

Substance Flow Analysis of Phosphorous in China

Bing Li, Irina Boiarkina, Brent Young, and Wei Yu

Abstract—Phosphorous is an essential natural resource that is projected to run out rapidly. Environmental pollution and resource scarcity pressures require the development of a phosphorous management system in China. One of the fundamental steps to achieve this is to understand the way that phosphorous flows throughout the country. It helps to find out the current phosphorous utilization conditions and provide reliable evidence for both technology and strategy development. Based on these reasons, substance flow analysis of phosphorous was thus conducted to investigate phosphorous flow types and quantify stream values for China. The result indicates that phosphate rock resources in china will run out within 35 years at the current consumption rate, which indicates the urgency of phosphorous recovery. The substance flow analysis will also provide a guide for efficient recovery schemes design in future work. Overall, with a phosphorous crisis approaching in China, it is suggested that work be carried out into phosphorous recovery techniques and management policies.

Index Terms—Phosphorous crisis, substance flow analysis, environment management.

I. INTRODUCTION

Phosphorous (P) is an essential element in biological organisms and food production. Most of the phosphorous used is sourced from mined phosphate rock, a non-renewable resource with no feasible substitute. Phosphorous fertilizer application is of great importance for plant growth in agriculture and horticulture -it provides and replenishes the required plant nutrients. However, overuse of fertilizer has resulted in nutrient imbalances within local ecosystems, enriching phosphorous concentration in water environments and leading to environmental problems such as red tide and eutrophication [1]. By 2010, more than 90% of the mined phosphate rock was used for fertilizer production [2]-[4], a demand driven by population growth via food requirements. It is estimated that the world population will reach nine billion by around 2050 [5], putting more pressure on the food supply system, and thus an increase in phosphate rock consumption. However, the world phosphate rock reserve is estimated to run out within the next 70-140 years [6]-[8], especially with the current low phosphorous utilization efficiency- nearly 90% of phosphorous is lost to the environment after primary consumption [9]. Thus, it is necessary to develop a deep understanding of how phosphate flows within society and control these environmental and

resource risks.

China is one of the main phosphate rock producers and consumers in the world with estimated phosphate rock reserves of around 370,000 million tons in 2013. As shown in Fig. 1 (a), estimated phosphate rock reserves in China decreased significantly during the last ten years, whereas the amount of rock mined has been doubled. When comparing historical data from developed countries (Fig. 1 (b)), China is still in the early stage of phosphorous fertilizer consumption such as developed countries (USA) in the period 1960 to 1970. Thus, phosphorous fertilizer usage in China will increase in the next decade [10]. As a result, the phosphate rock resource will be quickly depleted [11], [12]. Based on these reasons, it is important to investigate phosphorous flows and the utilization efficiency in China to address both the environmental and resource scarcity problems. A key first step to deal with this crisis is to conduct a substance flow analysis (SFA), which can provide fundamental information for advanced nutrient management, as well as promoting the development of a sustainable society.

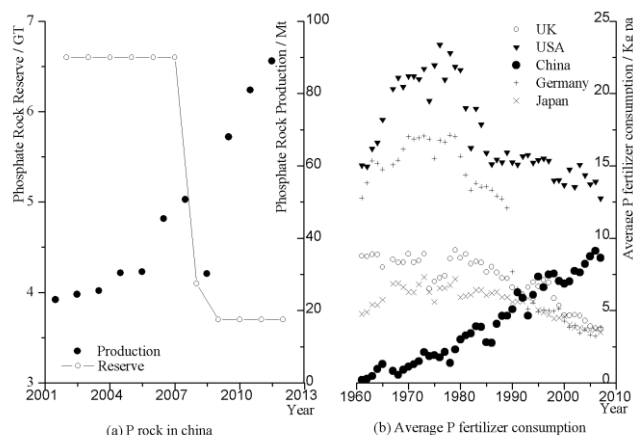


Fig. 1. Phosphorous utilization in different countries (Data: USGS, 2014; Gapminder, 2014).

