Supporting Information

for

Global Supply Chain Drivers of Agricultural Antibiotic Emissions in China

Xuechun Yang [1, 2], Qiumeng Zhong [3], Sai Liang [3, *], Yumeng Li [2], Yafei Wang [4], Xiaobiao Zhu [5], Yu Liu [6, 7]

[1] Institute of Circular Economy, Faculty of Materials and Manufacturing, Beijing University of Technology, Beijing 100124, China.

[2] School of Environment, Beijing Normal University, Beijing, 100875, China.

[3] Key Laboratory for City Cluster Environmental Safety and Green Development of the Ministry of Education, School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou, 510006, China.

[4] School of Statistics, Beijing Normal University, Beijing, 100875, China.

[5] College of Chemical Engineering, Beijing University of Chemical Technology, Beijing, 100029, China.

[6] Institutes of Science and Development, Chinese Academy of Sciences, Beijing 100190, China.

[7] School of Public Policy and Management, University of Chinese Academy of Sciences, Beijing 100049, China.

* Corresponding author: liangsai@gdut.edu.cn (Sai Liang).

Pages: 47

Figures: 12

Tables: 4

Supplemental Methods

This study considers two sources of agricultural antibiotic emissions in mainland China: animal husbandry (including the raising of bovine, swine, and poultry) and aquaculture. For animal husbandry, the animal species considered are the most common livestock and poultry species in mainland China. Antibiotics are widely used in the feeding of these animal species. For each type of animal, we first estimate the amount of feces. Then, we calculate the antibiotics entering the environment after waste disposal, based on typical waste treatment processes and antibiotic concentrations obtained from previous studies. For aquaculture, different farming forms are considered for the estimations of antibiotic emissions.

Estimations of Feces from Livestock and Poultry

- **Swine**

The amounts of swine feces for 2014 in each province of mainland China are calculated by equations (1).

$$W_{sf} = M_s \times T_{nursery} \times F_{nursery} + M_s \times T_{fattern} \times F_{fattern} \quad (1)$$

The notation W_{sf} indicates the total weight of swine feces in 2014; M_s represents the number of swine in each province of mainland China in 2014; $T_{nursery}$ is the nursery period (days); $F_{nursery}$ represents the feces producing coefficient for swine in nursery, namely the feces produced per day by per head of swine in nursery; $T_{fattern}$ is the fattening period (days); and $F_{fattern}$ represents the feces producing coefficient for swine in the fattening period.

The average culturing period is 179 days,[1] which is less than a year. Therefore, the number of swine in 2014 is considered as their marketing number.[2] The nursery period $T_{nursery}$ is usually 75 to 80 days[3], and the fattening period $T_{fattern}$ = 179 - $T_{nursery}$.

The minimum, average, and maximum values of each parameter are plugged into the above equations for estimations. The values of parameters in equations (1) are shown in Data S3 and S4 in the Supporting Data. The data are from statistical yearbooks, previous studies, and government documents.[1, 3-5]

- **Bovines**

The calculation of bovine feces depends on the raising pattern. For captive raising, all the feces produced are considered to contain antibiotics. For grazing, bovines are fed artificially during the grass-withering period (lasting for six months), and the feces contain antibiotics. During the other six months, bovines are grazed without intaking feedstuff. The feces do not contain antibiotics. In this study, only the feces containing antibiotics are considered. The feces producing coefficients of bovine types are different. Existing investigation provides feces producing coefficients of cows and beef cattle.[5] Considering the data availability, the bovine cattle are classified into three categories, including cows, beef cattle, and other cattle. Here, other cattle refer to cattle for other uses. In China, the bovine cattle on hand are mainly beef cattle and cows, with a small number of cattle for other uses. Therefore, we used the feces producing coefficient of beef cattle to represent the coefficient of cattle for other uses. The feces weight of different bovine cattle based on captive raising and grazing are calculated, respectively, based on equations (2) to (7).

$$W_{c-cow} = M_{c-cow} \times 365 \times F_{cow} \tag{2}$$

$$W_{c-cattle} = M_{c-cattle} \times 365 \times F_{cattle} \tag{3}$$

$$W_{g-cow} = M_{g-cow} \times 365 \times F_{cow} \times \frac{1}{2} \tag{4}$$

$$W_{g-cattle} = M_{g-cattle} \times 365 \times F_{cattle} \times \frac{1}{2} \tag{5}$$

$$W_{b-cow} = W_{c-cow} + W_{g-cow} \tag{6}$$

$$W_{b-cattle} = W_{c-cattle} + W_{g-cattle} \tag{7}$$

The notation $W_{c\text{-}cow}$ represents the feces weight of captive cows; $M_{c\text{-}cow}$ indicates the number of captive cows on hand in 2014; F_{cow} is the feces producing coefficient of cows, namely the feces produced per day by per head of cow; $W_{c\text{-}cattle}$ represents the total feces weight of captive beef and other cattle; $M_{c\text{-}cattle}$ indicates the sum of captive beef and other cattle on hand in 2014; F_{cattle} is the feces producing coefficient of beef cattle; $W_{g\text{-}cow}$ represents the feces weight of grazing cows; $M_{g\text{-}cow}$ indicates the number of grazing cows on hand in 2014; $W_{g\text{-}cattle}$ is the total feces weight of grazing beef and other cattle; $M_{g\text{-}cattle}$ is the sum of grazing beef and other cattle on hand in 2014; $W_{b\text{-}cow}$ represents the total feces weight of cows; and $W_{b\text{-}cattle}$ is the total feces weight of cattle. The raising period of bovine cattle is generally more than one year. Thus, the number of bovines in 2014 is considered as their stocks on hand, and the feeding days of a year is 365 days.[2]

The values of parameters in equations (2) to (5) are shown in Data S5 and S6 in the Supporting Data. The minimum, average, and maximum values of each parameter are plugged into the above equations for estimations. The data are from statistical yearbooks and government documents.[4-6]

- **Poultry**

The feces producing coefficients of meat poultry and laying poultry are different. However, the statistical yearbooks provide only the total number of poultry slaughter and poultry on hand.[4] To calculate the poultry feces, we first estimate the numbers of meat poultry and laying poultry separately in 2014. From the view of purposes, poultry farms raise meat poultry for slaughter and raise laying poultry for producing eggs. Generally, the raising period of meat poultry (mainly chicken, ducks, and gooses) is 50 to 70 days,[7] while the raising period of laying poultry is approximate 500 days.[8] Therefore, we consider the number of meat poultry as the slaughter number. The number of laying poultry is the number of laying poultry on hand, which is estimated based on slaughter number, the stock on hand, and slaughter frequency in 2014. There is generally an empty period of 10 days between two slaughter batches. Thus, the slaughter frequency is calculated using equation (8).

$$SL = {}^{365}/(T_{mp} + 10) \quad (8)$$

The notation SL represents the slaughter frequency of meat poultry, and T_{mp} indicates the raising period of meat poultry.

The number of laying poultry on hand was calculated by equation (9).[9]

$$M_{lp} = M_p - M_{mp}/SL \tag{9}$$

The notation M_{lp} is the number of laying poultry on hand; M_p represents the total poultry on hand at the end of 2014; and M_{mp} indicates the slaughter number of meat poultry in 2014.

For laying poultry, the proportion of poultry in the laying period (PLP) is about 22/29. The rest 7/29 of laying poultry is in incubation and growing period.[10] We assume that the proportion of PLP in laying poultry remains stable every day, then the amount of poultry feces is estimated by equations (10) to (12)

$$W_{mp} = M_{mp} \times T_{mp} \times F_{mp} \tag{10}$$

$$W_{lp} = M_{lp} \times 22/29 \times 365 \times F_l + M_{lp} \times 7/29 \times 365 \times F_g \tag{11}$$

$$W_{pc} = W_{mp} + W_{lp} \tag{12}$$

The notation W_{mp} indicates the feces weight of meat poultry; F_{mp} is the feces producing coefficients of meat poultry; W_{lp} represents the feces weight of laying poultry; F_l is the feces producing coefficients of PLP; F_g indicates the feces producing coefficients of laying poultry in incubation and growing period; and W_{pc} represents the total feces weight of poultry. The values of parameters in equations (10) and (11) are shown in Data S7 and S8 in the Supporting Data. The data are from previous studies, statistical yearbooks, and government documents.[4, 5, 7]

The minimum, average, and maximum values of each parameter are plugged into the above equations for estimations.

Antibiotic Emissions from Livestock and Poultry Raising

We focus on 15 kinds of antibiotics belonging to three antibiotic categories. The antibiotic types are shown in Table S1. The antibiotic concentrations of animal feces from different studies were collected and integrated. After data selection and processing, we use the data to calculate antibiotic emissions from livestock and poultry raising. Details for data selection and processing are described in section Data Processing.

- **Swine**

It is estimated that 20% of livestock feces enter wastewater streams, and the rest of 80% will be collected and used as composts.[11]The antibiotics contained in solid feces enter the environment with composts. The estimation is based on equation (13). The antibiotic emissions from effluents are estimated by equation (14).

$$p_{sf} = W_{sf} \times 80\% \ / \ (1 + r_{swine}) \times C_{sf} \times (1 - R_f) \tag{13}$$

$$p_{se} = W_{sf} \times 20\% \ / \ (1 + r_{swine}) \times C_{sf} \times (1 - R_w) \tag{14}$$

The notation p_{sf} and p_{se} indicate the antibiotic emissions from solid swine feces and effluents, respectively; W_{sf} represents the weight of swine feces; r_{swine} is the moisture content (dry basis, the percentage of water weight in dry weight of samples) of swine feces;[12] C_{sf} is the antibiotic concentration of swine feces (dry matter); R_f is the antibiotic removal rate of animal feces treatment;[13] and R_w indicates the antibiotic removal rate of wastewater treatment.[14]

Data for C_{sf} and r_{swine} are shown in Data S9 and S11 in the Supporting Data. Data for R_f and R_w are shown in Data S12 in the supporting Data. The minimum, average, and maximum values of each parameter are plugged into the above equations for estimations.

- **Bovines**

In the condition of artificial management, 20% of the bovine feces enter wastewater and 80% of the feces remain solid.[11] For bovine cattle, the antibiotics contained in solid feces enter the environment with composts. They are estimated by equations (15) and (16).

$$p_{bf-cow} = W_{b-cow} \times 80\% \ / \ (1 + r_{cow}) \times C_{bc} \times (1 - R_f) \quad (15)$$

$$p_{bf-cattle} = W_{b-cattle} \times 80\% \ / \ (1 + r_{cattle}) \times C_{bc} \times (1 - R_f) \quad (16)$$

The notation $p_{bf\text{-}cow}$ represents the antibiotic emissions from cow feces; $W_{b\text{-}cow}$ is the weight of cow feces; r_{cow} and r_{cattle} indicates the moisture content (dry basis) of cow feces and cattle feces, respectively;[12] C_{bc} represents the antibiotic concentration of bovine feces (dry matter); $p_{bf\text{-}cattle}$ indicates the antibiotic emissions from feces of beef and other cattle; and $W_{b\text{-}cattle}$ is the weight of feces from beef and other cattle; and R_f represents the antibiotic removal rate of animal feces treatment.[13]

The antibiotics emitted with bovine effluent are estimated by equations (17) and (18).

$$p_{be-cow} = W_{b-cow} \times 20\% \ / \ (1 + r_{cow}) \times C_{bc} \times (1 - R_w) \quad (17)$$

$$p_{be-cattle} = W_{b-cattle} \times 20\% \ / \ (1 + r_{cattle}) \times C_{bc} \times (1 - R_w) \quad (18)$$

The notation $p_{be\text{-}cow}$ represents the antibiotic emissions from cow effluents; $p_{be\text{-}cattle}$ represents the antibiotic emissions from beef and other cattle effluents; and R_w indicates the removal rate of antibiotics after wastewater treatment.[14] Data for C_{bc} are shown in Data S9 in the Supporting Data. Data for r_{cow}, and r_{cattle} are shown in Data S11 in the Supporting Data. The minimum, average, and maximum values of each parameter are plugged into the above equations for estimations.

- **Poultry**

The poultry farms barely produce wastewater, and all the feces are collected for composting. The antibiotics contained in poultry feces enter the environment with composts. The estimation is shown in equation (19).

$$p_{pc} = W_{pc} / (1 + r_{poultry}) \times C_{pc} \times (1 - R_f) \quad (19)$$

The notation p_{pc} indicates the antibiotic emissions from poultry feces; W_{pc} represents the total feces weight of poultry; $r_{poultry}$ is the moisture content of poultry feces (dry basis);[12] C_{pc} indicates the antibiotic concentration of poultry feces (dry matter); and R_f represents the antibiotic removal rate of animal feces treatment.[13] Data for C_{pc} are shown in Data S9 in the Supporting Data. Data for $r_{poultry}$ and R_f are shown in Data S11 and S12, respectively. The minimum, average, and maximum values of each parameter are plugged into the above equation for estimations.

Antibiotic Emissions from Aquaculture

The antibiotic concentration data for aquaculture water were collected from different studies. The data were selected and integrated for calculation. The calculations are based on different fishing patterns.

