The Phosphorus Flow in China: A Revisit from the Perspective of Production

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Abstract

With phosphorus (P) one of the three essential nutrients for plant growth on Earth, global P scarcity and sustainable P management are emerging as two of the greatest challenges facing humans in the 21st century. China is the biggest producer and consumer of phosphate fertilizer, exerting profound influence on the sustainability of global P flows. This paper depicts the static P flow in China in 2012 from the production perspective, including the mining and extraction of phosphate rock (PR) ores, manufacturing of intermediate and end-use products and waste discharge. The results show that, with the second largest P mining resources in the world, China is also confronting a serious P scarcity problem. It is predicted that the current P reserves could sustain only the next three generations in China. In 2012, 1 g of P consumed domestically in China required 2 g of P extraction throughout the production chain, and the life-cycle P-use efficiency (PUE) is much higher than those of the food production system in China, the United States and worldwide. The P supply chain also saw waste production of 2,369 Gg P in 2012, with only 20% of the wastes recycled. The current recycling activities, however, lock in P instead of recovering it, which does not serve the purpose of mitigating P scarcity.

Key words: China, elemental phosphorus, phosphorus flow, production, wet-process phosphoric acid

1. Introduction

Phosphorus (P), one of three essential nutrients (together with nitrogen and potassium) for all living organisms on Earth, is a non-renewable and non-substitutable element for sustaining global food production. With population increase, economic development and depletion of limited P resources, a global P scarcity or crisis has been identified as one of the greatest challenges that human beings face in the 21st century (Chowdhury *et al*., 2014; UNEP, 2011). In nature, P is cycled through weathering and dissolution of phosphate rocks (PRs) in very small quantities, then transported and deposited into aquatic systems (Chen *et al*., 2008). Anthropogenic activities, however, have significantly intensified natural P cycling and accelerated the mobilization of P, resulting in significant P losses into water and causing serious eutrophication of freshwater systems (Smil, 2000; Liu *et al*., 2008; Cordell, *et al*., 2009).

China, as the biggest producer and consumer of phosphate fertilizer, is exerting profound influences on the global sustainability of P management. As the country with the largest population, most rapid economic development and scarce P resources, China also has major concerns over its long-term supply of P resources and relevant environmental problems (Ma *et al*., 2012). Therefore, research on P flow analysis has attracted scientists as well as policy makers. Several studies have investigated the national P flows in China, such as Liu *et al*. (2004), Chen *et al*. (2008) and Ma *et al*. (2013). So far, however, all of these studies have focused on consumption-driven P flows and none have depicted P flows from a production perspective, which could have a greater P recycling potential and feasibility. For this reason, this paper focuses specifically on industrial phosphate flows at a national scale in China, from mining and production to use and loss through emissions and as solid waste, so as to identify inefficiencies and opportunities for P management in P mining and processing in China.

2. Methods and Data

A substance flow analysis (SFA) was used in this paper to develop a static P flow model, and that was applied to China in 2012. The statistic SFA model for P

