Development of Integrated Phosphorus Cycle Input Output Model and Its Applications

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Abstract

Phosphorus is present only as a trace element on the Earth, but is one of the important strategic resources for agricultural food production and for the chemical industry. Natural phosphate ore is traded worldwide, mainly as a raw material for fertilizer. Approximately 147 × 10^3 kt of phosphate ore was mined in the world during 2005. Of this, 24.7% (36.3 × 10^3 kt) was produced in the USA, 20.7% (30.4 × 10^3 kt) in China, and 17.1% (25.2 × 10^3 kt) in Morocco, while there are essentially no deposits of phosphate ore in Japan or the EU. It is of concern that, due to growing world demand for fertilizers, deposits of high-grade phosphate ore could be exhausted within the next 100 years, and the average price of the ore in 2008 was approximately doubled that in 2007. Concerning the restricted supplies of phosphorus resource, it is important to consider the quantity and availability of phosphorus resources that currently remain untapped.

With this in mind, we developed the Integrated Phosphorus Cycle Input Output (IPCIO) model to estimate the phosphorus requirement for economic activities and evaluate the recycling effects of reutilization of phosphorus resources which are currently untapped. The accounting framework of IPCIO has 4 natural resources and 25 phosphorus related commodities in physical term and 389 intermediate sectors of the Japanese economy in 2005 year. As empirical studies, phosphorus recovery and recycling scenarios are considered for future phosphorus resource management.

Keywords: IPCIO, Phosphorus, Recycle, Substance flow analysis, Hybrid Input Output model

1. Introduction

Phosphorus is present only as a trace element on the Earth, but is one of the important strategic resources for agricultural food production and for the chemical industry. Natural phosphate ore is traded worldwide, mainly as a raw material for fertilizer. Approximately 147 × 10^3 kt of phosphate ore was mined in the world during 2005. Of this, 24.7% (36.3 × 10^3 kt) was produced in the USA, 20.7% (30.4 × 10^3 kt) in China, and 17.1% (25.2 × 10^3 kt) in Morocco, while there are essentially no deposits of phosphate ore in Japan or the EU (USGS,2012). It is of concern that, due to growing world demand for fertilizers, deposits of high-grade phosphate ore could be exhausted within the next 100 years (Vaccari 2009), and the average price of the ore in 2008 was approximately doubled that in 2007. Concerning the restricted supplies of phosphorus resource, it is important to consider the quantity and availability of phosphorus resources that currently remain untapped.

Various authors have analyzed P flow from the economical use and recycling perspective (Smil 2000), (Li, He et al. 2007) (Neset, Bader et al. 2008; Matsubae-Yokoyama, Kubo et al. 2010). From these snapshots we might better be able to go beyond the “once-through mode of societal phosphorus metabolism” (Liu, Villalba et al. 2008). However, it is difficult to trace the supply chain of all the materials used in products throughout the country by using the bottom-up approach. The fact that phosphorus and other plant nutrients are one of the most widely used elements in our society calls for taking a bird’s-eye view for a better understanding of the flow of phosphorus including agricultural products and meat products(Goodlass, Halberg et al. 2003). Input–output analysis (IOA) is one of the most widely used tools of industrial ecology for describing the economy-wide activities and their environmental implications.

The purpose of this study is to provide a phosphorus accounting database based on input output table and a new tool, Integrated Phosphorus Cycle Input Output model(IPCIO) to evaluate phosphorus flows into agricultural production and other economic activities, and the effect of utilization of phosphorus resources which are currently untapped.

2. Data and Method

2.1 Flow of Phosphorus in Economics activities

For this analysis, it was necessary to classify the phosphorus flow by demand. Thus, we first evaluated the phosphorus flow of the Japanese economy. Secondly, focusing on the agricultural demand of phosphorus, the phosphorus requirement for one unit of agricultural production was estimated on the basis of fertilizer statistics and lifecycle inventory data of livestock feed. While the authors worked on the phosphorus flow of Japan in 2002 (Matsubae-Yokoyama, Kubo et al. 2009), the domestic phosphorus flow was evaluated partly with reference to the data from previous studies. In particular, the agricultural and related sectors were analyzed in more detail with the Japanese input-output table in 2005 (MIC, 2009), food balance sheet (MAFF, 2009b) and other agricultural statistics.