- **Marine aquaculture**

In mainland China, marine aquaculture patterns are divided into seven categories, including pond culture, cage culture, deep-sea cage culture, hanging cage culture, industrialized culture, raft culture, and bottom sowing culture. The raft culture does not involve water deep, and its area just occupies a small portion of the total marine aquaculture area in mainland China. Therefore, we excluded the raft culture in the calculations. Moreover, there is no artificial feeding for the bottom sowing culture. Thus, the bottom sowing culture does not discharge antibiotics and is not considered in our calculations. Cage culture, deep-sea cage culture, hanging cage culture are typical open-water culture. For China, the industrialized culture is currently in the initial stage, and the water cycling systems are not well-developed. Therefore, we considered industrialized culture as an open-water culture. We assume that water is renewed and recharged every day for open-water culture. For pond culture, water renewal is based on water change frequency. The antibiotic emissions from open-water culture are calculated by equation (20).

$$p_{mo} = Q_{mo} \times H_{mo} \times C_{mo} \times 365 \qquad (20)$$

The notation p_{mo} indicates the antibiotic emissions from marine aquaculture farms (open-water); Q_{mo} is the area of marine aquaculture farms; H_{mo} is the depth of marine aquaculture zone; C_{mo} represents the antibiotic concentrations of water in marine aquaculture farms (open-water).

The antibiotic emissions from pond culture are calculated by equation (21).

$$p_{mp} = Q_{mp} \times H_{mp} \times C_{mp} \times {}^{365}/_{S_{mp}} \qquad (21)$$

The notation p_{mp} indicates the antibiotic emissions from pond culture farms; Q_{mp} is the area of pond culture farms; H_{mp} is the depth of pond farms; C_{mp} represents the antibiotic concentrations of water in pond farms; and S_{mp} is the water renewal frequency of pond culture. The variable S_{mp} is generally 10 to 15 days. Data for Q_{mo}, Q_{mp} are based on statistical yearbook (Data S14, Supporting Data),[15] H_{mo}, and H_{mp} are based on the specification of aquaculture equipment (Data S15, Supporting Data). Data for C_{mo} and C_{mp} are shown in Data S16 in the Supporting Data. The minimum, average, and maximum values of each parameter are plugged into the above equation for estimations.

- **Freshwater aquaculture**

In mainland China, freshwater aquaculture patterns are divided into three categories, including pen culture, cage culture, and industrialized culture. These three patterns are all considered as open-water aquaculture in the estimations. The antibiotic emissions from freshwater aquaculture are estimated by equation (22).

$$p_{fa} = Q_{fa} \times H_{fa} \times C_{fa} \times 365 \quad (22)$$

The notation p_{fa} indicates the antibiotic emissions from freshwater aquaculture farms (open-water); Q_{fa} is the area of freshwater aquaculture farms; H_{fa} is the depth of freshwater aquaculture zone; and C_{fa} represents the antibiotic concentrations of water in freshwater aquaculture farms (open-water). Data for Q_{fa} and H_{fa} are based on statistical yearbook[4] and the specification of aquaculture equipment, respectively (Data S14 and S15, Supporting Data). Data for C_{fa} are shown in Data S18 in the Supporting Data. The minimum, average, and maximum values of each parameter are plugged into the above equation for estimations.

The Combined Multi-Regional Input-Output (MRIO) Framework

In this study, we combine China's MRIO table in 2014 with the Global Trade Analysis Project (GTAP) data to investigate the connections between China's provinces and foreign nations/regions. The MRIO framework is shown in Figure SM1. The combined MRIO framework involves 31 provinces of mainland China (the first 31 regions in the MRIO table) and 140 nations and regions outside mainland China. The notation $Z_{i\,j}^{k\,t}$ is an element in intermediate matrix **Z**, which indicates intermediate input from sector *i* in province/nation *k* to sector *j* in province/nation *t*. The notation $f_i^{k\,t}$ represents province/nation *t*'s final demand for products of sector *i* in province/nation *k*; x_i^k is the total output of sector *i* in province/nation *k*; h_j^t is the primary input of sector *j* in province/nation *t*; x_j^t is the total input of sector *j* in province/nation *t*; the notation p_j^t represents antibiotic emissions of sector *j* in province *t*. Detailed information on $Z_{i\,j}^{k\,t}$, $f_i^{k\,t}$, x_i^k, h_j^t, x_j^t, and $p_j^t$is shown in Figure SM2, taking $Z_{i\,j}^{1\,32}$, $f_i^{1\,32}$, x_i^1, h_j^2, x_j^2, and p_j^2 as examples.

Thus, the row vector $p = \begin{bmatrix} p_1^1 & p_2^1 & \cdots & p_j^{31} & 0 & \cdots & 0 \end{bmatrix}$; the column vector $f = \begin{bmatrix} f_1^{1\,t} \\ f_2^{1\,t} \\ \vdots \\ f_i^{171\,t} \end{bmatrix}$, the final demand of province/nation *t* is plugged into column vector *f*; the row vector $h = [h_1^1 \quad h_2^1 \quad \cdots \quad h_j^{171}]$; the column vector $x = \begin{bmatrix} x_1^1 \\ x_2^1 \\ \vdots \\ x_i^{171} \end{bmatrix}$.

The direct input coefficient matrix **A** is calculated by equations (23) and (24)

$$\mathbf{A} = \begin{bmatrix} a_{1\,1}^{1\,1} & \cdots & a_{1\,n}^{1\,171} \\ \vdots & a_{i\,j}^{k\,t} & \vdots \\ a_{n\,1}^{171\,1} & \cdots & a_{n\,n}^{171\,171} \end{bmatrix} \tag{23}$$

$$a_{j\,i}^{k\,t} = Z_{j\,i}^{k\,t} / x_i^t \qquad k, t = 1,2\cdots171;\ i,j = 1,2\cdots n \tag{24}$$

The direct output coefficient matric **B** is calculated by equations (25) and (26)

$$\mathbf{B} = \begin{bmatrix} b_{1\,1}^{1\,1} & \cdots & b_{1\,n}^{1\,171} \\ \vdots & b_{i\,j}^{k\,t} & \vdots \\ b_{n\,1}^{171\,1} & \cdots & b_{n\,n}^{171\,171} \end{bmatrix} \tag{25}$$

$$b_{j\,i}^{k\,t} = Z_{j\,i}^{k\,t} / x_j^k \qquad k, t = 1,2\cdots171;\ i,j = 1,2\cdots n \tag{26}$$

		Intermediate use							Final demand						Total output
		P1	**P2**	**…**	**P31**	**N32**	**…**	**N171**	**P1**	**…**	**P31**	**N32**	**…**	**N171**	
Intermediate input	**P1**	$Z_{i\,j}^{1\,1}$	$Z_{i\,j}^{1\,2}$	$Z_{i\,j}^{1\,t}$	$Z_{i\,j}^{1\,31}$	$Z_{i\,j}^{1\,32}$	$Z_{i\,j}^{1\,t}$	$Z_{i\,j}^{1\,171}$	$f_i^{1\,1}$	$f_i^{1\,t}$	$f_i^{1\,31}$	$f_i^{1\,32}$	$f_i^{1\,t}$	$f_i^{1\,171}$	x_i^1
	P2	$Z_{i\,j}^{2\,1}$	$Z_{i\,j}^{2\,2}$	$Z_{i\,j}^{2\,t}$	$Z_{i\,j}^{2\,31}$	$Z_{i\,j}^{2\,32}$	$Z_{i\,j}^{2\,t}$	$Z_{i\,j}^{2\,171}$	$f_i^{2\,1}$	$f_i^{2\,t}$	$f_i^{2\,31}$	$f_i^{2\,32}$	$f_i^{2\,t}$	$f_i^{2\,171}$	x_i^2
	…	$Z_{i\,j}^{k\,1}$	$Z_{i\,j}^{k\,2}$	$Z_{i\,j}^{k\,t}$	$Z_{i\,j}^{k\,31}$	$Z_{i\,j}^{k\,32}$	$Z_{i\,j}^{k\,t}$	$Z_{i\,j}^{k\,171}$	$f_i^{k\,1}$	$f_i^{k\,t}$	$f_i^{k\,31}$	$f_i^{k\,32}$	$f_i^{k\,t}$	$f_i^{k\,171}$	x_i^k
	P31	$Z_{i\,j}^{31\,1}$	$Z_{i\,j}^{31\,2}$	$Z_{i\,j}^{31\,t}$	$Z_{i\,j}^{31\,31}$	$Z_{i\,j}^{31\,32}$	$Z_{i\,j}^{31\,t}$	$Z_{i\,j}^{31\,171}$	$f_i^{31\,1}$	$f_i^{31\,t}$	$f_i^{31\,31}$	$f_i^{31\,32}$	$f_i^{31\,t}$	$f_i^{31\,171}$	x_i^{31}
	N32	$Z_{i\,j}^{32\,1}$	$Z_{i\,j}^{32\,2}$	$Z_{i\,j}^{32\,t}$	$Z_{i\,j}^{32\,31}$	$Z_{i\,j}^{32\,32}$	$Z_{i\,j}^{32\,t}$	$Z_{i\,j}^{32\,171}$	$f_i^{32\,1}$	$f_i^{32\,t}$	$f_i^{32\,31}$	$f_i^{32\,32}$	$f_i^{32\,t}$	$f_i^{32\,171}$	x_i^{32}
	…	$Z_{i\,j}^{k\,1}$	$Z_{i\,j}^{k\,2}$	$Z_{i\,j}^{k\,t}$	$Z_{i\,j}^{k\,31}$	$Z_{i\,j}^{k\,32}$	$Z_{i\,j}^{k\,t}$	$Z_{i\,j}^{k\,171}$	$f_i^{k\,1}$	$f_i^{k\,t}$	$f_i^{k\,31}$	$f_i^{k\,32}$	$f_i^{k\,t}$	$f_i^{k\,171}$	x_i^k
	N171	$Z_{i\,j}^{171\,1}$	$Z_{i\,j}^{171\,2}$	$Z_{i\,j}^{171\,t}$	$Z_{i\,j}^{171\,31}$	$Z_{i\,j}^{171\,32}$	$Z_{i\,j}^{171\,t}$	$Z_{i\,j}^{171\,171}$	$f_i^{171\,1}$	$f_i^{171\,t}$	$f_i^{171\,31}$	$f_i^{171\,32}$	$f_i^{171\,t}$	$f_i^{171\,171}$	x_i^{171}
Primary input		h_j^1	h_j^2	h_j^t	h_j^{31}	h_j^{32}	h_j^t	h_j^{171}							
Total input		x_j^1	x_j^2	x_j^t	x_j^{31}	x_j^{32}	x_j^t	x_j^{171}							
Antibiotic emission		p_j^1	p_j^2	p_j^b	p_j^{31}	0	0	0							

Figure SM1. The combined MRIO framework. The "P1, P2, …, P31" represent "Province 1, Province 2, …, and Province 31"; the "N32, …, N171" represent "Nation 32, …, and Nation 171". Yellow shadow indicates the trade between provinces in mainland China; green shadow indicates the trade between provinces of mainland China and the rest of the world; blue shadow indicates the trade between nations and regions outside mainland China; and light shadow (i.e., light yellow and light blue) indicates the trade within the same region.

$Z_{i\,j}^{1\,32}$		Intermediate use (Nation 32)			
		Sector 1	Sector 2	Sector 3	…
Intermediate input (Province 1)	Sector 1	$Z_{1\,1}^{1\,32}$	$Z_{1\,2}^{1\,32}$	$Z_{1\,3}^{1\,32}$	$Z_{1\,j}^{1\,32}$
	Sector 2	$Z_{2\,1}^{1\,32}$	$Z_{2\,2}^{1\,32}$	$Z_{2\,3}^{1\,32}$	$Z_{2\,j}^{1\,32}$
	Sector 3	$Z_{3\,1}^{1\,32}$	$Z_{3\,2}^{1\,32}$	$Z_{3\,3}^{1\,32}$	$Z_{3\,j}^{1\,32}$
	…	$Z_{i\,1}^{1\,32}$	$Z_{i\,2}^{1\,32}$	$Z_{i\,3}^{1\,32}$	$Z_{i\,j}^{1\,32}$

$f_i^{1\,32}$ and x_i^1		Final demand	Total output
		Nation 32	
Province 1	Sector 1	$f_1^{1\,32}$	x_1^1
	Sector 2	$f_2^{1\,32}$	x_2^1
	Sector 3	$f_3^{1\,32}$	x_3^1
	…	$f_i^{1\,32}$	x_i^1

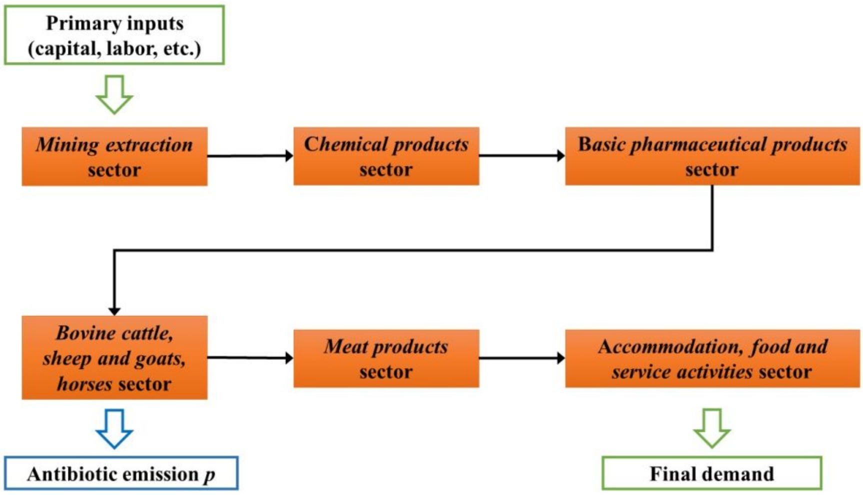
h_j^2, x_j^2, and p_j^2	Province 2			
	Sector 1	Sector 2	Sector 3	…
Primary input	h_1^2	h_2^2	h_3^2	h_j^2
Total input	x_1^2	x_2^2	x_3^2	x_j^2
Antibiotic emission	p_1^2	p_2^2	p_3^2	p_j^2

Figure SM2. Details for elements $Z_{i\,j}^{k\,t}$, $f_i^{k\,t}$, x_i^k, h_j^t, x_j^t, and p_j^t, taking $Z_{i\,j}^{1\,32}$, $f_i^{1\,32}$, x_i^1, h_j^2, x_j^2, and p_j^2 as examples.

