Supporting Information for

Unlocking Potassium Constraints for China's Food Security

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S1. Supplement background

S1.1 Abbreviated letter index table

Table S1. List of abbreviations

Abbreviation	Full name	Abbreviation	Full name
K	Potassium	Germany	DEU
P	Phosphorus	France	FRA
N	Nitrogen	Italy	ITA
BAU	the business-as-usual scenario	The United Kingdom	GBR
DA	the diet adjusted scenario	Canada	CAN
IMFA	increasing mineral K fertilizer application scenario	China	CHN
EMMFA	European model mineral K fertilizer application scenario	Japan	JPN
NAMMFA	North American model mineral K fertilizer application scenario	Korea	KOR
Netherlands	NLD	Russia	RUS
Belarus	BLR	Israel	ISR
Jordan	JOR	The United States	USA
Laos	LAO	Chile	CHL

S1.2 The regional classification of the 31 provinces

China is divided into seven regions: Northeast China (i.e., Liaoning, Jilin, Heilongjiang), North China (i.e., Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia), East China (i.e., Shandong, Jiangsu, Shanghai, Zhejiang, Anhui, Jiangxi, Fujian), Central China (i.e., Hunan, Hubei, Henan), South China (Guangdong, Guangxi, Hainan), Southwest China (i.e., Sichuan, Chongqing, Guizhou, Yunnan, Tibet), and Northwest China (i.e., Gansu, Shaanxi, Xinjiang, Ningxia, Qinghai).

Fig. S1 The regional classification of the 31 provinces in China in this study.

S1.3 Global potash reserve

The global reserve of potash exceeds 4.8 billion tons in 2023. However, the potash reserve in China is only 180.0 Mt in 2023, accounting for less than 3.8% of the global reserve.

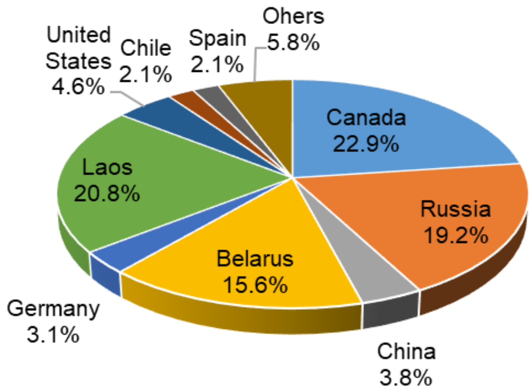


Fig. S2 Global potash reserve in 2023

S1.4 Global potash production

(1) Global potash production in 2023

The global production of potash is concentrated in a few countries, primarily Canada, Russia, China, and Belarus. In 2023, the total global potash production reached 43.3mt/year, with Canada, Russia, China, and Belarus accounting for 76.2% of the total production, while other countries contributed only 23.8%.

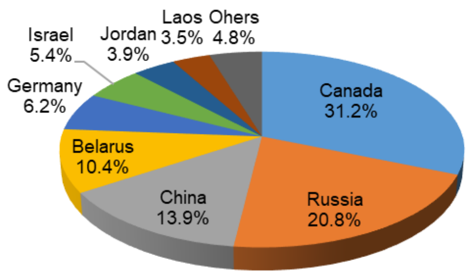


Fig. S3 Global potash production in 2023

Africa's annual demand for potash is approximately 1,110 kt (K_2O), but the continent is entirely dependent on imports. The primary potash suppliers to Africa are Europe, Russia, and Jordan. However, the Israel-Palestine conflict has severely affected the Red Sea and surrounding waters, leading to reduced transport capacity through the Suez Canal. This will inevitably impact potash exports from Europe and Jordan to Southern Africa. Additionally, drought-induced challenges at the Panama Canal have constrained Canada's potash export capacity. The ongoing Russia-Ukraine conflict further increases the uncertainty of the global potash supply chain. Although production has risen in Southeast Asia, particularly in Laos and Thailand, their supply is primarily directed toward East Asia[1].

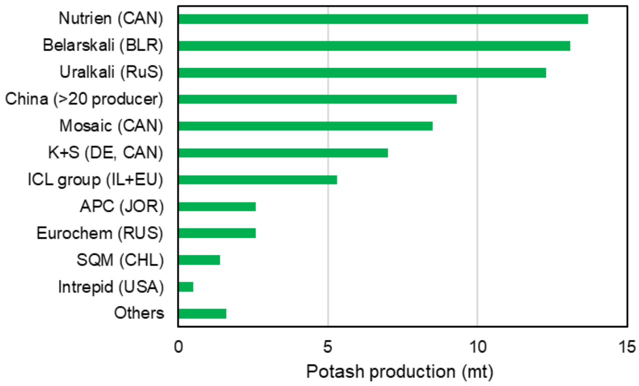


Fig. S4 Potash production in 2021

Reference: [2]

S1.5 Mineral K fertilizer production

Global mineral K fertilizer production has shown a slow upward trend, reaching 42.91 mt/year in 2022, approximately 1.8-fold compared with that in 1992. The cumulative global mineral K fertilizer production totaled 1,014.7 from 1992 to 2021. Notably, China has been the fastest-growing country in mineral K fertilizer production, reaching 4.134 mt/year in 2022, accounting for 9.6% of the global total production.

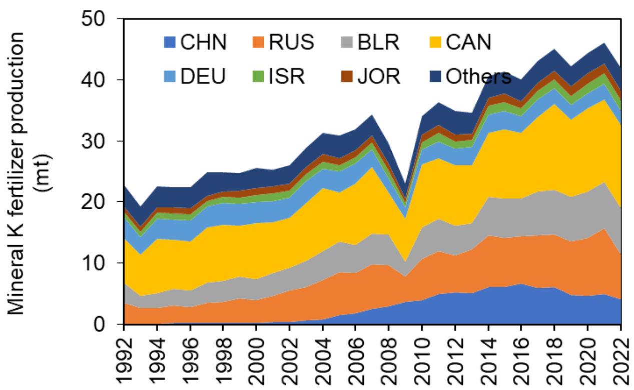


Fig. S5 Mineral K fertilizer production from 1990 to 2022

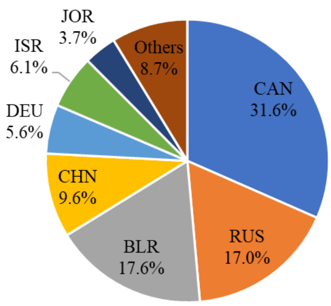


Fig. S6 Distribution of mineral K production in 2022

S1.6 The import volume of mineral K fertilizer

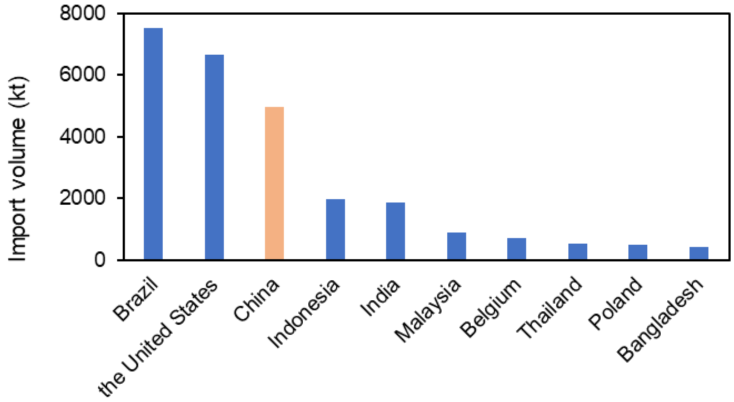


Fig. S7 The top 10 importers of mineral K fertilizer

S1.7 Food Consumption and Dietary Structure of 31 Provinces in China in 2022

There are significant regional differences in dietary patterns across China's 31 provinces. For example, in 2022, the proportion of plant-based food consumption in total food consumption ranged from 83% to 86% in northwestern provinces such as Gansu, Shaanxi, and Ningxia. In contrast, in southern provinces like Guangdong and Hainan, the proportion was around 70%.