Country wide SFA for phosphorous has already been carried out for the USA [13], Japan [14], UK [15], France [16], Australia [17] and Finland [18]. However, these analyses are country specific, based on different economic and societal structures and thus not directly translatable to China. Phosphorous flow in China has been carried out by Chen [19] and Gao [20]. However, these works only focus on agriculture and with the rapid growth being experienced in china, the data has aged quickly. At the same time, a lack of systematic data analysis has therefore failed to provide an alternative method to validate data obtained from literature. It is for these reasons that detailed studies, investigating the influence of current economic and social organizations on phosphorous cycles nationwide are still required. STAN 2.5 developed by Vienna University of Technology was used to

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build the phosphorous flow system and calculate unknown variables in the system. A stock balance sheet was built to check the accuracy of the data utilized, and data uncertainty and validation was considered to improve the reliability of the system. These results were then analyzed to explain the current situation of phosphorous utilization in China.

II. METHODS

In this paper, a SFA focusing on phosphorous in China is conducted, irrespective of what form it may appear in [21]. To avoid confusion, all phosphorous flows and stocks are measured in thousands of tons of elemental phosphorous if not specified. This paper concentrates on phosphorous flows in mainland China. Marine environments far from the land area are thus ignored. The main phosphorous flow types are identified based on primary import and export data from governmental reports [22]. A base year of 2012 was chosen to represent the phosphorous quantity sourced from different documents, as the largest amount of data was available for 2012. Data from other years was modified and reconciled to improve the accuracy. This is thus a statistical model and annual variations from different industry sectors might influence the result. However, the analysis is still able to illustrate the basic phosphorous flow situation due to the consistency of economic activity.

Phosphorous flows in China can be divided into three parts: inputs (labeled as 'I' in Fig. 2), outputs (labeled as 'E' in Fig. 2) and domestic consumption (labeled as 'F.W, WB' in Fig. 2). Based on previous reports and the main commodities consumed in China [22] - domestic phosphorous flow can be divided into three subsystems: agriculture, industry and waste treatment. To simplify the system, phosphorous flows in the food processing industry are listed separately. This is because nearly 90% of the mined phosphorous is applied as fertilizer worldwide [2] and food processing is one of the largest economic industries in China. STAN 2.5 was utilized for phosphorous flow system design and mass balance calculations. This program is designed to perform material flow analysis according to the Austrian standard ÖNorm S 2096 (Material flow analysis - Application in waste management). After building a graphical model with predefined components (such as processes, flows, system boundary, and text fields), known data (mass flows, stocks, concentrations, and transfer coefficients) were entered to calculate unknown quantities. All flows can be displayed Sankey-style, which means the width of a flow is proportional to its value. Microsoft Excel was used as the interface for data import and export.

The accuracy of the study depends on the data used for calculations, and thus the data was sourced from multiple and varied sources where possible. Most of the data collected were from the following sources: the National Bureau of Statistics of China, the Ministry of Land and Resources of China and U.S. Geological Survey published reports and research papers. Phosphorous quantities in each flow were quantified by multiplying the amount of the commodity consumed with the respective phosphorous concentration (shown in Eqn 1), when the value was not given directly in the literature.

$$P = P_i \times C_i \quad (1)$$

where, P_i is the percentage of phosphorous in flow i , C_i is the amount consumed of flow i , and i represents different types of flow. If one flow is required to be calculated from two or more sources of unspecified data, it can be quantified as,

$$P = \sum (P_i \times C_i) \quad (2)$$

For each stock, accumulation of phosphorous (A) is the difference between the amount of phosphorous flowing in and flowing out, namely,

$$A = P_{in} - P_{out} \quad (3)$$

Data that is currently not available was calculated based on the system mass balance equations in Stan 2.5. However, the software defaults to no accumulation in any process, whereas some accumulation may occur in the systems, e.g., on agricultural land where the phosphorous concentration may increase over time. Thus, we first conducted an agricultural analysis (agricultural land, food, feed and animals) using data obtained from literature to calculate the phosphorous accumulated in the soil. This value was then used to calibrate the negative value obtained when conducting calculations within the whole system. These values are shown in the system flow San-key diagram in Fig. 2.