Income-based and Consumption-based Accounting Framework

This study considers global supply chain drivers of agricultural antibiotic emissions in mainland China from both the supply and demand sides. First, the direct agricultural antibiotic emissions (aka production-based agricultural antibiotic emissions) of provinces in mainland China are estimated. Then the antibiotic emission footprints of each province/nation sector are quantified from the supply side via income-based accounting and from the demand side via consumption-based accounting. For example, a supply chain starts from the *mining extraction* sector, passes through the *chemical products*, *basic pharmaceutical products*, *bovine cattle, sheep and goats, houses*, *meat products* sectors, and ends at *accommodation, food, and service activities* sector (Figure SM3). The *bovine cattle, sheep and goats, houses* sector is the direct antibiotic emitter in the supply chain. The primary inputs are supplied to the *mining extraction* sector, then mining products are provided for downstream users for further production. The final products of the *accommodation, food, and service activities* sector are purchased by consumers.

From the supply side, the primary inputs (e.g., capital and labor) of the *mining extraction* sector enable downstream production, thereby indirectly enabling downstream antibiotic emission p. It means the income-based antibiotic emissions of the *mining extraction* sector is p. Namely, the contribution of the *mining extraction* sector from the supply side is p. From the demand side, the final demand of products from the *accommodation, food, and service activities* sector drives upstream production, thereby indirectly leading to upstream antibiotic emission p. It indicates that the consumption-based antibiotic emissions of the *accommodation, food, and service activities* sector is p. Thus, the contribution of the *accommodation, food, and service activities* sector from the demand side is p. In this example, the *mining extraction* sector and the *accommodation, food, and service activities* sector are critical supply-side driver and demand-side driver, respectively.



	Production-based (production-side)	Income-based (supply-side)	Consumption-based (demand-side)
Mining extraction	0	*p*	0
Chemical products	0	0	0
Basic pharmaceutical products	0	0	0
Bovine cattle, sheep and goats, horses	*p*	0	0
Meat products	0	0	0
Accommodation, food and service activities	0	0	*p*

Figure SM3. An example showing the income-based accounting and consumption-based accounting.

Agricultural Antibiotic Emission Inventory

According to the sectoral classification of the Global Trade Analysis Project (GTAP) database (version 10),[16] the *bovine cattle, sheep and goats, horses*, *animal products*, *raw milk*, and *fishing* sectors are directly related to agricultural antibiotic emissions. Based on sector definitions, the antibiotic emissions from beef and other cattle are considered as the antibiotic emissions of the *bovine cattle, sheep and goats, horses* sector; the antibiotic emissions from swine and poultry raising are considered as the antibiotic emissions of the *animal products* sector; the antibiotic emissions from cows are considered as the antibiotic emissions of the *raw milk* sector; the antibiotic emissions from aquaculture are considered as the antibiotic emissions of the *fishing* sector. The research purpose is to analyze global supply chain drivers of agricultural antibiotic emissions in mainland China. Therefore, the agricultural antibiotic emission inventory includes only direct emissions of agricultural sectors in mainland China. The direct antibiotic emissions in other nations and regions outside mainland China are considered as zero (As shown in Figure SM1).

Data Processing

To determine the antibiotic concentrations of animal feces and aquaculture water in each province, studies related to antibiotic detection of animal feces and aquaculture water are collected and reviewed. We selected the most suitable studies as data sources based on the following criteria. First, the data in each study should match the considered 15 antibiotics as closely as possible. Second, the studies should cover as many provinces as possible. Third, the focus year of each study should be around 2014. Under the circumstance that several studies focus on the same province, we calculated the average antibiotic concentrations of these studies as the data for this province. For provinces with no qualified data, we use the data of surrounding provinces as substitutes. If data for surrounding provinces are also missing, we then use default values for these provinces. The default values are obtained by averaging the data from the selected studies.

For livestock and poultry, the selected studies involve the Beijing-Tianjin-Hebei Region, Jiangsu, Zhejiang, Anhui, Jiangxi, Henan, Guangdong, Guangxi, Hainan, Guizhou, Yunnan, and Xinjiang, etc.[17-27] For aquaculture, the selected studies involve Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Hubei, Guangdong, and Guangxi, etc.[28-38]

Uncertainty and Sensitivity Analysis

The uncertainties in our study mainly come from the estimations of antibiotic emissions from China's agriculture. This study calculates agricultural antibiotic emission ranges with the ranges of parameters concerning animal feeding, livestock and poultry wastes, aquaculture scale, and antibiotic concentrations. For instance, the maximum value of animal waste is calculated using parameters that lead to the largest amount of animal waste based on practical experience and rational inference. The maximum value of antibiotic emissions is estimated according to the maximum value of animal wastes. Based on the minimum and maximum parameter values, we estimated the range of agricultural antibiotic emissions in China. Subsequently, we calculated the ranges of agricultural antibiotic emissions driven by the final demand and primary inputs of provinces and nations.

The matrix-based method is employed to analyze the sensitivity of the results in this study.[39] We first calculate the sensitivity coefficients, which are the change in antibiotic emissions caused by a marginal change in each parameter. The sensitivity coefficients are namely the coefficients on the variance of independent parameters in the error-propagation method.[40, 41] For antibiotic emissions driven by global final demand, the sensitivity coefficients for antibiotic emission intensity of province/nation sector i, each element T_{ij} in the intermediate transaction matrix **T** of the MRIO table, and the final demand of province/nation sector i are calculated using equations (27) to (29), respectively.

$$\frac{\partial c}{\partial e_i} = (\mathbf{L}f)_i \tag{27}$$

$$\frac{\partial c}{\partial T_{ij}} = \frac{(e\mathbf{L})_i(\mathbf{L}f)_j}{x_j} \tag{28}$$

$$\frac{\partial c}{\partial f_i} = (e\mathbf{L})_i \tag{29}$$

The notation **L** indicates the *Leontief Inverse* matrix, and $\mathbf{L} = (\mathbf{I} - \mathbf{A})^{-1}$; $\frac{\partial c}{\partial e_i}$, $\frac{\partial c}{\partial T_{ij}}$, and $\frac{\partial c}{\partial f_i}$ denote the sensitivity coefficients for antibiotic emission intensity, intermediate transaction matrix of the MRIO table, and final demand, respectively.

The calculations of elasticities further eliminate the effect caused by the statistical units of the parameters. For the antibiotic emissions driven by global final demand, the elasticities are defined as the ratios between the changing rate of antibiotic emissions driven by the final demand and the changing rate of the parameters. The dimensionless elasticities for antibiotic emission intensity of province/nation sector i, each element T_{ij} in the intermediate transaction matrix **T** of the MRIO table, and final demand of province/nation sector i are calculated using equations (30) to (32).

$$EL_{e_i}^{c} = (\mathbf{L}f)_i \times \frac{e_i}{c} \quad (30)$$

$$EL_{T_{ij}}^{c} = \frac{(e\mathbf{L})_i(\mathbf{L}f)_j}{x_j} \times \frac{T_{ij}}{c} \quad (31)$$

$$EL_{f_i}^{c} = (e\mathbf{L})_i \times \frac{f_i}{c} \quad (32)$$

The notations $EL_{e_i}^{c}$, $EL_{T_{ij}}^{c}$, and $EL_{f_i}^{c}$ represent the elasticities for antibiotic emission intensity, intermediate transaction matrix of the MRIO table, and final demand, respectively.

For antibiotic emissions enabled by primary inputs, the sensitivity coefficients for antibiotic emission intensity of province/nation sector *i*, each element T_{ij} in the intermediate transaction matrix **T** of the MRIO table, and primary inputs of province/nation sector *i* are calculated using equations (33) to (35).

$$\frac{\partial s}{\partial e_i} = (h\mathbf{G})_i \quad (33)$$

$$\frac{\partial s}{\partial T_{ij}} = \frac{(h\mathbf{G})_i(\mathbf{G}e)_j}{x_i} \quad (34)$$

$$\frac{\partial s}{\partial h_i} = (\mathbf{G}e)_i \quad (35)$$

The notation **G** indicates the *Gosh Inverse* matrix, and $\mathbf{G} = (\mathbf{I} - \mathbf{B})^{-1}$; $\frac{\partial s}{\partial e_i}$, $\frac{\partial s}{\partial T_{ij}}$, and $\frac{\partial s}{\partial h_i}$ represent the sensitivity coefficients for antibiotic emission intensity, intermediate transaction matrix of the MRIO table, and primary inputs, respectively.

The elasticities for antibiotic emission intensity of province/nation sector *i*, each element T_{ij} in the intermediate transaction matrix **T** of the MRIO table, and primary inputs of province/nation sector *i* are calculated using equations (36) to (38).

$$EL_{e_i}^{s} = (h\mathbf{G})_i \times \frac{e_i}{s} \quad (36)$$

$$EL_{T_{ij}}^{s} = \frac{(h\mathbf{G})_i(\mathbf{G}e)_j}{x_i} \times \frac{T_{ij}}{s} \quad (37)$$

$$EL_{h_i}^{s} = (\mathbf{G}e)_i \times \frac{h_i}{s} \quad (38)$$

The notations $EL_{e_i}^{s}$, $EL_{T_{ij}}^{s}$, and $EL_{h_i}^{s}$ denote the elasticities for antibiotic emission intensity, intermediate transaction matrix of the MRIO table, and primary inputs, respectively.

Supplemental Results

Comparison with studies on other environmental pressures

Major inter-provincial relationships for agricultural antibiotic emissions are different from those for other environmental pressures (e.g., CO_2 and mercury-related health impacts). From the demand side, critical inter-provincial connections for CO_2 emissions and mercury-related health impacts are mainly between western areas and eastern areas in China (Table S3).[42-44] From the supply side, the critical inter-provincial connections for mercury-related health impacts are mainly between inland areas[44]. In contrast, for agricultural antibiotic emissions, critical inter-provincial relationships are mainly within Central China, North China, and East China, especially between Central China and East China. This is related to dietary patterns that influence agricultural antibiotic emissions and population distribution. Populations are dense in eastern provinces, leading to heavy demand for foods. Moreover, people living in economically developed eastern provinces are likely to afford more animal and aquatic products, inducing large amounts of agricultural antibiotic emissions.

The sectoral hotspots for agricultural antibiotic emissions are also different from those for other environmental emissions (e.g., CO_2, $PM_{2.5}$, and mercury, Table S4). For example, the critical sectors driving greenhouse gas emissions from the demand side mainly include sectors providing energy, metals, foods, agricultural products, and services.[45-47] Critical primary suppliers are mainly sectors providing agricultural products, energy, minerals, transportation services, and other services.[46, 47] For air pollution such as $PM_{2.5}$, the construction sector, machinery and equipment sectors, transport sectors, metal sectors, food sectors, and energy sectors are critical sectors from the demand side.[48-50] In terms of atmospheric mercury emissions, critical demand-side sectors are primarily construction sectors, energy sectors, food sectors, machinery, and equipment sectors; and critical primary suppliers mainly include the resource mining and energy sectors.[51, 52] In contrast, critical demand-side sectors driving agricultural antibiotic emissions are mostly food and textile sectors, such as the *fishing*, *manufacture of food and tobacco*, *manufacture of textile wearing apparel, footwear, caps, leather, fur, feather and its products*, and *accommodation, food and service activities* sectors. In particular, the textile-related sectors are not crucial for CO_2, $PM_{2.5}$, and mercury emissions. However, they are important in driving agricultural antibiotic emissions. Furthermore, the critical primary suppliers enabling agricultural antibiotic emissions include the food-related sectors and chemical-related sectors, which are different from the critical primary suppliers for greenhouse gas, $PM_{2.5}$, and mercury emissions. This indicates that the hotspots for trade-related policies in reducing agricultural antibiotic emissions are unique and not covered in the findings of previous studies. Thus, the findings of this study provide specific hotspots for reducing agricultural antibiotic emissions.

Sensitivity analysis

We evaluated the sensitivity of the results to all the parameters by calculating their elasticities. Most of the parameters show small elasticities (Figures S9 and S10), indicating low sensitivity for the results. For antibiotic emission intensity, the parameter of the *fishing* sector in Hubei has the highest elasticity (0.187). This means that, if the antibiotic emission intensity of the *fishing* sector in Hubei changes by 10%, the agricultural antibiotic emissions driven by the final demand or enabled by primary inputs will change by 1.87%. For the final demand, the parameter of the *fishing* sector in Hubei has the largest elasticity (0.074). For the intermediate transaction matrix, the direct input of the *fishing* sector in Hubei for unitary output of the *manufacture of food and tobacco* sector in Hubei has the largest elasticity (0.037). For primary inputs, the parameter of the *fishing* sector in Hubei has the largest elasticity (0.118). Full results of sensitivity analysis for all the parameters are shown in Data S20-27 in the Supporting Data.

