Phosphorus Flows in the Asian Region

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Abstract

In just about every aspect of life, dependency can be equated with vulnerability, and in the case of phosphorus, this vulnerability potentially puts whole nations at significant risk. Phosphorus is vital in the semi-conductor industry, automobile industry, fertilizer industry and all aspects of agriculture. With one third of the world's population housed in Asia and the numbers steadily rising, the demand for phosphorus is growing rapidly. The cultural shifts and changes in consumption that come with economic improvements and urbanization throughout Asia are pushing the demand for phosphorus to grow at an ever faster rate. Confidence that the rising populations of Asia will have sufficient food in the future can only come from the knowledge that the necessary phosphorus will be readily available. In order to ensure this and to ensure industry will have the phosphorus it requires, it is essential to understand the flow of phosphorus in the region and the nature and risks associated with phosphorus dependence.

Key words: Asia, dependency, international trade, virtual phosphorus

1. Introduction

As the demand for phosphorus in developed countries rises, high grade phosphate ore reserves are becoming more depleted and concerns about access to phosphate ore are being voiced. Phosphorus security is a particularly pressing issue precisely because there is no alternative to phosphorus in agriculture: cell growth does not occur in the absence of phosphorus. It has been suggested that economically viable deposits may be exhausted within 100 years. The three largest producers of phosphorus ore are China (37%), the USA (15%) and Morocco (15%), which account for two thirds of all the phosphate rock mined. It is estimated that Moroccan reserves account for more than one third of all the phosphate rock reserves in the world. While China has considerable phosphate ore reserves, the fact is that the vast majority of Asian countries have no phosphate reserves of their own and are completely dependent on imports. In the case of Japan, its entire phosphorus needs are met by China, Morocco and the United States. While each country has its own unique phosphorus story, the need to feed the burgeoning populations in the booming economies of India and China make them worthy of special attention: India because of its limited phosphate reserves, phosphorus-poor soil and heavy dependence on phosphorus imports (85%); and China because of its own phosphorus requirements to feed the people and satisfy what seems to be an insatiable appetite for meat, which threaten to bring about the day when China no longer exports phosphate ore or phosphate products. This will pose a serious problem for each and every country in Asia.

The urgency of sustainable phosphorus has long been understood in Europe. Many European based initiatives have been undertaken, including the Global Partnership of Nutrient Management (GPNM), and Global TraPs, which focuses on transdisciplinary approaches to sustainable phosphorus worldwide. There is a European Phosphorus Platform, and also a Sustainable Phosphorus Initiative in the United States, funded by the National Science Institute. There is a solid working group in Australia based at the Institute of Sustainable Futures in the University of Technology, and Japan has established a Phosphorus Recycling Promotion Council. The United Nations has embarked upon some programs to heighten phosphorus awareness particularly in developing countries. A Sustainable Phosphorus Summit has been held biannually to provide an opportunity for participants involved in different groups and having different disciplines to learn from each other. While almost all developed countries are well represented in all of these activities, there are whole regions which are clearly under-represented. While there are researchers working on phosphorus use and management in these regions, Latin America, Africa and Asia lack clear platforms, and many countries are being left out. A region-based approach to phosphorus sustainability would help make sure that all countries have access to the phosphorus they need in the long term.

In order to set up effective working groups at a regional level, information and data about the particular region and the various phosphorus contexts of the countries in the region is essential. Stocks and flows of phosphorous have been well-summarized from global perspectives (Liu *et al.*, 2008; Bouwman *et al.*, 2009; Carpenter & Bennett, 2011; Elser & Bennett, 2011; Mihelcic *et al.*, 2011). Both nation- and region-wide case studies have charted P-flows in Japan (Matsubae-Yokoyama *et al.*, 2009; Matsubae *et al.*, 2011), China (Qiao *et al.*, 2011; Yuan *et al.*, 2011), Korea (Jeong *et al.*, 2009) and other regions (Neset *et al.*, 2008; Cooper, 2013). These studies are all recent, and there is still a clear need for further studies, particularly in countries and regions with burgeoning populations and rapidly changing demographics.

In this study, we analyzed phosphorus resource flows to determine the extent of the dependency of Asian countries on other countries to meet their phosphorus requirements, and we conducted a virtual phosphorus flow analysis to determine future phosphorus demand in various Asian countries. Future phosphorus scenarios in Asia are discussed based on the findings of these analyses.

2. Methods

2.1 International phosphorus flow analysis

The first step was to estimate the phosphorus material flow of each commodity in each country. The international trade database, Base pour l' Analyse du Commerce International (BACI) (CEPII 2005), covers 231 countries, and 286 commodities could be extracted from the HS code. All data used in this study were from 2005. The commodities used in this study were separated into four categories: those involving phosphate ore, yellow phosphorus, 16 types of phosphorus compounds or 11 types of fertilizer. Table 1 provides a full list of these commodities and their assumed phosphorus content.