Fig.1 shows the substance flow of phosphorus in Japan. The flow was estimated from statistical data based on 2005 data. To simplify the analysis, the total phosphorus flow was evaluated by considering each of the sectors shown in the flow taking into account the total mass balance. Although there are other much smaller input and output flows, we omitted those with values smaller than 10 kt from the figure.

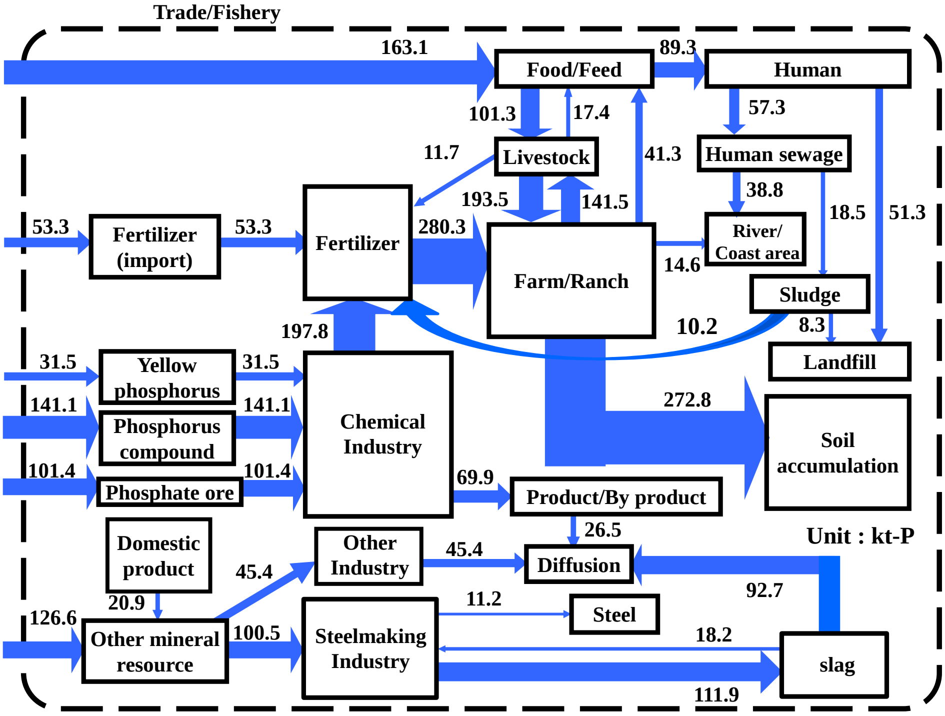

Figure 1 Phosphorus flow in Japan

The Material Flow Analysis(MFA) reveals the estimates of the domestic stock and flow of phosphorus in Japan. The total input of phosphorus into Japanese society is estimated to be 616 kt. In the input, 40% (251.1 kt) is used as fertilizer, and 26% (163.1 kt) is consumed by humankind and livestock. The phosphorus that goes through both routes finally ends up either in the soil or water. In addition, 16% (100.5 kt) flow into the steel industry as mineral resources, most of which is condensed in steelmaking slag. By contrast, most of the other phosphorus is used as chemical industrial products (except for the manufacture of fertilizer). The total amount is expected to be 45.4 kt , accounting for 7.4% of the total phosphorus input. The uses and concentrations of phosphorus for chemical industrial products are various. To date, there are no clear data that show how much phosphorus exists in such various products from the chemical industry, and where exactly it is.

Considering phosphorus flow accounting or recycling, the flow of phosphorus compounds should be clarified, thus we estimated the phosphorus flows related chemical products as shown in Table 1 based on the market survey and interviewed data.