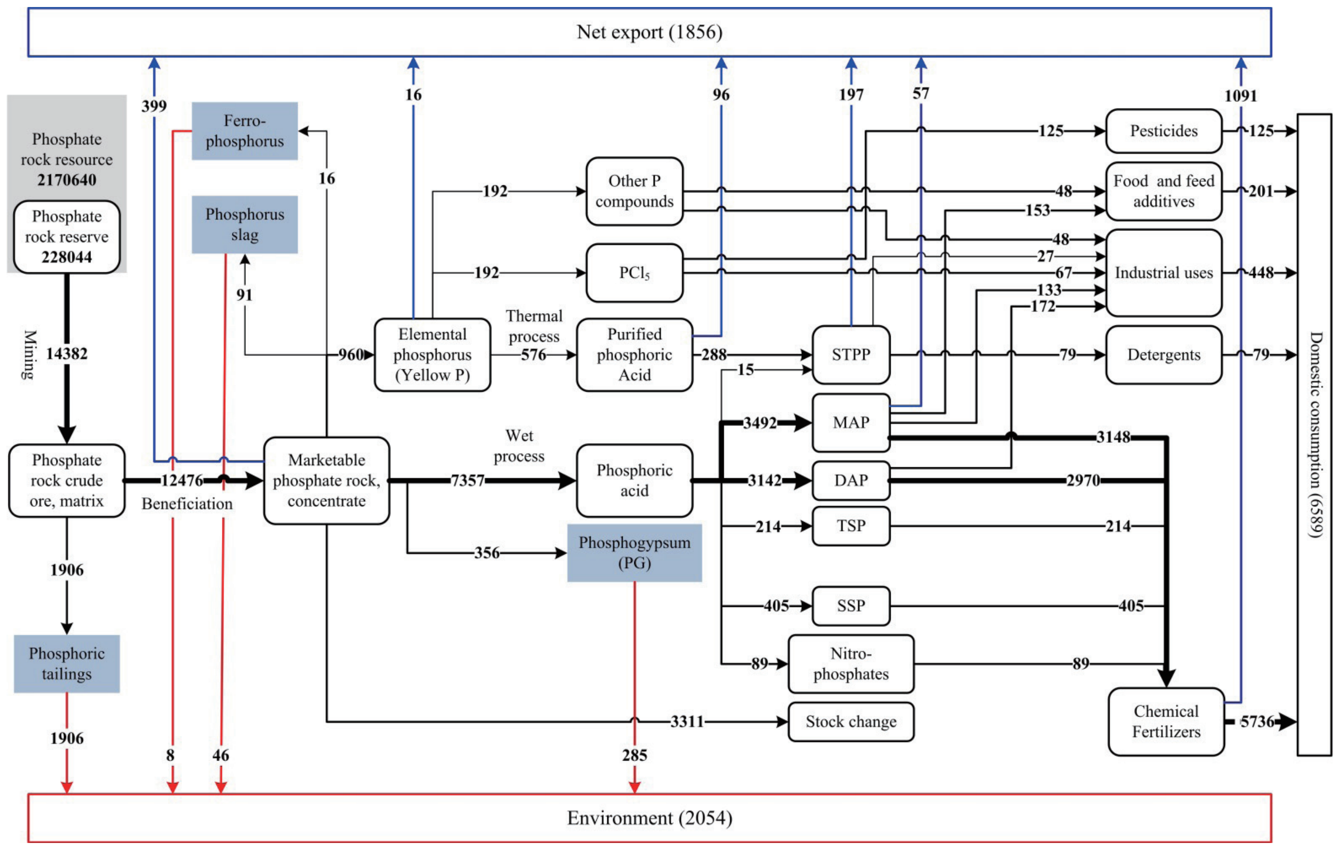

Fig. 1 The national P flows from production side in 2012 (Gg P).

could describe the basic metabolism of P from the production perspective, including extraction and processing of phosphorus ore; production of intermediate and end-use P products; exports, imports and uses of P products; and P waste discharges and reuse in the industrial system (Fig. 1). Based on the characterization of industrial metabolism, 53 balance equations were established to generate estimates of the national industrial metabolism of P in China for the year 2012 (Table 1). All coefficient values for the calculation are listed in Table 2. Note that values in the closest year were used as a proxy if we could not find the exact value for 2012 in the literature.

Like all other P flow analyses at the national scale, this study is subject to significant uncertainties, which may impair the soundness and robustness of the conclusions. These uncertainties are mainly associated with the conceptualization of the system, data/coefficients variations and spatial/temporal variability (Chen *et al.*, 2008). So far, however, it has been difficult to quantify the uncertainties due to scarcity of data. As all the equations in this paper are linear, it is possible to evaluate the impact of each coefficient on the flows with changes in the value of each coefficient listed in Table 2.

3. Results

Figure 1 illustrates the national P budget of China from mining, extraction and processing of PRs to intermediate and end uses of major P products. The figure also describes four kinds of waste streams from mine extraction, processing and production processes, namely phosphoric tailings, phosphorus slag, ferrophosphorus and phosphogypsum, and discusses their current recycling status in China.