Equation (1) was used to estimate phosphorus flow accompanying trade in commodities.

$$P_{ij} = T_{ij} * (1 - W_{ij}) * Cont_{ij} \quad (1)$$

where P_{ij}, T_{ij}, W_{ij}, and $Cont_{ij}$ refer to the amount of phosphorus flowing to country *j* (or from country *j*) accompanying commodity *i*; the amount of commodity *i* flowing (import volume or export volume in country *j*, according to the BACI data); the water content of commodity *i*; and the phosphorus content of commodity *i*, respectively (W_{ij} and $Cont_{ij}$ are estimated with reference to existing databases).

Table 1 Classification of trade commodities and their P contents.

Commodities		HS Code	P contents
Phosphate ore		251010 251020	13.46%
Yellow phosphorus		280470	100%
Phosphorus compounds	Diphosphorus pentaoxide	280910	42.33%
	Phosphoric acid and polyphosphoric acids	280920	26.87%
	Sulphides of non-metals except carbon disulphide	281390	56.34%
	Phosphinates and phosphonates	283510	21.78%
	Mono- or dis-odium phosphates	283522	23.81%
	Trisodium phosphate	283523	18.89%
	Potassium phosphates	283524	14.59%
	Calcium hydrogen-orthophosphate	283525	22.76%
	Calcium phosphates except hydrogen-orthophosphate	283526	24.38%
	Phosphates of metals	283529	21.04%
	Sodium triphosphate	283531	25.25%
	Polyphosphates of metals except sodium triphosphate	283539	20.74%
	Phosphides	284800	30.45%
	Phosphoric esters, their salts and derivatives	291900	10.00%
	Thiophosphoric esters (phosphorothioates), salts, derivs	292010	19.86%
	Lecithins and other phosphoaminolipids	292320	4.23%
Fertilizer products	Animal or vegetable fertilizers, in packs >10 kg	310100	11.35%
	Superphosphates, in packs >10 kg	310310	7.42%
	Phosphatic fertilizers, mixes, nes, pack >10kg	310390	11.38%
	Fertilizer mixes in tablets etc or in packs <10 kg	310510	12.90%
	Nitrogen-phosphorus-potassium fertilizers, pack >10kg	310520	2.73%
	Diammonium phosphate, in packs >10 kg	310530	22.29%
	Monoammonium phosphate & mix with diammonium, <=10 kg	310540	25.59%
	Fertilizers with nitrates and phosphates, nes, <=10kg	310551	19.75%
	Fertilizers with nitrogen and phosphorus nes, <=10kg	310559	12.90%
	Fertilizers containing phosphorus & potassium, <=10kg	310560	2.73%
	Fertilizers, mixes, nes	310590	12.90%

2.2 Dependency analysis

In order to determine the extent of the dependency of one country on another to meet its phosphorus demand, we employed the Herfindahl–Hirschman Index (HHI). The HHI is an economic concept widely applied in competition law and antitrust and market investigations, and can be defined as follows:

$$H_{ij} = \sum_{j=1}^{N} s_j^2 \quad (2)$$

where H_{ij} represents the HHI of imported commodity j in country i. The HHI is based on the sum of the squares of the market shares and ranges from 0 to 1.0, ranging from a large number of very small shareholders to a single monopolistic market.

For example, given a market of a traded commodity with two importers who have equally distributed market shares, $H_{ij} = 0.5^2+0.5^2 = 0.5$. Now compare that to a situation with ten importers who have equally distibuted market shares; $H_{ij} = 10 \times 0.1^2 = 0.1$. This indicates that the market with ten players is less concentrated. Thus, a normalized Herfindahl index can serve as a measure of equality of distribution but is less suitable for assessing concentration.

Here, the HHI of phosphate ore, yellow phosphorus, chemical compounds and fertilizers are calculated from the perspective of phosphorus accounting (Tables 2, 3, 4 and 5). Note that statistics from 2005 were chosen for analyzing whole trade flows and calculating HHI, because 2005 is the most recent year for which both a set of full trade data and a Japanese input-output table are available.

Table 2 HHI of phosphate ore.

