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Improving the Imbalanced Global Supply Chain of Phosphorus Fertilizers

Haozhe Yang[1], Ying Liu[2], Junfeng Liu[1], Jing Meng[3], Xiurong Hu[1], and Shu Tao[1]

[1]Laboratory for Earth Surface Processes, College of Urban and Environmental Sciences, Peking University, Beijing, China, [2]School of Statistics, University of International Business and Economics, Beijing, China, [3]The Bartlett School of Construction and Project Management, University College London, London, UK

Key Points:
- The international trade of commodities greatly contributes to the unbalanced use of phosphorus fertilizers
- The phosphorus fertilizers embodied in commodities are commonly exported from large emerging countries to developed countries
- Improving the supply chain of phosphorus fertilizers could result in substantial mutual benefits among countries

Supporting Information:
- Supporting Information S1
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Correspondence to:
J. Liu and J. Meng,
jfliu@pku.edu.cn;
mjhustese@gmail.com

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Abstract The unbalanced use of phosphorus fertilizers at the global scale has resulted in phosphorus fertilizer scarcity in less developed areas as well as eutrophication problems in developed and large emerging countries. Historically, the uneven distribution of phosphate rock has been regarded as the major reason for this unbalanced use. However, the international trade of commodities may also play an important role in the unbalanced use of phosphorus fertilizers. By tracing the trade flows of commodities, we found that nearly 5.2 Tg of phosphorus fertilizer was embodied in traded commodities, which were mainly exported from large emerging countries (with low phosphorus use efficiencies) to developed countries (e.g., the US, Western Europe and Japan, commonly with high phosphorus use efficiencies). Furthermore, among the 5.2 Tg of phosphorus fertilizer embodied in traded commodities, 2.5 Tg was embodied in the trade of commodities from industry, construction, and services. Our results indicate that this trade pattern could create substantial mutual benefits if improvements are made to the phosphorus supply chain. With technology transfer and financial support from developed countries, large emerging countries could use phosphorus fertilizers more efficiently, thereby reducing the risk of eutrophication and lowering the cost of agricultural production. The phosphorus fertilizers saved by large emerging countries could be partially used to enhance food production in Sub-Saharan African countries. This optimized supply chain could reduce eutrophication, conserve phosphate rock resources, and enhance global agricultural production.

1. Introduction

Phosphorus is an essential nutrient for crop production (Bumb & Baanante, 1996). To feed the rapidly growing population of the twentieth century, phosphorus fertilizers have been extensively applied to crops (Smil, 2003; Stewart et al., 2005). Each year, 20 million tons of phosphate rock is extracted, and 90% is then processed to generate phosphorus fertilizers for agricultural use; however, these phosphorus fertilizers are unevenly distributed via the global supply chain, which leads to imbalanced phosphorus accessibility (Günther, 1997; Smil, 2003; Steen, 1998; United States Geological Survey, 2011). In large emerging countries and many developed countries, excessive phosphorus fertilizer use commonly elevates the phosphorus levels in freshwater and estuarine ecosystems through runoff and erosion (Garnache et al., 2000; Smith et al., 2010; Stewart et al., 2005). As a key limiting nutrient in the eutrophication process, increased levels of phosphorus contribute to eutrophication in aquatic systems (Conley et al., 2009; Hecky & Kilham, 1988; Schindler, 1977; Smith, 2003), which results in water-quality degradation and fewer harvestable fish (Dodds et al., 2009; Smith et al., 1999). Although more than a third of the world's supply of high-quality phosphate rock is located in Moroccan and Western Saharan Africa (International Fertilizer Industry Association, 2006), many countries in Sub-Saharan Africa are experiencing phosphorus deficits due to phosphorus fertilizer shortages (Macdonald et al., 2011). Nearly 30% of the population in Sub-Saharan Africa is undernourished, primarily because 75% of agricultural soils are phosphorus deficient and provide low crop yields (Smaling et al., 2006). Therefore, these phosphorus imbalance issues must be investigated.

Previous studies have focused primarily on addressing the phosphorus imbalance by recycling phosphorus from waste products (Childers et al., 2011; Garnache et al., 2000; Runge-Metzger, 1995). Annually, 60% of the phosphorus in agricultural harvests is used for animal feed, food, and fiber and 55% of the phosphorus in food ends up in bodies of water or landfills (Smil, 2003). Because so much phosphorus is returned to the soil, Sattari et al. (2012) suggested that phosphorus fertilizer use could be greatly reduced by utilizing residual phosphorus in the soil.

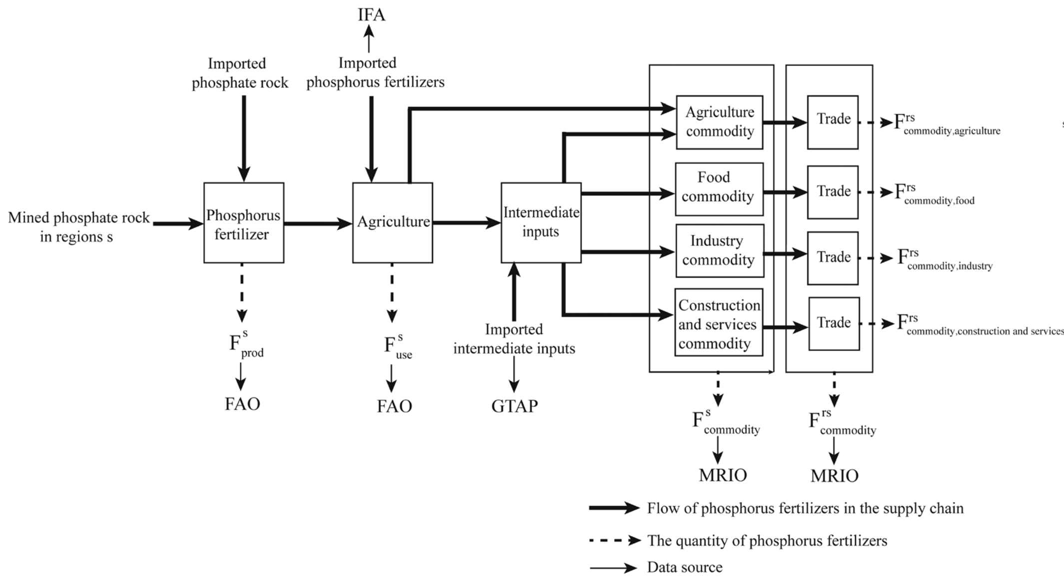

Figure 1. Supply chain of phosphorus fertilizers in country s. The solid arrows show how phosphorus fertilizer use is driven by commodities along the supply chain. In other words, the solid arrows show how the phosphorus fertilizers become embodied in commodities. Here we do not consider the phosphorus fertilizer loss to soil or waste products because we are attempting to determine the amount of phosphorus fertilizer use that is driven by the consumption of the commodity rather than the actual phosphorus content in the commodity. FAO = Food and Agriculture Organization; IFA = International Fertilizer Industry Association; GTAP = Global Trade Analysis Project; MRIO = multiregional input-output.