Supplemental Figures

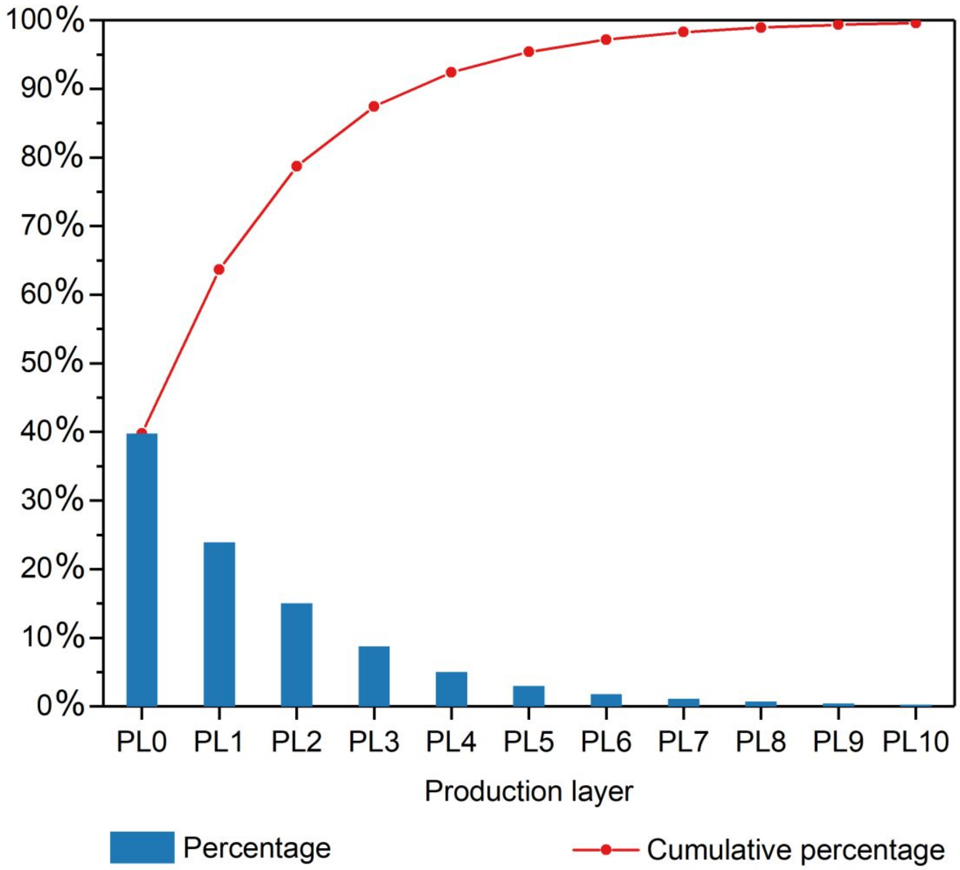


Figure S1. Contribution of top 10 production layers to agricultural antibiotic emissions. The line shows cumulative contribution of top production layers, and the bar shows the contribution of each production layer. The "PL" represents production layer.

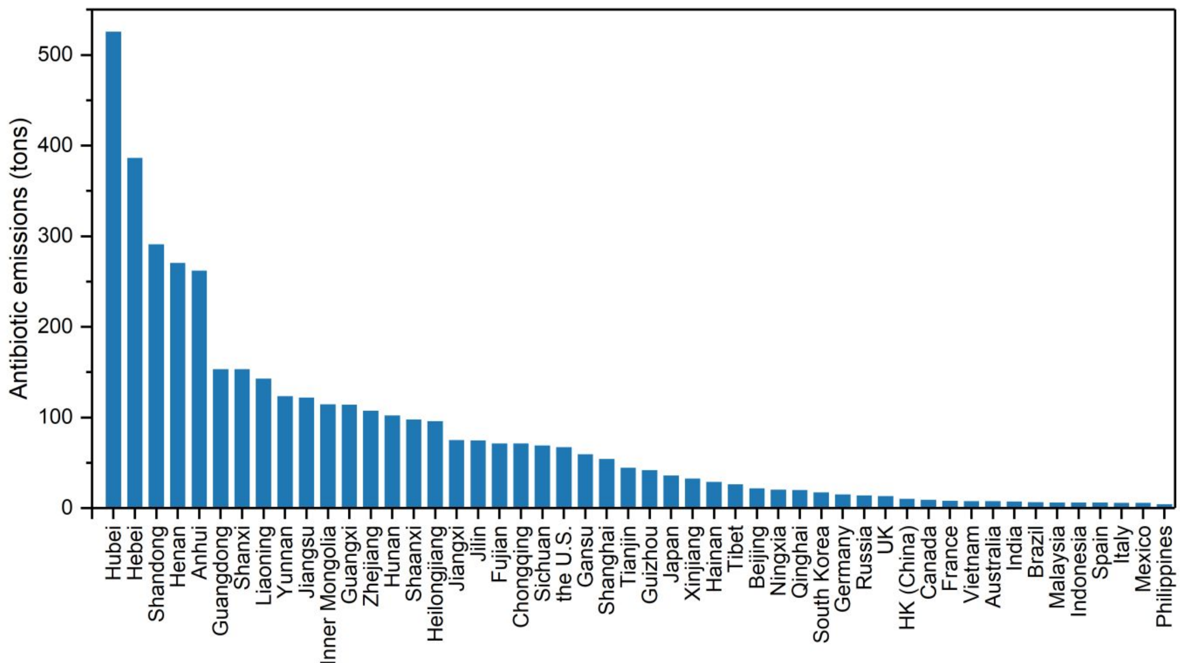


Figure S2. The top 50 provinces/nations driving China's agricultural antibiotic emissions through final demand. The "HK (China)" represents Hong Kong (China).

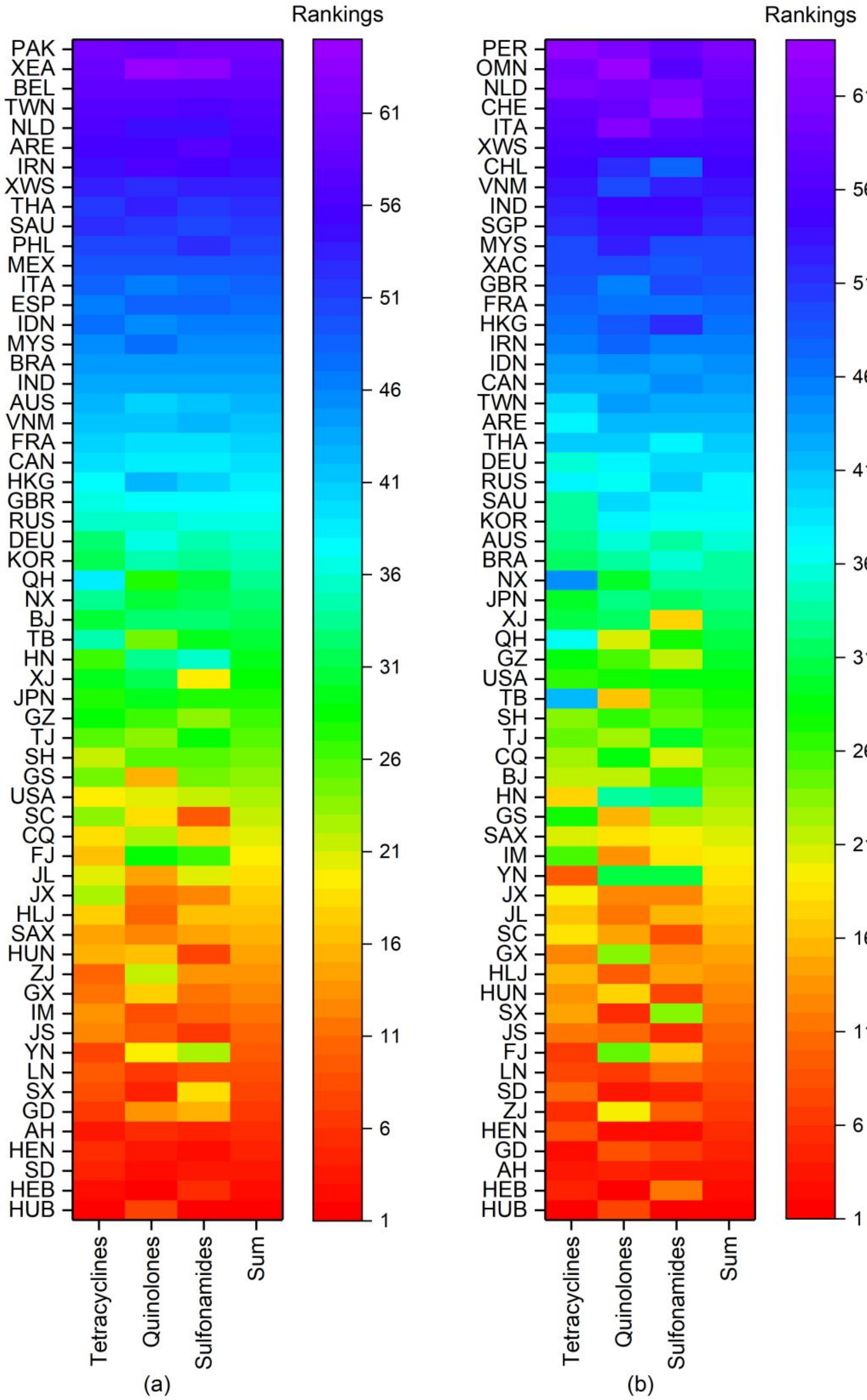


Figure S3. Rankings of provinces/nations by China's agricultural antibiotic emissions driven by the final demand of each province/nation (a) and enabled by primary inputs of each province/nation (b). Full names of province/nation codes are shown in Table S2.

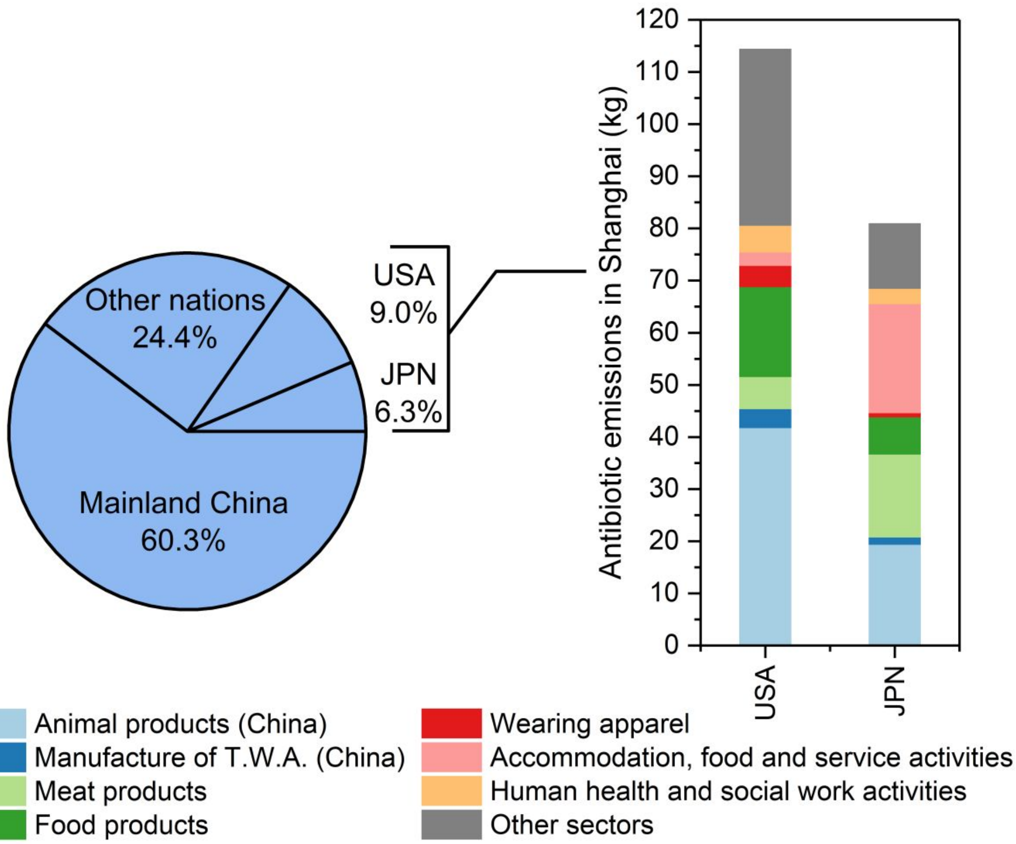


Figure S4. Contributions of critical final consumers to agricultural antibiotic emissions in Shanghai. The bar graph shows the amounts of agricultural antibiotic emissions driven by critical final consumers. The colors of bars indicate sectors providing final products. USA represents the U.S. and JPN represents Japan.

