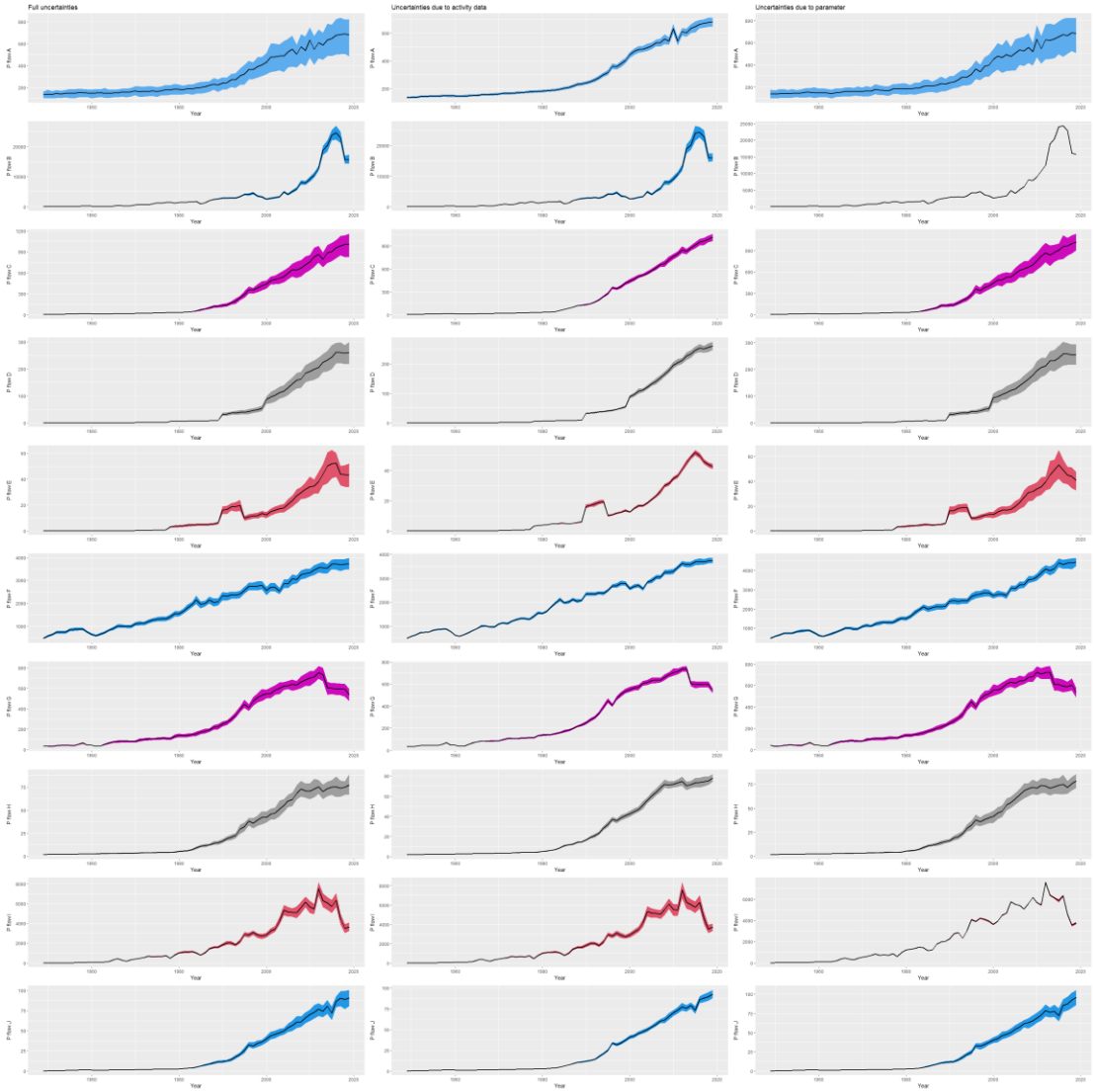

Figure S4. Uncertainty analysis results.