Recent research has further found that phosphorus imbalances are tightly linked to the global supply chain of phosphorus fertilizers. The distribution of phosphate rock is geographically concentrated in a few countries; therefore, international trade is required to redistribute phosphate rock and phosphorus fertilizers to other regions (Jasniski, 2008). Matsubae et al. (2011) calculated the virtual phosphate rock import demand of the Japanese economy. Nesme et al. (2016) indicated that the European Union has outsourced its domestic consumption of phosphorus fertilizers by importing many agricultural products. Schipanski and Bennett (2012) and Nesme et al. (2018) studied the effects of agricultural trade on the global phosphorus cycle and found that major agricultural exporters had an increased risk of water pollution and resource depletion. However, these studies all focused on the trade of agricultural products. Latest studies (Hamilton et al., 2018; Oita et al., 2016) indicate that the trade of nonfood commodities could also drive the circulation of phosphorus fertilizers around the world. Because the international trade of commodities may play an important role in the distribution of phosphorus fertilizers; improving this global supply chain may help solve problems associated with unbalanced use.

In this study, we use global data on the phosphorus fertilizer trade and multiregional input-output (MRIO) analysis to trace the phosphorus fertilizers embodied in trade flows of agricultural products, food products, industrial products, and services. This approach can be used to determine the role of each country in this supply chain and suggest policies to alleviate the global phosphorus imbalance. Additionally, we have also compared the phosphorus fertilizers embodied in traded commodities with the direct trade flows of phosphorus fertilizers to identify hidden patterns in global trade.

2. Materials and Methods

2.1. Quantifying Phosphorus Fertilizers in Different Stages of the Supply Chain

As shown in Figure 1, the supply chain of phosphorus fertilizers presents three stages: production of phosphorus fertilizer, consumption of phosphorus fertilizer, and consumption of commodities in which phosphorus fertilizers are embodied. Phosphorus fertilizer production (F^{s}_{prod}) represents the quantity of phosphorus fertilizers produced in region s; the phosphate rock used to produce phosphorus fertilizers is the sum of both imported rock and rock mined in region s. Phosphorus fertilizer consumption (F^{s}_{use}) quantifies the phosphorus fertilizers that are used in the agriculture sector in region s. Phosphorus fertilizers embodied in commodities ($F^{s}_{commodity}$) quantifies all phosphorus fertilizers directly or indirectly used to produce commodities consumed in region s (Lenzen et al., 2007; Peters, 2008). In other words, $F^{s}_{commodity}$ is the footprint of phosphorus fertilizers used to produce the commodities consumed in region s. Phosphorus fertilizers embodied in the trade of commodities from region r to region s ($F^{rs}_{commodity}$) is the phosphorus fertilizer use in region r due to the consumption of commodities in region s. The term "commodity" is defined as the portion of the output that is finally consumed by residents of the region, and the term "intermediate input" is defined as the part of the output used to produce the commodity. The term "embodied" is defined as the phosphorus fertilizers used in the supply chain of a commodity.

The net import of phosphorus fertilizers in different stages can be calculated using equations (1) and (2).

$$F^{s}_{use} - F^{s}_{prod} = I^{s}_{use} - E^{s}_{use} \tag{1}$$

$$F^{s}_{commodity} - F^{s}_{use} = I^{s}_{commodity} - E^{s}_{commodity} \tag{2}$$

where E^{s}_{use} and I^{s}_{use} are the quantities of phosphorus fertilizers exported from and imported to region s, respectively, and $E^{s}_{commodity}$ and $I^{s}_{commodity}$ are the quantities of phosphorus fertilizers embodied in commodities exported from and imported to region s, respectively. Equations (1) and (2) represent the net import of phosphorus fertilizers and phosphorus fertilizers embodied in the final consumption of commodities, respectively. The values of F^{s}_{prod} and F^{s}_{use} were obtained from the Food and Agriculture Organization (FAO) of the United Nations (http://www.fao.org/faostat/en/data/RF).

2.2. MRIO Analysis

Phosphorus fertilizers embodied in commodities ($F^{s}_{commodity}$) are calculated based on MRIO, which links local environmental issues to final consumption (Davis & Caldeira, 2010; Li et al., 2016; Meng et al., 2015; Meng et al., 2016). The Global Trade Analysis Project (GTAP V9) database was used to derive the monetary MRIO table, and agricultural subsectors were merged into one agriculture (agriculture and forestry) sector in the table (the process of merging the agriculture sectors is shown in the supporting information (SI)). The MRIO table includes monetary flows among multiple regions and sectors and final consumption (i.e., household consumption, government consumption and investment) in 140 countries or regions. The following formulas can be derived from the MRIO table to calculate the phosphorus fertilizers embodied in commodities and phosphorus fertilizers embodied in the trade of these commodities. More detailed information can be seen in the SI.

In a standard MRIO model, we assume that there are N sectors in a region and M regions in total:

$$x^{r}_{i} = \sum_{s=1}^{M} \sum_{j=1}^{N} z^{rs}_{ij} + \sum_{s=1}^{M} y^{rs}_{i} \tag{3}$$

where x^{r}_{i} represents the economic outputs of sector i in region r; y^{rs}_{i} is defined as the commodity and represents sector i's outputs produced in region r and consumed in region s; and z^{rs}_{ij} is defined as the intermediate input and represents the inputs from sector i in region r required to produce the total outputs from sector j in region s. All of these data can be directly derived from GTAP.

Next, we derive the direct input coefficient $\mathbf{a^{rs}_{ij}}$, which represents inputs from sector i in region r required to produce unitary outputs from sector j in region s:

$$\mathbf{a^{rs}_{ij}} = \mathbf{z^{rs}_{ij}} / \mathbf{x^{s}_{j}} \tag{4}$$

Based on equations (3)–(4), we derive equation (5)

$$\begin{bmatrix} \mathbf{X}^1 \\ \vdots \\ \mathbf{X}^r \\ \vdots \\ \mathbf{X}^M \end{bmatrix} = \begin{bmatrix} \mathbf{A}^{11} & \cdots & \mathbf{A}^{1s} & \cdots & \mathbf{A}^{1M} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{A}^{r1} & \cdots & \mathbf{A}^{rs} & \cdots & \mathbf{A}^{rM} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ \mathbf{A}^{M1} & \cdots & \mathbf{A}^{Mr} & \cdots & \mathbf{A}^{MM} \end{bmatrix} \begin{bmatrix} \mathbf{X}^1 \\ \vdots \\ \mathbf{X}^r \\ \vdots \\ \mathbf{X}^M \end{bmatrix} + \sum_{s=1}^{M} \mathbf{Y}^s \quad (5)$$

where X^r is defined as an $N \times 1$ vector representing the total outputs of the N sectors in region r, Y^s is an $(M \times N) \times 1$ vector representing the commodities produced in region r and consumed in region s, and A^{rs} is an $N \times N$ direct input coefficient matrix showing the direct purchases from the sectors of region r by the unitary outputs of each sector in region s.