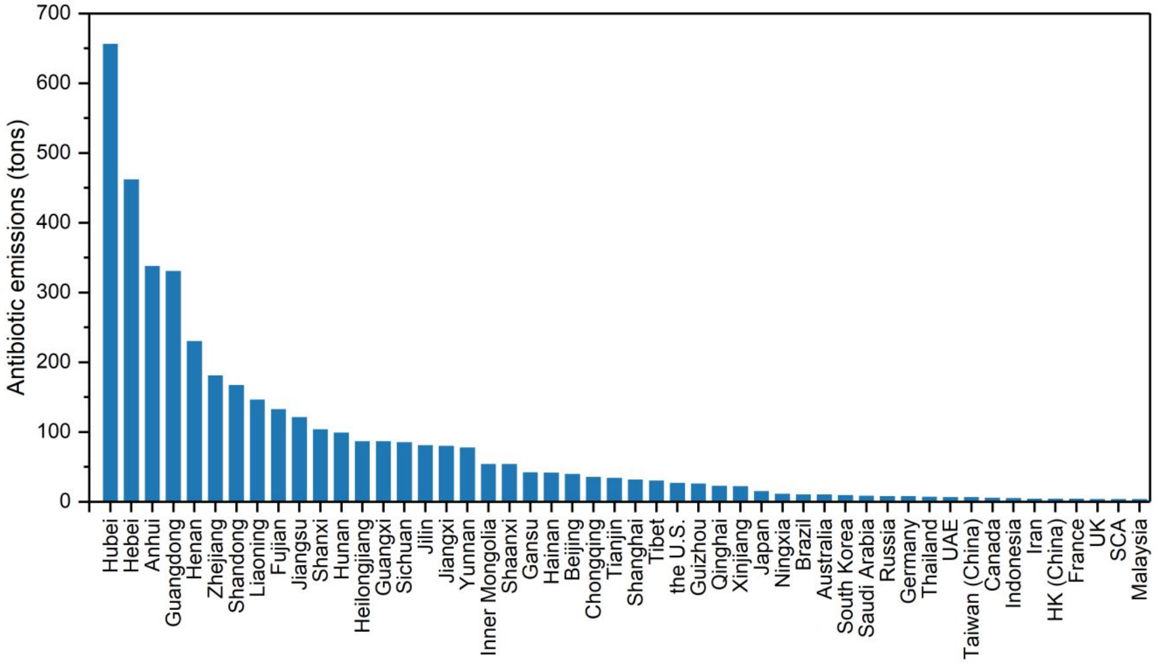


Figure S5. The top 50 provinces/nations enabling China's agricultural antibiotic emissions through primary inputs. The "UAE" represents the United Arab Emirates; "HK (China)" represents Hong Kong (China); and "SCA" represents South Central Africa.

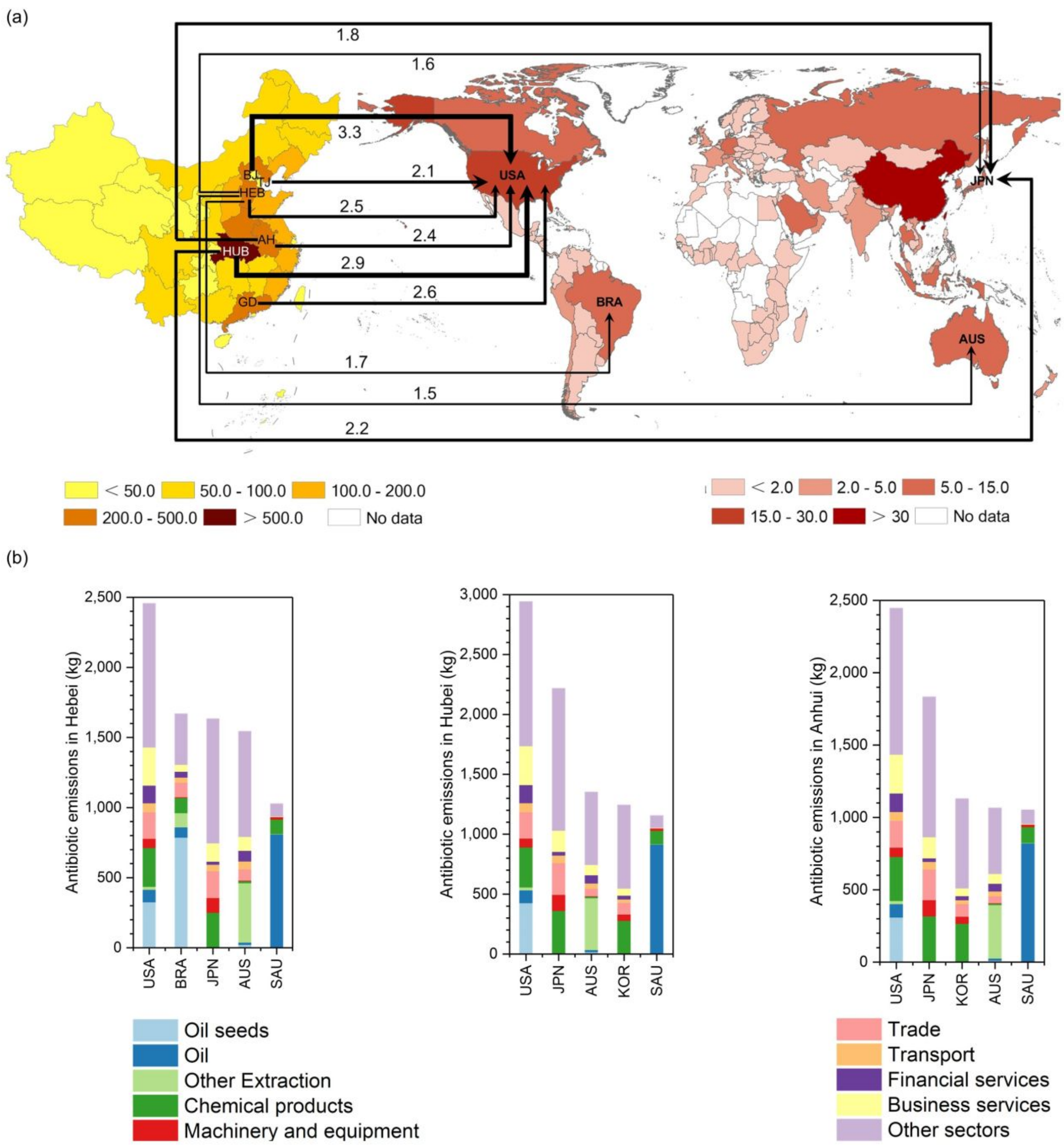


Figure S6. Critical international primary suppliers enabling agricultural antibiotic emissions in mainland China. Panel (a) shows major influences of critical primary suppliers on provinces in China. The colors of provinces/nations in the map indicate agricultural antibiotic emissions in China (tons) enabled by the primary inputs of provinces/nations. The arrows start from direct emitters of agricultural antibiotics and end at primary suppliers. The number and width of the arrows indicate values of antibiotic emissions enabled by primary inputs (tons). Panel (b) shows the amounts of agricultural antibiotic emissions in Hebei, Hubei, and Anhui enabled by critical international primary suppliers. BJ, TJ, HEB, AH, HUB, and GD represent Beijing, Tianjin, Hebei, Anhui, Hubei, and Guangdong. respectively. USA, BRA, JPN, AUS, SAU, and KOR represent the U.S., Brazil, Japan, Australia, Saudi Arabia, and South Korea, respectively.

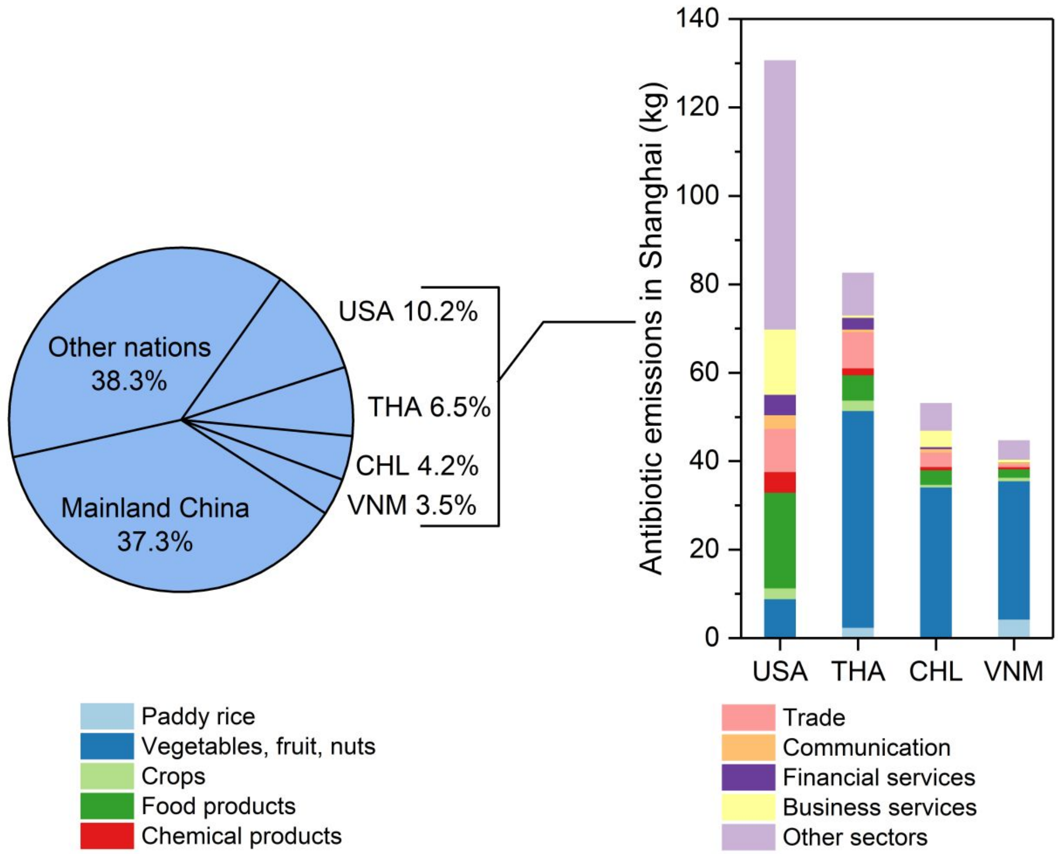


Figure S7. Contributions of critical primary suppliers to agricultural antibiotic emissions in Shanghai. The bar graph shows the amount of agricultural antibiotic emissions enabled by primary inputs of major nation sectors. USA, THA, CHL, and VNM represent the U.S., Thailand, Chile, and Vietnam, respectively.

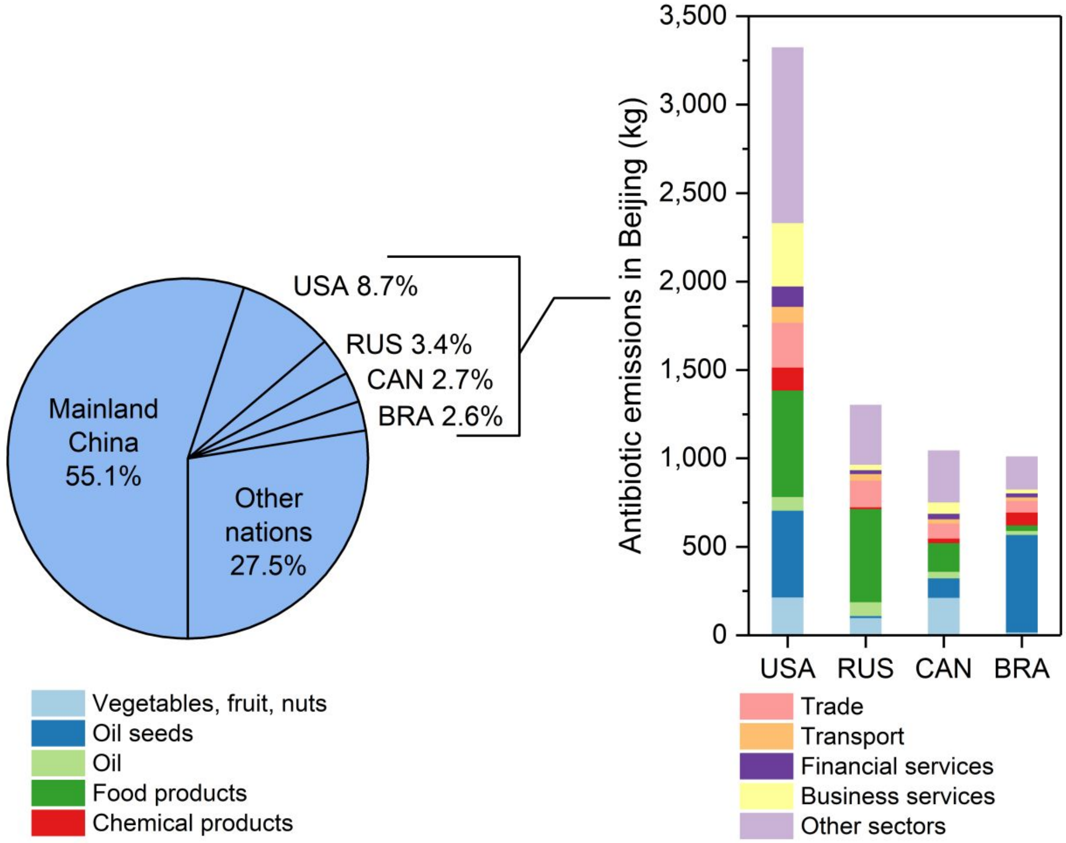
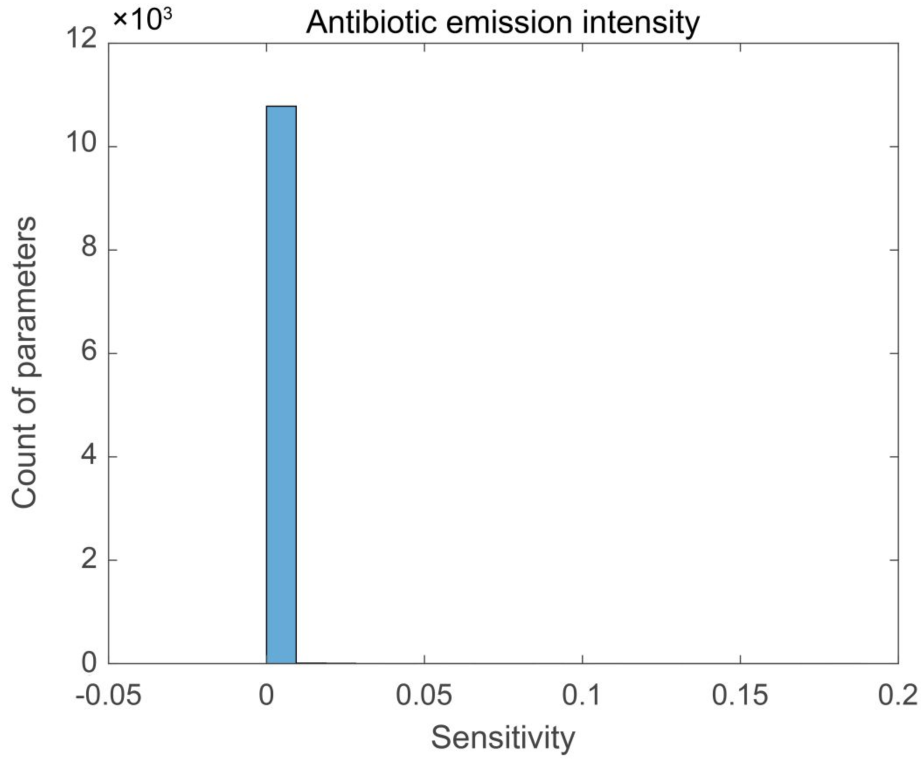