Despite our efforts to balance and harmonize the information from these disparate data sources, the data applied are subject to varying degrees of uncertainty. Original results were cross checked to ensure the accuracy during the analysis. Most of the data obtained share at least two methods of calculation, with similar results confirming the accuracy of the data. Average values for each flow were then used to represent the real value of each phosphorous flow in the year 2012. To make the SFA result more reliable, a method was developed by other researchers to calculate the uncertainties, in which the uncertainties usually cannot be analyzed by traditional statistical methods [18], [23]. This method was applied by Cooper and Carliell-Marquet, [15], for phosphorous SFA in the UK, and ameliorated over SFAs where uncertainty was taken account of in the balance for some or all of the data. It analyses uncertainty levels from various data sources, such as official statistics and results from journal papers, and applies intervals to each level [15]. The uncertainty intervals of the different data sources are listed in Table I.

TABLE I: UNCERTAINTY INTERVALS

Interval		Source information	Example
1	\times/\div	China official statics report	China
	1.05		livestock census
2	\times/\div	Published data with calculation method	Annual human P intake
	1.1		
3	\times/\div	Official statics scale up to china scale	P in WWTP effluent
	1.2		
4	\times/\div	Literature without reference or method	Domestic food consumption
	1.33		

The uncertainty range of each flow is determined on the

basis of literature information and is propagated during the system calculation [23]. For example, if the number of cows is 1000, and the uncertainty factor of the number of cows is $\times/1.05$, the uncertainty range is $1000/1.05 = 952$ and $1000 \times 1.1 = 1050$.