We further simplify equation (5) into equation (6):

$$\mathbf{X}=\mathbf{AX}+\mathbf{Y} \quad (6)$$

By transforming equation (6), we derive the core equation of MRIO:

$$\mathbf{X}=(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} \quad (7)$$

where **I** is the identity matrix.

We then calculate the phosphorus fertilizers embodied in the final consumption of commodities in each region by equations (8)–(15).

The phosphorus fertilizer consumption F^r_{use} is used for agricultural production in region r; therefore, we derive the direct phosphorus fertilizer intensity per unit of output from the agriculture sector in region r as follows:

$$e^r_{agriculture} = F^r_{use}/x^r_{agriculture} \quad (8)$$

The direct phosphorus fertilizer intensity per unit of output of sector i in region r equals zero because phosphorus fertilizers are used directly only for agriculture.

$$e^r_i = 0, i \notin agriculture \quad (9)$$

We then derive the phosphorus fertilizer intensity vector h and the corresponding diagonal matrix $\hat{\mathbf{h}}$ as below:

$$h = \left(e^1_{agriculture,} e^1_2, \ldots, e^1_N, \ldots, e^i_{agriculture,} e^i_2, \ldots, e^i_N, \ldots, e^M_{agriculture,} e^M_2, \ldots, e^M_N\right) \quad (10)$$

$$\mathbf{h} = \mathrm{diag}\mathbf{h} \quad (11)$$

where $\hat{\mathbf{h}}$ is a diagonal matrix representing the phosphorus fertilizer intensity per unit of output of a sector.

The phosphorus fertilizers embodied in the trade of commodities are calculated as follows:

$$\mathbf{F}=\hat{\mathbf{h}}(\mathbf{I}-\mathbf{A})^{-1}\left[\mathbf{Y}^1 \cdots \mathbf{Y}^s \cdots \mathbf{Y}^M\right] \quad (12)$$

$$\mathbf{F}=\begin{bmatrix} F^{11} & \cdots & F^{1s} & \cdots & F^{1M} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ F^{r1} & \cdots & F^{rs} & \cdots & F^{rM} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ F^{M1} & \cdots & F^{Mr} & \cdots & F^{MM} \end{bmatrix} \quad (13)$$

$$F^{rs}_i = \begin{cases} F^{rs}_{agriculture}, i \in agriculture \\ 0, i \notin agriculture \end{cases} \quad (14)$$

$$F^{rs}_{com\,modity} = \sum_{i=1}^{N} F^{rs}_{i} \tag{15}$$

$$F^{s}_{com\,modity} = \sum_{r=1}^{M} F^{rs}_{com\,modity} \tag{16}$$

where **F** is the matrix representing phosphorus fertilizers embodied in the final consumption of commodities; $F^{rs}_{agriculture}$ is the quantity of phosphorus fertilizers used in the agriculture sector in region r due to the final consumption of commodities in region s; and $F^{rs}_{com\,modity}$ is the phosphorus fertilizer use in region s due to the consumption of commodities in region s, that is, the phosphorus fertilizer use embodied in the trade of commodities from region r to region s. $F^{s}_{com\,modity}$ is the phosphorus fertilizers embodied in commodities that are finally consumed in region s. The process for calculating the phosphorus fertilizers embodied in commodities from sector i ($F^{s}_{com\,modity,i}$) is shown in the SI.

2.3. Data Sources

The data on trade flows of phosphorus fertilizers were obtained from the Global Fertilizer Trade Map, which is compiled by the International Fertilizer Industry Association and Chemical Industry News and Chemical Market Intelligence (2016). The MRIO table data from 2011 were collected from GTAP V9. The regional fertilizer production and consumption data were obtained from the Food and Agriculture Organizations of the United Nations (2011). In this study we use the mass of element P to calculate the masses of phosphorus fertilizers and phosphorus fertilizers embodied in commodities.

3. Results

3.1. Substantial Phosphorus Fertilizers Embodied in Traded Commodities

Figure 2a shows the flows of phosphorus fertilizers in the global supply chain. In 2011, 19.8 Tg of phosphorus fertilizers was used for agricultural production, and the agricultural outputs embodying 6.1 Tg phosphorus fertilizers were directly used to produce commodities from the agriculture (agriculture and forestry) sector. The other agricultural outputs, which consumed 13.7 Tg of phosphorus fertilizers, were then used as intermediate inputs or to produce intermediate inputs (including intermediate inputs from all sectors). These intermediate inputs were then used to produce commodities from the agriculture sector, food sectors, industry sectors, and construction and services. Through this supply chain, the 19.8 Tg of phosphorus fertilizers used on agricultural land (the sum of areas of cropland and pasture) was finally embodied in the commodities. More importantly, we found that 26.3% (5.2 Tg) of all phosphorus fertilizers were embodied in the international trade of commodities. Specifically, 4.3 Tg (83.6%) of the 5.2 Tg of phosphorus fertilizers were embodied in the trade of commodities from food sectors, industry sectors, and construction and services. Although the largest amount of phosphorus fertilizers, 7.2 Tg, was embodied in agricultural commodities, only 11.7% of those fertilizers were embodied in trade. Compared with the agriculture sector, 27.1%, 60.9%, and 32.4% of the phosphorus fertilizers embodied in food commodities, industry commodities, and construction and services were traded, respectively.

Figure 2b further shows the quantity of phosphorus fertilizers embodied in the trade of commodities from 44 sectors. Collectively, 2.7 Tg (52.2%) of phosphorus fertilizers were embodied in the trade of commodities from the agricultural and food sectors. Of the 1.4 Tg of phosphorus fertilizers embodied in industry sectors, the clothing sector embodied 0.69 Tg and the equipment manufacturing sector embodied 0.46 Tg. Among the 1.1 Tg of phosphorus fertilizers embodied in construction and services, 0.33 Tg was embodied in the trade sector (representing retail, hotels, and restaurants in GTAP); 0.27 Tg was embodied in the public administration, defense, health, and education sectors, and 0.25 Tg was embodied in construction and services.