Table 1 Phosphorus flow related with chemical products

	Injection （t-P）	Amount by use （t-P）								
		Food additive	Plasticizer	dye	Medicine	Surface acting agent	Cosmetics	Pesticide	Metal-surface treatment	Other Product
Phosphoric acid	35683.2	1591.5		71.4	1613.1	6088.0			16477.6	9841.6
Sodium phosphate	6832.2	2933.4		16.2	743.8				2011.5	1127.3
Anhydrous phosphoric acid	2269.7				290.9	216.6		1475.0		287.3
Phosphorus chloride	9753.5		1999.7		131.9	2337.8		1504.8		3779.2
Ammonium phosphate	968.4	140.6		54.5						773.3
Potassium phosphate	1241.9	917.8								324.1
Calcium phosphate	12036.2	9781.8			566.9		566.9			1120.6
Red phosphorus	261.4								25.8	235.7
Other	865.7							60.4		805.3
Total	69912.3	15365.2	1999.7	142.1	3346.6	8642.4	566.9	3040.2	18514.8	18294.3
Proportion by use(%)	100.0	22.0	2.9	0.2	4.8	12.4	0.8	4.3	26.5	26.2

2.2 Integrated Phosphorus Cycle Input Output Table

2.2.1 Disaggregation of Phosphorus-related Commodities in the Input-Output Table

The IPCIO is a model for the purpose of quantitative evaluation of the effects of a recycling use of phosphorus. However, since many phosphorus-related commodities, such as phosphorus ore and phosphoric acid, do not exist as independent sectors in the conventional input-output table, it is not possible to discuss the recycling use of phosphorus by analyses employing the conventional input-output table. For example, phosphorus ore is aggregated in the sector called “other nonmetallic minerals” excluding such items as limestone and ceramic mineral raw materials, and phosphorus compounds such as phosphoric acid and calcium phosphate are aggregated in the sector called “other inorganic industrial products". Therefore, in constructing the IPCIO, first the sector classification of the conventional input-output table was revised to disaggregate into sectors, such as phosphorus ore and phosphoric acid, which had been aggregated as parts of conventional sector classifications. Further, with regard to waste material such as iron and steel slag and sewage sludge which are considered to be secondary resources of phosphorus, new sectors were created since they do not exist in the sector classification of the conventional input-output table.

In disaggregating and creating sectors, the method of classification differs depending on whether the row or the column of the input-output table is considered. For example, since phosphorus ore can only be "raw material" for phosphorus products, it is not necessary to add "phosphorus ore" as a sector in the column which represents supply destinations. On the other hand, since phosphoric acid, at the same time as it is the supply destination for phosphorus ore (wet and dry phosphoric acid are produced from phosphorus ore), is also raw material for various phosphorus products, it functions as both supply source and destination, and disaggregation of sectors in both the row and the column are required. In this study, taking into account the foregoing considerations, the conventional input-output table was extended as in Table 2, and an accounting matrix which explicitly accounts for the flow of phosphorus-related commodities was produced.

The procedure for the allocation of the quantity of phosphorus in each phosphorus- related commodity to each of the supply destinations is broadly classified into the following three methods.

A) Entry of the value of the quantity supplied to each sector is determined based on the material flow estimated from industry statistics and hearings.

B) In cases in which the supply/demand relationships with the supply destinations of the phosphorus-related commodity can be ascertained quantitatively from the production value tables by sector and commodity which are appended to the input-output table, allocations are made of the domestic quantity of supply of a phosphorus-related commodity i according to the proportions of the monetary values of the intermediate demand. For example, estimations were made for natural resources as well as for secondary products of phosphorus, such as coal and surfactants, by this method. In the case of coal, this means that all industrial sectors use coal with the same concentration of phosphorus. However, in the case of surfactants, although there actually are differences which are not small, depending on the industry, in the proportions of use of phosphate surfactants and other surfactants, a strong condition would be imposed that all industries use phosphate and other surfactants in the same proportions.

C) In addition to the method in (B), the use or non-use of a given phosphorus-related commodity in an intermediate demand sector is classified in the form of binary data of 1, 0 from technical information, and this is used to complement the information on the proportions of the allocations of the monetary value.

