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Influences of international agricultural trade on the global phosphorus cycle and its associated issues

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ABSTRACT

Industrial phosphorus (P) fertilizer has substantially improved global food production, but has also led to environmental impacts. Intensive global agricultural trade has increased and the impacts of trade on aggravating or alleviating future P scarcity must be examined, especially for the most vulnerable countries. We combined data to estimate the global P trade among countries and its impacts on global P flows, based on global agricultural trade, cropland soil P budgets and crop P fertilizer footprints (the amount of industrial P fertilizer applied for producing one unit of P in the harvested crop). The global agricultural P trade represented a fraction of 16% of P in harvested crops in 2014, half of which was exported from the United States of America, Brazil and the European Union and one fifth imported by China. Virtual P fertilizer flows (about 2.60 Tg P y^{-1}) referred to industrial P fertilizers applied to traded crops by exporting countries; thus, 1/3 of global virtual P fertilizer flows were associated with the international soybean trade. P use efficiency (PUE), the ratio of the harvested crop-P to the total external P inputs, is a larger problem for tropical than temperate countries. Global crop trade had brought in a net 0.2 Tg P y^{-1} savings of industrial P fertilizers globally, compared to crop production in export and import countries. >0.50 Tg y^{-1} of the gross global accumulation of soil P and P in freshwater were associated with global agricultural trade. Global PUE, however, could be improved considerably, and thus global cooperation and improving PUE could help to solve the problem of future P scarcity. Vulnerable countries should also propose urgent national plans to address their own situations of P scarcity or low PUE.

1. Introduction

Agricultural production is still the leading contributor to present transgressions of planetary boundaries (Tilman & Clark, 2014; Rasmussen et al., 2018; Varah, 2020), especially for global P cycle. Future population growth, economic development and dietary change will continue to increase the demand of agricultural food products, which could further lead to more overall environmental burdens (Marques et al., 2019). Agricultural food production and consumption differ markedly among countries and crops (Ringeval et al., 2014; Lun et al., 2018), due to their distinct local natural resources, available cropland area, population, culture and so on. Therefore, global food security strongly relies on international agricultural trade, especially due to the spatial mismatch between agricultural production and food consumption (O'Rourke, 2014; Kinnunen et al., 2020). Agricultural trade bridges spatial unbalances between food demand and food production, but also influences important nutrient flows embodied in agricultural food (Schipanski et al., 2016; Gerten et al., 2020). In the case of P, its quantity translocated by international trade has increased nearly eight-folds between 1961 and 2011, and the traded fraction accounted for 20% of total harvested crops in 2010 (Nesme et al., 2018). This rapid increase of international agricultural trade does not only provide key knowledge for

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understanding the disconnect between natural resources and food production on one hand (Holland et al., 2015; Oterosrozas et al., 2015; Sun et al., 2018), but also their associated environmental impacts on the other hand, including water use (Dalin et al., 2012; Marston et al., 2015; Qu et al., 2018; Liu et al., 2019), land-use change (D'Odorico et al., 2014; Chaudhary and Kastner, 2016), biodiversity (Lenzen et al., 2012), nitrogen flows (Kastner et al., 2014; Lassaletta et al., 2014, 2016) and pollution (Otia, 2016; Hamilton et al., 2018). These studies can support national policies and sustainability assessments from global viewpoints, due to the inclusion of natural resources and environmental impacts via international trade (Holland et al., 2015).

Phosphorus (P) is an essential element for plant growth, but P ore is the non-renewable resource (Elser & Bennett, 2011; Penuelas et al., 2013; Tonini et al., 2019). The extensive P ore mining for fertilizers has forced global P cycle beyond its sustainable planetary boundary, and thus the crisis of P scarcity in future could pose a growing risk to global economy (Cordell et al., 2009; Richardson et al., 2015; O'Neill et al., 2018; Withers, 2019; Li et al., 2018). Thus, to better explore global agricultural P cycles is key for achieving global sustainable developmental goals (SDGs) and also for proposing polices of sustainable P management (Bennett and Elser, 2012; MacDonald et al., 2012, 2015). Agricultural P budgets, especially cropland soil P budget, are determined by their total P inputs and outputs, and thus excessive or insufficient external P fertilizer application could lead to severe problems (Lun et al., 2018). The excessive and therefore less efficient P application, could lead to persistent soil P accumulation and thus drive local surface water eutrophication, like in croplands of some East Asian countries (Liu et al., 2016; Pretty et al., 2018; Yang et al., 2019); however, some African countries suffer serious cropland soil P deficits or P depletion due to limited access to P fertilizers, which could further limit their food production (MacDonald et al., 2011; Obersteiner et al., 2013; Der Velde et al., 2013). Furthermore, cropland P budgets and associated P issues differ significantly among countries and crops, due to their distinct natural resources and social-economic levels (Lun et al., 2018).

International agricultural trade has changed global P cycles, and the economic activities of one nation could leave large imprints on cropland soil P budgets of distant countries. Although P pollution and P scarcity are usually managed locally, P-related issues have global origins and may exert global impacts, especially under present globalization and intensive international trades (Cordell et al., 2012; Nesme et al., 2018; Kinnunen et al., 2020). Thus, it is of high importance for vulnerable nations (like Japan) and vulnerable crops (like fruits) to analyze the impacts of international agricultural trade on global P cycles and their associated implications, and then it can provide suggestions to policymakers and local governments. Only a few large-scale estimates have reported the impacts of international agricultural trade on global P cycles and their associated issues, not to mention detailed trade matrix among different specific crops (Nesme et al., 2018; Yang et al., 2019). The limited number of studies on global syntheses of all crops and associated environmental impacts could lead to a mismatch between local-scale understanding and its global implementation. Further studies should thus be conducted to better understand how international agricultural trade influences global P cycles and the associated impacts in order to reach a sustainable development of the earth system.

Therefore, our study aimed first to calculate all the trade balances among countries for specific crop commodities, and second to identify the necessary changes to save P resources, avoid environmental impacts and increase food security. Besides, our in-depth analysis also aimed to provide suggestions on possible policy pathways for different vulnerable countries, considering their cropland P budget, international agricultural trade and global P scarcity. More detailed, we used P-fertilizer footprint, defined as the amount of industrial P fertilizer applied for producing one unit of P in the harvested crop, to illustrate the total P inputs for specific agricultural food (Jiang et al., 2019). The concept of virtual P fertilizer, in a similar way to the concept of virtual water of Dalin et al. (2012), was used to represent the amount of P fertilizer applied in export countries for traded crops consumed in import countries. Besides, the P dynamics of global crop trade and its associated issues were illustrated by the network analysis of crop P footprints and virtual P flows. We systematically quantified the global trade of agricultural P in 2014 based on a detailed trade matrix of 165 types of food data from FAOSTAT, cropland soil P budgets and P fertilizer footprints (PFFs); then, we analyzed how international agricultural trade influenced global agricultural P cycles, cropland soil-P budgets, P discharge into freshwater systems, as well as global P fertilizer consumption. Finally, we examined the vulnerability of different countries and then proposed different pathways to face future P scarcity, considering their cropland soil P budgets and international P flows.

2. Methods

In this study, we developed a hybrid approach for quantifying P flows embedded in traded agricultural food products, based on substance flow analysis and footprint analysis. Global agricultural P cycle here referred to domestic cropland soil P budgets and international agricultural P flows, including physical P flows embodied in traded food and virtual P fertilizer flows with traded products. The domestic cropland soil P budgets were determined by their total P inputs and outputs; more detailed, cropland P inputs here included P fertilizers, atmospheric deposition & weathering, livestock manure and returned crop residues, while cropland soil P outputs included crop harvests, removed crop residues, leaching and runoff. The physical P flows embodied in traded food can be estimated by the amount of traded agricultural food and their P contents for each food; simultaneously, the virtual P fertilizer flows can be estimated with the amount of traded food and their cropland PFFs of export countries. Furthermore, it can be concluded how the international agricultural trade influence global P fertilizer consumption, comparing PFFs in export countries and import countries. More detailed information was presented as follows.

2.1. Cropland soil P budget

We obtained data for 165 types of food crops and 18 types of livestock products for 235 countries. Reports of the International Fertilizer Association divided all crops into 12 types (International Fertilizer Association (IFA) and International Plant Nutrition Institute (IPNI), 2017), including wheat, rice, maize, other cereals, soybean, palm oil, other oil crops, sugar crops, roots and tubers, fruit, vegetables and other crops. All countries could be divided into 29 countries or regions, including EU28 (including Britain) and the rest of the world (180 countries, ROW) (see the Supporting Information, SI). Cropland soil P budget was balanced with its total P inputs and outputs, based on methods described by Lun et al. (2018). Cropland soil P inputs included P fertilizer, atmospheric deposition, manure and returned crop residues, while its P outputs included the crops, crop residues, leaching and runoff. More detailed information was presented in SI.