3.1 P mining and extraction

China has among the largest PR reserves in the world, second only to Morocco. With an average grade of 17%, much lower than world average of 30% (Li & Cui, 2013), as of 2012, PRs in China presented a reserve of 228 Tg P and only accounted for 6% of world total P reserves (USGS, 2014) (Fig. 1). At the same time, China contributed more than 40% to world PR production and is seeing the world's fastest rate of depletion of PRs resources (USGS, 2014). On average, the extraction rate of PR ores in China is 100–300 Tg per year, equivalent to 7–22 Tg P per year. In 2012, the total extraction of P ores was estimated at 14 Tg P with 1906 Gg P going to the phosphoric tailings. It is predicted that China's PR reserves will be depleted within 30–50 years and its high-grade PR reserves, within 10–15 years (Hu *et al.*, 2007; Huang *et al.*, 2012). This is much sooner than the world depletion time of 50–100 years, not to mention the new global positive projection of 300–400 years (Cordell *et al.*, 2009; van Kauwenbergh, 2010). Consequently, the Ministry of Land and Resources (MoER) has listed P as one of 20 kinds of minerals in China for which supply has not been able to keep up with demand arising from national economic development since 2010 (Huang *et al.*, 2012).

Due to the low grade of PR ores as well as the small-scale of most mining activities, the mining effi-

Table 1 Calculation process for analysis of phosphorus flow in China.

Flow	Description (Gg P)	Calculation	Input data description	Sources of input data
P1	Phosphate rock reserve	P1=I1×K1×K2	I1: Phosphate rock reserve	NBS, 2013b
P2	Quantity of phosphate rock handled	P2=P3+P15		
P3	Phosphate rock production (concentrate)	P3=I2×K3×K2	I2: Phosphate rock production (30% P_2O_5)	NBS, 2013a
P4	Surface domestic consumption of phosphate rock	P4=P3-P7		
P5	Real domestic consumption of phosphate rock	P5=P9+P10+P11+P12+P13+P14+P15+P17+P18+P19		
P6	Change in domestic stocks of phosphate rock	P6=P4-P5		
P7	Net export of phosphate rock	P7=I3×K3×K2	I3: Net export of phosphate rock (30% P_2O_5)	MCDB, 2014
P8	Production of phosphate fertilizer	P8=I4×K2	I4: Phosphate fertilizer production (P_2O_5)	NBS, 2013a
P9	Monoammonium phosphate (MAP) production	P9=I5×K4	I5: MAP production (raw)	DRC, 2013
P10	Diammonium phosphate (DAP) production	P10=I6×K5	I6: DAP production (raw)	DRC, 2013
P11	Triple superphosphate (TSP) production	P11= I7×K6	I7: TSP production (raw)	BIN, 2014
P12	Single superphosphate (SSP) production	P12= I8×K7	I8: SSP production (raw)	BIN, 2014
P13	Nitrophosphate production	P13= I9×K8	I9: Nitrophosphate production (raw)	BIN, 2014