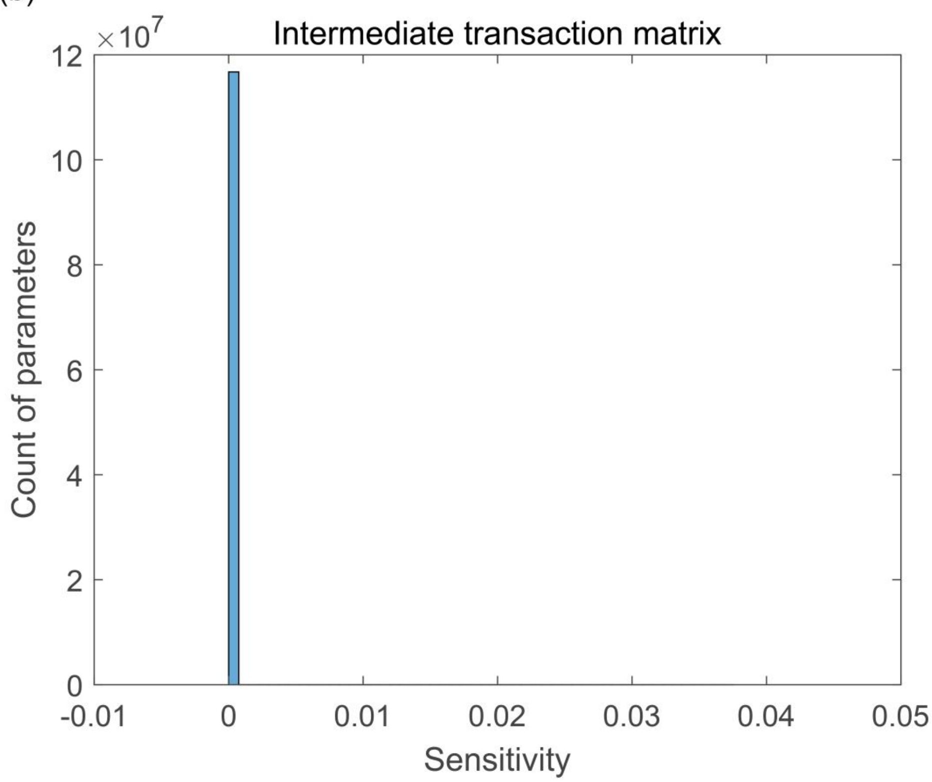
Figure S8. Contributions of critical primary suppliers to agricultural antibiotic emissions in Beijing. The bar graph shows the amount of agricultural antibiotic emissions enabled by primary inputs of major nation sectors. USA, RUS, CAN, and BRA represent the U.S., Russia, Canada, and Brazil, respectively.

(a)



×10³
Antibiotic emission intensity
Count of parameters
Sensitivity
12
10
8
6
4
2
0
-0.05
0
0.05
0.1
0.15
0.2

(b)



×10⁷
Intermediate transaction matrix
Count of parameters
Sensitivity
12
10
8
6
4
2
0
-0.01
0
0.01
0.02
0.03
0.04
0.05

(c)

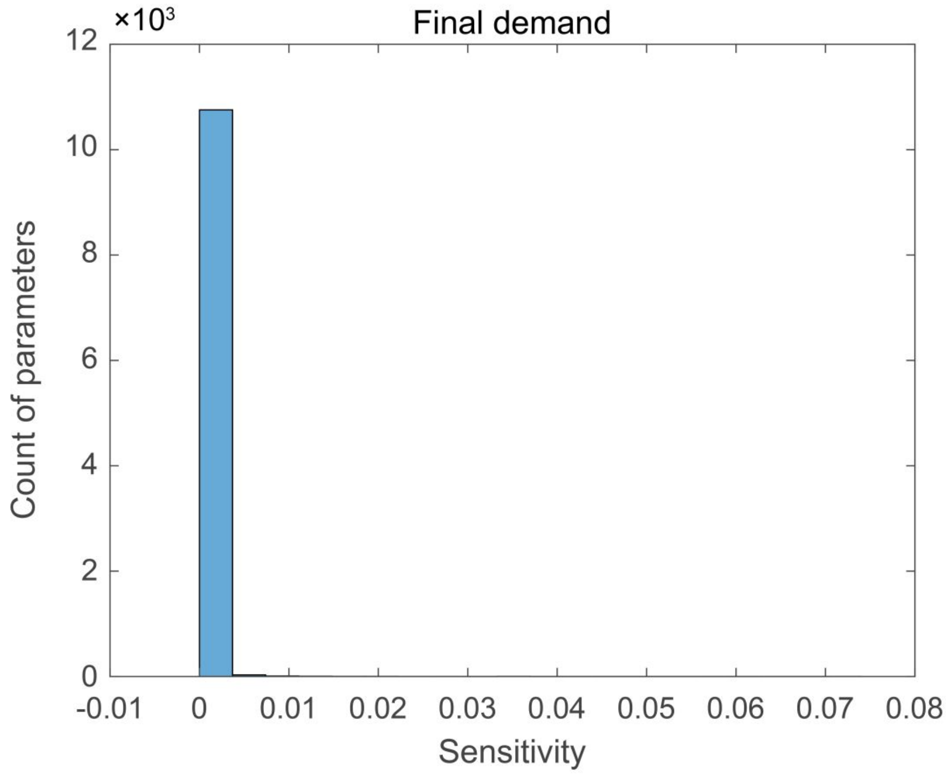
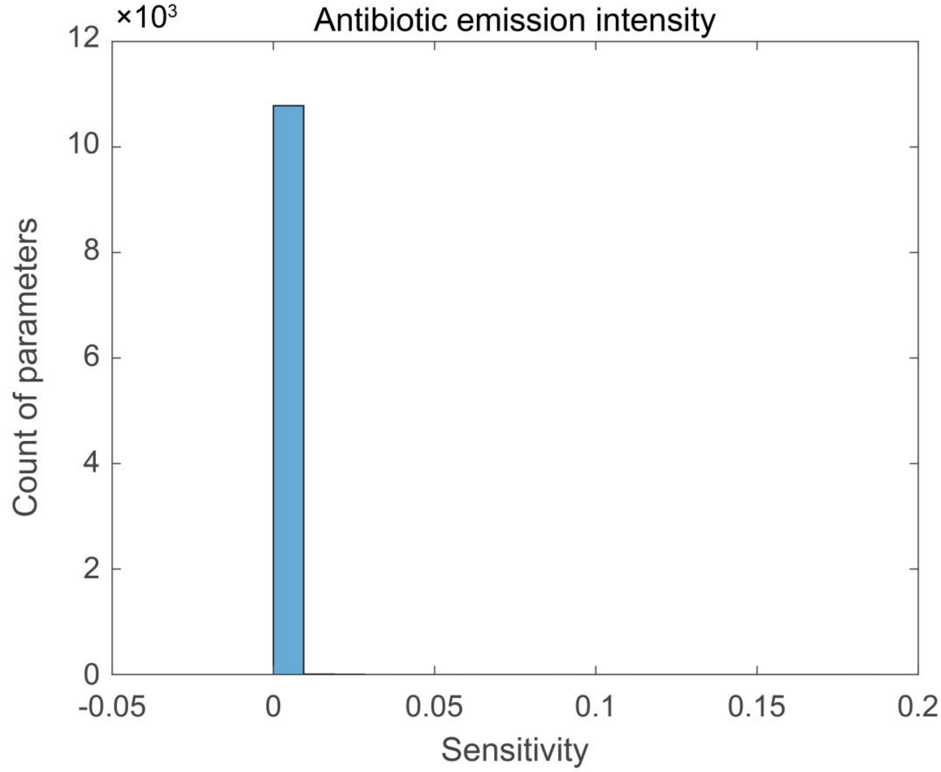


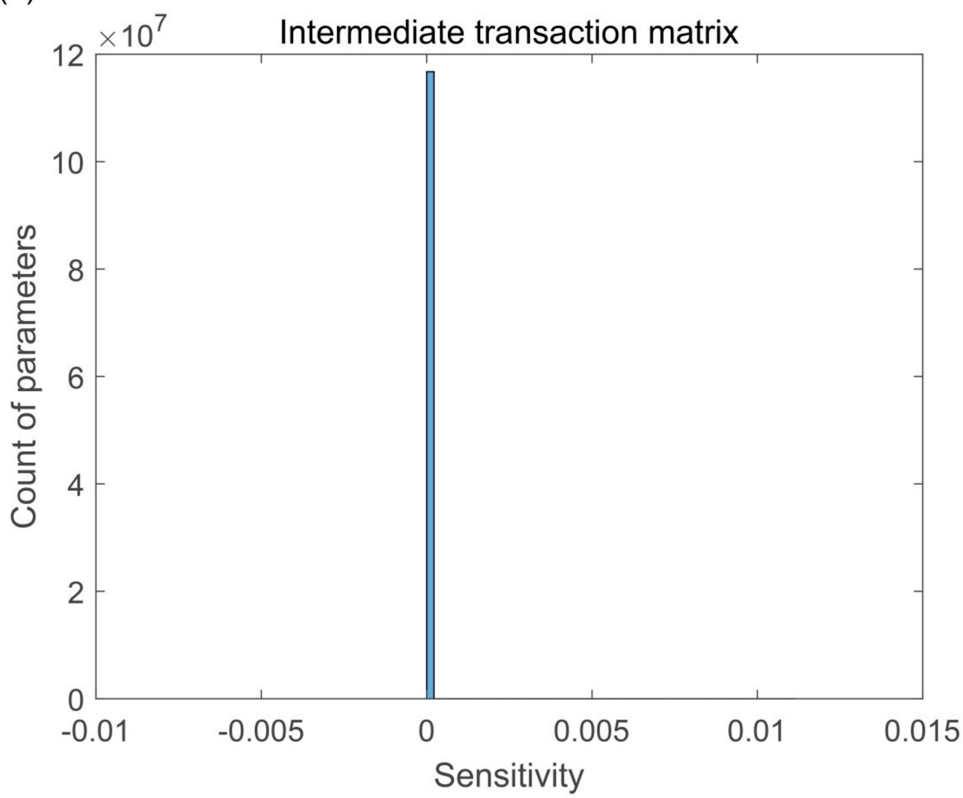
Figure S9. Distributions of the elasticities of agricultural antibiotic emissions driven by the final demand to all the parameters. Panel (a) shows the elasticities of the parameters in antibiotic emission intensity; panel (b) shows the elasticities of the parameters in the intermediate transaction matrix; and panel (c) shows the elasticities of parameters in final demand. The X-axis represents the elasticities, and the Y-axis represents the count of parameters.