P fertilizer input (***P_{fer}***): IFA reports (2017) provided detailed consumptions of P fertilizer for each specific crop for these 29 countries or regions, and hereby P fertilizer inputs can be calculated with P fertilizer consumption and their P contents.

Atmospheric P deposition (***P_{atm}***): P_{atm} in croplands was calculated separately for each country based on gridded global P-deposition results from Wang et al. (2014, 2015)), using agricultural land-use maps and the LMDz-INCA aerosol chemistry transport model.

Manure P inputs (***P_{man}***): FAOSTAT provided data for N application of manure into croplands for different animals; thus, we can calculate P inputs from livestock manure, based on N inputs and their P:N ratios for different livestock manure (MWPS-18, 1985; OECD, 1991; Levington Agriculture, 1997; Sheldrick et al., 2003; ASAE, 2005).

Crop residues (***P_{res}***) **and** ***returned crop residues*** (***$P_{re\text{-}res}$***): According to Liu et al. (2008), we assumed that half of crop residues were recycled back to croplands as soil P inputs. FAOSTAT provided the amount of crop residues, and thus total P outputs in total crop residues and recycled crop residues can be estimated with their specific amounts and their P contents.

***Crop* (P_{crop})**: P_{crop} was estimated by crop production data from FAOST and their crop P contents (COMIFER, 2007; USDA-NRCS, 2009; Waller, 2010).

***Leaching and runoff* (P_{runoff})**: We used previous results to represent P losses from croplands due to leaching and runoff, which referred to 12.5% of total cropland P inputs (Bouwman et al., 2013).

The cropland soil-P budget (ΔP) was balanced between all P inputs (P_{in}) and all P outputs (P_{out}), calculated as:

$$\Delta P = P_{in} - P_{out} P_{in} = P_{fer} + P_{atm} + P_{man} + P_{re-res} P_{out} = P_{crop} + P_{res} + P_{runoff}$$

2.2. P-Fertilizer footprint and international virtual P fertilizer flows

The cropland P footprint was defined as the total P inputs (unit: kg P) for producing one unit amount of P in harvested crops, so the P fertilizer footprint (PFF) referred to the consumption of physical P fertilizer for one unit amount of P in harvested crops (kg P/kg P), and thus they can be calculated as:

$$PFF = \frac{P_{fer}}{P_{crop}}$$

International virtual P fertilizer flows (*VPFFs*) can be calculated by multiplying crop trade (*T*) and crop PFF of export countries, and the equation method was as follows. The detailed crop-trade matrix came from the database of FAOSTAT.

$$VPPF = PPF \times T$$

2.3. Global P fertilizer saving or wasting due to international agricultural trade

International agricultural trade could influence global P fertilizer consumption, due to different P use efficiencies or P footprints between import countries and export countries. It is of high importance to explore how global agricultural trade influence global P fertilizer consumption, and thus here we quantified them by the indicator of ***Global P Fertilizer Consumption Saving*** ($GPFCS_{i,j,x}$). The indicator of $GPFCS_{i,j,x}$ was defined to evaluate global P fertilizer consumption saving or wasting, due to crop × trade from export country *i* to import country *j*.

$$GPFCS_{i,j,x} = T_{i,j,x} \times (PPF_{j,x} - PPF_{i,x})$$

where *i*, *j* and × correspond to the export country, the import country and traded crops, respectively; $T_{i,j,x}$ is the volume of crop × traded from country *i* to country *j*; $PFF_{j,x}$ and $PFF_{i,x}$ refer to the PFF of import country *j* and import country *I*, respectively. The positive results of $GPFCS_{i,j,x}$ (>0) indicates that crop × traded from country *i* to country *j* could lead to a global saving of P fertilizer; conversely, the negative results of $GPFCS_{i,j,x}$ (<0) indicates this trade could lead to a global waste of P fertilizer. Hereby, the following equation can be used to how international agricultural trade influence global P fertilizer consumption. More detailed, the result of GPFCS>0 illustrated that international agricultural trade would save global total P fertilizer consumption; otherwise, international agricultural trade resulted in global P fertilizer wasting.

$$GPFCS = \sum_{x} GPFCS_x = \sum_{x} \sum_{(i,j)} GPFCS_{i,j,x}$$

3. Results

3.1. Global agricultural P trade

The total global trade of agricultural P was 2.78 Tg P y^{-1} in 2014, about 95% embodied in crops and 5% embodied in livestock products (Figs. 1 and 2). The amount of traded crop P was 16% of the total P included in harvested biomass. More than half of this amount (1.53 Tg P y^{-1}) was exported from the United States of America (USA), Brazil and the 28 countries of the European Union (EU28, including the United Kingdom). There were two big (China and EU28) and many small importers of crop P, and more than one fifth was imported by China. Considering their imports and exports, only 12 countries were net exporters of agricultural P, with the USA, Brazil, Canada, Argentina and Ukraine exporting > 0.1 Tg P y^{-1} in 2014.

The global trade of soybean P contained the largest share (0.71 Tg P y^{-1}) of the global P trade in 2014, followed by wheat (0.66) and maize (0.54). Together, these three crops comprised 69% of global trade of agricultural P. Global soybean trade was dominated by only a few countries; more detailed, 80% of globally traded soybean was originally produced in the USA and Brazil, while China imported nearly 2/3 of globally traded soybean. EU28, Canada, Russia and Australia exported large amounts of wheat, while EU28, Argentina and Ukraine were important maize exporters. Pork contributed one half of globally traded P embodied in livestock products, followed by chicken (18%), beef (13%) and milk (10%).

>1/3 of exported agricultural P from the USA was imported by China, 83.5% of which was due to the large soybean trade (Fig. 3 and

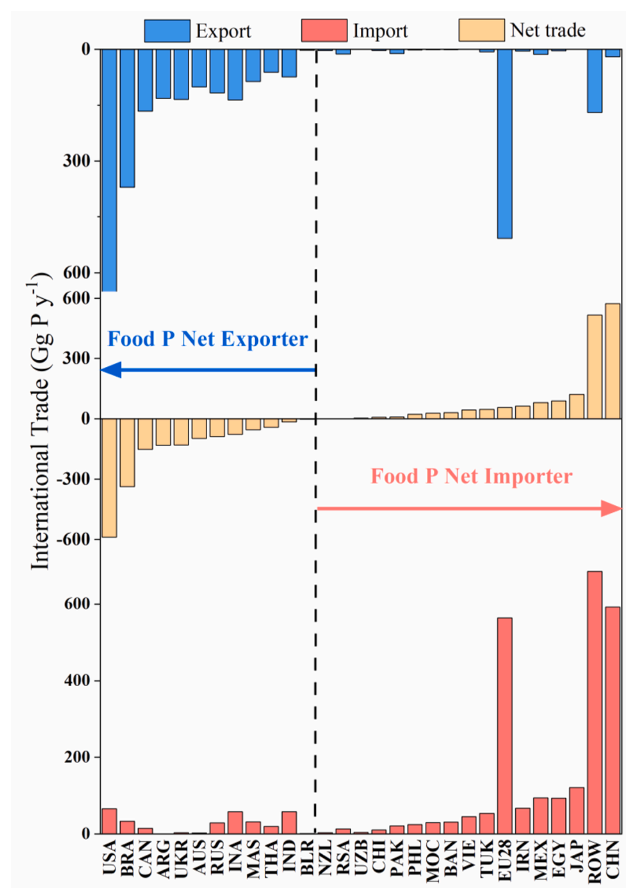

Fig. 1. Agricultural P exports, imports and net trade for countries or regions. The dashed line separates net agricultural P exporters (countries to the left) from net importers. Countries further away from the dashed line represent larger net exporters and importers, respectively. ARG, Argentina; AUS, Australia; BAN, Bangladesh; BLR, Belarus; BRA, Brazil; CAN, Canada; CHI, Chile; CHN, China; EGY, Egypt; IND, India; INA, Indonesia; IRN, Iran; JAP, Japan; MAS, Malaysia; MEX, Mexico; MOC, Morocco; NZL, New Zealand; PAK, Pakistan; PHL, Philippines; RSA, Republic of South Africa; RUS, Russia; THA, Thailand; TUK, Turkey; UKR, Ukraine; VIE, Vietnam; USA, the United States of America; UZB, Uzbekistan; EU28, 28 countries of the European Union; ROW, rest of the world.