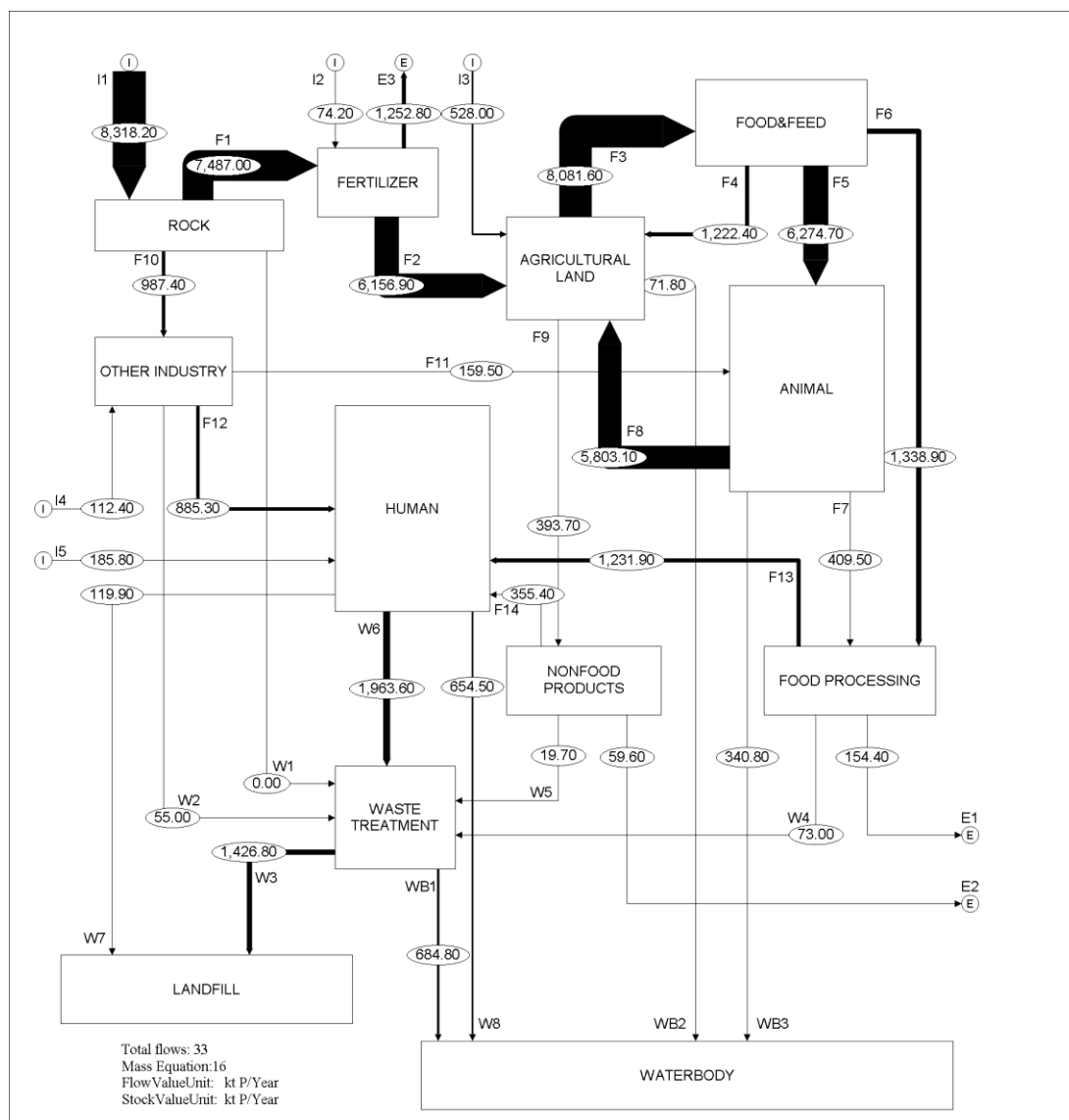
III. RESULTS AND DISCUSSION

The phosphorous substance flow analysis for China is shown in Fig. 2. A mass balance of each stock is summarized in Table II, where the data uncertainty of each flow is also shown based on the method provided and then propagated during the calculation.

As shown in Table II, variation means the quotient between accumulation and the input of the stock. Most of the

variations are under 10% and all are within the uncertainty level of the stock (except 'agricultural land'). Therefore, the value of every phosphorous flow is in good agreement with each other and thus is reliable. The variation in agricultural land is 38%.

The reason is a significant amount of phosphorous applied accumulates in the soil [24], which is a major loss during phosphorous utilization [9]. The variation in the non-food sector is around 10%, and this is because the phosphate rock exports of 41.4kt are also included in the calculation, but are not sourced from agricultural land. After excluding the phosphate rock from the calculation, the variation in the non-food sector is then estimated to be 0.03%, which is very low.



I1: DOMESTIC MINING
I2: FERTILIZER IMPORT
I3: NATURE PRECIPITATION
I4: MINERAL IMPORT
I5: FOOD IMPORT
F1: P PRODUCTION
F2: P APPLICATION
F3: PLANT UPTAKE
F4: PLANT RESIDUAL

F5: LIVESTOCK GRAZING
F6: CROP PRODUCTION
F7: LIVESTOCK PRODUCT
F8: LIVESTOCK MANURE
F9: OTHER PRODUCTS
F10: P ROCK OTHER
F11: LIVESTOCK FEED
F12: OTHER INDUSTRY
F13: DOMESTIC FOOD

F14: DOMESTIC OTHER
W1: FERTILIZER LOSS
W2: OTHER LOSS
W3: WASTE LANDFILL
W4: FOOD LOSS
W5: NONFOOD LOSS
W6: HUMAN WASTE
W7: SLUDGE LANDFILL
W8: DIRECT LOSS

WB1: WWYP EFFLUENT
WB2: CROP LAND LOST
WB3: LIVESTOCK LOST
E1: FOOD EXPORT
E2: OTHER EXPORT
E3: FERTIER EXPORTED

Fig. 2. Substance flow analysis of phosphorous flow in China (Stan 2.5).

TABLE II: PHOSPHOROUS BALANCE IN DIFFERENT SECTORS

Stock name	In	Out	Difference (%)	Uncertainty (%)
Rock	8318	8474	2	[±3660]
Fertilizer	7561	7410	2	[±3327]
Agriculture	13710	8547	38	[±3565]
Food& Feed	8081	8836	9	[±4364]
Animal	6434	6553	2	[±3475]
Food	1748	1459	17	[±372]
Non-food	393	435	10	[±61]
Human	2658	2738	3	[±1053]
Other	1099	1100	0	[±171]
Waste	2084	2111	3	[±688]
Landfill	1547	0	N/A	N/A
Water body	2052	0	N/A	N/A

Variation in food processing is around 16.5%, this is because the volume of domestic food consumption is estimated from the rural food consumption structure and thus the real value should be slightly larger when applied nationwide. This difference is ignored here because of a lack of data. Based on the volume of different phosphorous streams, a breakdown of the overall phosphorous inputs and outputs in China is shown in Fig. 3 (in units of thousands tons of elemental phosphorous), where percentage means the proportion of different phosphorous flow in the total input and output flows.