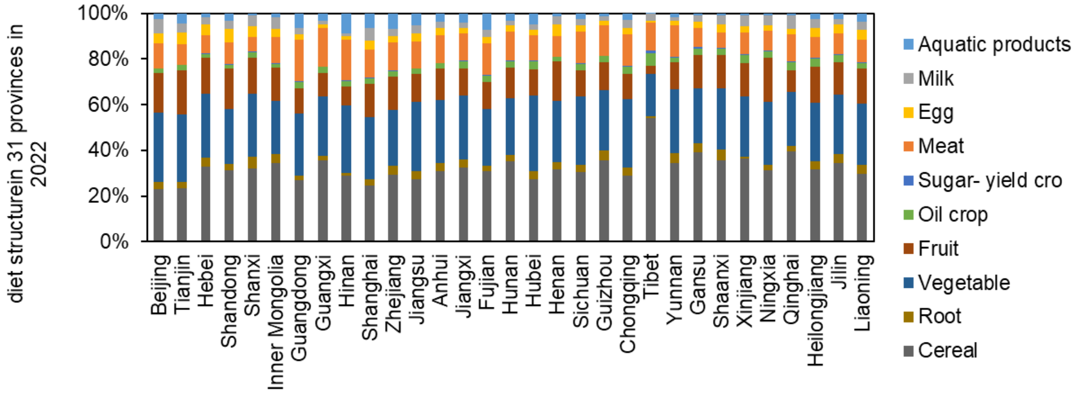


Fig. S8 Dietary structure of 31 provinces in China in 2022

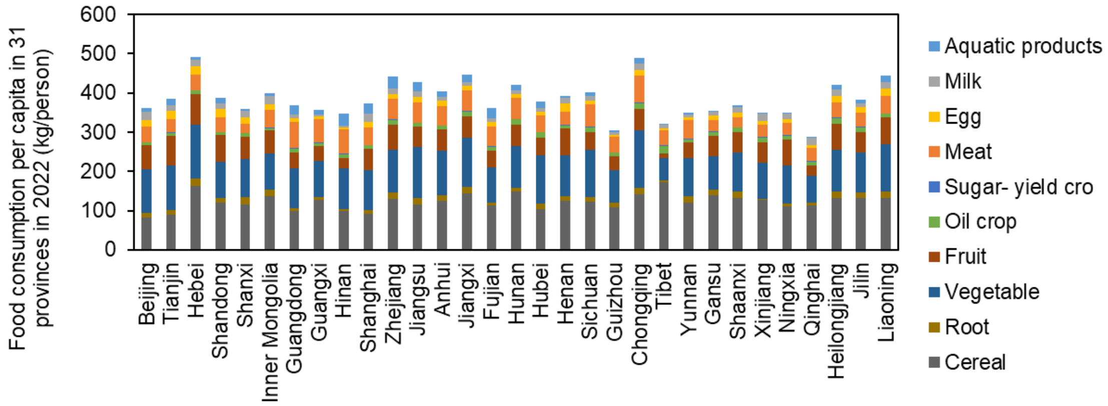


Fig. S9 Food consumption of 31 provinces in China in 2022

S2. MATERIALS AND METHODS

S2.1 Framework for mapping China's K cycle

The Fig. S10 is shown the framework to quantify the flows and stocks of K along its cycle in mainland China during the period 1990-2022. The K cycle can be divided into four dominating stages: production, fabrication and manufacturing, use, and residue management and reuse.

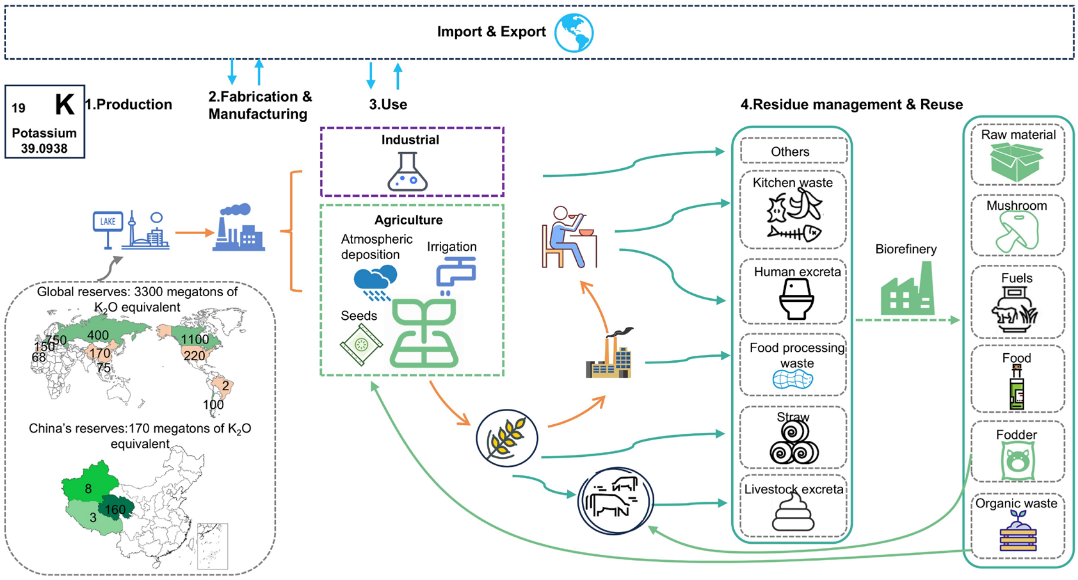


Fig. S10 Framework for mapping China's K cycle

S2.2 K demand

S2.2.1 K demand of industrial subsystem

Industrial grain refers to cereals used for the production of products such as liquor, beer, alcohol, and starch. According to the National Bureau of Statistics and related studies, the per capita consumption of industrial grain in 2022 was 69.1 kg/person. The average annual growth rate of per capita industrial grain demand is approximately 0.75%. By 2050, as China is expected to complete its industrialization, the annual growth rate will stabilize at 0%[3]. The K demand of industrial grain is calculated as follows by Eq. (1):

$$F_{GI,inflow} = C_{cc} * P_{HM}(t) * C_{crop,1} \quad (1)$$

Where $F_{GI,inflow}$ is the K demand of industrial grain, C_{cc} refers industrial grain demand, $C_{crop,1}$

refers the K content in grain crops, and $P_{HM}(t)$ is the population.

S2.2.2 K demand of other subsystems

The calculation method for potassium demand in cotton and tobacco is as follows:

$$F_{IC,inflow} = C_{co} * C_{crop,8} + C_{to} * C_{crop,9} \quad (2)$$

Where $F_{IC,inflow}$ is the K demand of cotton and tobacco, C_{co} and C_{to} refer cotton and tobacco demand, respectively. $C_{crop,8}$ and $C_{crop,9}$ are the K content in cotton and tobacco, respectively.

S2.3 K residues generation prediction and reusing model

(1) Crop farming system

The K generation of straw, and leaching and runoff can be calculated by Eq. (3)-(4).

$$W_{1,1}(t) = \sum_1^i P_{C,i}(t) \times R_{GS,i}(t) \times C_{CS,i}(t) \quad (3)$$

$$W_{1,2}(t) = L_{C,L}(t) \times LL_{C,L}(t) \quad (4)$$

Where $W_{1,1}(t)$ refers the straw K generation; $P_{C,i}(t)$ represents the crops demand, $R_{GS,i}(t)$ refers to the grain-straw ratio, $C_{cs,i}(t)$ refers to the straw K content, i represents the crop species (i=1, 2, 3, …, 9). $W_{1,2}(t)$ refers K loss to environment form leaching and runoff, $L_{C,L}(t)$ is the national cultivated land; $LL_{C,L}(t)$ is K loss of yield per unit cultivated area.

(2) Resident consumption system

K generation of resident excrement and kitchen waste can be calculated by Eq. (5)-(7)

$$W_{2,1}(t) = \sum_i P_{HM}(t) * RU_{HM}(t) * (G_{HME}(t) * C_{HME}(t) + G_{HMU}(t) * C_{HMU}(t)) * 365 \quad (5)$$

$$W_{2,2}(t) = \sum_i P_{HM}(t) * (1 - RU_{HM}(t)) * (G_{HME}(t) * C_{HME}(t) + G_{HMU}(t) * C_{HMU}(t)) * 365 \quad (6)$$

$$W_{2,3}(t) = \sum_i P_{HM}(t) * AV_{KW}(t) * R_{KW}(t) * C_{KW}(t) \quad (7)$$

Where $W_{2,1}(t)$ and $W_{2,2}(t)$ are the urban residents excrement K generation and rural residents excrement K generation, respectively. $P_{HM}(t)$ refers the population, $RU_{HM}(t)$ refers urbanization rate, $G_{HME}(t)$ and $C_{HME}(t)$ refer the daily manure and manure K content; $G_{HMU}(t)$ and $C_{HMU}(t)$ refer the daily urine and urine K content. $W_{2,3}(t)$ is the kitchen waste K generation, $G_{KW}(t)$ is the household waste discharged to the environment, $R_{HW}(t)$ is the proportion of kitchen waste, $C_{KW}(t)$ is the K content in the kitchen waste.