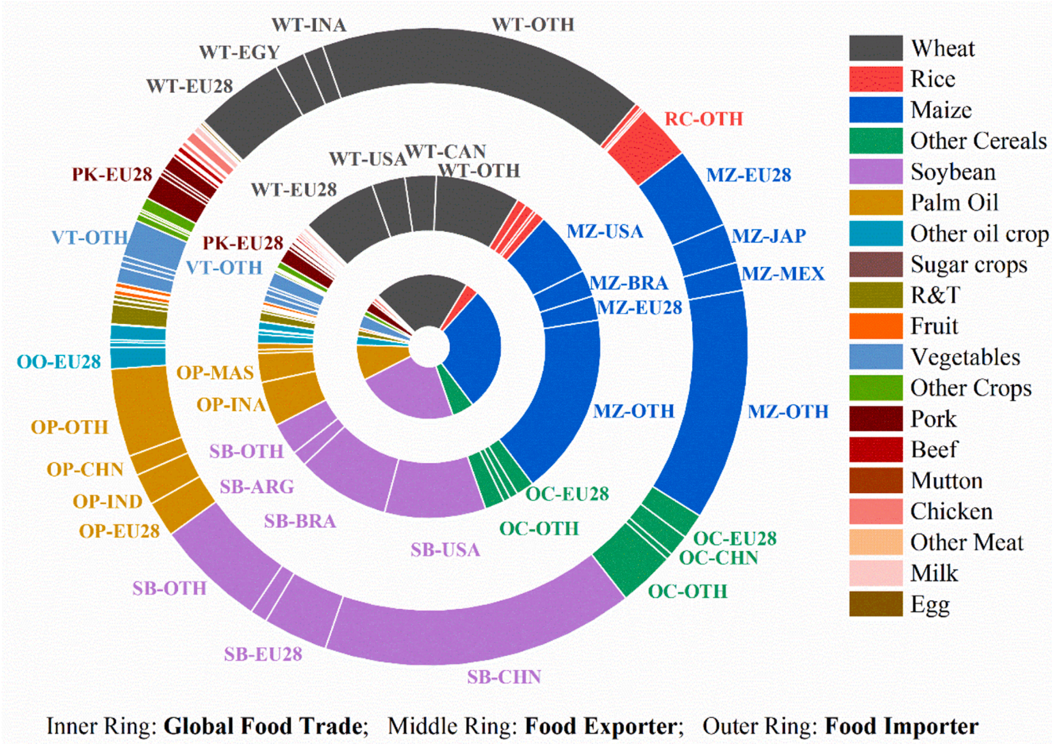

Fig. 2. Global agricultural trade and main exporters and importers for crops and livestock products. The inner ring represents the global agricultural trade and its composition. The middle ring represents the three largest exporters for each agricultural item. The outer ring represents the three largest importers for each agricultural item. This figure contains countries whose specific trade of crop P was > 1% of the total trade of agricultural P. WT, RC, MZ, OC, SB, OP, OO, VT and PK represent wheat, rice, maize, other cereals, soybean, palm oil, other oil crops, vegetables and pork, respectively. For example, WT-EU28 in the middle ring illustrates that exports of wheat P from EU28 was > 1% of the total trade of crop P, and SB-CHN in the outer ring illustrates that soybean P imported by China was > 1% of the global trade of crop P. See Fig. 1 for the country abbreviations.

figures in Supporting Information). The USA and China were thus strongly linked with their agricultural trade, which accounted for 8% of global total agricultural P trade. The USA also exported large amounts of agricultural P to Mexico and Japan, about 0.082 and 0.076 Tg P y^{-1}, respectively. Soybean, maize and wheat constituted 90% of agricultural P exports from the USA. The largest trade of agricultural P, however, was the soybean trade from Brazil to China (0.20 Tg P y^{-1}), and soybean exports accounted for about 3/4 of its total agricultural P exports from Brazil.

About 2/3 of the EU28 agricultural P trade was among its member countries, but these countries still demanded a great deal of agricultural imports from other regions. For example, EU28 still imported large amounts of soybean from Brazil and the USA and large amounts of maize from Ukraine. Hereby, EU28 presented a big net importer of agricultural P.

China was the largest net importer of agricultural P, with gross imports of 0.57 Tg P y^{-1} and gross exports of 0.02 Tg P y^{-1}. Soybean was the largest imported crop in China, most of which were imported from Brazil (0.20 Tg P y^{-1}), the USA (0.19) and Argentina (0.04). China also imported large amounts of other crops (>0.01 Tg P y^{-1}) from other countries, such as Australia (wheat), Canada (soybean and vegetables), Indonesia (palm oil), Malaysia (palm oil) and Thailand (rice and roots & tubers). Vegetables contributed almost one half of agricultural P exports from China, which were mainly exported to Japan and Vietnam. More than half of agricultural P consumed in Japan was imported from other countries, and thus Japan strongly depended on international agricultural trade. >60% of Japanese imported agricultural P was originally produced in the USA, followed by Canada and Brazil. Maize represented the largest import of agricultural P in Japan, nearly one half of its totally imported agricultural P.

3.2. *Crop P fertilizer footprints and flow of virtual P fertilizer*

Crop P fertilizer footprint (PFF) refers to the amount of industrial P fertilizer applied to cropland for producing 1 kg of P in the harvested crops (in kg P kg P^{-1}); hereby, PFF can be a measure of the P fertilizer consumption for human food. Besides, crop PFF can also be used as an indicator of crop P fertilizer use efficiency (PUE), which is assumed to the ratio of harvested crop P to P fertilizer inputs. Thus, the larger PFF referred to the lower PUE. Global crops consumed a total amount of 19 Tg P y^{-1} of industrial P fertilizers in 2014, about 3/4 of which was applied into wheat, rice, maize, soybean, fruits and vegetables. However, PFFs differed greatly among crops and countries (Fig. 4). Crops with high economic value consumed more industrial P fertilizers due to their high economic benefits, and thus their PFFs were much higher for fruit (9.52) and vegetables (3.07) than wheat (1.06), rice (1.36) and soybean (1.06). However, the PFF for Maize was only 0.70 kg P kg P^{-1}, excluding external P inputs of livestock manure, recycled residues and deposition.

PFFs were higher for China, Brazil, Japan, New Zealand and Morocco due to their intensive application of industrial P fertilizer, while their PFFs were lower for the USA, EU28, Russia, Ukraine and Argentina. The USA and Brazil were two important agricultural exporters in the world, especially of soybean; however, their soybean PFFs presented great differences for these two countries and its was four-fold higher for Brazil than for the USA. It was because that there was lowly available soil P for plants in Brazilian soybean croplands. More industrial P fertilizer could be consumed globally in future if soybean exports from Brazil still continue to increase. Fruit PFFs also varied markedly among countries, with the largest (25 kg P kg P^{-1}) in Malaysia. High PFFs and low PUEs for crop production were therefore clearly a larger problem in tropical than temperate countries, due to their old and weathered soils that rapidly