HHI of P ore imports	Country
0.9 < HHI <=1	Israel, Jordan, Yemen, Singapore, Myanmar, Sri Lanka, Afghanistan, Nepal, Hong Kong
0.8 < HHI <=0.9	Cyprus, Thailand, Oman, United Arab Emirates
0.7 < HHI <=0.8	Lebanon, Vietnam
0.6 < HHI <=0.7	Bahrain, Qatar
0.5 < HHI <=0.6	China
0.4 < HHI <=0.5	Cambodia, South Korea, Kuwait, Bangladesh, Pakistan, Iran
0.3 < HHI <=0.4	Turkey
0.2 < HHI <=0.3	Saudi Arabia, Philippines, Taiwan, Japan, India, Indonesia
0.1 < HHI <=0.2	Malaysia
0 < HHI <=0.1	
HHI=0	Iraq, Syrian Arab Republic, The West Bank and Gaza Strip, Brunei, Laos, Maldives, Timor-Leste, Bhutan, North Korea, Mongolia, Macau

Table 3 HHI of yellow phosphorus.

HHI of yellow phosphorus imports	Country
0.9 < HHI <=1	Oman, Bangladesh, Nepal, North Korea, United Arab Emirates
0.8 < HHI <=0.9	Sri Lanka, India, Taiwan, Japan
0.7 < HHI <=0.8	Pakistan, Malaysia
0.6 < HHI <=0.7	South Korea, Saudi Arabia
0.5 < HHI <=0.6	Philippines
0.4 < HHI <=0.5	Vietnam
0.3 < HHI <=0.4	Israel, Hong Kong, Thailand, Turkey
0.2 < HHI <=0.3	China
0.1 < HHI <=0.2	Indonesia
0 < HHI <=0.1	Singapore
HHI=0	Iraq, Bahrain, Kuwait, Jordan, Syrian Arab Republic, Lebanon, Yemen, The West Bank and Gaza Strip, Cyprus, Brunei, Cambodia, Laos, Myanmar, Maldives, Timor-Leste, Afghanistan, Bhutan, Iran, Mongolia, Macau

2.3 Virtual phosphorus flow analysis

While phosphate fertilizers are used extensively for growing crops, there are limits to the amount of phosphorus uptake that can take place in the plant before the product is harvested. Further phosphorus loss occurs due to adsorption in soil and in the wasted residual portions of agricultural products. While livestock grazing does not require the direct application of phosphorus to the animals, the indirect phosphorus demand in the feeding of livestock through the food chain can be calculated. This virtual phosphorus (VP) requirement was estimated as follows:

$$V_i = P_{i:h} + P_{i:c} \quad (1)$$

where V_i refers to the amount of VP for product i. V_i is the sum of the hidden phosphorus input $P_{i:h}$ and the phosphorus contained in products $P_{i:c}$.

Each of the following was taken into consideration when calculating the hidden phosphorus input $P_{i:h}$:

1. The amount of phosphorus in fertilizer not taken up by the plant and lost to the soil
2. The phosphorus contained in the non-edible parts of the plants or in plant residues.
3. The phosphorus requirement to produce agricultural products as feedstuffs for the lifetime consumption of livestock

Note that VP in this paper refers to the amount of phosphorus, not the amount of ore as was the case in the previous study (Matsubae *et al.*, 2011). While these definitions are essentially the same, the units are different.

Table 4 HHI of chemical compound imports.

HHI of chemical compound imports	Country
0.9 < HHI <=1	Afghanistan, Bhutan
0.8 < HHI <=0.9	Myanmar, Cambodia, North Korea, Yemen
0.7 < HHI <=0.8	Laos, The West Bank and Gaza Strip, Thailand
0.6 < HHI <=0.7	Pakistan, Nepal, Bahrain
0.5 < HHI <=0.6	Vietnam
0.4 < HHI <=0.5	Iraq, Korea
0.3 < HHI <=0.4	Mongolia, Japan, Maldives, Brunei
0.2 < HHI <=0.3	Kuwait, Oman, Lebanon, Macau, Bangladesh, Qatar, Malaysia, China, Saudi Arabia
0.1 < HHI <=0.2	Taiwan, Iran, Sri Lanka, Israel, Hong Kong, Indonesia, Philippines, Jordan, Singapore, India, United Arab Emirates
0 < HHI <=0.1	Cyprus, Turkey, Syrian Arab Republic
HHI=0	Timor-Leste

Table 5 HHI of fertilizer imports.