In Figure 2b, we decomposed the phosphorus fertilizers embodied in traded commodities into phosphorus fertilizers embodied in intermediate inputs and those from the direct input of phosphorus fertilizers (we show the method of decomposing phosphorus fertilizers in the SI). Of the 0.84 Tg of phosphorus fertilizers embodied in traded agricultural commodities, 0.63 Tg was directly used to produce commodities and the remainder (0.21 Tg) was embodied in intermediate inputs. Nearly all of the 1.8 Tg of phosphorus fertilizers embodied in food commodities originated from intermediate inputs from the agriculture sector and food sectors. Figure 2b also reveals the source of phosphorus fertilizers embodied in commodities from

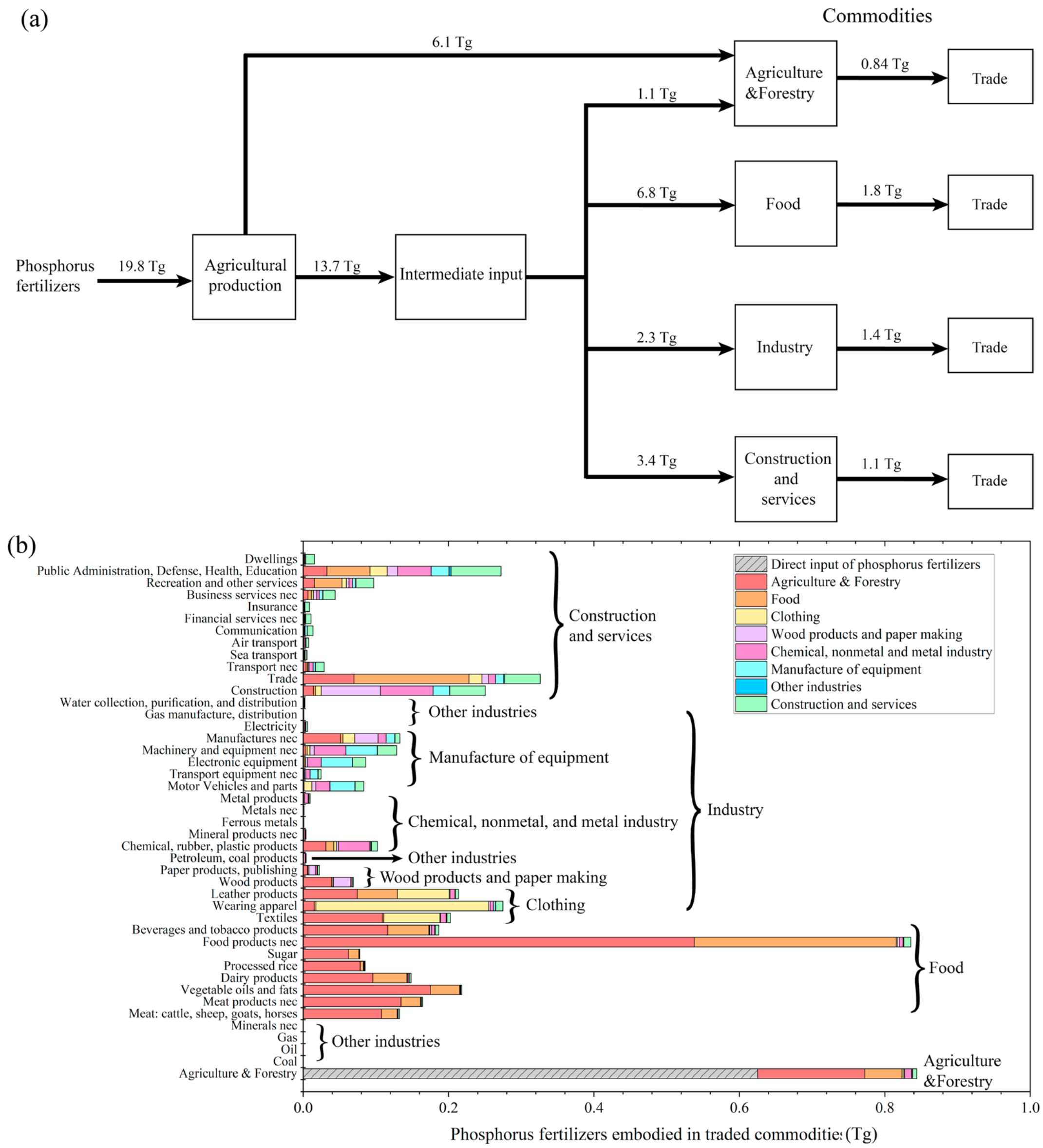

Figure 2. (a) Flow of phosphorus fertilizers in the global supply chain. (b) Phosphorus fertilizers embodied in traded commodities from 44 sectors. The columns without stripes represent the phosphorus fertilizers embodied in intermediate inputs from different sectors. The gray column with stripes indicates direct phosphorus fertilizer input to produce the agricultural commodity. Based on the use of the 19 industry sectors, we divided them into five groups. "nec" is the abbreviation for the term "not elsewhere classified." The detailed classifications and definitions of the 44 sectors can be found in Table S4. Original data of Figure 2b can be seen in Table S8.

industry and construction and services. Among the 1.4 Tg of phosphorus fertilizers embodied in industry sectors, the majority of phosphorus fertilizers embodied in commodities was sourced from the intermediate inputs of clothing (31.2%), the agriculture sector (24.2%), chemical, nonmetal, and metal industries (13.0%), and the manufacture of equipment (11.2%). As for construction and services, 38.1% of the 1.1 Tg of phosphorus fertilizers was embodied in intermediate inputs from the agricultural and food sectors, along with 24.1% from construction and services, 13.6% from chemical, nonmetal, and metal industries, and 10.9% from wood products and papermaking.

Here we also give a typical supply chain of how the phosphorus fertilizers were embodied in the trade of the construction sector (Figure S2 and Table S8). Producing chemical products required the input from the agriculture sector and thus indirectly consumed phosphorus fertilizers. The chemical products were then used to produce mineral products. Next, chemical and mineral products were used to produce metal