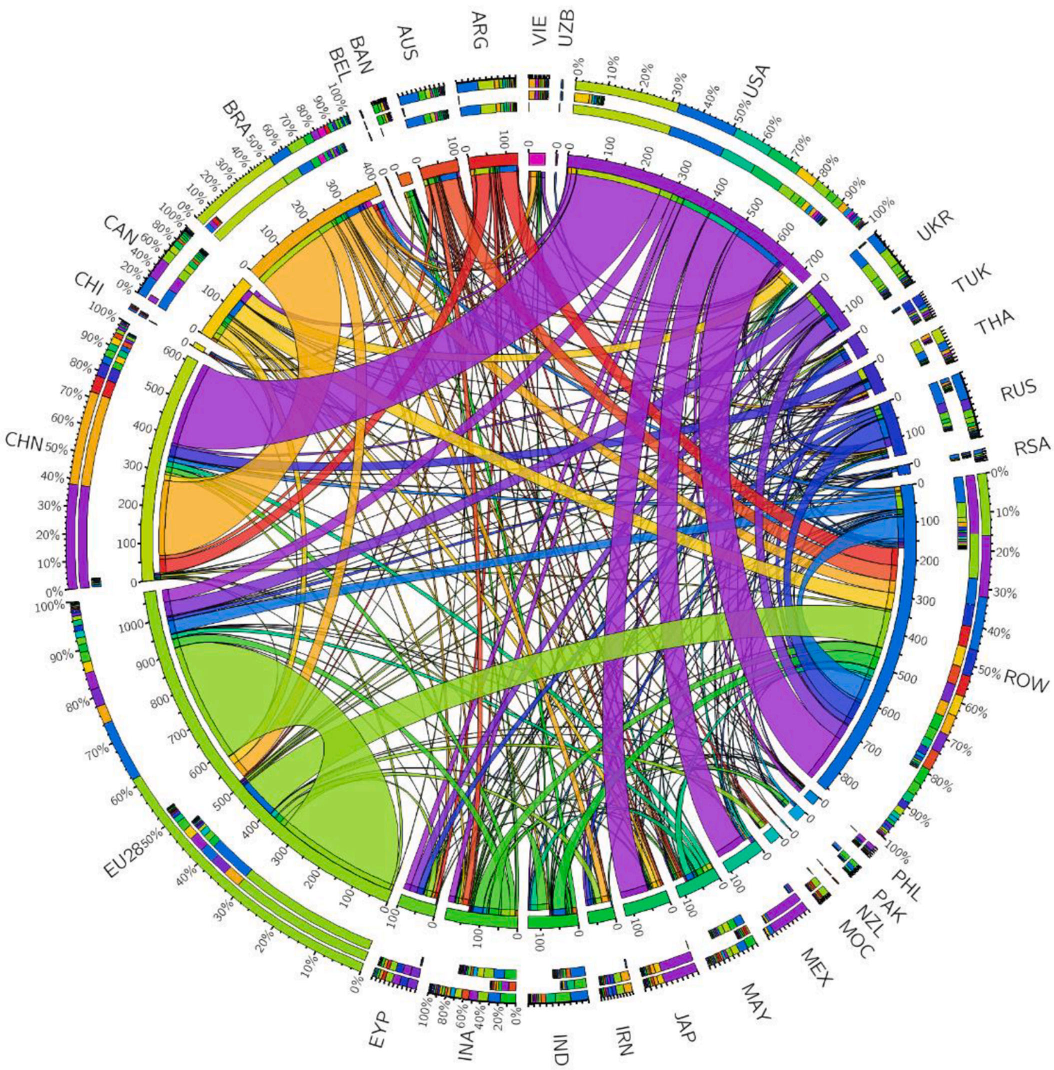

Fig. 3. Global trade of agricultural P among countries or regions in 2014, including crop and livestock products. The main trade matrix is illustrated there, with the P trade of > 1.0 Gg P y^{-1}. The numbers indicate the trade of agricultural P in Gg P, and the link colors correspond to the export countries or regions. See Fig. 1 for the country abbreviations.

occlude added P (Mekonnen & Hoekstra, 2018; Withers et al., 2018; Pavinato et al., 2020); besides, this low P availability is also common in all tropical regions (Gemenet et al., 2016; Alewell et al., 2020). Therefore, tropical countries should fully consider P management for crop production in the future.

The international flow of virtual P fertilizer could be estimated based on the PFFs of export countries (Fig. 5). The global total flow of virtual P fertilizer amounted to 2.60 Tg P y^{-1} in 2014, accounting for 14% of the annual industrial P fertilizer consumption. Almost 1/3 of the flows was due to the global soybean trade, representing 43% of all industrial P fertilizer consumed by soybean in the world. Thus, effective soybean production and treatment could reduce the global consumption of industrial P fertilizer. The trades of wheat and maize both contributed > 0.3 Tg P y^{-1} to the global flow of virtual P fertilizer.

Although the USA was the largest agricultural P exporter, Brazil has turned to the largest virtual P fertilizer exporter due to its high PFFs, with its exported virtual P fertilizer being 2 times of its exported agricultural P (Fig in SI). Virtual soybean P fertilizer exports were 4-fold higher from Brazil than from the USA, although their amounts of soybean trade were almost the same. The USA, EU28 and Canada were the main gross virtual P-fertilizer exporters, which together accounted for about 3/4 of global virtual P-fertilizer exports. China and New Zealand also exported larger amount of gross virtual P fertilizer, compared with their agricultural P exports; it was because these two countries mainly exported highly P-intensive fruits.

The main gross virtual P fertilizer importers were China (0.72), EU28 (0.46) and Japan (0.13). However, their imported virtual P fertilizers were originally from different countries. More detailed, China imported 2/3 of its virtual P fertilizers from Brazil, due to higher PFFs there, while 44% of Japanese virtual P fertilizer imports were originally from the USA. Almost one half of their virtual P-fertilizer flows in EU28, however, originated from its own member countries.

The largest share of global flows of virtual P fertilizer due to agricultural trade was from Brazil to China, about 0.45 Tg P y^{-1} of which was from their intensive soybean trade. Virtual P fertilizer flows were also large for the soybean trade from the USA to China and from Brazil to EU28. Other large virtual P fertilizer flows were for the wheat trade from Australia to Indonesia and the maize trade from the USA to Japan and Mexico.

Brazil was the largest net exporter of virtual P fertilizer, at 0.66 Tg P y^{-1}. Other major net exporters of virtual P fertilizer included the USA, Canada, Australia, India and Argentina. However, Brazil, Australia and Argentina were also large importers of P fertilizer (Lun et al., 2018), but they then re-exported large amounts of P embodied in crops (like

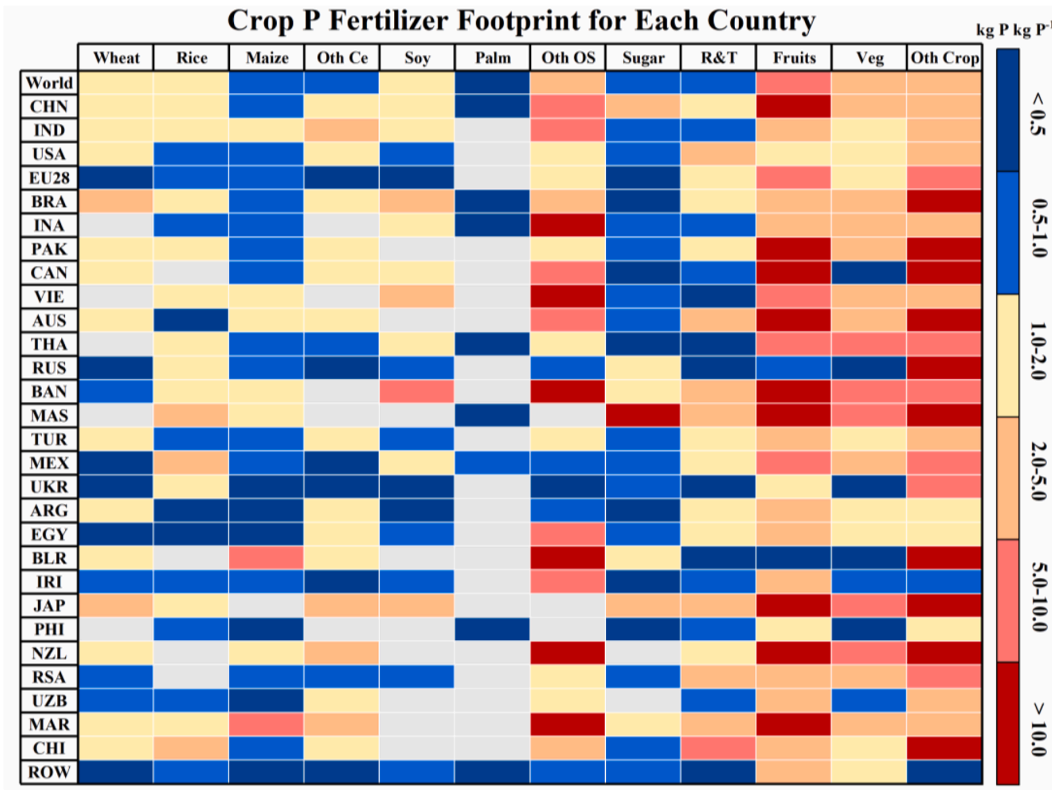

Fig. 4. Crop P-fertilizer footprint for each country or region. Grey cells represent no data in these countries or regions. See Fig. 1 for the country abbreviations.

soybean and wheat). For Brazil, one half of its imported P fertilizers could be finally and virtually re-exported to other countries by the international crop trade. Consequently, the question of sustainable and efficient use industrial P fertilizer in these countries should be raised in the future, especially for facing P scarcity in future.

3.3. Impacts of international agricultural trade on global industrial P fertilizer consumption

Crop trade can lead to global savings of industrial P fertilizer if directed from countries with lower PFF to countries with higher PFFs, which otherwise could lead to an increase of global industrial P fertilizer consumption. The international crop trade saved about 1% of the total global consumption of industrial P fertilizer in 2014 (0.20 Tg P y^{-1}), equivalent to the annual industrial P fertilizer consumption in Argentina (Figs. 6-8). Most crop trades were beneficial for saving global industrial P fertilizers, especially global wheat and vegetable trades; more detailed, international trades of wheat and vegetable saved about 0.07 and 0.06 Tg P y^{-1} of industrial P fertilizer consumption in 2014, respectively. Meanwhile, global soybean trade could also lead to 0.04 Tg P y^{-1} of industrial P fertilizer savings in 2014. However, global trades of rice, oil palm, other oil crops and sugar crops increased global consumption of industrial P fertilizers in 2014.

The largest global saving of industrial P fertilizer was associated with the soybean trade from the USA to China, thanks to the low soybean PFF in the USA. The annual industrial P fertilizer savings were about 0.19 Tg P y^{-1} due to the crop trade from the USA to China. Crop trade from the USA to Japan and Mexico also led to large global industrial P fertilizer savings. Together with other trades, crop exports from the USA saved a total of 0.26 Tg P y^{-1} of industrial P fertilizers.