HHI of fertilizer imports	Country
0.9 < HHI <=1	Timor-Leste, Nepal
0.8 < HHI <=0.9	Mongolia, Afghanistan, Laos
0.7 < HHI <=0.8	North Korea, Bhutan
0.6 < HHI <=0.7	Brunei
0.5 < HHI <=0.6	The West Bank and Gaza Strip, Korea, Iraq, Qatar, Yemen
0.4 < HHI <=0.5	Maldives, Cyprus
0.3 < HHI <=0.4	Vietnam, Israel, Saudi Arabia, China
0.2 < HHI <=0.3	Philippines, India, United Arab Emirates, Kuwait, Singapore, Hong Kong, Syrian Arab Republic
0.1 < HHI <=0.2	Pakistan, Sri Lanka, Bangladesh, Turkey, Bahrain
0 < HHI <=0.1	Macau, Lebanon, Jordan, Thailand, Oman, Indonesia, Iran, Malaysia
HHI=0	

In order to determine the quantity of each agricultural product distributed and the phosphorus content of each of these products, we referred to various Japanese statistical databases, including the Food Balance Sheet, Food Composition Database and a variety of other references (MAFF, 2013a; MEXT, 2013). To determine the amount of phosphorus contained in animal-based food and the phosphorus requirement to produce this animal-based food, including beef, pork, chicken, lamb, fish and dairy foods, we consulted the *Yearbook of Fertilizer Distribution*, *Food Balance Sheet* and a variety of other references (MAFF, 2013b; MEXT, 2013). The information in these Japanese statistics and databases provided us with phosphorus contents and the virtual phosphorus required for each of the commodities, and the results for each commodity were assumed to be consistent with the same commodity in different countries of Asia. Because China and India stand out among all other Asian countries due to their significant economic and population growth, we have focused our analysis on these countries.

3. Results

3.1 Phosphorus resources in Asia

According to the 2005 BACI trade data, more than two thirds of all phosphate ore mined originates from the three largest producers. China supplied 37% of the phosphorus traded, and the United States and Morocco both supplied 15%. According to a recent USGS report, more than one third of the phosphate rock reserves worldwide are in Morocco. The two largest suppliers of phosphorus to the Asian region are China and Jordan.

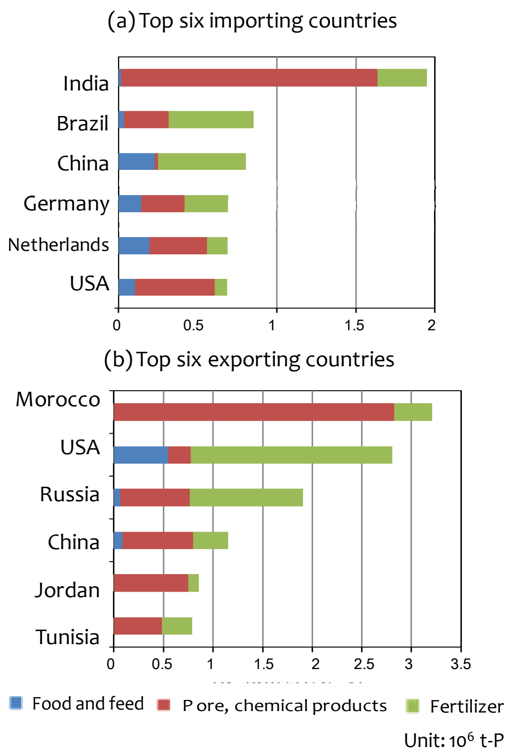

Fig. 1 Major phosphorus exporting and importing countries of the world.

Figure 1 shows the major importers of phosphorus around the world. India imports more than twice as much as Brazil, which is the next largest net importer of phosphorus, and most of this phosphorus was imported in form of phosphate ore and chemical compounds, as shown in Fig.1(a). As Fig. 1(b) shows, China exports approximately the same quantity of phosphate ore and chemical products as Russia and Jordan, and Morocco exports more than triple the quantity that each of these countries exports. It should be noted that only China appears in both Figs. 1(a) and 1(b), indicating that only China is both a major exporter and importer of phosphorus on the world stage.

Figure 2 shows the quantities of phosphate ore imported by Asia's six largest importers, India, Indonesia, Japan, South Korea and Thailand. According to the trade data alone, in 2012 India imported more than double the 4903 kt of phosphate ore it imported in 2005. The trade value of the phosphorus India imported was US$340 million in 2005 and US$1,807 million in 2012, which means that, considering commodity prices, the cost of importing phosphate ore rose by a factor of 2.5 times per unit over seven years, whereas demand approximately doubled over the same period.

Regarding dependency on phosphate ore imports, high HHIs were found for Thailand (HHI=0.95), Lebanon (HHI=0.89) and South Korea (HHI=0.53). They imported 58 kt, 104 kt and 140 kt of phosphate ore, respectively. Notably, Thailand was almost completely dependent on Morocco to meet its phosphate ore requirements. With no phosphate reserves of its own, Japan also imported all its phosphate ore from overseas, as did South Korea, but this ore originated from four countries, Morocco, China, Jordan and Indonesia. As a result, Japan's HHI for phosphate ore was 0.3, which was lower than Pakistan's (imported ore = 58 kt, HHI=0.51), Iran's (imported ore = 47 kt, HHI=0.50) and Turkey's (imported ore = 42 kt, HHI=0.45).