(3) Animal husbandry system

K generation of livestock excrement can be calculated by Eq. (8)

$$W_{3,1}(t) = F_{AM,inflow} \qquad (8)$$

Where $W_{3,1}(t)$ is K generation of livestock excrement, $F_{AM,inflow}$ is the K demand for animal-based foods.

(4) Food processing system

K generation of food processing waste can be calculated by Eq. (9)

$$W_{4,1}(t) = \sum_1^j D_{FP,j}(t) * R_{FP,j}(t) * KC_{FP,j}(t) \qquad (9)$$

Where $W_{4,1}(t)$ is the food processing waste K generation, $D_{FP,j}(t)$ is the crops demand,; $R_{FP,j}(t)$ refers the ratio of food processing, $KC_{FP,j}(t)$ is the K content in the food processing waste, j represents the form of by-products (j=1, 2, 3, …, 4).

(5) Industry system

Other chemical products can be calculated by Eq. (10)

$$W_{5,1}(t) = C_{OC}(t) \qquad (10)$$

Where $W_{5,1}(t)$ is other chemical products discharged to the environment, $C_{OC}(t)$ is the consumption of other chemical products.

S2.4 Potash Supply Forecasting Model

The Hubbert supply curve, proposed by Hubbert in 1956 in response to the issue of oil supply[4-6], is based on the growth factor and the recoverable resource reserves. The curve has since been applied to the supply studies of various minerals, including copper[7], lithium [7], iron[7], aluminum[7], zinc[7], manganese[7], and potash[4].

Ultimate recoverable resource is a key factor influencing the accuracy of the model. The ultimate recoverable resource include both historical cumulative production and reserves in 2023[4,8]. The historical cumulative production is 83.868 mt from 1961 to 2022, and the potash reserve in 2023 is 170 mt.

Table S2. Potash supply scenarios

Scenario setting	Description
High scenario	The ultimate recoverable resource includes the cumulative production from 1961 to 2022 and a potash reserve that is 2.0 times the present (2023) potash reserve.
Medium scenario	The ultimate recoverable resource includes the cumulative production from 1961 to 2022 and a potash reserve that is 1.5 times the present (2023) potash reserve.
Low scenario	The ultimate recoverable resource includes the cumulative production from 1961 to 2022 and the present (2023) potash reserve.

S2.5 Data sources

Table S3. Data sources

Products	Data sources
K_2O production	United States Geological Survey
Global K_2O reserve	United States Geological Survey
China's K_2O reserve	Statistical table of National mineral resources and reserves in 2021 (Ministry of Natural Resources)
Mineral K fertilizer production	Food and Agriculture Organization of the United Nations
Mineral fertilizer consumption	Food and Agriculture Organization of the United Nations
Import and export trade	UN Comtrade
Crop production	Food and Agriculture Organization of the United Nations, State Statistics Bureau
Per capita food consumption	State Statistics Bureau
Urban and rural population	State Statistics Bureau
Arable land area in 31 provinces	China Rural Statistical Yearbook
Kitchen waste	State Statistics Bureau
GDP per capita (2015 constant US $)	The World Bank

S3. Key parameters

S3.1 Population, per capita GDP, urbanization rate

Table S4. Population, per capita GDP, urbanization rate of 31 provinces in 2050

2050	BAU scenario			DA scenario		
	GDP per capita (10^3 CNY (2010 constant price))	Population (million)	Urbanization rate	GDP per capita (10^3 CNY (2010 constant price))	Population (million)	Urbanization rate
Beijing	167.6	23.67	97.80%	153.6	24.18	97.80%
Tianjin	271.2	14.12	94.20%	267.0	14.49	94.20%
Hebei	134.3	72.21	77.40%	124.3	76.79	73.30%
Shanxi	78.0	34.39	75.60%	71.6	36.04	72.10%
Inner Mongolia	170.5	23.32	83.40%	160.3	24.14	80.40%
Liaoning	178.2	34.42	82.00%	185.6	34.53	79.70%
Jilin	133.9	21.44	63.40%	134.2	21.96	62.80%
Heilongjiang	88.5	29.43	68.30%	82.0	29.59	67.10%
Shanghai	248.1	27.65	95.70%	247.8	28.13	95.70%
Jiangsu	274.4	76.74	88.60%	266.9	77.11	79.20%
Zhejiang	271.0	62.58	85.90%	245.1	64.77	82.50%
Anhui	104.6	55.17	76.30%	93.7	59.32	72.40%
Fujian	212.1	39.77	85.80%	200.1	41.70	82.20%
Jiangxi	93.0	44.17	76.60%	81.6	47.44	72.70%
Shandong	299.1	89.27	74.20%	281.9	93.39	71.10%
Henan	162.4	92.00	75.70%	167.0	98.40	71.90%
Hubei	151.5	52.69	73.60%	139.8	55.66	70.70%
Hunan	122.1	61.90	75.70%	107.1	66.11	72.10%
Guangdong	152.3	133.68	84.20%	125.9	140.74	81.50%
Guangxi	52.3	53.06	72.90%	43.7	58.57	69.80%
Hinan	94.6	10.66	74.80%	86.0	11.55	71.60%
Chongqing	124.1	24.79	88.10%	116.0	26.01	83.80%
Sichuan	120.6	66.09	74.40%	113.9	68.96	70.90%
Guizhou	40.3	38.65	67.00%	34.2	42.98	64.60%
Yunnan	65.7	48.27	73.10%	57.1	52.07	69.80%
Tibet	59.0	3.15	45.60%	52.6	3.34	45.60%
Shaanxi	121.3	34.28	76.10%	112.3	35.72	72.40%
Gansu	80.0	25.04	71.70%	73.8	26.70	68.70%
Qinghai	85.5	6.12	70.10%	76.3	6.58	67.70%
Ningxia	112.3	7.15	76.10%	94.8	7.70	72.40%
Xinjiang	77.8	27.37	65.60%	76.0	29.72	63.90%

Reference: [9,10]

S3.2 Animal-based foods consumption and GDP per capita

Table S5. Animal-based foods consumption and GDP per capita during peak period

Animal-based foods	Pork	Beef	Mutton	Poultry	Eggs
Peak consumption (kg/person)	52.5	9.5	5.15	22.0	31.5
peak per capita GDP/ 10,000 CNY	12~12.5	14.0~15.0	14~14.5	13.2~13.7	12.1~12.6

Reference: [11]

Table S6. Animal-based foods consumption and GDP per capita during peak period in this study under the BAU scenario

Animal-based foods	Pork	Beef	Mutton	Poultry	Eggs	Milks
Peak consumption (kg/person)	52.5	9.5	5.15	22.0	31.5	69.0
peak per capita GDP/ 10,000 CNY	10~15	15~20	15~20	12~15	15~20	12~15

S3.3 Feed conversion ratio

Table S7. Feed conversion ratio

Animal-based foods	Conversion coefficient of feed grain	Animal-based foods	Conversion coefficient of feed grain
Pork	2.76~2.80	Eggs	1.7~2.19
Beef	1.0~1.95	Milks	0.3~0.37
Mutton	1.0~1.95	Aquatic products	0.9~1.06
Poultry	2.0~2.22		

Reference:[12,13]

S3.4 Harvested crop K for unit of economic yield of different crops

K in harvested crop is the amount of K contained in the plant material that has been removed from a particular area[14]. When total K accumulation in harvested crop organs increases, the rate of K removal per unit area increases.

Table S8. Harvested crop K for unit of economic yield of different crops

Crops	Crops Content ($Kg\ K_2O\ t^{-1}$)
Grain	23.39
Oil crop	31.49
Root	13.19
Fruit	10.81
Vegetable	4.85
tobacco	75.65
Cotton	60.03
Sugar-yielding crop	43.27

Data source:[15-17]

S3.5 Coefficients for straw collection and K content

Table S9. Coefficients for straw collection and K content

Major Crop Category	Crop Subcategory	Grain-straw ratio	K content (K_2O equivalence)	Collection efficiencies
Cereals		1.10	1.26%	0.86
Fruits and vegetables	Fruits	0.14	2.61%	0.55
	Vegetables	0.10	2.99%	0.55
Oil crop		1.84	1.61%	0.74
Root		0.54	1.16%	0.73
Industrial crop	Sugarcane and Sugarbeet	0.24	1.01%	0.96
	Cotton	2.47	1.02%	0.86
	Tobacco	1.60	3.00%	0.95

Data source: reference[16,17]

S3.6 Product category and trade

Table S10. International Convention for Harmonized Commodity Description and Coding System (HS) code of K-related products