(a)



Antibiotic emission intensity
×10³
Count of parameters
Sensitivity
12
10
8
6
4
2
0
-0.05
0
0.05
0.1
0.15
0.2

(b)



Intermediate transaction matrix
×10⁷
Count of parameters
Sensitivity
12
10
8
6
4
2
0
-0.01
-0.005
0
0.005
0.01
0.015

(c)

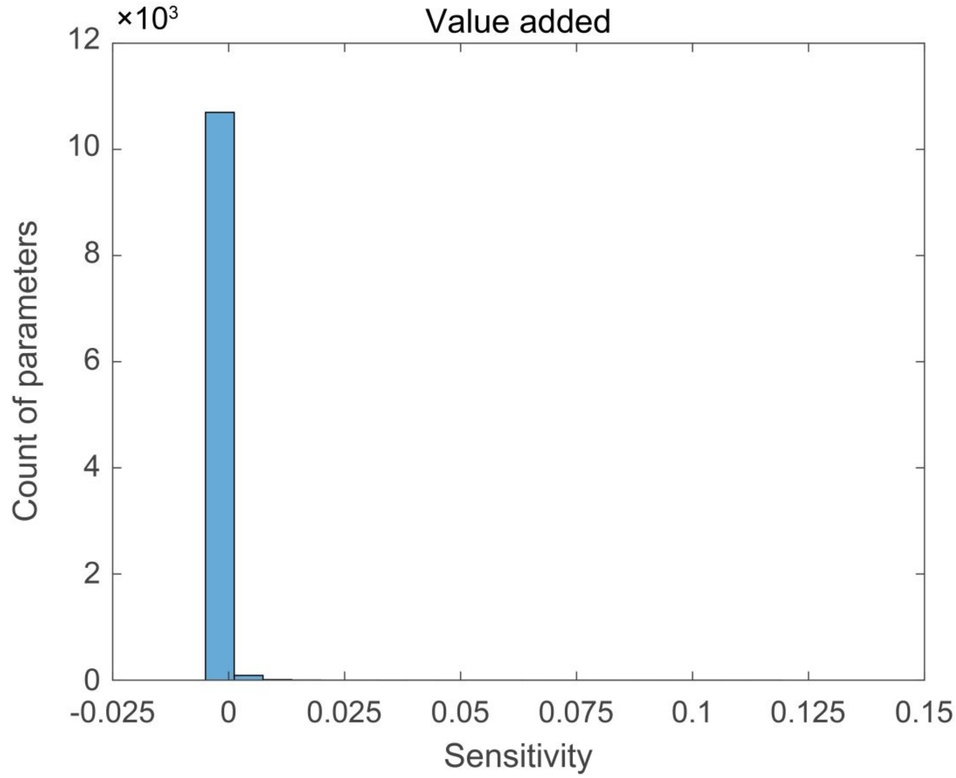


Figure S10. Distributions of the elasticities of agricultural antibiotic emissions enabled by primary inputs to all the parameters. Panel (a) shows the elasticities of the parameters in antibiotic emission intensity; panel (b) shows the elasticities of the parameters in the intermediate transaction matrix; and panel (c) shows the elasticities of parameters in primary inputs. The X-axis represents the elasticities, and the Y-axis represents the count of parameters.

Supplemental Tables

Table S1. Antibiotics considered in this study.

Categories	Antibiotics	Abbreviations
Sulfonamides	Sulfadiazine	SDZ
	Sulfamethoxazole	SMX
	Sulfadimidine	SM2
	Sulfamonomethoxine	SMM
	Sulfathiazole	STZ
	Sulfadimethoxine	SDM
	Sulfamerazine	SMR
Tetracyclines	Tetracycline	TC
	Oxytetracycline	OTC
	Chlortetracycline	CTC
	Doxycycline	DOC
Quinolones	Norfloxacin	NFC
	Ofloxacin	OFC
	Ciprofloxacin	CFC
	Enrofloxacin	EFC

Table S2. Codes and corresponding full names of China's provinces and nations/regions.

Indexes	Codes	Full names
1	BJ	Beijing
2	TJ	Tianjin
3	HEB	Hebei
4	SX	Shanxi
5	IM	Inner Mongolia
6	LN	Liaoning
7	JL	Jilin
8	HLJ	Heilongjiang
9	SH	Shanghai
10	JS	Jiangsu
11	ZJ	Zhejiang
12	AH	Anhui
13	FJ	Fujian
14	JX	Jiangxi
15	SD	Shandong
16	HEN	Henan
17	HUB	Hubei
18	HUN	Hunan
19	GD	Guangdong
20	GX	Guangxi
21	HN	Hainan
22	CQ	Chongqing
23	SC	Sichuan
24	GZ	Guizhou
25	YN	Yunnan
26	TB	Tibet
27	SAX	Shaanxi
28	GS	Gansu
29	QH	Qinghai
30	NX	Ningxia
31	XJ	Xinjiang
32	AUS	Australia
33	NZL	New Zealand
34	XOC	Rest of Oceania
35	HKG	Hong Kong (China)
36	JPN	Japan
37	KOR	South Korea
38	MNG	Mongolia
39	TWN	Taiwan (China)
40	XEA	Rest of East Asia
41	BRN	Brunei Darussalam
42	KHM	Cambodia
43	IDN	Indonesia

44	LAO	Lao People's Democratic Republic
45	MYS	Malaysia
46	PHL	Philippines
47	SGP	Singapore
48	THA	Thailand
49	VNM	Vietnam
50	XSE	Rest of Southeast Asia
51	BGD	Bangladesh
52	IND	India
53	NPL	Nepal
54	PAK	Pakistan
55	LKA	Sri Lanka
56	XSA	Rest of South Asia
57	CAN	Canada
58	USA	United States of America
59	MEX	Mexico
60	XNA	Rest of North America
61	ARG	Argentina
62	BOL	Bolivia
63	BRA	Brazil
64	CHL	Chile
65	COL	Colombia
66	ECU	Ecuador
67	PRY	Paraguay
68	PER	Peru
69	URY	Uruguay
70	VEN	Venezuela
71	XSM	Rest of South America
72	CRI	Costa Rica
73	GTM	Guatemala
74	HND	Honduras
75	NIC	Nicaragua
76	PAN	Panama
77	SLV	El Salvador
78	XCA	Rest of Central America
79	DOM	Dominican Republic
80	JAM	Jamaica
81	PRI	Puerto Rico
82	TTO	Trinidad and Tobago
83	XCB	Rest of Caribbean
84	AUT	Austria
85	BEL	Belgium
86	BGR	Bulgaria
87	HRV	Croatia
88	CYP	Cyprus
89	CZE	Czech Republic

90	DNK	Denmark
91	EST	Estonia
92	FIN	Finland
93	FRA	France
94	DEU	Germany
95	GRC	Greece
96	HUN	Hungary
97	IRL	Ireland
98	ITA	Italy
99	LVA	Latvia
100	LTU	Lithuania
101	LUX	Luxembourg
102	MLT	Malta
103	NLD	Netherlands
104	POL	Poland
105	PRT	Portugal
106	ROU	Romania
107	SVK	Slovakia
108	SVN	Slovenia
109	ESP	Spain
110	SWE	Sweden
111	GBR	United Kingdom
112	CHE	Switzerland
113	NOR	Norway
114	XEF	Rest of European Free Trade Association
115	ALB	Albania
116	BLR	Belarus
117	RUS	Russia
118	UKR	Ukraine
119	XEE	Rest of Eastern Europe
120	XER	Rest of Europe
121	KAZ	Kazakhstan
122	KGZ	Kyrgyzstan
123	TJK	Tajikistan
124	XSU	Rest of Former Soviet Union
125	ARM	Armenia
126	AZE	Azerbaijan
127	GEO	Georgia
128	BHR	Bahrain
129	IRN	Islamic Republic of Iran
130	ISR	Israel
131	JOR	Jordan
132	KWT	Kuwait
133	OMN	Oman
134	QAT	Qatar
135	SAU	Saudi Arabia

136	TUR	Turkey
137	ARE	United Arab Emirates
138	XWS	Rest of Western Asia
139	EGY	Egypt
140	MAR	Morocco
141	TUN	Tunisia
142	XNF	Rest of North Africa
143	BEN	Benin
144	BFA	Burkina Faso
145	CMR	Cameroon
146	CIV	Cote d'Ivoire
147	GHA	Ghana
148	GIN	Guinea
149	NGA	Nigeria
150	SEN	Senegal
151	TGO	Togo
152	XWF	Rest of Western Africa
153	XCF	Central Africa
154	XAC	South Central Africa
155	ETH	Ethiopia
156	KEN	Kenya
157	MDG	Madagascar
158	MWI	Malawi
159	MUS	Mauritius
160	MOZ	Mozambique
161	RWA	Rwanda
162	TZA	United Republic of Tanzania
163	UGA	Uganda
164	ZMB	Zambia
165	ZWE	Zimbabwe
166	XEC	Rest of Eastern Africa
167	BWA	Botswana
168	NAM	Namibia
169	ZAF	South Africa
170	XSC	Rest of South African Customs Union
171	XTW	Rest of the World

532

Table S3. Critical interregional connections for China's environmental pressures in previous studies

Environmental pressures	Studied Year	Interregional connections from the demand side	Interregional connections from the supply side	References
CO_2	2012	Yangtze River Delta, Pearl River Delta, Beijing, Tianjin, and Hebei in China → The U.S., Hong Kong (China), and Japan	/	Yang et al., 2020[45]
	2007, 2010, 2012	Northwest China → Central China and Central Coast of China (2012) Central China → Central Coast of China (2012) North China → Central China (2012) China → North America and Western Europe (2007) China → Latin America and the Caribbean (2012)	/	Mi et al., 2017[42]
	2007	Central and Northwest China → Beijing, Tianjin, Central Coast and South Coast of China	/	Feng et al., 2013[43]
Mercury related health impacts	2010	Shanghai, Southern Jiangsu, and Northern Zhejiang → the U.S., Western Germany, the United Kingdom Sichuan and Chongqing → Yellow River, Weihe River catchment and Xinjiang Yangtze River Delta → Central China	Southwest China (including Chengdu, Chongqing, the border of Yunnan and Guizhou, and Eastern Guangxi) → Japan, Indonesia, India, Australia, Latin America, and Northwest Iran Sichuan and Chongqing → Yellow River catchment, Southern Lanzhou, Qinghai, and Xinjiang	Li et al., 2020[44]

Note: The arrows indicate driven relationships between regions. Regions on the left-hand side of the arrows represent where the environmental pressures are directly generated; and the corresponding regions driving environmental pressures are on the right-hand side of the arrows.

Table S4. Sectoral hotspots for environmental pressures in previous studies

Environmental pressures	Studied Year	Studied Area	Critical sectors from the demand side	Critical sectors from the supply side	References
CO_2	2012	China	Production and supply of electricity, steam, gas, and water sector; smelting and processing of metals sector; nonmetallic mineral products sector; petroleum refining, coking, and processing of nuclear fuel sector; chemical products sector	/	Yang et al., 2020[45]
Greenhouse gas	1995-2009	The U.S.	Electricity, gas and water supply sector; food, beverages and tobacco sector; health and social work sector; public administration and defense & compulsory social security sector	Electricity, gas and water supply sector; agriculture, hunting, forestry and fishing sector; mining and quarrying sector; inland transport sector; renting of machinery & equipment and other business activities sector	Liang et al., 2016[46]
	1995-2009	The world	Electricity sector in the U.S.; agriculture sector in China; agriculture sector of India	Electricity sector in the U.S.; electricity sector in China; agriculture sector in China; mining sector in China; agriculture sector in India; renting and other business sector in the U.S.; mining sector in the U.S.	Liang et al., 2017[47]
$PM_{2.5}$	2007	The world	Construction sector; service sector; machinery and equipment sector	/	Meng et al., 2016[48]
BC, OC, primary $PM_{2.5}$, SO_2, NO_x,	2004-2011	The world	Construction sector, machinery and equipment	/	Meng et al., 2019[49]

NH_3, and NMVOCs			sector, and transport sector in East Asia; metal sector, food products sector, and energy sector in South Asia		
SO_2, NO_x, $PM_{2.5}$, and VOC	2010	China	Construction sector; equipment, machinery, and devices manufacturing sectors; food and tobacco sector; chemical sector; public administration, education, culture, and associated sectors	/	Huo et al., 2014[50]
Mercury	2015	The world	electricity, gas, water supply, sewerage, waste, and remediation service sector in China, India, and rest of the world; other mineral in rest of the world; wholesale and retail trade in rest of the world	Mining and quarrying of non-energy-producing product sector in Indonesia, Columbia, Peru, and rest of the world; electricity, gas, water supply, sewerage, waste, and remediation service sector in China and rest of the world; other mineral sector in China; Basic metals in China.	Qi et al., 2019[51]
	2007	China	Construction sector; electrical equipment sector; general and special equipment sector; food and tobacco sector; transport equipment sector	/	Liang et al., 2014[52]

Notes: $PM_{2.5}$ represents fine particulate matter with an aerodynamic diameter of 2.5 µm or less; SO_2 represents sulfur dioxide; NO_x represents nitrogen oxides; NH_3 represents ammonia; BC represents black carbon; OC represents organic carbon; NMVOCs represents non-methane volatile organic compounds; and VOC represents volatile organic compounds.

Supplemental References

(1) Bao, W.; Liu, J.; An, J.; Xie, G. Discussion on value-taking of relative parameters for assessment of livestock and poultry excrement resource in China (in Chinese with English abstract). *Transactions of the Chinese Society of Agricultural Engineering* **2018,** *34*, (24), 314-322.

(2) Lu, W. Waste Recycling System Material Metabolism Analysis Model and Its Application (in Chinese with English abstract). PhD, Tsinghua University, 2010.

(3) Tan, L. Growth characteristics of pigs in nursery and feeding management (in Chinese). *Chinese Journal of Animal Husbandry and Veterinary Medicine* **2019**, (11), 129.