Table 2 Sector disaggregation in IPCIO database

Raw section (before)	**Raw section (after)**	
Other nonmetal mineral	Phosphate ore	Other nonmetal minerals
Egg	Poultry manure	Other egg products
Broiler	Poultry manure	Other broiler products
Pig	Pig manure	Other pig products
Beef cattle	Beef cattle manure	Other beef cattle products
Other dairy products	Dairy manure	Other dairy products
Organic manure	Organic manure (animal)	Organic manure (plant)
	Non-phosphorus organic manure	
Chemical fertilizer	Phosphate fertilizer	Complex fertilizer
	Non-phosphorus chemical fertilizer	
—	Waste manure	
—	Steel making slag	
—	Sewage, sludge	
—	Food residual	
Other inorganic chemistry industrial products	Wet phosphoric acid	Phosphorus chloride
	Thermal phosphoric acid	Ammonium phosphate
	Yellow phosphorus	Potassium phosphate
	Phosphoric acid	Calcium phosphate
	Sodium phosphate	Red phosphorus
	Anhydrous phosphoric acid	Other phosphorus compound
	Other inorganic chemistry industrial products	
Other chemistry end products	Metal-surface treatment	Other chemistry end products

Column section (before)	**Column section (after)**
Organic manure	Organic manure (animal)
	Organic manure (plant)
	Non-phosphorus organic manure
Chemical fertilizer	Phosphate fertilizer
	Complex fertilizer
	Non-phosphorus chemical fertilizer
—	Waste manure
Other inorganic chemistry industrial products	Wet phosphoric acid
	Thermal phosphoric acid
	Yellow phosphorus
	Phosphoric acid
	Sodium phosphate
	Anhydrous phosphoric acid
	Phosphorus chloride
	Ammonium phosphate
	Potassium phosphate
	Calcium phosphate
	Red phosphorus
	Other phosphorus compound
	Other inorganic chemistry industrial products
Soap, Detergent, Surface acting agent	Soap, Detergent
	Surface acting agent
Other chemistry end products	Metal-surface treatment
	Other chemistry end products

2.2.2 Hybrid IO Model with an Integrated Phosphorus cycle

Based on the phosphorus flow data estimated so far, we proposed IPCIO database and its analytical model with following setups,

- ✓ IPCIO database with phosphorus contained goods flow,
- ✓ Phosphorus yield loss coefficient considering the difference between phosphorus input as intermediate goods and output as produced commodities,
- ✓ Phosphorus recovery technology matrix as scenario parameters.

The main framework of IPCIO model follows WIO-MFA model(Nakamura, Nakajima et al. 2007). Its framework is given as follows. The amount of input i necessary to produce a unit of output j (i, j = 1,..., n) is assumed to be a_{ij}. A matrix of size $n \times n$ (input coefficient matrix), which treats the input as element i, j, is assumed to be A. The action of two matrices on A yields $\tilde{A}$, which describes the actual output composition. The first matrix is a material flow filter Φ, eliminating substance flow that cannot be expressed in terms of mass. This $n \times n$ matrix gives ϕ_{ij} = 1 when the input makes up the output mass, and ϕ_{ij} = 0 in other cases. For instance, when the input does not have the mass as in the case of service businesses, or when the input has the mass but the output is limited to supplemental purposes, the matrix gives ϕ_{ij} = 0. The action of Φ on A enables a description only of the substance flow necessary for materials flow analysis (MFA). The second matrix is the yield coefficient matrix Γ. All raw materials used as input do not always form products in actual processes. Some of the materials are emitted as a process loss. Therefore, Γ consists of a proportion γ_{ij}, defined as the ratio of the output to the input. The action of this matrix on A can eliminate input flow that will not be directed to the output. In other words, $\tilde{A}$ is calculated by equation (1), in which $\otimes$ is the Hadamard product, and element i, j of $\tilde{A}$ is $\gamma_{ij}\phi_{ij}a_{ij}$.