Commodity code in HS	Product description	Content (K_2O)	Data source
310410	Carnallite, sylvite, crude potassium salts nes, >10kg		[18]
310420	Potassium chloride, in packs >10 kg	60%	[18,19]
310430	Potassium sulphate, in packs >10 kg	49%	[18,19]
310490	Potassic fertilizers, mixes, nes, pack >10 kg	14%	[20]
310510	Fertilizer mixes in tablets etc or in packs <10 kg	6%	[18,19]
310520	Nitrogen-phosphorus-potassium fertilizers, pack >10kg	6%	[18,19]
310560	Fertilizers containing phosphorus & potassium, <=10kg	6%	[18,19]
281520	Potassium hydroxide (caustic potash)	83%	[19]
281530	Peroxides of sodium or potassium	83%	[19]
282919	Chlorates of metals except sodium	0.384	
283330	Alums	0.115	
283421	Potassium nitrate	39%	[19]
283524	Potassium phosphates	34%	[19]
283640	Potassium carbonates	0.69	

Table S11. International Convention for Harmonized Commodity Description and Coding System (HS) code of grain

Commodity code in HS	Product description
1001	Wheat and meslin
1002	Rye
1003	Barley
1004	Oats
1005	Maize (corn)
100610	Rice in the husk (paddy or rough)
1007	Grain sorghum
1008	Buckwheat, millet and canary seed, other cereals
0701	Potatoes, fresh or chilled
0713	Vegetables, leguminous dried, shelled
0714	Manioc, arrowroot, salep etc, fresh, dried, sago pith
1201	Soya beans

S4. Supplement results

S4.1 Supply chain of China's K cycles in 2022

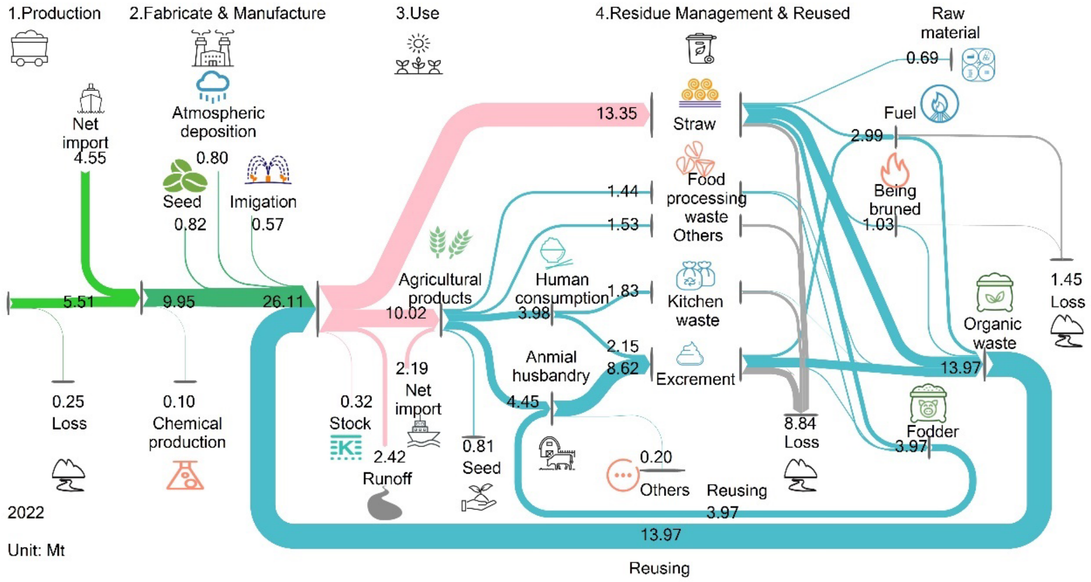


Fig. S11 Supply chain of China's K cycles in 2022

S4.2 Temporal and Spatial of Mineral K Fertilizer consumption in China

At the provincial level, compared with 1990, mineral K fertilizer consumption in all 31 provinces of China increased significantly by 2010. Provinces with the most substantial growth included Ningxia, Inner Mongolia, Heilongjiang, Gansu, Xinjiang, Liaoning, and Henan, with consumption reaching 40.0kt, 26.5 kt, 56.0 kt, 111.0 kt, 18.7kt, 22.3 kt, and 1.121 mt, respectively, in 2010, approximately 21.8-fold, 20.8-fold, 12.8-fold, 12.2-fold, 11.4-fold, 11.1-fold, and 10.3 t-fold compared with 1990. All seven provinces are located in northern China. Notably, mineral K fertilizer consumption in 2022 decreased by 15.9% compared to 2010. However, Xinjiang, Ningxia, Gansu, Yunnan, Inner Mongolia, and Heilongjiang still experienced growth, approximately 2.2-fold, 1.2-fold, 1.2-fold, 1.2-fold, 1.1-fold, and 1.1 -fold compared with 2010, respectively. The remaining 25 provinces showed a declining trend.

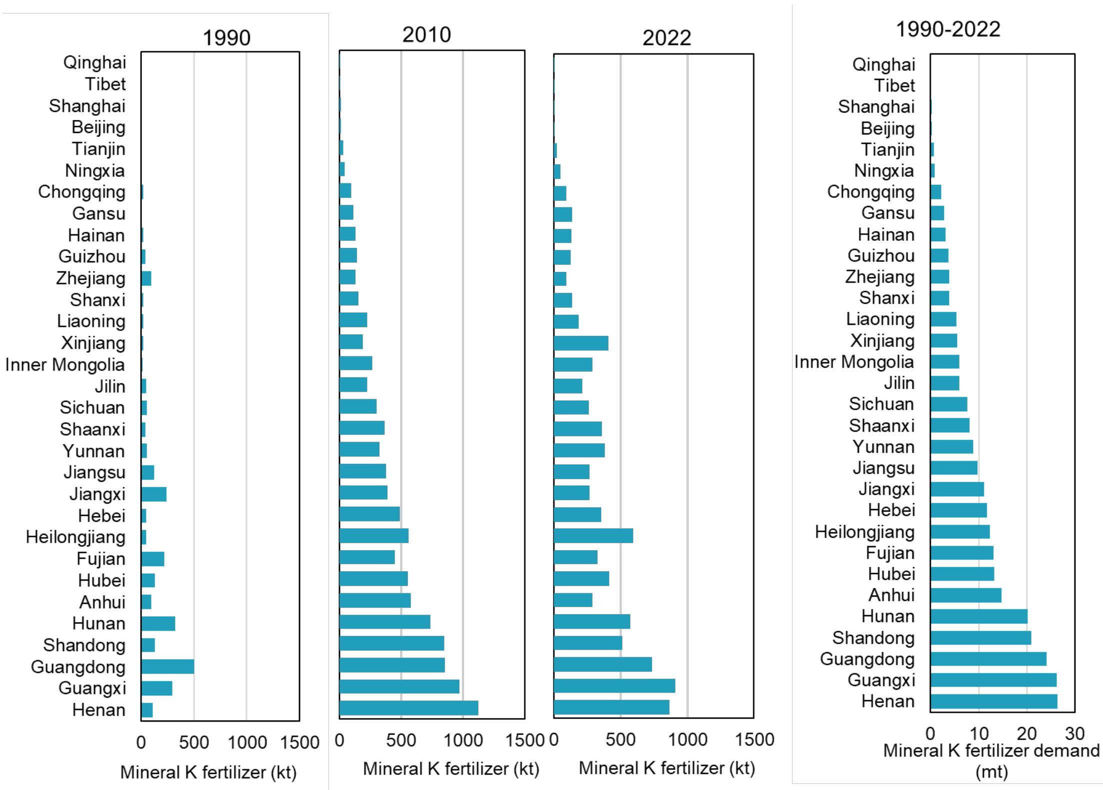


Fig. S12 Mineral K fertilizer consumption in 31 provinces in 1990, 2010, and 2022, and the cumulative consumption in China from 1990 to 2022

S4.3 Demand for plant-based foods during 2023-2050

Grain demand exhibits a gradual downward trend, projected to reach 240 mt/ year by 2050. In contrast, the demand for roots, fruits, and vegetables is expected to increase, reaching 64.86 mt/ year, 200 mt/ year, and 660 mt/ year, respectively, by 2050. The cumulative demand is estimated at 7.07 billion tonnes for grains, 1.49 billion tonnes for roots, 4.97 billion tonnes for fruits, and 18.40 billion tonnes for vegetables during 2023-2050.