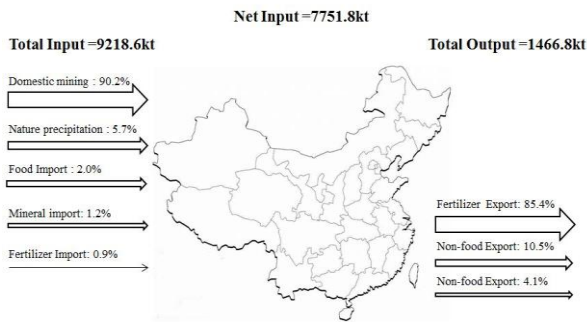


Fig. 3. P input and output in China.

As described, the total phosphorous input to China is 9219 kt, and the majority comes from phosphate rock mining; total output is 1467 kt, mainly in the form of fertilizer. This led to a phosphorous accumulation of 7752 kt in 2012. Excluding phosphorous leachate from soil to water bodies, 20% of the waste phosphorus ends up in landfills, 27% runs off into water bodies and the remainder is left in the soil. These results indicate that the phosphorous flow system in China is self-sufficient, with a significant amount of phosphorous lost to the environment after primary usage. To better understand the phosphorous utilization efficiency in agriculture, a detailed soil phosphorous mass balance sheet was established below.

TABLE III: SOIL PHOSPHOROUS MASS BALANCE SHEET (KT P/YEAR)

	Inputs		Outputs
Fertilizer	6685	Crops/forage	7614
Manure	5803	Other products	394
Plant residue	1222	Surface runoff	413
Total in	13710	Total out	8420

In the balance sheet, soil phosphorous leaching is not considered. It indicates that 5291 kt phosphorous is stabilized in the agricultural land, and this is nearly 43% of the total fertilizer applied (both chemical fertilizer and animal manure). Agricultural land took up 56% of the total national land area in 2012 [24], which suggests an average phosphorous input of 26 kg P/ha and average phosphorous output of 16 kg P/ha. Thus, the phosphorous utilization efficiency in agriculture is 62%. It should be noted that this kind of accumulation is likely to be magnified in intensive livestock farms, due to the challenges posed by transport and effective phosphorous distribution.

As can be seen from the above analysis, the phosphorous rock resource in China is under risk. The total phosphorous rock reserves in terms of elemental phosphorous is around 285 million tons when considering the average P_2O_5 content in China's phosphate rock to be 17.5% [25]. The phosphorous mined in 2012 was around 8.35 million tons [26] in the form of elemental phosphorous, which means the phosphorous resources will deplete in 35 years without proper management. Major environmental problems caused by excessive phosphorous application are red tide and eutrophication. The largest contributor of phosphorous loss to water bodies in China is from diffuse source run off, estimated to be around 1067 kt in 2012. This number would be larger when considering the phosphorous leaching from agricultural land and landfill sites. Total phosphorous loss from point sources is estimated to be 685 kt. Therefore, phosphorous pollution from diffuse sources poses greater environmental risk to water bodies in China and thus control strategies should be developed.

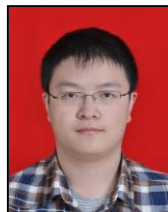
IV. CONCLUSION

A systematic substance flow analysis of phosphorous in China was conducted and revealed different phosphorous flows nationwide for the first time. The phosphorous resources in China are going to be depleted in 35 years under the current consumption structure. Annual phosphorous inputs and outputs in China are 9219kt and 1467kt respectively. Analysis shows that agriculture is the most phosphorous-intensive sector with phosphorous utilization efficiency at around 62% and that a significant amount phosphorous is lost to the environment after primary usage. What is more, it is proved that diffuse sources, rather than point sources pose greater risk for eutrophication in China's water bodies. To achieve higher phosphorous utilization efficiency in China, improving nutrient recovery efficiency and reducing soil phosphorous accumulation is recommended.

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Bing Li obtained his master degree in energy and environment engineering from the University of Sheffield, UK and is now a PhD candidate from the University of Auckland, New Zealand. He is now working on phosphorous recovery schemes and techniques to provide suggestions and solutions for the coming phosphorous crisis.

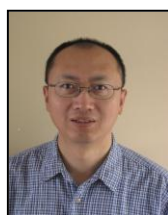


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