The crop trade from Argentina to other countries also led to large industrial P fertilizer savings due to the limited inputs of P fertilizer and low PFFs there. More attentions, however, should be paid to the sustainability of crop production in Argentina with limited P-fertilizer inputs, although crop exports from Argentina could decrease global industrial P fertilizer consumption. Besides, it should also attract more attentions on global P flows for considering negative consequences and positive ones.

Conversely, it could lead to the increase of global industrial P fertilizer consumption for the agriculture trade from countries with higher PFF to countries with lower PFF. Thus, we defined the increase of global industrial P fertilizer consumption as global P fertilizer wasting due to global agriculture trade. For example, soybean exports from Brazil to other countries lead to a total 0.28 Tg P y^{-1} waste of industrial P fertilizer in 2014, since industrial P fertilizer inputs into its tropical soils simply become occluded by their soils and add to their overall soil P pools there. The soybean trade from Brazil to China and EU28 led to 0.18 and 0.07 Tg P y^{-1} of global industrial P fertilizer wasting, respectively. Expanding cropland by deforestation for soybean production was not a sustainable economic strategy in Brazil and negatively affected local ecosystem services. The crop trade from Canada to the USA, EU28 and Mexico also globally wasted $>$ 0.01 Tg P $y^{-1}$of industrial P fertilizers. Crop exports from some tropical countries (Australia, Brazil and Indonesia) led to less efficient use of industrial P fertilizer (about a 0.36 Tg P y^{-1} waste of global industrial P fertilizer), because their low soil P availabilities led to their high PFFs and low PUEs. Decreasing crop exports from tropical countries as much as possible could be better for future sustainable consumption of industrial P fertilizer as well as P ores, despite these difficulties.

Cropland soil P budget was estimated by its external P inputs and its P outputs, and thus global croplands has resulted in a net soil P accumulation of 4.16 Tg P y^{-1} in 2014 (Figs. 9 and 10). More detailed, 47% of global cropland area had experienced soil P deficits, with gross soil P losses of 4.57 Tg P, but a gross of 8.73 Tg P y^{-1} was accumulated in the remaining croplands in 2014. Global crop trade led to a total gross soil-P accumulation in croplands of 0.71 Tg y^{-1}, with 0.62 Tg P y^{-1} of gross soil-P deficits; therefore, a net soil P accumulation of 0.09 Tg P y^{-1} was associated with global crop trade in 2014.

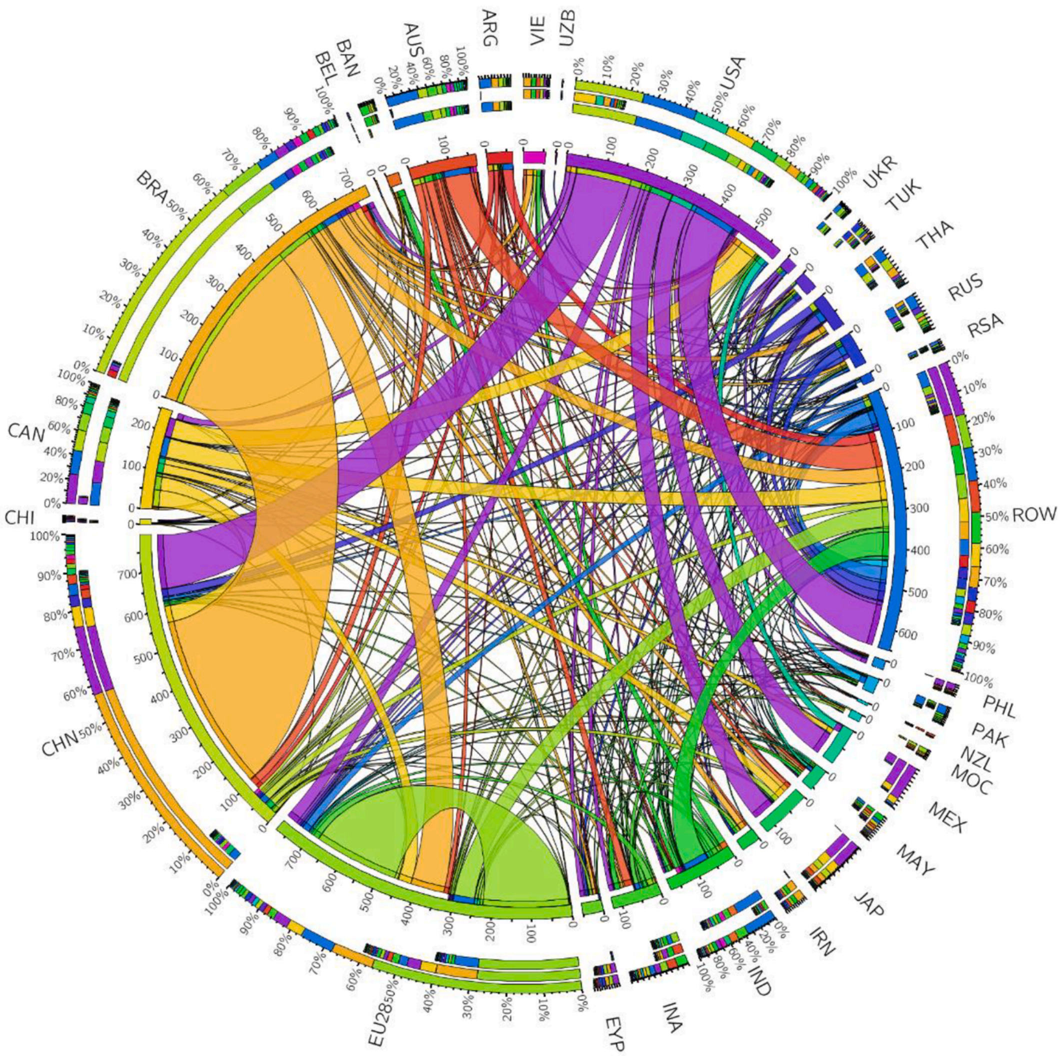

Fig. 5. Global flows of virtual P fertilizer by crop trade among countries or regions in 2014. The main trade matrix is illustrated there, with the virtual P fertilizer trade of > 1.0 Gg P y^{-1}. The numbers indicate the virtual P-fertilizer flows in Gg P, and the colors of the links correspond to the export countries or regions. See Fig. 1 for the country abbreviations.

These cropland soil P budgets masked large differences among regions and crops for the year of 2014. Decades of over-fertilization in the past have led to high and long-lasting soil P stocks in some regions (like EU countries and the USA), and thus limited external cropland P inputs could not influence their crop production (Le NOE et al., 2020). Their negative value of cropland soil P balance could not lead to their cropland soil P deficits in one short period, and they neither could reflect the legacy effects from previous management and fertilization practices (Lun et al., 2014). Thus, here we only focused on cropland soil P increase or decrease in one year, due to external P inputs and P outputs. Almost all global fruit and vegetable croplands accumulated large amounts of soil P in the year of 2014, especially in China, where 1.31 and 1.18 Tg of P accumulated in fruit and vegetable cropland soils that year. Chinese croplands thus had a net of 3.72 Tg soil P accumulation in 2014, followed by India and Brazil. >0.25 Tg of soil P was lost from soybean cropland in the USA and Argentina but a larger amount of P was accumulated in Brazilian soybean croplands, which would leach out or discharge into freshwater systems in the future. Global soybean cropland together still presented a net accumulation of soil P. Global wheat and rice croplands also accumulated P in their soils, with their amounts of 0.33 and 0.49 Tg P y^{-1}, respectively. Ninety percent of global maize croplands, however, had bad soil P deficits or losses, totaling to 1.31 Tg P in 2014. Furthermore, low PFF but high maize yield in USA had resulted in about 0.54 Tg of soil P loss; however, this high yield could not last long time under this soil P deficit, in spite of large soil P accumulation before.

The largest trade of crop P, from the USA to China, led to a soil P loss of 0.07 Tg P y^{-1} in the USA, mostly in soybean croplands. Maize exports to Japan and Mexico also contributed > 0.1 Tg P each to the American cropland soil P deficits. The soybean trade from Brazil to China, however, led to a total soil P accumulation of 0.18 Tg in local soybean croplands, almost 3/4 of the totally gross cropland soil P accumulation there. Wheat exports from Ukraine to EU28, Egypt and China also led to local deficits of cropland soil P. Fruit and vegetable trade among EU28 member countries led to the accumulation of 0.02 Tg P y^{-1} each in local cropland soils. China faced serious soil P accumulation in vegetable croplands due to its high and intensive external P inputs.