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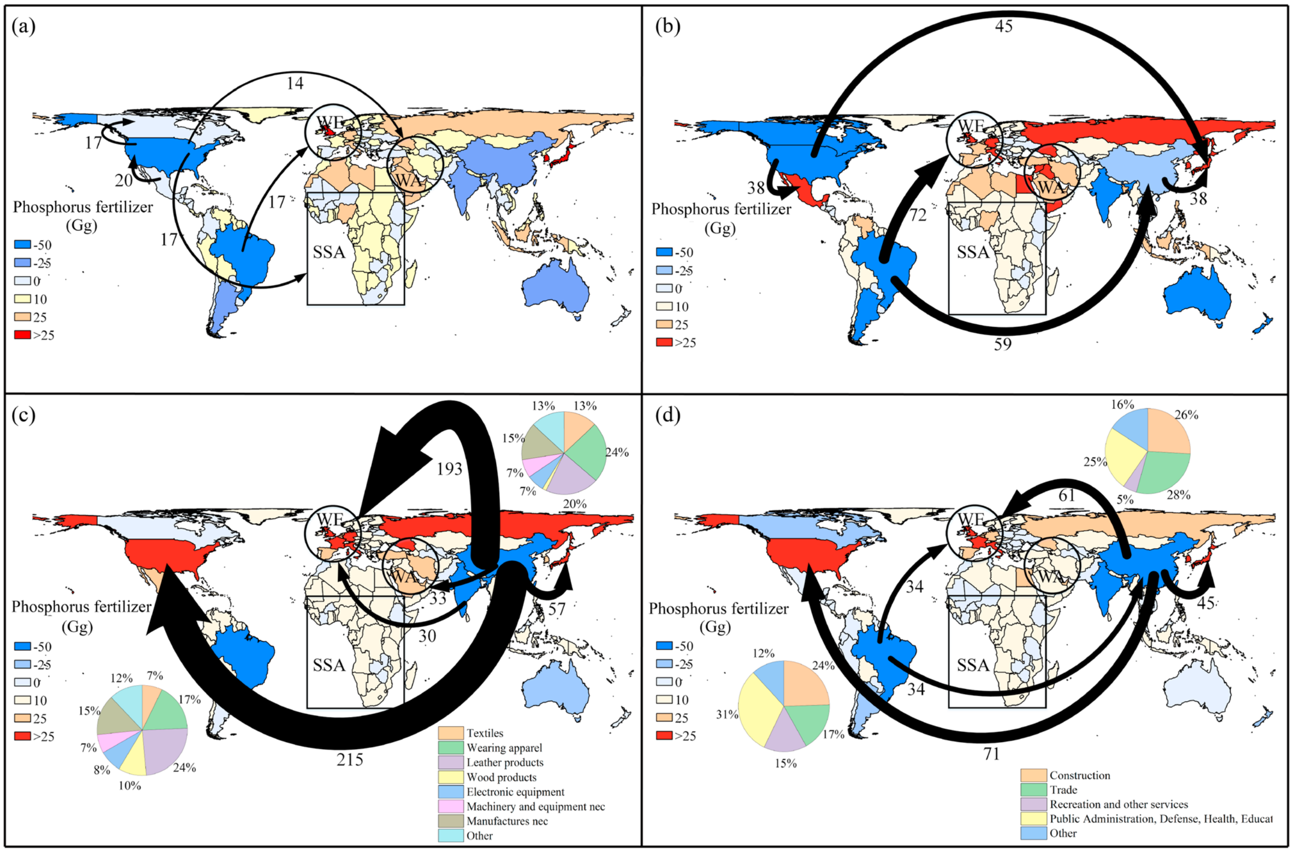

Figure 3. Phosphorus fertilizers (Gg) embodied in the trade of commodities from the (a) agriculture (agriculture and forestry) sectors, (b) food sectors, (c) industry sectors, and (d) construction and services in 2011. The color of each country indicates the net import of phosphorus fertilizers embodied in commodities. In each case, arrows depict the five largest interregional fluxes of phosphorus fertilizers from net exporting countries (blue) to net importing countries (red). Fluxes to and from WE, SSA, and WA are aggregated to include all countries in the region. A detailed classification of the regions is shown in Table S3, and a classification of the sectors is listed in Table S4. The pie charts in Figures 3c and 3d show the phosphorus fertilizers embodied in specific sectors in the trade flows from China to the US and WE, respectively. SSA = Sub-Saharan Africa; WA = Western Asia; WE = Western Europe.

products. Finally, the intermediate inputs from chemical products, mineral products, and metal products were used to produce the traded commodities in the construction sector. Through this supply chain, the construction sector indirectly drove the use of phosphorus fertilizers in the agriculture sector.

3.2. Phosphorus Fertilizers Embodied in the International Trade Flows of Different Commodities

In Figure 3, we traced the trade flows of phosphorus fertilizers embodied in different commodities. Figure 3a shows the trade flows of phosphorus fertilizers embodied in agricultural commodities. Western Europe and Western Asia were the largest importers of phosphorus fertilizers embodied in agricultural commodities, importing 21.5% and 13.0% of those embodied in trade, respectively (Figure S3). Large trade flows embodying phosphorus fertilizers often originated from the US, which contributed 16.1% of those embodied in traded agricultural commodities. Specifically, the US exported agricultural commodities embodying 0.017 Tg of phosphorus fertilizers to Sub-Saharan Africa, 0.017 Tg to Canada, and 0.014 Tg to Western Asia. Brazil was another major net exporter, with 0.017 Tg of phosphorus fertilizers embodied in agricultural commodities traded to Western Europe.

Figure S3 shows that 31.2% of the phosphorus fertilizers embodied in food commodities originated from Brazil and the US while 30.7% were destined for Europe and China. Figure 3b shows that Brazil exported 0.072 and 0.059 Tg of phosphorus fertilizers embodied in food commodities to Western Europe and China, respectively. Japan and Western Asia were another two major importers and accounted for 17.4% of the phosphorus fertilizers embodied in food commodities. For example, 0.045 and 0.038 Tg of phosphorus fertilizers were embodied in the food commodities traded from the US and China to Japan, respectively.

Phosphorus fertilizers embodied in commodities from industry sectors and construction and services were mainly traded from large emerging countries to developed regions. Figure S3 shows that Western Europe, the US and Japan collectively imported 54.1% of the phosphorus fertilizers embodied in industry commodities and 50.9% of those embodied in construction and services. Moreover, China exported 56.6% and 28.6% of the phosphorus fertilizers embodied in commodities from industry and construction and services, respectively. As shown in Figure 3c, a substantial amount of phosphorus fertilizers embodied in industry commodities (0.47 Tg) was traded from China to the US, Western Europe, and Japan. Compared with the trade of agricultural and food commodities, the US is a net importer of phosphorus fertilizers embodied in commodities from industry sectors, and it indirectly led to 0.22 Tg of phosphorus fertilizer use in China via the import of industry commodities. Of the 0.22 Tg of phosphorus fertilizers consumed in China, 49% were embodied in the clothing sector and 30% were embodied in commodities from the equipment and manufacturing sectors (electrical equipment, machinery, and equipment nec (not elsewhere classified), and manufactures nec). As another major net importer from China, Western Europe imported 0.19 Tg of phosphorus fertilizers embodied in industry commodities, 57% from the clothing sector and 29% from the equipment and manufacturing sectors. Figure 3d shows the trade flows of construction and services. As in Figure 3c, the largest trade flows embodying phosphorus fertilizers originated from China and were destined for the US (0.071 Tg), Western Europe (0.061 Tg), and Japan (0.045 Tg). Among these trade flows, phosphorus fertilizers were embodied mostly in the sectors of trade, public administration, defense, health, education, construction, recreation, and other services.