P14	Elemental phosphorus (yellow phosphorus) production	P14=I10	I10: Elemental phosphorus (yellow phosphorus) production	Hou *et al.*, 2012
P15	Phosphoric tailings production	P15=I2×K9×K10		
P16	Wet-process phosphoric acid production	P16=P9+P10+P11+P12+P13+P26		
P17	Phosphogypsum production	P17=P16×K11×K12/(30.974/(3+30.974+16×4))		
P18	Phosphorus slag production	P18=P14×K13×K14		
P19	Ferrophosphorus production	P19=P14×K15×K16		
P20	Thermal process phosphoric acid production	P20= P14×K17		
P21	Net export of thermal process phosphoric acid	P21= P14×K18		
P22	Thermal process sodium tripolyphosphate (STPP) production	P22= P14×K19		
P23	Phosphorus trichloride (PCl_3) production	P23= P14×K20		
P24	Net export of elemental phosphorus	P24=P14×K21		
P25	Other phosphorus compounds produced from elemental phosphorus (yellow phosphorus)	P25=P14-P20-P23-P24		
P26	Wet process STPP production	P26=P22×K22		
P27	Total STPP production	P27=P22+P26		
P28	Net export of STPP	P28=P27×K23		
P29	Other uses excluding STPP detergent	P29=P27×K24		
P30	Detergent use of STPP	P30=P27-P28-P29		
P31	Net export of phosphate fertilizer	P31=I11×K2	I11: Net export of phosphate fertilizer (P_2O_5)	Wu, 2013
P32	Fertilizer use of MAP	P32=(P8-P13)×K25		
P33	Fertilizer use of DAP	P33=(P8-P13)×K26		
P34	Fertilizer use of TSP	P34=(P8-P13)×K27		
P35	Fertilizer use of SSP	P35=(P8-P13)×K28		
P36	Fire extinguisher use of MAP	P36=I12×K29	I12: Fire extinguisher use of industrial grade MAP (raw)	CIC Sindh Industry Research Center, 2011
P37	Net export of industrial grade MAP (excluding fertilizer)	P37=I13×K29	I12: Net export of industrial grade MAP (excluding fertilizer, raw)	CIC Sindh Industry Research Center, 2011
P38	Food and feed additive use of industrial grade MAP	P38=P9-P32-P36-P37		
P39	Organophosphorus pesticide use of PCl_3	P39=P14×K30		
P40	Other uses of PCl_3	P40=P23-P39		
P41	Industrial uses of other phosphorus compounds from elemental phosphorus	P41=P25×K31		
P42	Food and feed additive use of other phosphorus compounds from elemental phosphorus	P42=P25-P41		
P43	Industrial uses of DAP	P43=P10-P33		
P44	Domestic consumption of phosphate fertilizer	P44=P8-P31		
P45	Domestic consumption of food and feed additives	P45=P38+P42		
P46	Domestic consumption of industrial uses of P products	P46= P29+P36+P40+P41+P43		
P47	Discharge of phosphoric tailings	P47=P15×(1-K32)		
P48	Discharge of phosphogypsum	P48=P17×(1-K33)		
P49	Discharge of phosphorus slag	P49=P18×(1-K34)		
P50	Discharge of ferrophosphorus	P50=P19×(1-K34)		
P51	Total export of phosphorus products	P51=P7+P21+P24+P28+P31+P37		
P52	Total domestic consumption of phosphorus products	P52=P30+P39+P44+P45+P46		
P53	Total discharge of phosphorus wastes	P53=P47+P48+P49+P50		