A total of 3.56 Tg P y^{-1} from global crop production flowed into global freshwater systems (Fig. 11), due to mismanagement. A fraction of 0.53 Tg P y^{-1} was associated with global crop trade in 2014, almost 2/3 of which was contributed by the trades of wheat, maize and soybean. Brazil crop exports led to the largest P discharge of 0.1 Tg P y^{-1} into local freshwater. The soybean trade from the USA to China also increased the P flow into American freshwater by 0.02 Tg, and a total of 0.03 Tg P y^{-1} flowed into freshwater due to the crop trade between these two countries. The total amount of P in freshwater was lower in the USA than

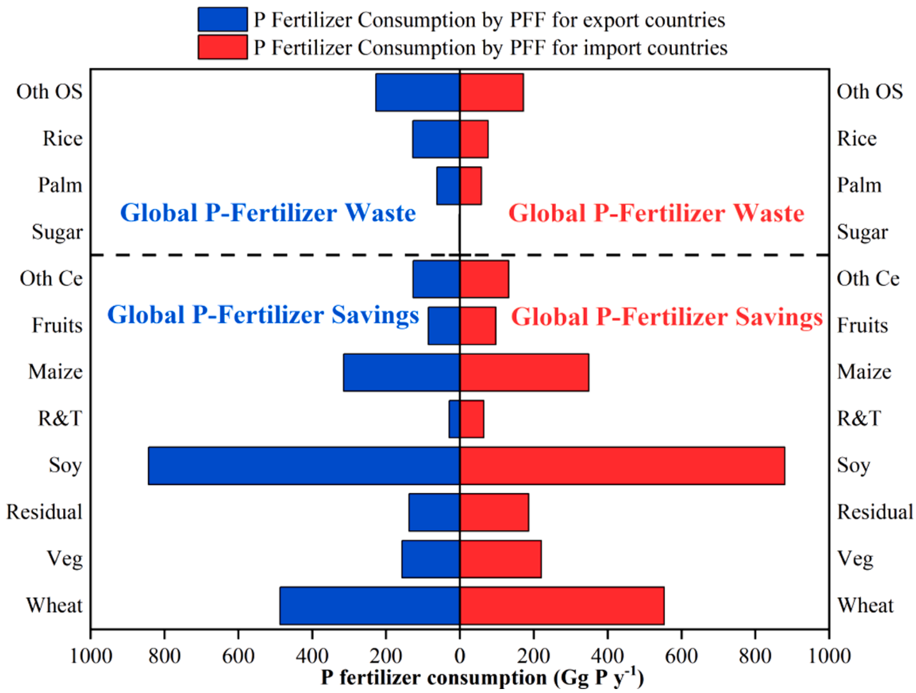

Fig. 6. Impacts on global industrial P fertilizer consumption due to crop trade. Compared with exporter countries, more P fertilizer consumption for traded crops is demanded for producing crops in imported countries, and thus global crop trade could lead to global P fertilizer saving; otherwise, it could be global P fertilizer waste. The abbreviations are as follows: Veg, Vegetables; Soy, Soybean; Residual, Other Crops; R & T, Roots & Tubers; Oth Ce, other cereals; Sugar, Sugar Crops; Palm, Palm Oil; Oth OS, Other Oil Crops.

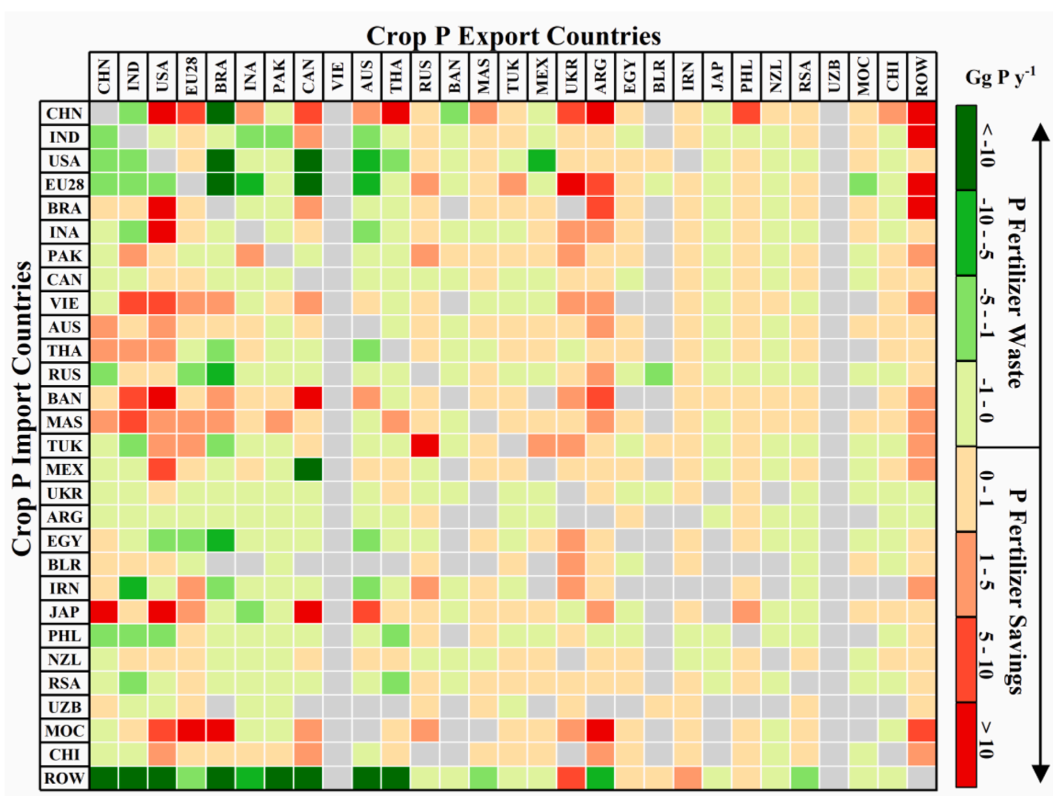

Fig. 7. Global savings or waste of industrial P fertilizer consumption due to crop trade among countries in 2014. For example, the cell in row 1 and column 3 refers to crop P exported from the USA to China, which can save > 10 Gg P of global industrial P fertilizers in 2014. Grey cells represent no data. See Fig. 1 for the country abbreviations.

Brazil due to the international crop trade, even though the USA was the largest exporter of crop P. About 0.07 Tg P y^{-1} flowed into freshwater systems was from their internal crop trades among EU28 member countries. Therefore, water resource issues should be managed with the help of local government and international cooperation.

4. Discussion

P fertilizer trade and virtual P fertilizer flows embodied in crop trade strongly redistributed the consumption of global P around the world (Metson et al., 2016; Jiang et al., 2019). The redistribution may even

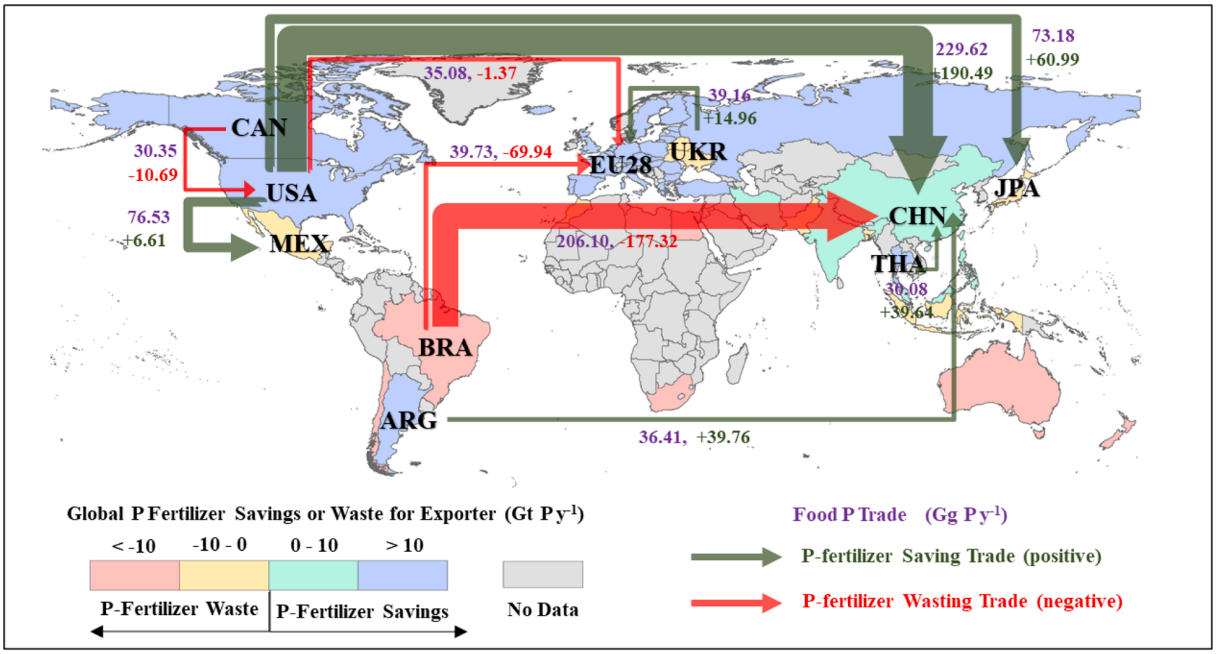

Fig. 8. Map of global P-fertilizer saving or wasting due to crop trade among countries in 2014. Important crop trades are also presented. The green and red lines represent global P-fertilizer saving and wasting, respectively. See Fig. 1 for the country abbreviations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