3.3. Imbalanced Interregional Fluxes of Phosphorus Fertilizers and Phosphorus Fertilizers Embodied in Commodities

To further investigate the global supply chain of phosphorus fertilizers, we compared the interregional flows of phosphorus fertilizers as well as those embodied in the trade of all commodities. Figure 4a shows that the majority of phosphorus fertilizers were traded to countries that had low phosphorus use efficiencies. Among the 5.6 Tg of phosphorus fertilizers traded in 2011, nearly 50% was traded to India, Brazil, and Argentina, with India and Brazil subsequently presenting moderate or strong phosphorus surpluses. In these two large importers, additional phosphorus fertilizer inputs yielded few agricultural outputs due to low phosphorus use efficiencies. In contrast, African countries (especially Sub-Saharan African countries) commonly have much higher phosphorus use efficiencies due to low phosphorus inputs (countries with slight phosphorus surpluses) and the mining of soil phosphorus (countries with phosphorus deficits). However, only 0.02 Tg (or 0.4% of the 5.6 Tg) of all phosphorus fertilizers were traded to Sub-Saharan Africa.

Figure 4b shows that developed countries and China were major importers of phosphorus fertilizers embodied in commodities, while large emerging countries (China, Brazil, and India) and the US were the major exporters. In 2011, 5.2 Tg of phosphorus fertilizers were embodied in the trade of commodities, and 46% of these phosphorus fertilizers were sourced from China (27%), Brazil (12%), and India (7%), which all present low phosphorus efficiencies. Noticeably, developed countries (Western Europe and the US, which use residual phosphorus in soil) with medium or high phosphorus use efficiencies drove substantial phosphorus fertilizer use in large emerging countries with low phosphorus use efficiencies, which leads to inefficient phosphorus fertilizer use on a global scale. Collectively, 0.9 Tg of phosphorus fertilizer was embodied in commodities traded from large emerging countries to Western Europe and the US. Specifically, 0.31 Tg of phosphorus fertilizer was embodied in exports from China to Western Europe and the US, and 0.14 Tg of phosphorus fertilizer was embodied in commodities traded from Brazil to Western Europe.

3.4. The Roles of Countries in the Global Supply Chain of Phosphorus Fertilizers

To summarize the roles of countries and regions in the global supply chain, we quantified the production and consumption of phosphorus fertilizers in the major countries and regions in Figure 5a; the consumption of phosphorus fertilizers and phosphorus fertilizers embodied in commodities is shown in Figure 5b. Figure 5a demonstrates that emerging areas, including India, Brazil, and other Latin American countries, were commonly net importers of phosphorus fertilizers. Figure 5b shows a different trade pattern that considers the phosphorus fertilizers embodied in commodities. Some net importers of phosphorus fertilizers in Figure 5a reversed to be net exporters of phosphorus fertilizers embodied in commodities; this included India, Oceania, Canada, Brazil, and other Latin American countries. In contrast, several developed regions

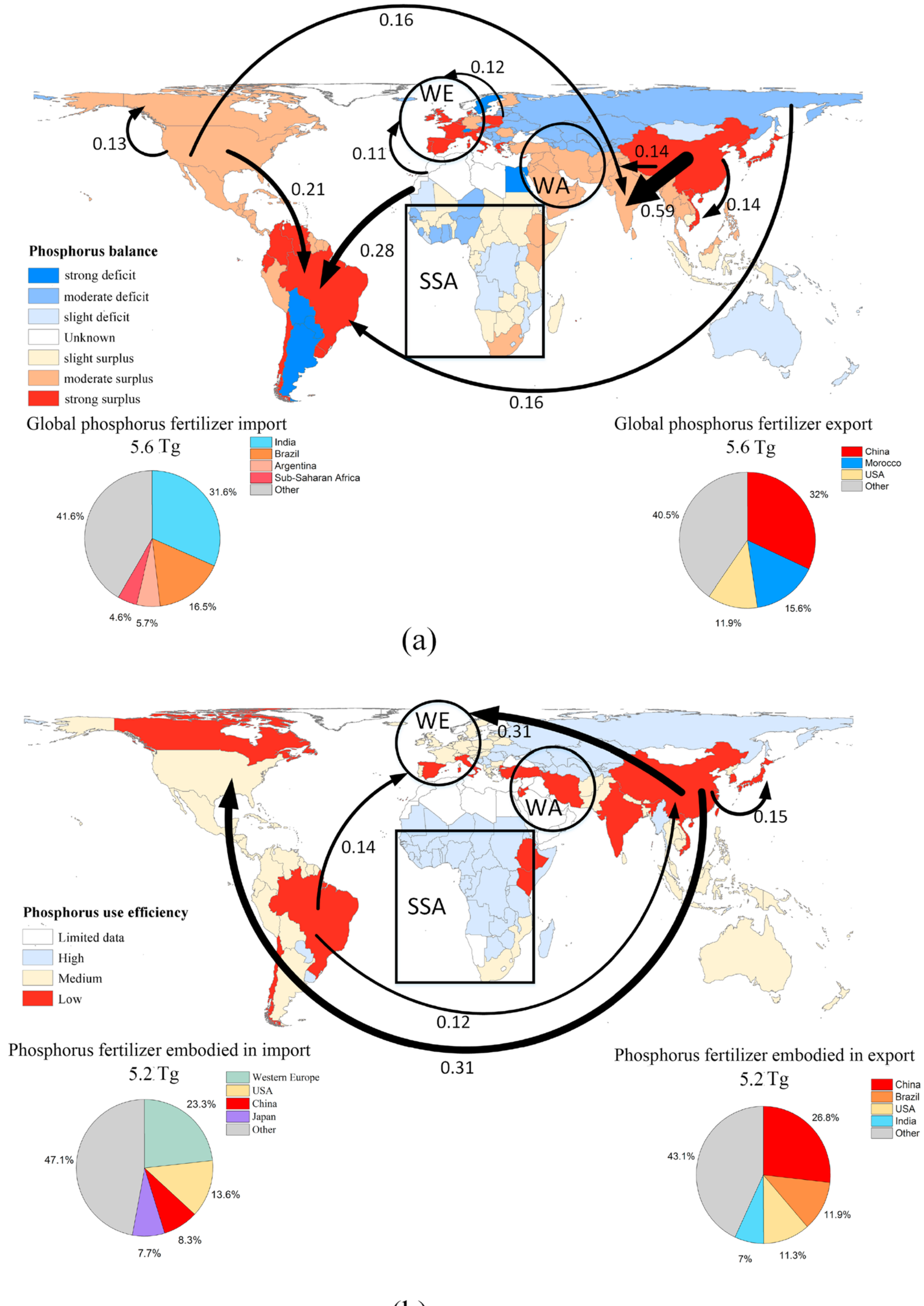

Figure 4. Key global trade fluxes of (a) phosphorus fertilizers (Tg) and (b) phosphorus fertilizers embodied in commodities (Tg). Arrows depict trade fluxes of more than 0.1 Tg of phosphorus fertilizers or the equivalent amount of phosphorus fertilizers embodied in final consumption. The phosphorus balance was calculated as the difference between total phosphorus inputs (phosphorus fertilizers and manure applications) and outputs (phosphorus in harvested crops), divided by the total cropland area. The phosphorus surpluses and deficits are classified according to quartiles: 0–25th percentile is classified as a slight deficit or surplus, 25–75th percentile is classified as a moderate deficit or surplus, and 75–100th percentile is classified as a strong deficit or surplus. Colors indicate phosphorus use efficiency (calculated as total crop dry-matter production divided by total P fertilizer and manure application). Phosphorus use efficiency is classified according to quartiles: 0–25th percentile is classified as low phosphorus use efficiency, 25–75th percentile is classified as medium phosphorus use efficiency, and 75–100th percentile is classified as high phosphorus use efficiency. The data for phosphorus balance and phosphorus use efficiency were adopted from Macdonald et al. (2011). SSA = Sub-Saharan Africa; WA = Western Asia; WE = Western Europe.