$$\tilde{A} = \Gamma \otimes \left(\Phi \otimes A \right) \tag{1}$$

Consider the phosphorus in the residues, such as waste water, livestock manure and slag. Input table describes the phosphorus input into each industrial sector. However, all the phosphorus contained fertilizer does not transfer into the agricultural products. The phosphorus which did not transferred into the products goes to accumulate in the soil, water and the other residues. For example, pig iron production uses 131 × 10^3 kt of iron ore, 20 × 10^3 kt of lime stone and 36 × 10^3 kt of coke respectively. Its accompanied phosphorus was 78.6kt-P, 2.5kt-P and 9.4kt-P. Phosphorus for steel products is one of the most important aversive substances, thu s almost all the phosphorus ends up being removed into steelmaking slag. In this case, the yield ratio of phosphorus in steel materials is almost zero.

Now, *n* is divided into three types of exclusive and non-empty groups, or *P*, *R*, and *M*, and $\tilde{A}$ is divided into 9 submatrices, as shown in equation (2), where $\tilde{A}_{PM}$ is $n_P \times n_M$, $\tilde{A}_{PR}$ is $n_P \times n_R$, and $n_P + n_M + n_R = n$.

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & \tilde{A}_{PM} & \tilde{A}_{PR} \\ \tilde{A}_{MP} & \tilde{A}_{MM} & \tilde{A}_{MR} \\ \tilde{A}_{RP} & \tilde{A}_{RM} & \tilde{A}_{RR} \end{pmatrix} \tag{2}$$

P, *M*, and *R* stand for Product, Material, and Resource, respectively. These meet the following conditions according to their processing levels.

(a) Resources are collected from the global environment and are not produced. $\tilde{A}_{iR} = 0$, $i = P, M, R$

(b) Materials are produced from resources. $\tilde{A}_{iM} = 0$, $i = P, M$

(c) A product is produced from materials and products. $\tilde{A}_{RP} = 0$

Under condition (a), resources are not produced within this system. In other words, this condition represents the lowest level of processing of materials. Under condition (b), materials are produced only from resources with a low level of processing, and not from the materials themselves. Owing to the equality of all levels of processing, these materials will not be introduced into other materials. This requirement is necessary to avoid double counting. Under condition (c), a product is made from materials with a lower level of processing, but a product with a low level of processing will be introduced into a product with a high level of processing owing to various levels of product processing. Resources are not inputted directly into a product.

The application of this condition to $\tilde{A}$ gives the submatrix in equation (3).

$$\tilde{A} = \begin{pmatrix} \tilde{A}_{PP} & 0 & 0 \\ \tilde{A}_{MP} & 0 & 0 \\ 0 & \tilde{A}_{RM} & 0 \end{pmatrix} \tag{3}$$

In the case where $\tilde{A}_{PP} = 0$, the material composition of a product is simply given by $\tilde{A}_{MP}$. The composition, however, generally forms $\tilde{A}_{PP} \neq 0$ because of the input of intermediate products such as parts. A matrix of the material composition C_{MP} is commonly given by equation (4).

$$C_{MP} = \tilde{A}_{MP}(I - \tilde{A}_{PP})^{-1} \tag{4}$$

Here, the element i, j represents the volume of materials that make up the unit product j. Thus, the column sum gives the weight of the unit output j. When a unit of a product is physically expressed, for instance, as one ton, the column sum of the applicable composition matrix also becomes one ton. When the product is expressed on a monetary basis, for instance, as one million yen, the column sum of the applicable composition matrix represents the weight per one million yen.

Here we defined phosphate ore, coal, iron ore, and limestone as resource (R), yellow phosphorus, dry phosphoric acid and wet phosphoric acid as materials (M).

2.2.3 Phosphorus recovery and recycling

There are multiple options about phosphorus recovery, such as MAP (Monoammonium Phosphate) method, HAP (Hydroxyapatite) method and magnetic separation. Different technology requires the different materials and energy. Recovered phosphorus also takes on different forms depending on its recovery technologies. For example, MAP method requires the ammonia and magnesium oxide, and the recovered phosphorus from sewage sludge was formed as MgNH4PO4 which can be substituted as the fertilizer material. The other waste water treatment requires the adsorbent material and calcium hydroxide, the recovered phosphorus was formed as hydroxyapatite which can be substituted for the fertilizer material or phosphorus ore. This table describes the inventory of each technology.