The HHI does not reflect the quality of traded commodities. It should be noted that, in the case of phosphate ore, naturally occurring radioactive material (NORM) contamination is an important consideration when

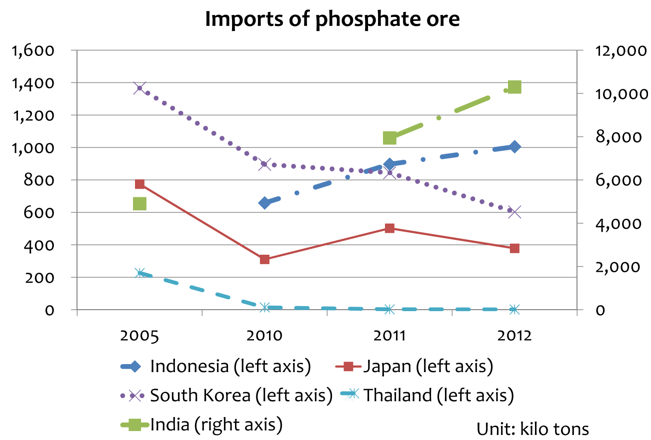

Fig. 2 Major Asian phosphate ore importing countries and amounts imported.

selecting sources of resources. The NORM contamination of Chinese phosphate ore is relatively low. For this reason alone, the chemical and fertilizer industries prefer to use Chinese ore, or use it in mixtures to dilute the high NORMs contained in other phosphate ores, such as Moroccan ore. This suggests that even in the case the low HHI countries, dependency on other countries for natural resources cannot easily be changed, since each country imports according to the abilities and limits of its refinery technologies, infrastructure and environmental regulations in place in these countries for the treatment of waste.

3.2 Industrial use of phosphorus in Asia

Approximately 50% of the yellow phosphorus demand from industry around the world was met by Chinese exports in 2005. Approximately one sixth of the entire global yellow phosphorus demand was from Japan, where the automobile industry uses it as a steel surface pretreatment prior to painting vehicles, and where it is also used for galvanizing machine parts and as an etching agent in the semi-conductor industry. Japan imported 32 kt of phosphorus as yellow phosphorus from China in 2005, which accounted for 30% of Chinese exports. The high HHI for yellow phosphorus in Japan, 0.95, is evidence that Japanese industry is almost totally reliant on China for its purified phosphorus.

The next largest consumer of Chinese yellow phosphorus in 2005 was India. India accounted for approximately 20% of all of China's yellow phosphorus exports, indicating that Indian industry has a strong demand for yellow phosphorus as a galvanizing agent. Like Japan, India relied almost exclusively on China for its yellow phosphorus, importing just 1% from Europe (HHI=0.98). It can be expected that Indian demand for yellow phosphorus will grow considerably over time as its industry, particularly the automobile industry, develops. Even though the demand for yellow phosphorus dropped significantly by 2012 in Japan and South Korea, Indian demand remained largely unchanged, as shown in Fig. 3. China continued to supply almost all the yellow phosphorus required by these countries over this period.

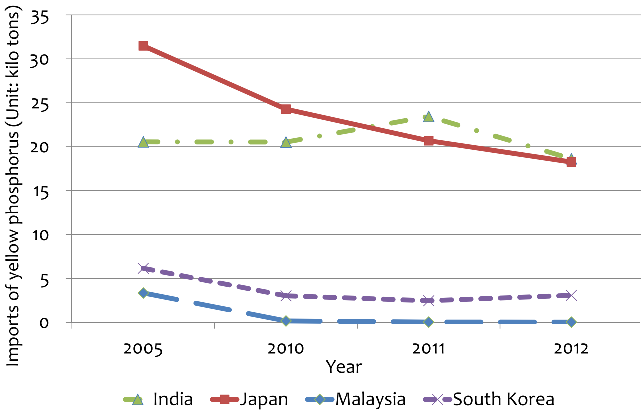

Fig. 3 Major Asian yellow phosphorus importing countries and amounts imported.

With regard to supply, Vietnam is the only country besides China that supplies yellow phosphorus to the Asian market. The amount, however, totaled less than 1% of the yellow phosphorus provided to Asia by China (1 kt from Vietnam, and 104 kt from China).

3.3 Fertilizer in Asia

Approximately 60% of all the fertilizer produced around the world is consumed in the Asian region, and roughly half of that 60% was consumed in China in 2005 (Fig. 4). China stands alone as the world's biggest fertilizer consumer and importer. The 345 kt of phosphorus imported as fertilizer was largely supplied by the United States, China remained one of the world biggest phosphorus suppliers, supplying many Asian countries with fertilizer.