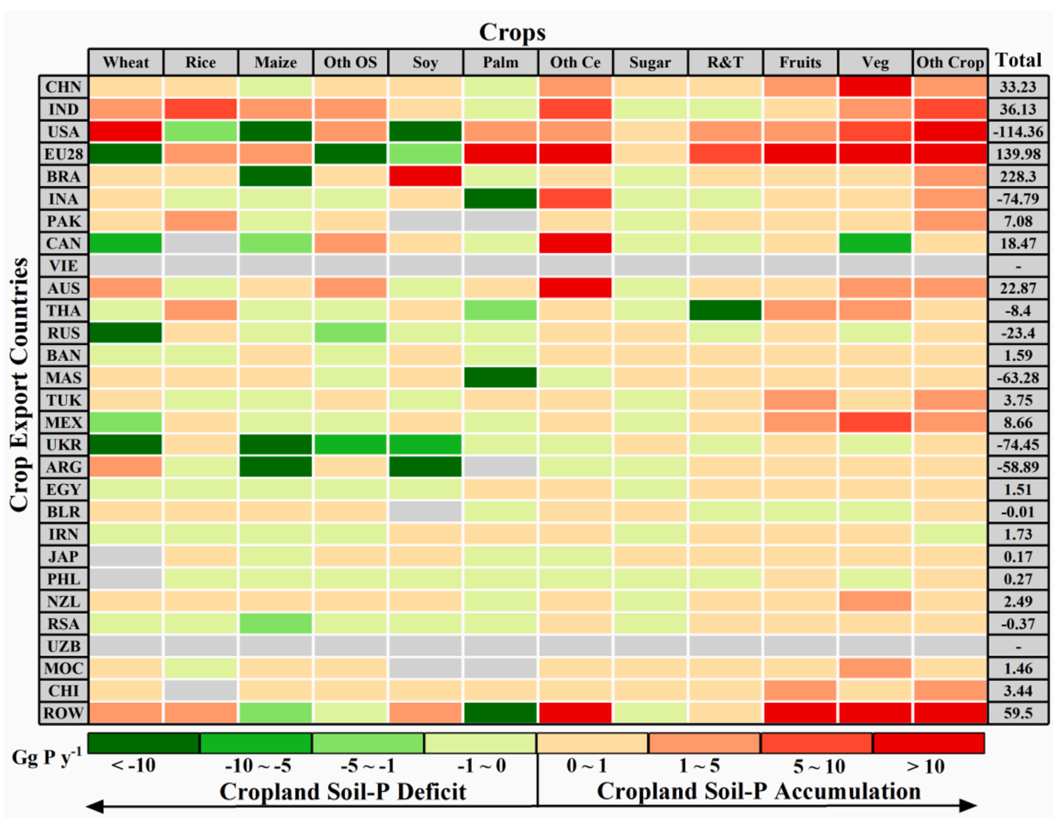

Fig. 9. National cropland soil-P budgets due to the crop trade in 2014. Each cell represents a cropland soil-P budget of total P inputs and outputs due to the export of a crop from a country. For example, the cell in row 1 and column 1 illustrates that wheat exports from China led to a total accumulation of 0–1 Tg P y^{-1} in wheat croplands. The total for row 1 represents a total accumulation of 33.23 Gg P y^{-1} in Chinese croplands due to its total crop exports. Grey cells represent no data. See Fig. 1 for the country abbreviations.

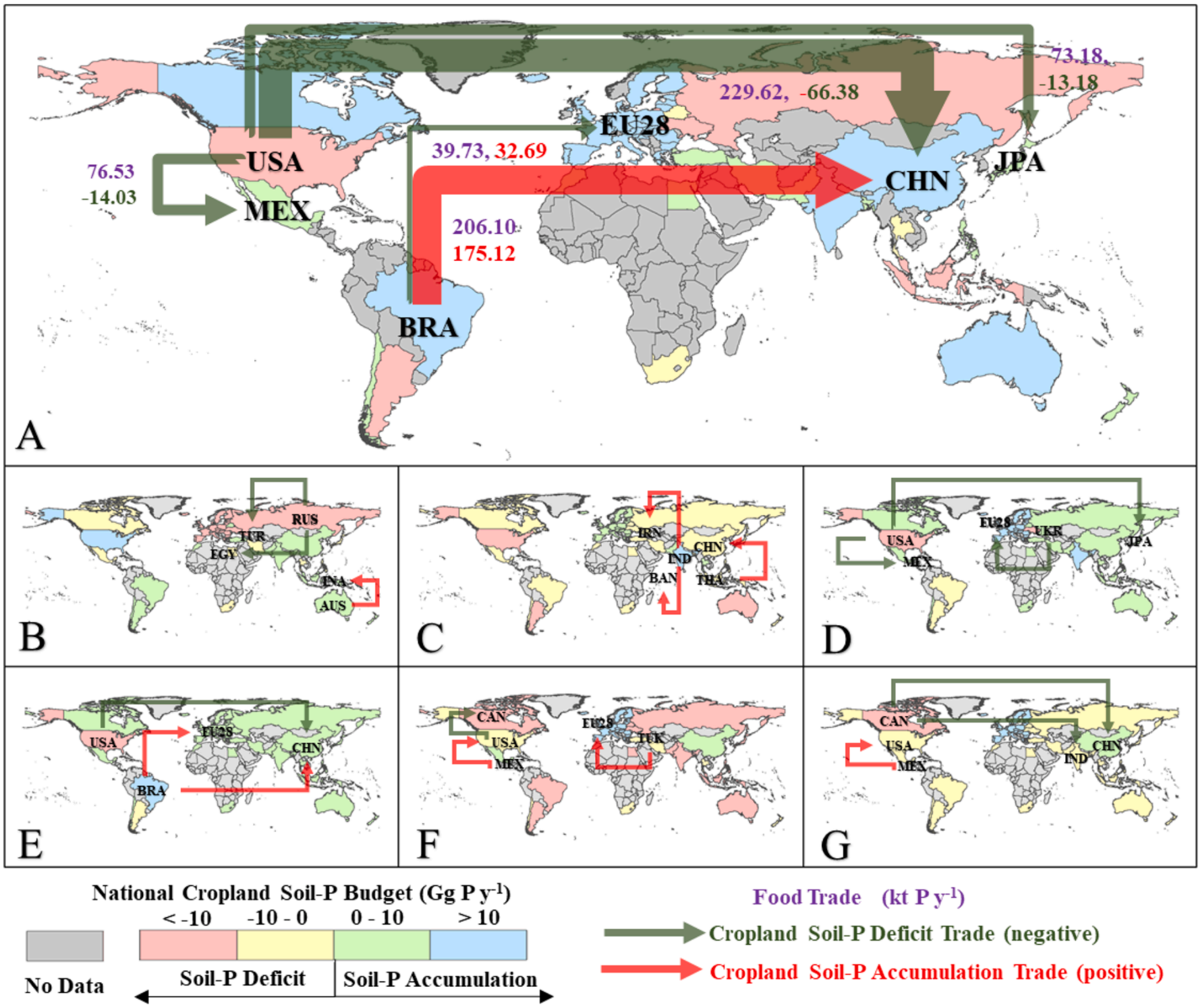

Fig. 10. Maps of the national cropland soil P budgets due to crop food trade for (A) total crops, (B) wheat, (C) rice, (D) maize, (E) soybean, (F) fruit and (G) vegetables. Important crop trades are also presented. Green lines indicate that the trade led to cropland soil-P deficits for export countries, and red lines indicate the accumulation of soil P. See Fig. 1 for the country abbreviations. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

have some potential benefits. Global physical P fertilizer and agricultural trade were strongly associated with local natural resources, and differed greatly among countries. Countries could be categorized into four groups based on global industrial P fertilizer and crop P trade (Lun et al., 2018). Countries such as the USA, where both industrial P fertilizer and crop food were mostly sourced domestically, had a less direct interest to manage agricultural P inputs to ensure P security and global food security. The USA can support 1.86 times its total P consumption, considering both physical industrial P fertilizers and virtual P fertilizers. Large population and shifting dietary compounded by limited croplands, China still required soft commodity imports (especially soybean) and virtual P fertilizer. However, Chinese net industrial P fertilizer exports were much larger than its virtual P fertilizer imports, with the net P fertilizer export of 1.13 Tg P y^{-1} in 2014. China could thus cooperate with countries where P reserves are limited but in food production is huge; these cooperation between different countries could benefit global P fertilizer savings and food security, gaining global win–win situation. For example, China could develop long-term strategies for food imports and industrial P fertilizer outputs with other countries that export a huge amount of crop food, like Argentina and Brazil if they could better improve its PUE.