(4) Ministry of Agriculture of the P. R. China, *2014 China Agriculture Statistical Report (in Chinese)*. China Agriculture Press: Beijing, 2015.

(5) Ministry of Agriculture of the P. R. China; Chinese Academy of Agricultural Sciences; Ministry of Ecological Environment, The first national survey of pollution sources: Handbook of pollution discharge coefficients for livestock and poultry farming (in Chinese). In 2009.

(6) Ministry of Agriculture of the P.R. China, *2015 China animal husbandry and veterinary yearbook (in Chinese)*. China Agriculture Press: Beijing, 2015.

(7) Wang, Z.; Yang, B. Best age and weight of meat poultry (in Chinese). *Journal of Rural animal-Production Technology* **2013**, (10), 68-69.

(8) Guo, W. Effects of Different Feeding Methods on Meat Performance and Plasma Biochemical Prameters of Eliminated Laying Hens (in Chinese with English abstract). Master, Yangzhou University, 2018.

(9) Zhang, Y.; Shao, L.; Leng, S.; Pang, L.; Jiang, K.; Lixia, W. Assessment of livestock and poultry excrement resources in Shandong and its fertilizer and energy utilization potential (in Chinese with English abstract). *China Biogas* **2019,** *37*, (3), 93-99.

(10) Yang, N. Current situation and development trends of chinese egg industry in 2014 (in Chinese with English abstract). *Chinese Journal of Animal Science* **2015,** *51*, (02),

32-37.

(11) Wu, S. The spatial and temporal change of nitrogen and phosphorus produced by livestock and poultry & their effects on agricultural non-point pollution in China (in Chinese with English abstract). PhD, Chinese Academy of Agricultural Sciences, 2005.

(12) Shen, X.; Huang, G.; Yang, Z.; Han, L. Compositional characteristics and energy potential of Chinese animal manure by type and as a whole. *Appl. Energ.* **2015,** *160*, 108-119.

(13) Zhang, M.; He, L. Y.; Liu, Y. S.; Zhao, J. L.; Liu, W. R.; Zhang, J. N.; Chen, J.; He, L. K.; Zhang, Q. Q.; Ying, G. G. Fate of veterinary antibiotics during animal manure composting. *Sci. Total Environ.* **2019,** *650*, (Pt 1), 1363-1370.

(14) Zhang, M.; Liu, Y. S.; Zhao, J. L.; Liu, W. R.; He, L. Y.; Zhang, J. N.; Chen, J.; He, L. K.; Zhang, Q. Q.; Ying, G. G. Occurrence, fate and mass loadings of antibiotics in two swine wastewater treatment systems. *Sci. Total Environ.* **2018,** *639*, 1421-1431.

(15) Fisheries Bureau of Ministry of Agriculture of the P. R. China, *2015 China Fishery Statistical Yearbook (in Chinese)*. China Agriculture Press: Beijing, 2015.

(16) Aguiar, A.; Chepeliev, M.; Corong, E.; McDougall, R.; van der Mensbrugghe, D. The GTAP Data Base: Version 10. *Journal of Global Economic Analysis* **2019,** *4*, (1), 1-27.

(17) Wang, J.; Ben, W.; Yang, M.; Zhang, Y.; Qiang, Z. Dissemination of veterinary antibiotics and corresponding resistance genes from a concentrated swine feedlot along the waste treatment paths. *Environ Int* **2016,** *92-93*, 317-23.

(18) Li, C.; Li, Y.; Li, X.; Ma, X.; Ru, S.; Qiu, T.; Lu, A. Veterinary antibiotics and estrogen hormones in manures from concentrated animal feedlots and their potential ecological risks. *Environ. Res.* **2021,** *198*, 110463.

(19) Liu, H.; Pu, C.; Yu, X.; Sun, Y.; Chen, J. Removal of tetracyclines, sulfonamides, and quinolones by industrial-scale composting and anaerobic digestion processes. *Environ Sci Pollut Res Int* **2018,** *25*, (36), 35835-35844.

(20) Zhou, X.; Wang, J.; Lu, C.; Liao, Q.; Gudda, F. O.; Ling, W. Antibiotics in animal manure and manure-based fertilizers: Occurrence and ecological risk assessment.

Chemosphere **2020,** *255*, 127006.

(21) Xie, W.-Y.; Yang, X.-P.; Li, Q.; Wu, L.-H.; Shen, Q.-R.; Zhao, F.-J. Changes in antibiotic concentrations and antibiotic resistome during commercial composting of animal manures. *Environ. Pollut.* **2016,** *219*, 182-190.

(22) Li, Q. Investigation on pollution situation of heavy metals, antibiotics and antibiotic resitance genes in composts and animal manures (in Chinese with English abstract). Nanjing Agricultural University, 2016.

(23) Liu, C.; Li, X.; Zheng, S.; Kai, Z.; Jin, T.; Shi, R.; Huang, H.; Zheng, X. Effects of wastewater treatment and manure application on the dissemination of antimicrobial resistance around swine feedlots. *J. Clean. Prod.* **2021,** *280*, 123794.

(24) Chu, Y. Determination of antibiotics in manure and their degradation during manure composting (in Chinese with English abstract). Zhejiang University of Science and Technology, 2018.

(25) Zhang, H.; Luo, Y.; Wu, L.; Huang, Y.; Christie, P. Residues and potential ecological risks of veterinary antibiotics in manures and composts associated with protected vegetable farming. *Environ. Sci. Pollut. Res.* **2015,** *22*, (8), 5908-5918.

(26) Zhi, S.; Shen, S.; Zhou, J.; Ding, G.; Zhang, K. Systematic analysis of occurrence, density and ecological risks of 45 veterinary antibiotics: Focused on family livestock farms in Erhai Lake basin, Yunnan, China. *Environ. Pollut.* **2020,** *267*, 115539.

(27) Liu, J. Distribution and pollution levels of antibiotics in typical point emission sources in northern Xinjiang (in Chinese with English abstract). Shihezi University, 2016.

(28) Li, J. Y.; Wen, J.; Chen, Y.; Wang, Q.; Yin, J. Antibiotics in cultured freshwater products in Eastern China: Occurrence, human health risks, sources, and bioaccumulation potential. *Chemosphere* **2021,** *264*, (Pt 1), 128441.

(29) Han, Q. F.; Zhang, X. R.; Xu, X. Y.; Wang, X. L.; Yuan, X. Z.; Ding, Z. J.; Zhao, S.; Wang, S. G. Antibiotics in marine aquaculture farms surrounding Laizhou Bay, Bohai Sea: Distribution characteristics considering various culture modes and organism species. *Sci. Total Environ.* **2021,** *760*, 143863.

(30) Han, Q. F.; Zhao, S.; Zhang, X. R.; Wang, X. L.; Song, C.; Wang, S. G. Distribution, combined pollution and risk assessment of antibiotics in typical marine aquaculture farms surrounding the Yellow Sea, North China. *Environ Int* **2020,** *138*, 105551.

(31) Chen, H.; Liu, S.; Xu, X. R.; Liu, S. S.; Zhou, G. J.; Sun, K. F.; Zhao, J. L.; Ying, G. G. Antibiotics in typical marine aquaculture farms surrounding Hailing Island, South China: occurrence, bioaccumulation and human dietary exposure. *Mar. Pollut. Bull.* **2015,** *90*, (1-2), 181-7.

(32) Wang, Z.; Han, M.; Li, E.; Liu, X.; Wei, H.; Yang, C.; Lu, S.; Ning, K. Distribution of antibiotic resistance genes in an agriculturally disturbed lake in China: Their links with microbial communities, antibiotics, and water quality. *J. Hazard. Mater.* **2020,** *393*, 122426.

(33) Zhong, Y.; Chen, Z. F.; Dai, X.; Liu, S. S.; Zheng, G.; Zhu, X.; Liu, S.; Yin, Y.; Liu, G.; Cai, Z. Investigation of the interaction between the fate of antibiotics in aquafarms and their level in the environment. *J. Environ. Manage.* **2018,** *207*, 219-229.

(34) Chen, H.; Liu, S.; Xu, X. R.; Diao, Z. H.; Sun, K. F.; Hao, Q. W.; Liu, S. S.; Ying, G. G. Tissue distribution, bioaccumulation characteristics and health risk of antibiotics in cultured fish from a typical aquaculture area. *J. Hazard. Mater.* **2018,** *343*, 140-148.

(35) Song, C.; Zhang, C.; Fan, L.; Qiu, L.; Wu, W.; Meng, S.; Hu, G.; Kamira, B.; Chen, J. Occurrence of antibiotics and their impacts to primary productivity in fishponds around Tai Lake, China. *Chemosphere* **2016,** *161*, 127-135.

(36) Yu, J. Contamination characteristics of antibiotics and antibiotic resistance genes (ARGs) in typical aquaculture environments of three kinds of crustaceans in Jiangsu Province (in Chinese with English abstract). Nanjing University of Information Science & Technology, 2020.

(37) Zhang, R.; Kang, Y.; Zhang, R.; Han, M.; Zeng, W.; Wang, Y.; Yu, K.; Yang, Y. Occurrence, source, and the fate of antibiotics in mariculture ponds near the Maowei Sea, South China: Storm caused the increase of antibiotics usage. *Sci. Total Environ.* **2021,** *752*, 141882.

(38) Zhang, R.; Pei, J.; Zhang, R.; Wang, S.; Zeng, W.; Huang, D.; Wang, Y.; Zhang,

Y.; Wang, Y.; Yu, K. Occurrence and distribution of antibiotics in mariculture farms, estuaries and the coast of the Beibu Gulf, China: Bioconcentration and diet safety of seafood. *Ecotoxicol. Environ. Saf.* **2018,** *154*, 27-35.

(39) Heijungs, R. Sensitivity coefficients for matrix-based LCA. *Int. J. Life Cycle Assess.* **2010,** *15*, (5), 511-520.

(40) Oita, A.; Malik, A.; Kanemoto, K.; Geschke, A.; Nishijima, S.; Lenzen, M. Substantial nitrogen pollution embedded in international trade. *Nat. Geosci.* **2016,** *9*, (2).

(41) Heijungs, R.; Lenzen, M. Error propagation methods for LCA—a comparison. *Int. J. Life Cycle Assess.* **2014,** *19*, (7), 1445-1461.

(42) Mi, Z.; Meng, J.; Guan, D.; Shan, Y.; Song, M.; Wei, Y. M.; Liu, Z.; Hubacek, K. Chinese CO2 emission flows have reversed since the global financial crisis. *Nat. Commun.* **2017,** *8*, (1), 1712.

(43) Feng, K.; Davis, S. J.; Sun, L.; Li, X.; Guan, D.; Liu, W.; Liu, Z.; Hubacek, K. Outsourcing CO2 within China. *Proc. Natl Acad. Sci. USA* **2013,** *110*, (28), 11654-11659.

(44) Li, Y.; Chen, L.; Liang, S.; Qi, J.; Zhou, H.; Feng, C.; Yang, X.; Wu, X.; Mi, Z.; Yang, Z. Spatially Explicit Global Hotspots Driving China's Mercury Related Health Impacts. *Environ. Sci. Technol.* **2020,** *54*, (22), 14547-14557.

(45) Yang, Y.; Qu, S.; Cai, B.; Liang, S.; Wang, Z.; Wang, J.; Xu, M. Mapping global carbon footprint in China. *Nat. Commun.* **2020,** *11*, (1).

(46) Liang, S.; Wang, H.; Qu, S.; Feng, T.; Guan, D.; Fang, H.; Xu, M. Socioeconomic drivers of greenhouse gas emissions in the United States. *Environ. Sci. Technol.* **2016,** *50*, (14), 7535-45.

(47) Liang, S.; Qu, S.; Zhu, Z.; Guan, D.; Xu, M. Income-based greenhouse gas emissions of nations. *Environ. Sci. Technol.* **2017,** *51*, (1), 346-355.

(48) Meng, J.; Liu, J.; Xu, Y.; Guan, D.; Liu, Z.; Huang, Y.; Tao, S. Globalization and pollution: tele-connecting local primary PM2.5 emissions to global consumption. *Proc. R. Soc. A-Math. Phys. Eng. Sci.* **2016,** *472*, (2195), 20160380.

(49) Meng, J.; Yang, H.; Yi, K.; Liu, J.; Guan, D.; Liu, Z.; Mi, Z.; Coffman, D. M.; Wang, X.; Zhong, Q.; Huang, T.; Meng, W.; Tao, S. The Slowdown in Global Air-Pollutant Emission Growth and Driving Factors. *One Earth* **2019,** *1*, (1), 138-148.

(50) Huo, H.; Zhang, Q.; Guan, D.; Su, X.; Zhao, H.; He, K. Examining air pollution in China using production- and consumption-based emissions accounting approaches. *Environ. Sci. Technol.* **2014,** *48*, (24), 14139-47.

(51) Qi, J.; Wang, Y.; Liang, S.; Li, Y.; Li, Y.; Feng, C.; Xu, L.; Wang, S.; Chen, L.; Wang, D.; Yang, Z. Primary suppliers driving atmospheric mercury emissions through global supply chains. *One Earth* **2019,** *1*, (2), 254-266.

(52) Liang, S.; Zhang, C.; Wang, Y.; Xu, M.; Liu, W. Virtual atmospheric mercury emission network in China. *Environ. Sci. Technol.* **2014,** *48*, (5), 2807-15.