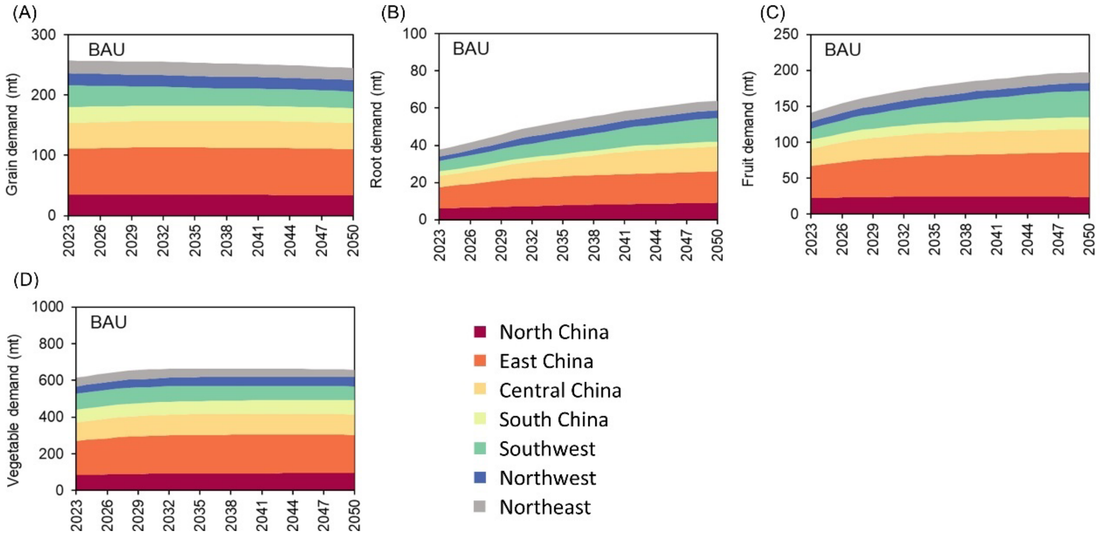


Fig. S13 Demand for plant-based foods during 2023-2050 under the BAU scenario

Grain demand exhibits a gradual downward trend, projected to reach 210 mt/ year by 2050. The cumulative demand is estimated at 6.57 billion tonnes for grains, 1.72 billion tonnes for roots, 5.57 billion tonnes for fruits, and 20.97 billion tonnes for vegetables during 2023-2050.