A close inspection of the Chinese import and export commodities and the quantities exported and imported indicates that China exports phosphate ore and yellow phosphorus as materials for fertilizers and for use in industry, and imports fertilizer and food as well. This suggests that due to Chinese population growth and the huge increase in domestic demand for phosphorus in China, it should come as no surprise if China were to embark on a new course in the near future, avoiding the export of phosphate ore, yellow phosphorus and other low-value-added phosphorus products. The countries which rely on China to supply their phosphorus needs are at serious risk if and when this course of action is taken. Not only are they at risk of experiencing a serious physical resource scarcity, but they are also at risk of experiencing some serious economic damage as well.

Both India and Pakistan are also large importers of phosphorus in fertilizer. In 2005, India and Pakistan imported 176 kt, and 143 kt of phosphorus in the form of phosphate fertilizer. Like China, India relied on the United States for more than 60% of its phosphate fertilizer requirements, but also imported another 20% from Russia. On the other hand, Pakistan, the third biggest fertilizer importer in Asia, did not have a strong dependency on the United States. The HHI in Pakistan for phosphorus in fertilizer was 0.27, which is significantly

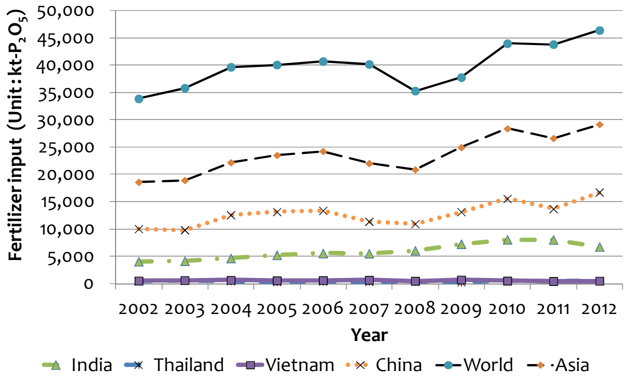

Fig. 4 Fertilizer inputs of major Asian agricultural countries.

lower than the 0.43 of China and the 0.36 of India.

Japan and Vietnam are the next two largest importers of fertilizer, with HHIs of 0.46 and 0.45, respectively. Japan relied on the United States in 2005, as did all the other major importers of fertilizer in Asia with the exception of Vietnam, which imported more than 60% of its phosphate fertilizer from China.

3.4 Food for Asia

According to current population growth projections, the world population will reach 9 billion in 2040. The two continents that are predicted to contribute the most to the global population are Africa and Asia. At 4.3 billion, Asia accounts for 60% of the world's population, and is expected to contribute more people than any other continent in the decades to come. In order to ensure this huge number of people can be adequately fed, focus is turning to the availability and supply of the natural resources required for agricultural production, including phosphorus.

It has been noted that in growing economies, people tend to change their consumption patterns and indulge in a more globalized diet, rich in protein and animal fat. To supply the market and provide the commodities required by this globalized diet, more phosphorus is required. Clearly, for instance, much more phosphorus is required to meet the demand for beef that typically goes up whenever richer consumers choose to eat beef instead of the beans they used to consume. Figure 5 shows the virtual phosphorus requirements of China and India. As shown in this figure, these two growing countries can only be expected to continue to require more and more phosphorus, not only because of the challenge of feeding their growing populations, but also because of changes to their diets. Despite the inevitable uncertainties involved in making these projections, due to the need to make strong assumptions and to decide where the limits may be, there can be absolutely no doubt that China will consume more meat in the future than in does at present, and that, as a result, the requirement for phosphorus will increase disproportionately to the increase in population in the Asian region, and that this will also impact phosphorus requirements in the many countries that supply animal-based foods to China.

India, which remains a largely vegetarian society, has seen a steady increase in per capita consumption, whereas the stagnant economy in Japan has seen overall food consumption fall off since 1990. While the virtual phosphorus required to feed India's population rose gradually with the rising economy and increased per capita consumption, low levels of meat consumption have resulted in a virtual phosphorus consumption in the range of 25% that required by China to feed a population of comparable size, as shown in Fig. 5.