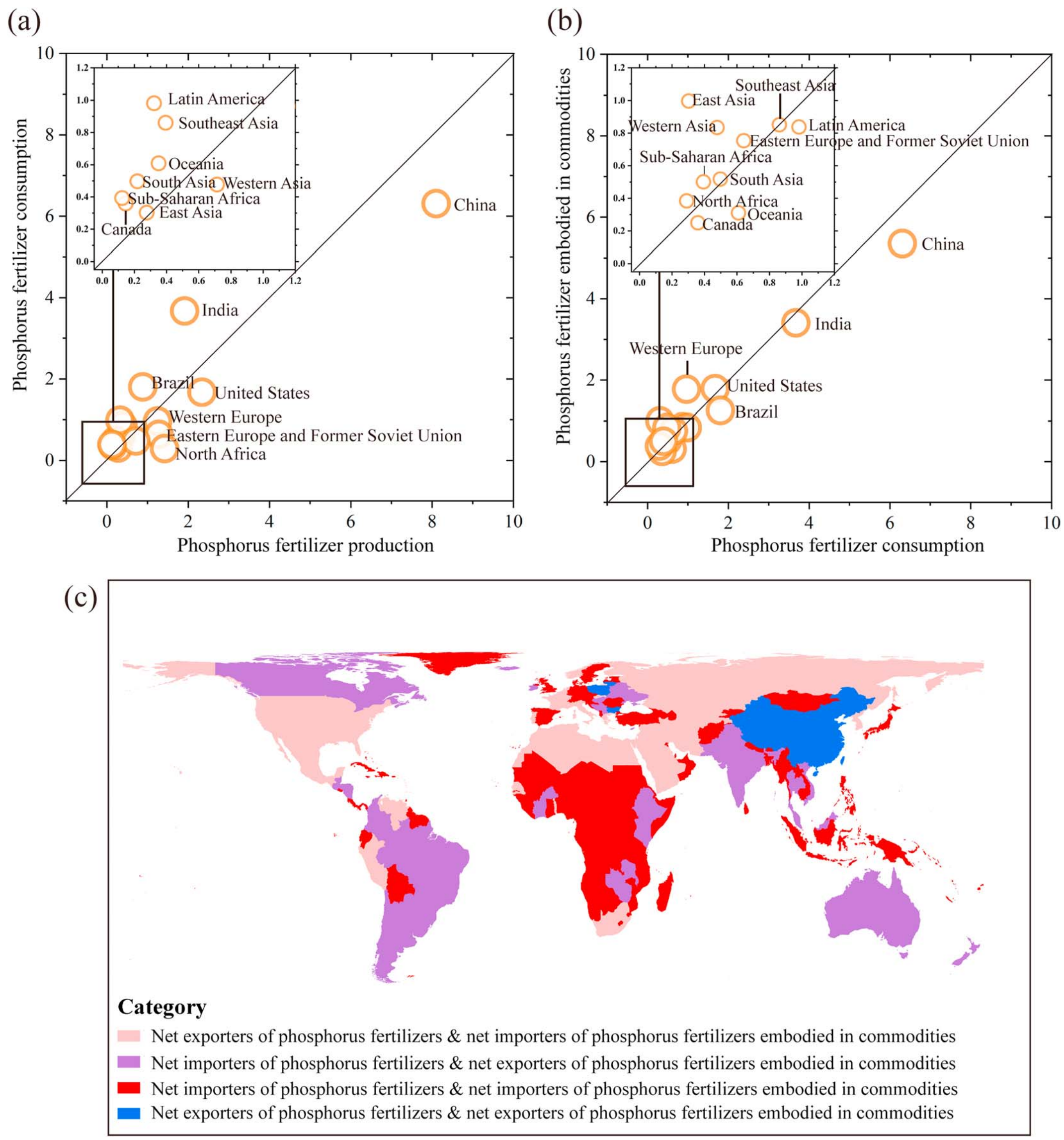

Figure 5. (a) Phosphorus fertilizer production (Tg) and phosphorus fertilizer consumption (Tg) of major countries and regions. (b) Phosphorus fertilizer consumption (Tg) and phosphorus fertilizers embodied in commodities (Tg) of major countries and regions. The inset box in the upper left corner of Figure 5a (Figure 5b) is a magnification of the box on the lower left. The solid line represents net zero imports in Figure 5a (Figure 5b). (c) Global patterns showing the net import of phosphorus fertilizers ($F^s_{prod}-F^s_{use}$) and the net import of phosphorus fertilizers embodied in commodities ($F^s_{use}-F^s_{commodity}$). The classifications of the 140 regions in our study are listed in Table S3.

and most of the resource-rich regions became net importers of embodied phosphorus fertilizers; this included the US, North Africa, and Eastern Europe and the former Soviet Union.

In Figure 5c, we divided the roles of countries in the global supply chain of phosphorus fertilizers into different categories based on the net import of phosphorus fertilizers and the net import of phosphorus fertilizers embodied in commodities. Figure 5c shows the spatial pattern of the roles among countries in the global supply chain. Major emerging countries (e.g., India, Brazil, and other Latin American countries) and several developed regions (Canada and Oceania) imported phosphorus fertilizers for agricultural production and then exported commodities embodying phosphorus fertilizers to foreign consumers. In contrast, resource-rich regions (including the US, North Africa, and Russia) exported phosphorus fertilizers and imported phosphorus fertilizers embodied in commodities. In several developed regions (Western Europe and Japan) and the least-developed region (Sub-Saharan Africa), most countries rely heavily on the import of phosphorus fertilizers for agricultural production, as well as the import of commodities embodying phosphorus fertilizers for consumption. China is an exception among these countries. With large reserves of phosphorus fertilizer resources, China exported the largest quantity of phosphorus fertilizers. At the same time, as an important international manufacturer, China also exported the largest quantity of phosphorus fertilizers embodied in commodities.