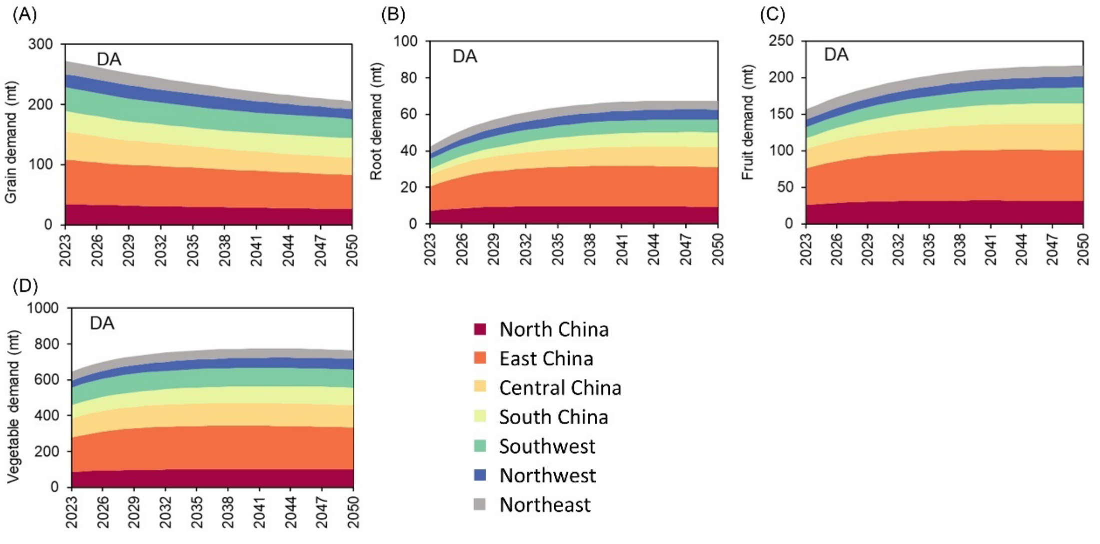


Fig. S14 Demand for plant-based foods during 2023-2050 under the DA scenario

S4.4 Demand for animal-based foods during 2023-2050

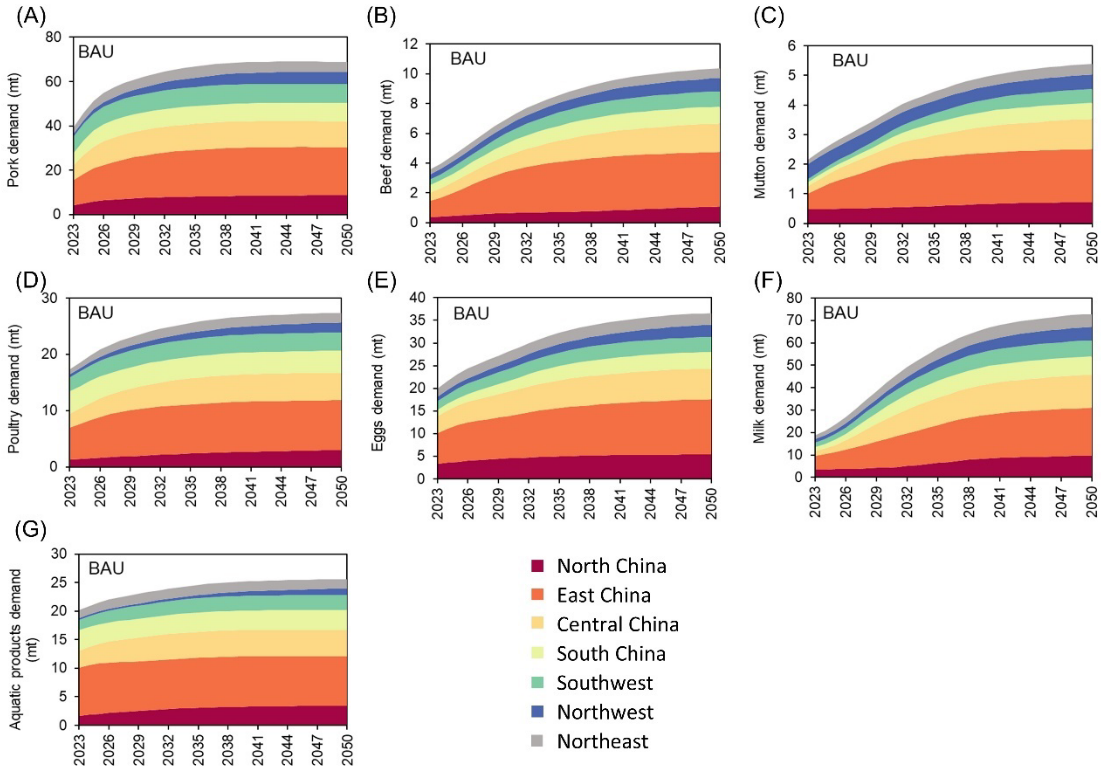


Fig. S15 Demand for animal-based foods during 2023-2050 under the BAU scenario

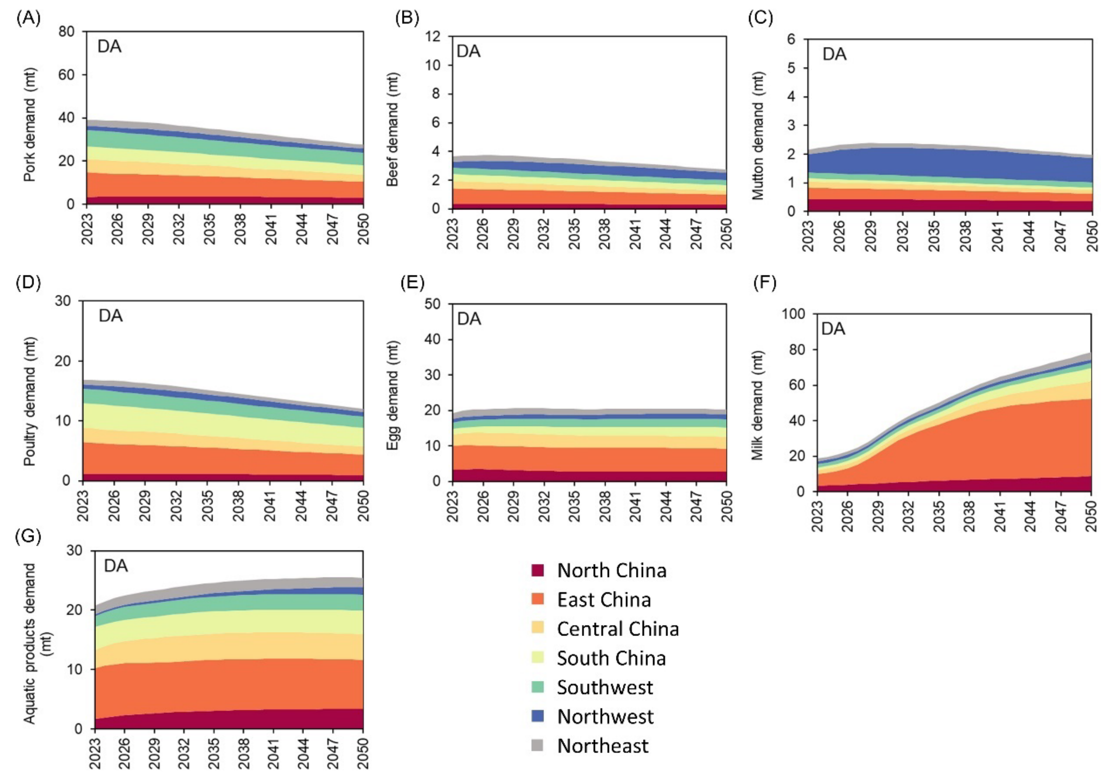


Fig. S16 Demand for animal-based foods during 2023-2050 under the DA scenario

S4.4 K Demand in 2050

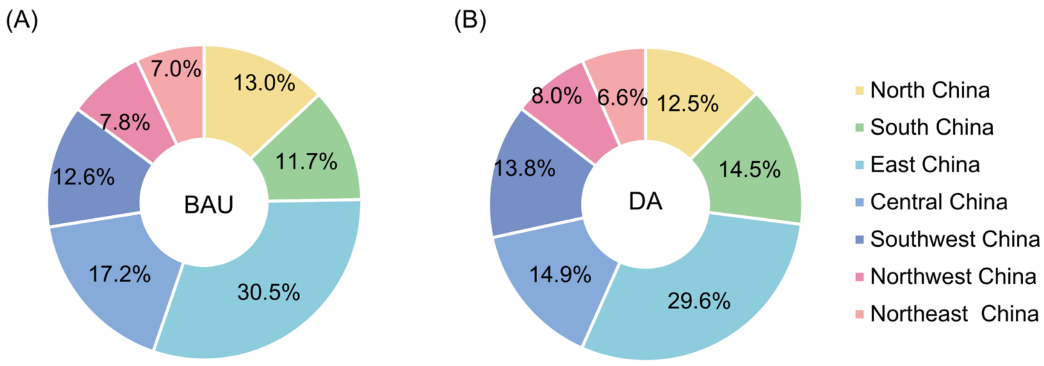


Fig S17 K Demand in 2050 under the BAU and DA scenarios

S4.5 K residues generation

(1) Crop farming subsystem K residues generation during 2023-2050

The total K residues generation by the crop farming system rises from 13.9Mt in 2023 to 18.0Mt in 2050 under the BAU scenario. The total cumulative K residues generation by crop farming system is 477.8 Mt during this period.

The total K residue generated by the crop farming system is projected to range from 13.3 Mt to 14.2 Mt between 2023 and 2050 under the DA scenario. The total cumulative K residues generation by crop farming system is 389.8 Mt during this period.

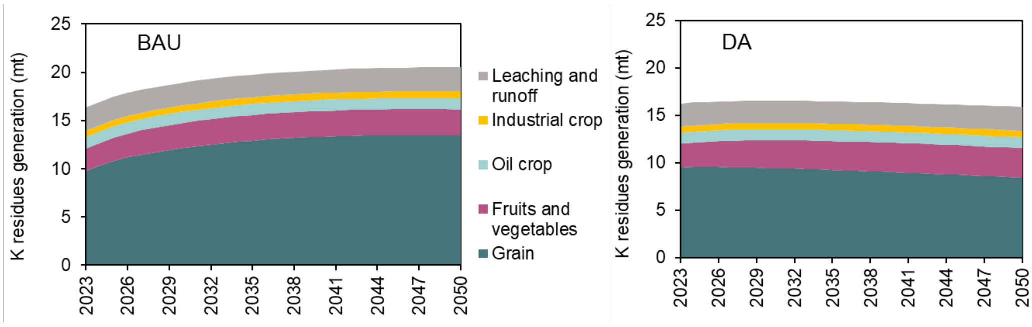


Fig. S18 Crop farming system K residues generation during 2023-2050 under the BAU and DA scenarios

(2) Total K residues generation during 2023-2050

The total K residues generation rises from 29.3Mt in 2023 to 40.4Mt in 2050 under the BAU scenario. The total cumulative K residues generation is 1051.7 Mt during this period.

The total K residue generated by the crop farming system is projected to range from 28.4 Mt to 29.8 Mt between 2023 and 2050 under the DA scenario. The total cumulative K residues generation of crop farming system is 820.8 Mt during this period.

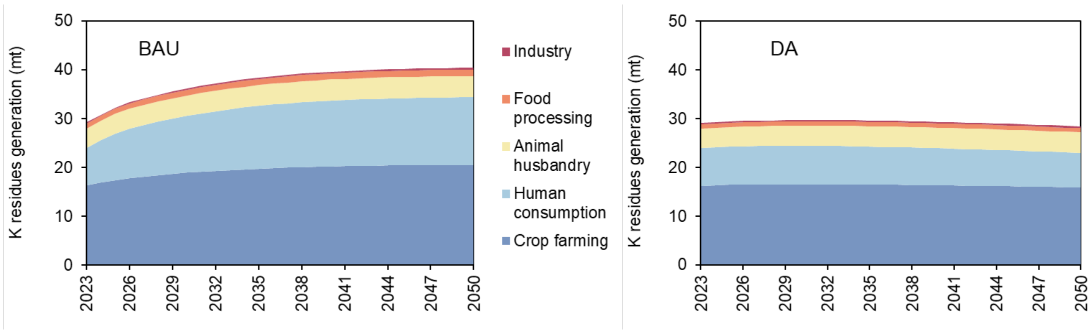


Fig. S19 K residues generation during 2023-2050 under the BAU and DA scenarios

S4.6 Potash supply potential

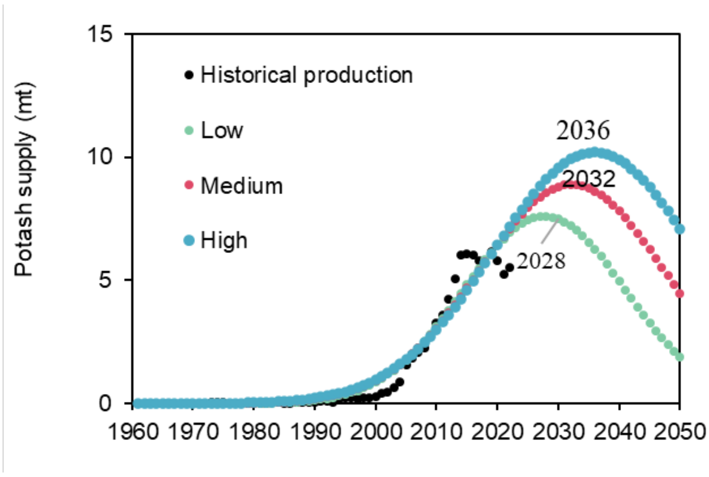


Fig. S20 Potash production during 1960-2022 and potash supply potential during 2023-2050

S4.7 The Relationship Between Economic Development and Crop Yields

This study selects nine countries from three regions—North America (the United States and Canada), Europe (Germany, France, the United Kingdom, Italy, and the Netherlands), and Asia (Japan and South Korea)—and focuses on four major crop categories: cereals, soybeans, potatoes, and vegetables. The objective is to analyze the evolution of crop yield in relation to levels of economic development. The results reveal that crop yields in all three regions exhibit an S-shaped trajectory as economic development progresses.