4. Discussion

4.1 Population growth

As mentioned in above, the Asian population accounts for 60% of the world population currently, and will be growing in coming decades. It is of vital importance that governments consider ways to ensure that phosphorus is available for the production of food for their future populations. Additionally, nutrient emissions generated from human activities should be managed in appropriate ways. Waste water treatment and utilization

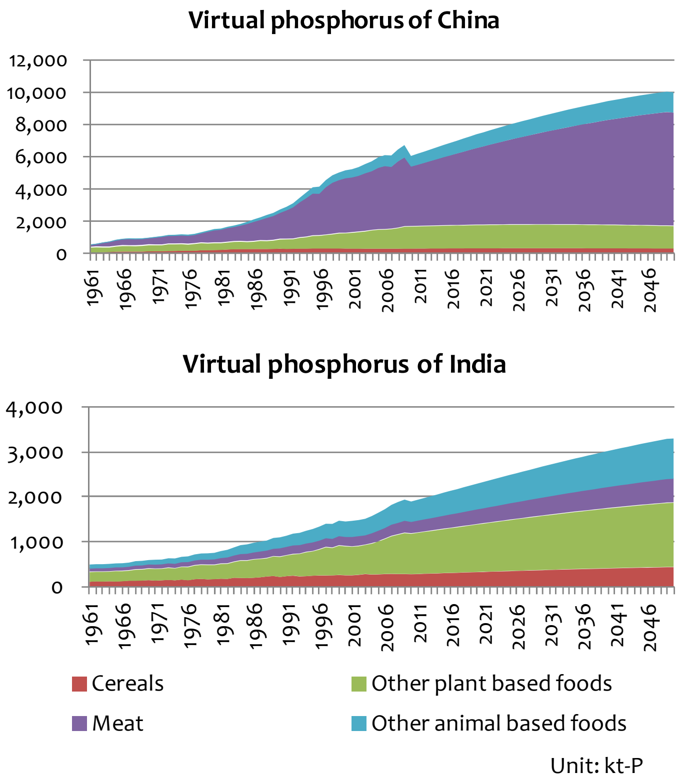

Fig. 5 Projection of virtual phosphorus for China and India.

of sewage sludge are keys phosphorus recycling and mitigating future phosphorus resource use. Waste treatment costs, however, in the context not of social costs but as real expenditures, are still higher than acceptable levels for many Asian developing countries. Technology transfer and international collaborative innovations for nutrient recovery and recycling would be more important.

4.2 Economic growth

First, economic growth enriches dietary life, and individual preferences shifts to foods of higher added value and quality. Previous work has estimated VP in Japan, showing that the phosphorus contained in "eaten" agricultural products was only 12% of virtual phosphorus (Matsubae *et al*., 2011). VP for food consumption differs with different levels of fertilizer input in agricultural production or of the recycling technology involved in each country, and in the case of efficient agricultural production for fertilizer input, VP should be lower. This strongly suggests the importance not only of appropriate fertilizer input, but utilization of secondary phosphorus resources which are recovered from waste streams.

Second, economic growth makes the cost of time for cooking and preparing each meal relatively higher due to the increased opportunity cost of time. This results in an increase in demand for processed or pre-prepared foods. The demand for processed food requires production of more food additives, which include phosphoric acid and other artificial substances to prolong the food's shelf life and soften its texture. This type of phosphoric acid is made mainly from thermal phosphorus, and in the Asian region, China plays a big role as a thermal phosphorus supplier. In this context, under the current situation of phosphorus demand and supply, urbanization is causing many Asian countries become more dependent on China for thermal phosphoric acid and yellow phosphorus imports.

Third, economic growth is expected to increase phosphorus losses. As shown in Fig.5, fertilizer inputs in India and China have increased, while the fertilizer price doubled in the seven years from 2005 to 2012. From this, it can be seen that economic growth has made it possible for farmers to purchase more fertilizer and this has accelerated the increase in fertilizer demand. Here, the land originally had low phosphorus accumulation, but in many cases, even after sufficient nutrient input, the farmers continue applying fertilizer as insurance, as much as their budget allows.

4.3 Urbanization

Population growth drives demand for urbanization. According to UN statistics, India was 17.9% urban in 1961, but 30.9% urban in 2010. By 2025, India is expected to be 37.2% urban. Urbanization in China has progressed at a remarkable rate: 16.2% of the population was urban in 1960, but 49.5% in 2010, and a projected 65.4% by 2025 (UNDESA, 2013). In China and India have quickly expanding economies and rapid urbanization (UNDESA-b,2013), which could have both positive and negative effects on phosphorus resource management.

As to the positive effects, the development of wastewater treatment infrastructure, which is gradually achieved as urbanization progresses, makes it possible to recover phosphorus from human waste streams and avoid polluting the hydrosphere. Needless to say, this does not come about naturally, but requires investing in the construction of appropriate infrastructure for wastewater treatment and nutrient removal and recovery.

As to the negative effects, urbanization promotes dietary changes from traditional fare to the "global" food. This is not to say that traditional meals are always better than global ones, but from the perspective of phosphorus consumption reduction, traditional Asian meals, which have smaller portions of meat and are often served with vegetables, are worth keeping rather than turning to "westernized" meat-based meals. Unless there is a significant slowdown in the growing demand for meat, the virtual phosphorus demand will increase dramatically as the population grows.