High contents of Fe and Al exist in soils of Brazil croplands, which results in very low available soil P for crop utilization, low PUEs and high PFFs there (Mekonnen & Hoekstra, 2018; Withers et al., 2018; Pavinato et al., 2020). Consequently, a huge amount of industrial P fertilizers should be applied into Brazilian croplands, in order to achieve high crop production. However, due to limited P reserves, Brazil strongly relied on other countries for industrial P fertilizer and about 2/3 of cropland industrial P fertilizer consumed in Brazil were imported from other countries. However, high agricultural production, especially soybean, have brought in large economic benefits for Brazilian, and thus its P-intensive agriculture has thus led to an increase of global industrial P fertilizer consumption and a decrease of global P use efficiency. Even worse, it also led to large cropland soil P discharge into local freshwater systems, with serious ecological issues (Lun et al., 2018). Meanwhile, Brazilian croplands has been increasing at a high cost of deforestation, especially in the Brazilian Amazon Basin (Morton et al., 2006; Barona et al., 2010; Richards et al., 2012; Kastens et al., 2017); however, local tropical soil presented low available nutrient absorption. Thus, it could also lead to continuous deforestation there for large soybean production, which turned to be one of global serious ecological issues. International cooperation and local policies should be implemented to increase cropland PUE, which will help to protect local Amazonian rainforests. Decreasing the soybean PFF to the global level could save about 1/3 of industrial P fertilizer consumption in Brazil and 3% of total global consumption (Obersteiner et al., 2013; Lun et al., 2018). This

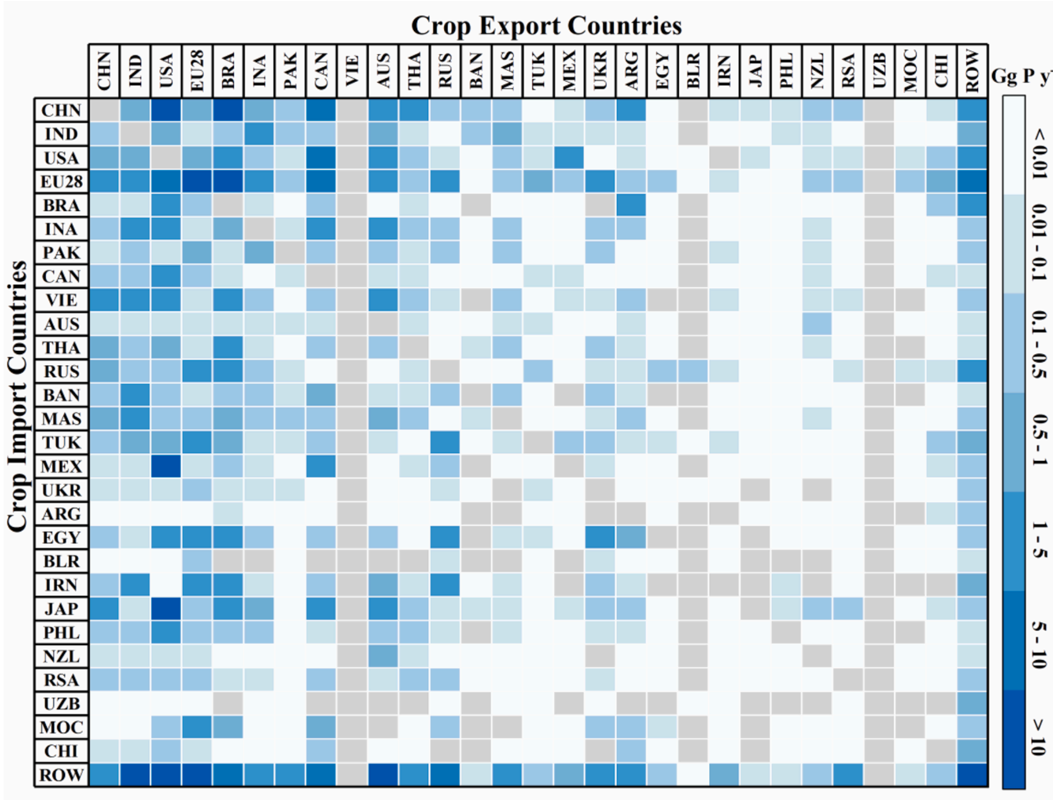

Fig. 11. Total amounts of P flowing into freshwater due to crop trade among countries. For example, the cell in row 1 and column 3 represents the total crop P exports from the USA to China, which led to > 10 Gg P y^{-1} flowing into American freshwater systems. Grey cells represent no data. See Fig. 1 for the country abbreviations.

implementation could also be beneficial for controlling future loss of Amazonian rainforest. Therefore, the nexus analysis of food, land, forest and nutrients should also be conducted in future studies, in order to achieve global SDGs.

In 2014, about 40% of global croplands have suffered cropland soil P losses due to their limited external P inputs, but some of which were important agricultural exporters (like Argentina and Australia). Local agricultural ecosystems could face more serious problems if these soil-P deficits continued. Achieving sustainable agriculture could thus become a great challenge for countries like Argentina, and thus to increase some inputs of industrial P fertilizer could benefit local agricultural production as well as their local ecosystems.

Japan, with its large population, had great shortages of arable land and P reserves, and thus it was entirely dependent on other countries for its agricultural P consumption, industrial P fertilizer trade and virtual P fertilizer flows. >90% of food P consumed in Japan originated from other countries; besides, direct industrial P-fertilizer trade and virtual P fertilizer flows each contributed 0.12 Tg P y^{-1} to Japanese agricultural P consumption in 2014. Hereby, Japan was highly vulnerable to global P scarcity in the future. Cropland PFFs were much higher in Japan than global average level, with a huge number of P leaching into freshwater systems and accumulating in soil. Therefore, Japan should pay more attentions to its cropland PUE as too much external industrial P fertilizers have been applied to their croplands. Besides, advanced P recovery technology would be of vital importance in future, considering the unrecycled P resources.

Last but not least, some limitations in our research should be noteworthy. First, an average of 12.5% of total P inputs was used to represent cropland soil P loss due to leaching and runoff; however, it is complicated to directly estimate soil P loss from leaching and runoff, considering their distinct and complex local natural conditions (like cropland location, land cover, and slope). Recent progresses on hydrological process models has attempted to estimate nutrient cycles and discharges, and thus these models can be incorporated for better estimating cropland soil P budgets. Second, P contents and the ratio of P:N ratio could have some influences of global P flows, with some uncertainties; therefore, we performed sensitivity analyses to test their impacts, considering crop P content. The total global trade of agricultural P would be around 2.45 ~ 3.13 Tg P y^{-1}, ranging between 88% and 112% of our results in 2014. Despite this relatively low uncertainty, a further effort to use more detailed data for estimating global P flows is warranted for future studies. Then, we here only focused on cropland soil P budgets for one year of 2014 and ignored the soil P stock that affluent countries have built up in the past. As we mentioned above, over-fertilization in the past decades could result in huge soil P stocks, and they can be released to be absorbed by plants. Therefore, there were still high crop production due to soil P accumulation in the past, in spite of limited external P inputs that year. In our study, we only focused on cropland soil P balance for one year, and thus a negative value indicated that some cropland soil P was lost and that the total amount of cropland soil P had decreased. Our results of cropland soil P budgets did not reflect the legacy effects from previous management and fertilization, but they are a useful metric to identify soil P balance at that time point. Consideration of the P legacy and studies for a longer period (we focused our detailed international agricultural trade analysis in the year of 2014 due to the limited available data for other years) are warranted for future studies.

5. Conclusion

The results confirmed that international agricultural trade strongly redistributed global P cycle, especially for soybean and P fertilizer consumption. About 1/6 of P in harvested crops was flowed with the international agricultural trade in 2014, and most of them were mainly concentrated in a few countries. Hot spots of embodied P were soybean trades from USA or Brazil to China. Cropland PUE and PFF differed significantly among crops and among countries. The low availability of P due to their old and weathered soils led to higher crop PFFs and lower crop PUEs in tropical countries than temperate countries. A gross waste of industrial P fertilizer occurred in specific agricultural trade from countries with higher PFF to countries with lower PFF, but agricultural trade from countries with lower PFF to countries with higher PFF results in a gross saving of industrial P fertilizer. The combined global international agricultural trades together led to net savings of global industrial P fertilizers in 2014. >0.50 Tg y^{-1} of P accumulated in cropland soils were related with international crop trade. Although USA was the largest agricultural crop-P exporter, Brazil has turned to be the largest virtual P fertilizer exporter due to its high PFFs. Some countries like Japan, are strongly depended on imports of fertilizers and agriculture commodities, so they are the most vulnerable to P scarcity. Global cooperation and cropland PUE improvement is highly demanded to mitigate P scarcity and its associated impacts, especially for vulnerable countries like Japan.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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