ciency in China is very poor. At least 2–3 tons of crude PR ores are consumed to produce 1 ton of PR concentrate, and the overall mining efficiency in China has been 33%–50% in the 2010s (Yang *et al.*, 2012). For some small-scale mining activities, the PR loss during the mining and beneficiation process could amount to 7–8 tons (Yang, *et al.*, 2012). This not only results in a massive waste of P resources, but also exerts significantly negative influences on the environment. It was reported that phosphoric tailings had polluted 0.6–1.3 million hectares of land directly or indirectly in the 2000s (Wu *et al.*, 2008).

Table 2 Coefficients for phosphorus flow analysis in China.

Coefficient	Descriptions (Unit)	Value	Range	Data Sources
K1	Average P_2O_5 content of phosphate rock reserve	0.17		Li & Cui, 2013
K2	Conversion coefficient from P_2O_5 to elemental P	0.4364		
K3	Average P_2O_5 content of phosphate ore concentrate in China	0.3		NBS, 2013a
K4	Average P content of monoammonium phosphate (MAP)	0.24	0.21–0.27	IPNI, 2014
K5	Average P content of diammonium phosphate (DAP)	0.2		IPNI, 2014
K6	Average P content of triple superphosphate (TSP)	0.2		IPNI, 2014
K7	Average P content of single superphosphate (SSP)	0.08	0.07–0.09	IPNI, 2014
K8	Average P content of nitrophosphates	0.08	0.03–0.13	IPNI, 2014
K9	Ratio of phosphoric tailings production to phosphate rock production (concentration) (t/t)	1	2/3–3/2	Jin *et al.*, 2012
K10	P content of phosphoric tailings	0.02	0.01–0.03	Dai, 2008; Huang *et al.*, 2009
K11	Ratio of phosphogypsum production to wet-process phosphoric acid (t/t 100% H_3PO_4)	4.5	4.5–5	Jiang & Xie, 2013
K12	P content of phosphogypsum	0.034	0–0.075	Li, 2012
K13	Ratio of phosphorus slag production to elemental phosphorus production (t/t)	9	8–10	Zhang, *et al.*, 2010
K14	P content of phosphate slag	0.0105	0.004–0.017	Zhang, *et al.*, 2010
K15	Ratio of ferrophosphorus production to elemental phosphorus production (t/t)	0.1		Wei, 1990
K16	P content of ferrophosphorus	0.16	0.16–0.175	Wei, 1990
K17	Percentage of elemental phosphorus used for thermal process phosphoric acid (including export)	0.6		Gong, 2006
K18	Percentage of elemental phosphorus used for exported thermal phosphoric acid	0.1		Chen SJ, 2006
K19	Percentage of elemental phosphorus used for sodium tripolyphosphate (STPP) production	0.3		Chen SJ, 2006
K20	Percentage of elemental phosphorus used for phosphorus trichloride (PCl_3) production	0.2		Gong SJ, 2006
K21	Percentage of elemental phosphorus used for export	0.1		Chen SJ, 2006
K22	Ratio of STPP produced from wet-processes to STPP from thermal processes	0.05		Chen SJ, 2009
K23	Percentage of STPP for export	0.65		Chen SJ, 2009
K24	Percentage of STPP used for other uses, excluding detergent or export	0.1		Chen SJ, 2003
K25	Percentage of phosphate fertilizer in the form of MAP	0.45		Wu, 2013*
K26	Percentage of phosphate fertilizer in the form of DAP	0.42		Wu, 2013*
K27	Percentage of phosphate fertilizer in the form of TSP	0.03		Wu, 2013*
K28	Percentage of phosphate fertilizer in the form of SSP	0.06		Wu, 2013*
K29	P content of industrial grade MAP	0.19	0.17–0.20	CIC Sindh Industry Research Center, 2011
K30	Percentage of elemental phosphorus used for organophosphorus pesticide	0.13		Chen, 2006
K31	Percentage of other P compounds used for industrial uses	0.5		Assumption
K32	Recovery rate of phosphoric tailings	0.1		Assumption
K33	Recycling rate of phosphogypsum	0.2		Jiang & Xie, 2013
K34	Recycling rate of phosphorus slag and by-products	0.5		Zhang *et al.*, 2010

* Recalculated based on data in the literature.

3.2 Production of intermediate products

Phosphoric acid and yellow (elemental) P are two common precursors for most P products in application, as shown in Fig. 1. At the global level, wet-process phosphoric acid accounted for 95% of marketable PR in 2004 (concentrate) (Villalba *et al.*, 2008). In China, however, only 59% of marketable PR concentrate (7,357 Gg P) went to wet-process phosphoric acid in 2012 and was used to produce major phosphate fertilizers, including monoammonium phosphate (MAP), diammonium phosphate (DAP), triple superphosphate (TSP), single superphosphate (SSP) and nitro-phosphates (Table 3). Even without considerations of losses, wet-process phosphoric acid only accounts for 88% of total production of P-related products, much lower than the world average. MAP and DAP, among the above five major intermediate P products, represented the most dominant products, accounting for 47.4% and 42.7% of total wet-process production.

Yellow P production in China in 2012 was 960 Gg, only constituting 7.7% of total marketable PR concentrates (Fig. 1). Sixty percent of yellow P production was

Table 3 Consumption and losses of marketable PR concentrate in 2012 in China.

Consumption	Quantity (Gg P)	Percentage (%)
Wet-process phosphoric acid	7357	59
Elemental phosphorus (yellow P)	960	8
Losses	463	4
Exports	399	3
Change in stocks	3311	26
Total consumption	12476	100

Table 4 End uses of P in 2012 in China.