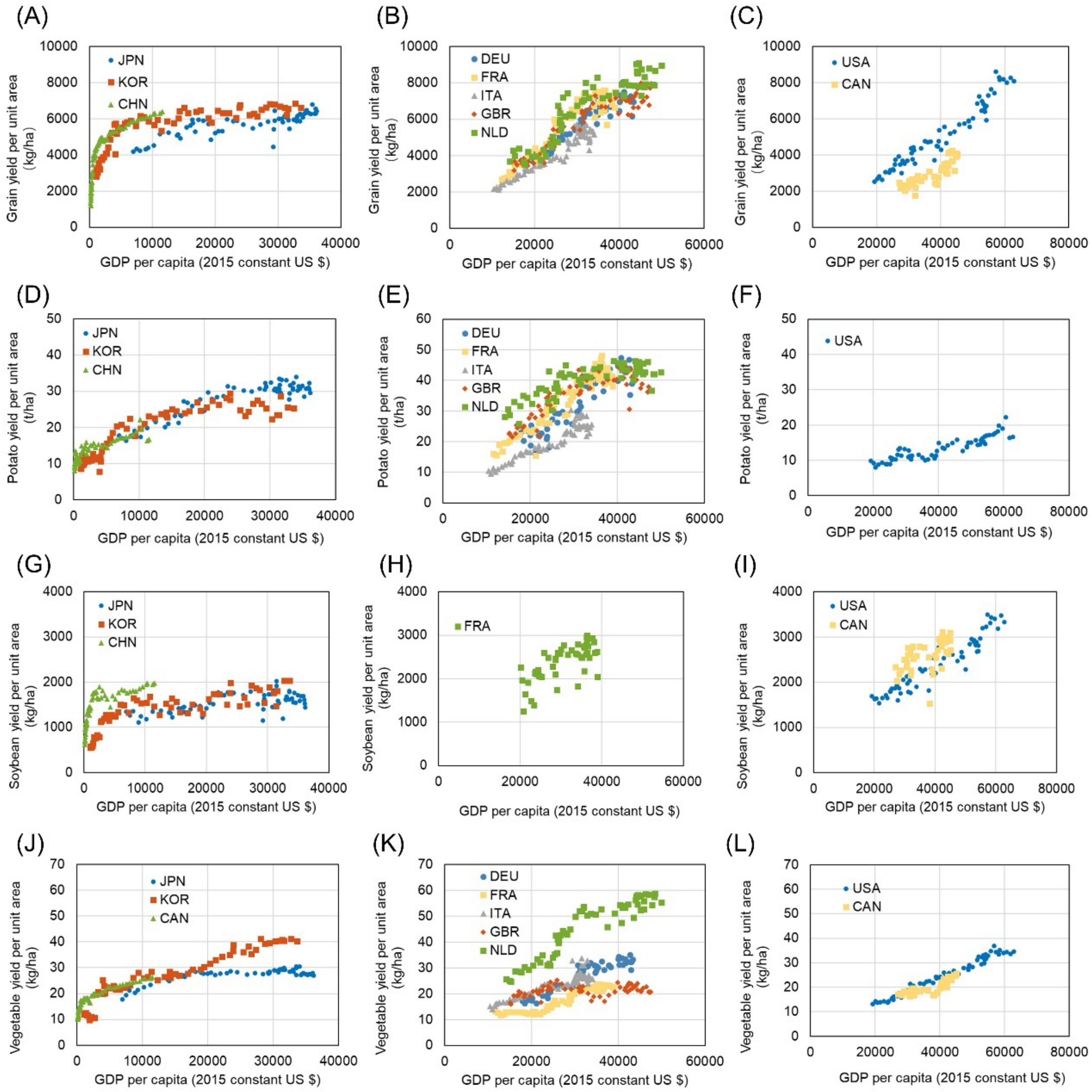


Fig. S21 The relationship between crop yield and per capita GDP between China and major developed countries

S4.8 The proportion of chemical K products imported by source country in 2022

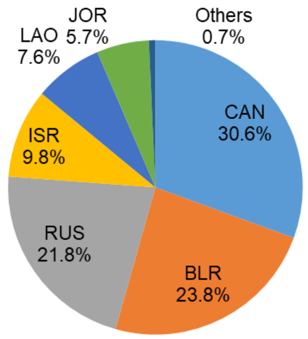


Fig. S22 The proportion of chemical K products imported by source country in 2022

S4.9 The total soil K nutrient outflow

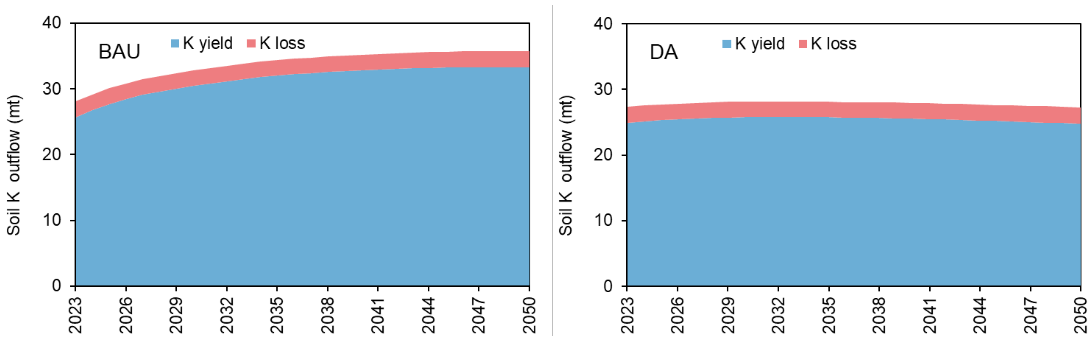


Fig. S23 The total soil K nutrient outflow under the BAU and DA scenarios

S4.10 Quantity of grain trade during 1990-2022

Since 2004, crop trade has been in a net import situation, with the net import volume continuing to grow. In 2022, the net import volume reached 150 million tons, accounting for 18.0% of total demand. The net import volume is 75.8 times that of 2004, primarily due to insufficient supply of feed grains. It is noteworthy that food demand continues to grow, reaching 1.0 billion tonnes (bt) by 2050 under the BAU scenario. The cumulative demand over the period 2023–2050 is projected to be 25.99 bt, which is 1.7 times the total consumption over the past 27 years (1995–2022).

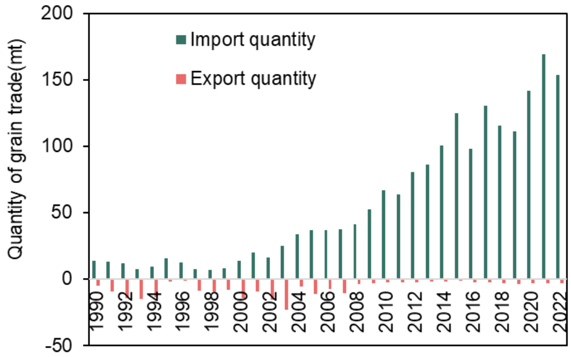


Fig. S24 Quantity of grain trade during 1990-2022

S4.11 Evolution of Mineral Fertilizer Application

Currently, analyses of mineral fertilizer consumption patterns mainly focus on indicators such as per capita mineral fertilizer consumption and mineral fertilizer application per unit of arable land. However, driven by improvements in mechanization and the implementation of 4R nutrient management, the crop yield has a more direct impact than population or arable land changes. This study therefore selects fertilizer application per unit of grain yield as the main research indicator. By conducting a comprehensive analysis of mineral fertilizer consumption data from 1961 to 2021 across major countries, this paper explores the relationship between mineral fertilizer use per unit of grain yield and per capita GDP.

Seven representative developed countries that have completed agricultural modernization were selected from three regions: Asia (South Korea, Japan), Europe (France, Italy, the United Kingdom, Germany), and North America (the United States). The analysis of historical mineral fertilizer application trajectories in these countries reveals an inverted U-shaped relationship between mineral fertilizer use per unit of grain yield and per capita GDP. Mineral fertilizer uses per unit of grain yield peaks when per capita GDP reaches approximately USD 15,000–25,000, and then gradually declines. Once per capita GDP surpasses USD 30,000, mineral fertilizer use per unit of grain yield tends to stabilize.