4. Discussion

Due to a rapid decline in access to high-quality phosphate rock reserves, a phosphorus shortage may threaten the long-term food security (Cordell et al., 2009). However, phosphorus fertilizer use is unevenly distributed and inefficient at the global scale. Many large emerging countries have low phosphorus use efficiencies and present serious eutrophication problems due to the excessive use of phosphorus fertilizers; other regions (e.g., Sub-Saharan Africa) are in desperate need of phosphorus fertilizers to improve crop yields and feed starving populations. Therefore, measures are urgently needed to address the unbalanced use of phosphorus fertilizers.

Recycling phosphorus from multiple sources and utilizing residual phosphorus in the soil are promising methods of addressing the unbalanced use of phosphorus. However, real barriers to fulfilling these goals are observed. Bulk waste products must be recycled due to their low phosphorus concentrations, and the financial investment to implement phosphorus recycling measures is high (Cordell et al., 2009). To recycle phosphorus from human waste, governments must construct new sewage systems that separate human waste and industrial waste (World Health Organization, 2006). Similarly, recycling urine requires the use of toilets that separate liquids from solids and the development of a system to collect urine, and it is a socio-technical process that is not managed by institutions or organizations (Cordell, 2006). Moreover, recycling phosphorus and using residual phosphorus in soil are not viable solutions in phosphorus-deficient areas, such as Sub-Saharan Africa, where these methods cannot meet the enormous phosphorus demand of agricultural production. To effectively feed the starving population, the total estimated phosphorus inputs to agriculture in Sub-Saharan Africa must increase by a factor of 2.3 to 11.7 (Sattari et al., 2012; van der Velde et al., 2014); however, recycling all phosphorus and improving phosphorus use efficiency to 100% could only double the current phosphorus supply (Figure S3).

Our study has found that improving the global supply chain of phosphorus fertilizers may provide additional opportunities to address the phosphorus imbalance beyond simply recycling or improving phosphorus fertilizer management. More than a quarter of global phosphorus fertilizer use is driven by the international trade of commodities, and approximately 85% of the traded phosphorus fertilizers are embodied in nonagricultural commodities. Globally, nearly half of the phosphorus fertilizers embodied in trade originate from large emerging countries, where phosphorus efficiencies are low. Furthermore, the consumption of nonagricultural commodities in developed countries drives much of the phosphorus fertilizer use in large emerging countries. Additionally, although many regions have high phosphorus use efficiencies (e.g., Sub-Saharan Africa), these regions are net importers of phosphorus fertilizers embodied in commodities.

The consumption data from the Food and Agriculture Organization only shows the total phosphorus fertilizer use in a country, without showing how many fertilizers are used in an agricultural subsector. Therefore, we aggregate all the subsectors (including the forestry sector) into one agriculture sector. We classify the forestry sector as the agriculture sector because phosphorus fertilizers are also used for forest cultivation (Binns, 1969; Miller, 1981; Stoeckeler & Arneman, 1960). This approach may cause an overestimation or an underestimation of certain sectors. For example, the wood sector required intermediate inputs from forestry sectors, which consumed less phosphorus fertilizers compared to other agricultural subsectors. However, in our research the forestry sector was merged into the agriculture sector, leading to an overestimation of the phosphorus fertilizers embodied in wood sectors. Though there might be some bias in certain sectors, the overall pattern was robust compared with the work of Hamilton et al. (2018), who found that 21% (26% in our research) of the phosphorus use was embodied in trade in 2011, and 49% (48% in our research) of the phosphorus embodied in trade were due to the consumption of nonfood commodities.

The results presented here suggest that an improved global supply chain of phosphorus fertilizers could benefit all countries in the supply chain. To achieve these goals, developed countries could provide funding or transfer technology to large emerging countries (e.g., China, India, and Brazil). At most, such measures could decrease phosphorus fertilizer use in large emerging countries by 50% (5.9 Tg) by recycling phosphorus from animal manure, organic waste, and human excreta and improving the phosphorus use efficiency (Figure S3). Some practical measures may include using treated or untreated wastewater to irrigate crops (Raschid-Sally & Jayakody, 2009), recovering struvite (ammonium magnesium phosphorus crystals that are high in phosphorus) from both urban and livestock wastewater (Reindl, 2007), reusing urine with ecological sanitation systems (Drangert, 1998), and optimizing soil conditions to increase soil phosphorus availability for plants (Roy et al., 2006). In large emerging countries, these approaches could also prevent eutrophication by minimizing the transport of phosphorus to lakes and rivers.

More importantly, because substantial capital investment is the major barrier for farmers to adopt advanced technologies, funding from developed countries could help farmers in large emerging countries implement technologies that improve phosphorus fertilizer use efficiency. As a result, fewer phosphorus fertilizers would be used to produce the same quantities of agricultural products and the prices of agricultural products would decrease. Then, the prices of commodities from industry sectors and services would correspondingly decrease due to lower costs for agriculture inputs. Thus, developed countries could import industry products and services from large emerging countries at a lower price. This savings could in turn compensate developed countries for the funding they provided. In addition, reducing phosphorus fertilizer demand in large emerging countries could allow Sub-Saharan countries to import more phosphorus fertilizers. To avoid the economic losses caused by reduced demand from large emerging countries, suppliers of phosphorus fertilizers would have to find new trading partners, and Sub-Saharan Africa could be the new major purchaser. As the supply of phosphorus fertilizers to Sub-Saharan Africa increases, the price of phosphorus fertilizers in this region would decrease. At the same time, with decreased demand from large emerging countries, Sub-Saharan African countries would face less intense competition when importing phosphorus fertilizers. Therefore, Sub-Saharan countries could purchase phosphorus fertilizers at a lower cost from exporters, which would benefit the exporters from Sub-Saharan Africa as well. Our results have shown that Sub-Saharan Africa imports large quantities of phosphorus fertilizers embodied in agricultural products. If agricultural output in Sub-Saharan Africa is increased due to higher phosphorus fertilizer use, then Sub-Saharan Africa would indirectly reduce phosphorus fertilizer use by its exporters.

Our estimates suggest that if 70% of the saved phosphorus fertilizers from large emerging countries were exported to Sub-Saharan countries (except South Africa), then phosphorus fertilizer consumption in Sub-Saharan Africa (except South Africa) could increase by 1,200%. Thus, the average phosphorus fertilizer used in arable regions of Sub-Saharan Africa (except South Africa) could reach approximately 20 kg/hectare (Table S2), which corresponds to a projected crop yield increase of 70%–190% (van der Velde et al., 2013). Such supply chain collaboration could substantially save phosphorus resources, decrease eutrophication, and increase the food production.

Debates on the allocation of responsibility would be the major barrier for the cooperation among countries, just as the disagreement that occurs in the global trade agreement. In the short term, it seems impossible that the cooperation mechanism would be established. However, similar to the threat of the climate change, potential phosphorus shortage would force all the countries to stand together and address the long-term food security problem with joint effort.

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Notes

The authors declare that they have no competing financial interests.

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