End uses	Quantity (Gg P)	Percentage (%)
Fertilizer	6827	88
Pesticides	125	2
Food and feed additives	201	3
Detergents	79	1
Other industrial uses	448	6
Total	7679	100

used for thermal-process phosphoric acid, and its other major uses include production of sodium tripolyphosphate (STPP, $Na_5P_3O_{10}$) for detergents and phosphorus trichloride (PCl_3) for organophosphorus pesticides (Chen, 2006, 2009; Gong, 2006).

In addition to useful products, large volumes of phosphogypsum are created during the wet process, and phosphorus slag and ferrophosphorus are produced during the production of yellow P. The total wastes accompanying production processes in 2012 in China amounted to 463 Gg P, amounting to 4% of total marketable PR concentrates production.

3.3 End uses of P

Major end-uses of P in China include phosphate fertilizers, pesticides, food and feed additives, detergents and other industrial uses (including water softeners, flame retardants, plasticizers, metal coating agents, etc.) (Table 4). In 2012, phosphate fertilizers presented the most important end use of P in China. In total, 6,827 Tg P was used for the production of phosphate fertilizers in 2012, and accounted for 88% of total end uses. Since P in fertilizer use cannot be substituted, it is alarming that there is only enough P for the next three generations in China. On the other hand, with increasing concerns about water-eutrophication impacts of P-containing detergents, the use of P products (STPP) in detergents is confronting more restrictions. In 2000, about 50% of STPP (about 130 Gg) production was used for producing detergents (Chen, 2003; Liu *et al*., 2005). In 2012, however, the ratio dropped to 25% and P for detergents came to a mere 79 Gg, just 1% of total end uses. With 448 Gg P, other industrial uses comprised the second largest end use of P in China, accounting for 6% of total end uses. Due to technology development and upgrading of China's P industry, it is predicted that in the future more high-quality P products will be required in order to produce all kinds of high-tech P products, such as batteries, catalysts and retardants. Food and feed additives and pesticides consumed 201 Gg P and 125 Gg P, respectively, which were 3% and 2% of total end uses.

3.4 Exports of products

China has been one of the world's most important P exporters. In 2012, its total exports of P from the supply chain reached 1,856 Gg, and accounted for 15% of total production of PR concentrate. With rapid depletion of PR ores, however, China has restricted PR ore exports and the major products exported have moved to the end part of supply chain, *i.e.*, phosphate fertilizer. In 2000, China accounted for 11% of the world total PR exports but 23% of the world total imports phosphate of fertilizer (Shao & He, 2001). Since 2004, China has overturned the tax rebate for PR ore exports and at the same time increased export duties on them, which has resulted in a continuous decrease of PR exports.

Before 2006, China was highly reliant on imported phosphate fertilizers, mainly DAP and compound phosphate fertilizers, from the United States and Russia (or the former Soviet Union). The net import reliance on phosphate fertilizer peaked at 39% in 2001 (Wu & Wu, 2010). In the past decade, however, China's phosphate fertilizer industry has developed very rapidly. Presently, the production capacity for phosphate fertilizer in China amounts to 8,600 Gg P per year (20 million metric tons P_2O_5 per year), exceeding domestic demand by 100% (CIC, 2011). China is the world's top exporter of phosphate fertilizer. Exports of phosphate fertilizers were half the total exports of P products in 2012, and accounted for about one fifth of the total world trade of phosphate fertilizer (Wu & Wu, 2010).

3.5 P wastes and recycling

Along the supply chain of P products, a large quantity of P ends up in various wastes, including phosphoric tailings, phosphogypsum, phosphorus slag and ferrophosphorus. The total P wastes from the P supply chain were estimated at 2,369 Gg P in 2012, equivalent to 19% of marketable PR concentrates. Among them, only 20% were recycled and the others (2,054 Tg) were stored in piles in the environment, presenting environmental hazards as well as a waste of P resources.

Phosphoric tailings are basically low-grade PR ores and it is extremely difficult to recover the phosphate economically from them due to their high impurity content, particularly of magnesium and calcium (Chen & Graedel, 2014). We estimated that the production of phosphoric tailings was 1,906 Gg P in 2012. Presently, no tailings are recycled in China and a minority of tailings is mixed with slimes for reclamation or backfill of mine works. Also, phosphogypsum represented the largest part (60%) of P-related wastes in 2012.