Another negative effect is that urbanization increases the distance between supply and demand for nutrients. This upsets the nutrient cycle balance and results in other environmental problems including increased carbon emissions. (Satterthwaite *et al*., 2010)

Reducing fertilizer use is one technical option available to us which has the potential to slow down future growth in virtual phosphorus demand. More efficient use of phosphate fertilizers in agricultural production combined with phosphorus recycling systems could contribute to reduced demand for phosphorus of natural origin to meet the requirements of the future food supply. With more education and the sharing of scientific knowledge, we can ensure that phosphorus is used more appropriately.

4.4 Challenges for phosphorus governance in the Asian region

First, reduction of fertilizer use and appropriate management of nutrients should be promoted in agricultural production. Excess nutrients not only have harmful effects on ecosystems, but pollute drinking water and pose additional risks to human health. Many Asian countries have been facing water scarcity. In that context, phosphorus resource management is strongly connected to these two important scarce resource issues, if not others. Actually, the value of land resources is now becoming higher as urbanization progresses. This causes demand for higher agricultural productivity per unit of farm land. To achieve this, fertilizer input becomes more important to agricultural production in economically developing countries. Furthermore, in the case of Japan, increased numbers of part-time farmers can make it difficult to engage in traditional sound nutrient cycles because these farmers tend to value their time and have enough money to purchase fertilizers and pesticides. In this context of current agricultural production in Asian countries, intensive, concentrated agricultural production has been promoted. This is partly realized by using more fertilizer and often causes the excess nutrient pollution of the environment. Achieving appropriate and sustainable nutrient management is one of the biggest challenges in agricultural production, not only in Asia, but also globally.

Recovery and recycling of phosphorus are one of our options for conserving phosphorus resources, but to achieve this, social involvement in advanced technologies and investment in infrastructure will be indispensable. Additionally, social agreements and consensuses are an essential requirement for using recovered phosphorus in agricultural production processes or for other industrial activities. Regarding this type of consensus-building, however, including discussing the social acceptability of additional costs for resource recovery or, on the other hand, no costs if we just landfill and dissipate wastes, societies often face difficulties in overcoming barriers to sharing knowledge and information among key stakeholders and in identifying good arguments. Even in a small community, this kind of agreement is tough to reach in actuality, but to achieve sound phosphorus cycling, just as with other useful resource recovery and recycling systems, international collaborative governance is another huge challenge to face toward efficient and effective technology transfer between developed and developing countries.

Additionally, such options to improve phosphorus resource efficiency would help decrease outside phosphorus dependency. Achieving higher phosphorus resource efficiency in each country currently depending on outside phosphorus resources could reduce geopolitical and environmental risks inherent in trading phosphorus resources.

5. Conclusion

First, we investigated international phosphorus material flows on the basis of statistical trade data for 2005 to clarify the situation in Asia with regard to phosphorus flows. Second, we evaluated the dependency of each Asian country on outside phosphorus resources by using the Herfindahl–Hirschman Index (HHI). Third, to enable discussion of future phosphorus requirements for the food supply, we estimated virtual phosphorus flows for the two Asian countries with highest growth, China and India.

Important findings our investigation turned up are that Asian countries currently consume more than 60% of globally produced fertilizer, and require even more phosphorus from a life-cycle perspective (virtual phosphorus) through international food trade. Many Asian countries rely heavily on foreign phosphorus resources from China, Morocco and the USA, through the international trade supply chain. They should become more aware not only of the economic and political risks, but environmental and resource risks surrounding phosphate ore extraction and refining processes. Another important finding is that in addition to population growth, urbanization and economic growth in the Asian region were suggested as being strong driving forces in future phosphorus demand growth.

The utilization of secondary phosphorus resources has the potential to improve foreign phosphorus dependency in many countries. In order to promote recycling and recovery, there are some significant bottlenecks which need to be overcome. Developing countries lack environmental regulations and the necessary infrastructure to collect phosphorus-containing wastes, including wastewater, sewage sludge and incinerated ash.

In developed countries, the market itself poses a problem: consumer preference is considered a difficult barrier to overcome in marketing recovered phosphorus.

There is a big technological and knowledge gap among countries and regions, however. International technology transfer, including social skills, would help to close these gaps. To achieve higher resource efficiency, better public awareness of the importance of phosphorus will be most important.

To achieve global sustainable phosphorus resource management, it will be necessary to recognize the importance of Asian phosphorus resource governance, including international collaborative networks for transferring the technology involved in recovery and recycling of phosphorus, to develop an Asian-wide market for trading secondary phosphorus resources, and to adopt regulations on the basis of monitoring and legislation.

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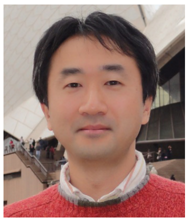

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