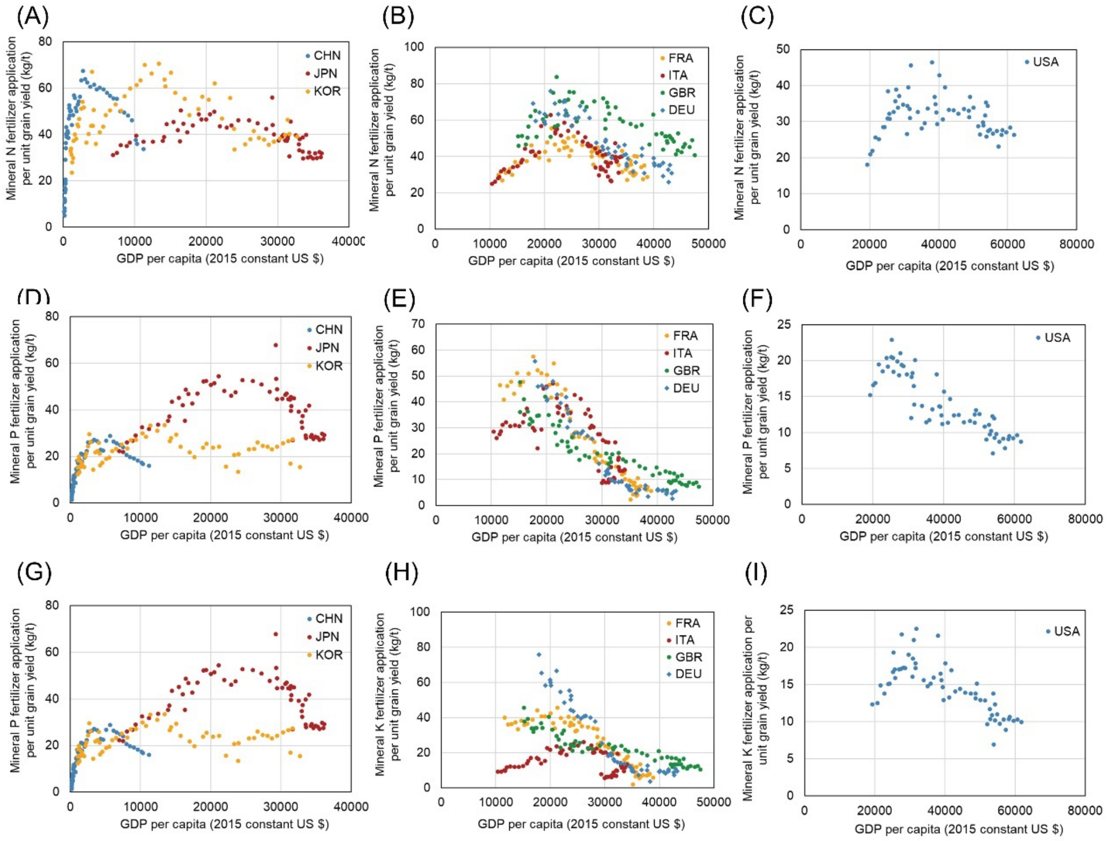
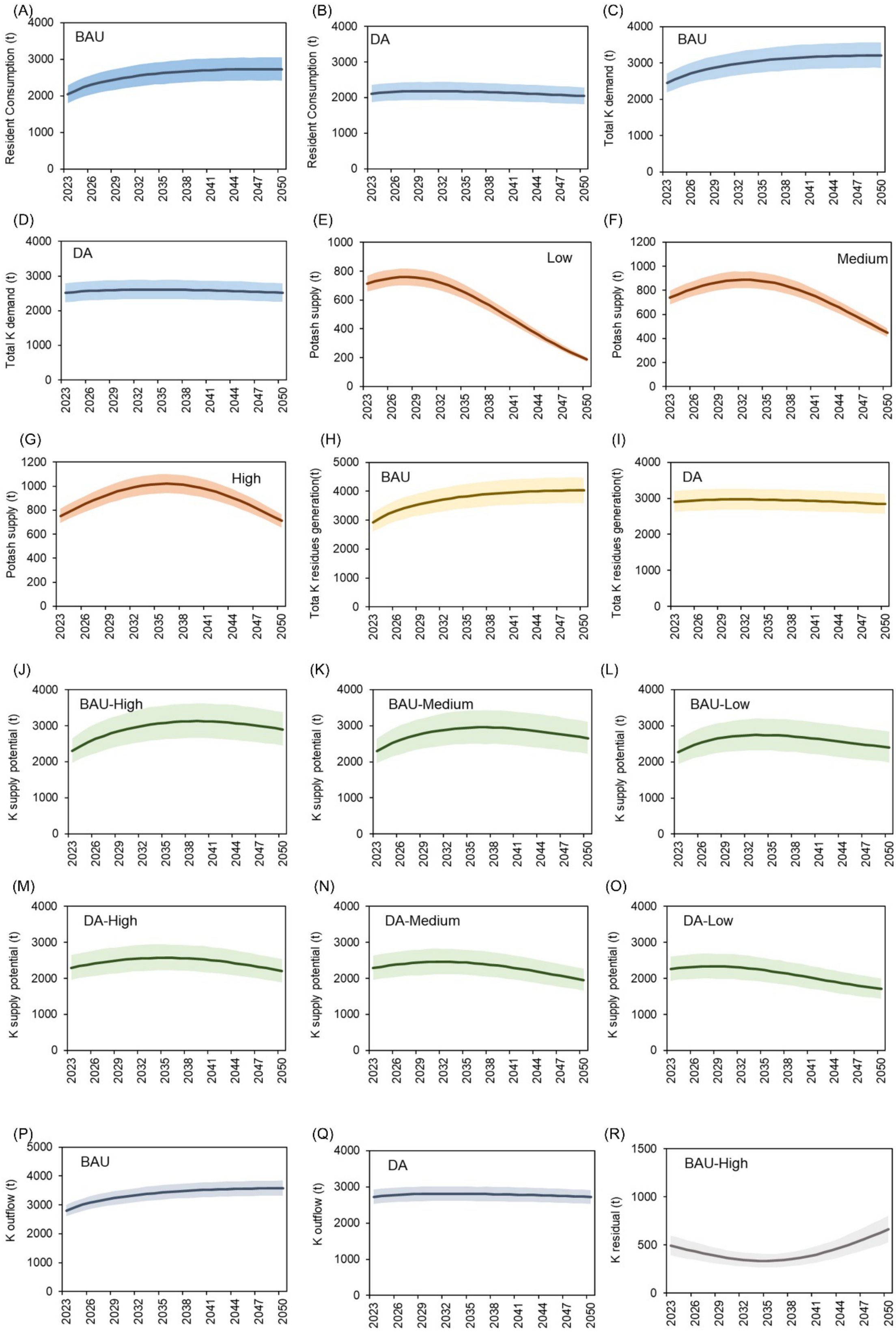


Fig. S25 Mineral fertilizer application, per capita GDP, and grain yield in major developed countries

S4.12 Uncertainty analysis



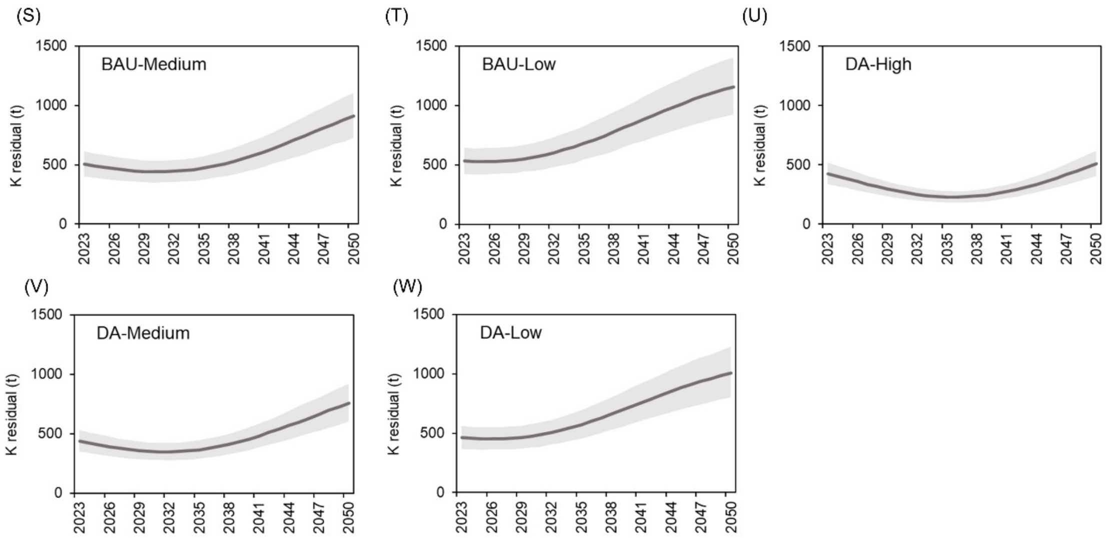


Fig. S26 Uncertainty analysis results of the flows of K in China during 2023-2050

(A-B) Residual consumption subsystem of K demand during 2023-2050 under the BAU and DA scenarios

(C-D) Total K demand during 2023-2050 under the BAU and DA scenarios

(E-G) Potash supply during 2023-2050 under the Low, Medium, and High scenarios

(H-I) Total K residue potential during 2023-2050 under the BAU and DA scenarios

(J-O) K supply potential during 2023-2050 under the BAU-High, BAU-Medium, BAU-Low, DA-High, DA-Medium, and DA-Low scenarios

(P-Q) Total K outflow during 2023-2050 under the BAU and DA scenarios

(R-W) K residual during 2023-2050 under the BAU-High, BAU-Medium, BAU-Low, DA-High, DA-Medium, and DA-Low scenarios

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