Phosphogypsum is an acidic byproduct of the phosphate fertilizer industry during the production of wet-process phosphoric acid. In China approximately 4.5–5 mass units of phosphogypsum are generated for each unit of phosphoric acid (Jiang & Xie, 2013) and the total P loss as phosphogypsum amounted to 356 Gg P in 2012. Currently, phosphogypsum cannot be used as a substitute for synthetic or natural gypsum due to the considerable number of impurities in it (Villalba *et al*., 2008). A lot of studies have been done on phosphogypsum recycling in China and it is reported that 20% of phosphogypsum is recycled or reused (Jiang & Xie, 2013). Phosphogypsum, however, is mainly used as cement, road materials or reclamation materials for mining sites (Han *et al*., 2012). Seldom have breakthroughs been achieved in the recovery of P in phosphogypsum, whether technical or economic.

Phosphorus slag and ferrophosphorus are byproducts of elemental phosphorus production. The production of phosphorus slag and ferrophosphorus were 91 Gg P and 16 Gg P, respectively, in 2012. Although phosphorus slag has applications similar to those of phosphogypsum, its recycling rate in China is much higher (about 50%) due to its lower impurity content (Zhang *et al*., 2010). Ferrophosphorus is recycled at a better rate and usually sold as an additive to the steel industry.

4. Discussion and Conclusions

As the country with the world's second largest P mining resources, China is also confronting a serious P scarcity problem. PR reserves in China will be depleted within 30–50 years, and P is one of 20 kinds of minerals in China in short supply. China also contributes to world P flows as one of the most dominant exporters of all kinds of P products, including PR ores, yellow P, STPP, MAP and phosphate fertilizers. Its total net exports accounted for 15% of marketable PR concentrates. As the world's top exporter of phosphate fertilizer, China, through the sustainability of its P management, will inevitably exert profound influences on global sustainability of P cycles.

Comparatively, the total domestic consumption of P in China was 61.6% of total marketable PR concentrates, and 53.3% of crude PR ores. From a perspective of life-cycle P use efficiency (PUE), 1 g of P consumed domestically in China requires 2 g of P extraction throughout the production chain, which is much higher than the life-cycle PUE for the food production system (5.8 g and 6 g for 1g P consumption in food worldwide and in the United States, respectively) (Cordell *et al.*, 2009; Suh & Yee, 2011). If net exports of P are considered, the life-cycle PUE in China increases to 66.3%, indicating that 1g P consumed domestically requires only 1.6 g of P extraction throughout the production chain. The life-cycle PUE for food production in China, however, is much lower. According to Chen S.J. (2009), 10–13g P was required to meet demand for 1 g P consumption in food in 2006 in China, almost 5–6 times higher than the production process. Roughly, the overall PUE for food consumption was 15%–20% in China, while the overall PUE for production could reach 50%–90%. This indicates that, from a system perspective, more P was lost during the consumption process, particularly the food consumption process, than in production processes.

As in other regions, wet processes play the most important role on the production side of P flows in China. Without consideration of waste production and net exports, wet-process phosphoric acid accounts for 83.7% of consumption of PR concentrate as products (8,793 Gg). This value, though, is still lower than that of the world average or of the United States (Villalba *et al.,* 2008; USGS, 2013). Elemental P production is also important in China, since yellow P is an important precursor to various products, such as PCl_3, STPP, phosphine (PH_3), oxides, etc. Wet processes have serious environmental impacts. Although about one fourth of 356 Gg P phosphogypsum is recycled, no P is recovered. This is also the case for the recycling activities of the other three P wastes from production processes. In this regard, although recycling of wastes is regarded one of the most significant means of mitigating P scarcity, current recycling activities are insufficient to serve the purpose.

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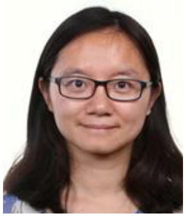

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