Table 3 Inventory of the phosphorus recovery technology

			Recovery Technology							
			Decreased fertilizer	Carbonization of manure	Magnetic separation	HAP method	MAP method	Alkaline elution og ash	Heatphos method	Reduction and melting of ash
per for recovery 1t-P	Secondary resources for recovery of 1t-P (t-P)	Fertilizer	1							
		Poultry manure		1.43						
		Slag			1.61					
		Sewage				1.25	1.1			
		Sludge						2.22	2.86	1.47
	Recovery rate		1	0.70	0.62	0.80	0.91	0.45	0.35	0.68
	Injection for recovery of 1t-P (million yen)	Electricity		0.250	0.040	0.058	0.058	0.117	0.259	0.270
		Chemical drug		0.022		0.219	0.244	0.283	0.546	
		Fuel		0.165						0.035
		Others		0.011	0.003					
		Total	0.000	0.448	0.043	0.277	0.302	0.400	0.806	0.305

Denote that $X^{P} = \{X_{ij}^{P}\}$, $X^{W} = \{X_{ij}^{W}\}$, and $X^{NP} = \{X_{ij}^{NP}\}$ are phosphorus related goods i which is used in sector j, phosphorus contained waste generation, the input of non-phosphorus related goods, respectively.

$$\widehat{X}_{ij}^{P} = R_i \, X_{ij}^{W} \tag{5}$$

$$\widehat{X}_{ij}^{NP} = g_{lm} \, X_{ij}^{P} \tag{6}$$

$R = \{R_i\}$ and $G = \{g_{lm}\}$ represent the recovery rate of phosphorus related goods i, and the recovery technology coefficient which denote that additional input of goods and services m to recover one unit of phosphorus related goods l shown in Table 3.

The Leontief inverse matrix sets an import and inflow endogenous type multiplier.

$$\widetilde{B} = [\, I - (I - m)\, \widetilde{A} \,]^{-1} \tag{7}$$

where

$\widetilde{A}$: Input coefficient matrix defined equation (3)

m : Diagonal matrix of the import ratio, which is the ratio of imports to total domestic demand.

Note that m of yellow phosphorus set in zero, while 100% of yellow phosphorus is imported due to no domestic facility to produce it in Japan. Thus in this analysis, the demand of yellow phosphorus means the demand of imported yellow phosphorus immediately.

In following scenario analyses, $\widetilde{A}'$ is calculated by additional inputs (both positive and negative value) plus default value of intermediate input. The innovative effects of new phosphorus recovery technology in each scenario are derived by

$$X' = [\, I - (I - m)\, \widetilde{A}' \,]^{-1} Y \qquad (7)$$

where Y is final demand vector.

3. Analysis

In the following, the IPCIO which has been prepared is used to estimate the demand for phosphorus-related commodities when there is a change in the final demand, and to analyze the ripple effects accompanying the introduction of recycling technologies.

3.1 Translation ratio of phosphorus in agricultural production

Fig.2 shows the results of estimating the amounts of phosphorus-related commodities required in order to satisfy a demand of one million yen in each of, among the food-related sectors, the rice, beef and food service sectors. It was shown that in producing one million yen of rice, 9.6kg of phosphorus is input as phosphorus fertilizer, that 9.5kg and 0.1kg of wet phosphoric acid and ammonium phosphate, respectively, are required in order to produce this and that, in turn, 9.87kg of phosphorus is input as phosphorus ore for their production. However, with regard to phosphorus ore, since the entire amount is imported, the demand for phosphorus ore which arises here may be interpreted to, in total, be the demand for imported phosphorus ore. Although ammonium phosphate is also mostly imported, some is produced domestically, and the present result is the demand for domestically produced ammonium phosphate.

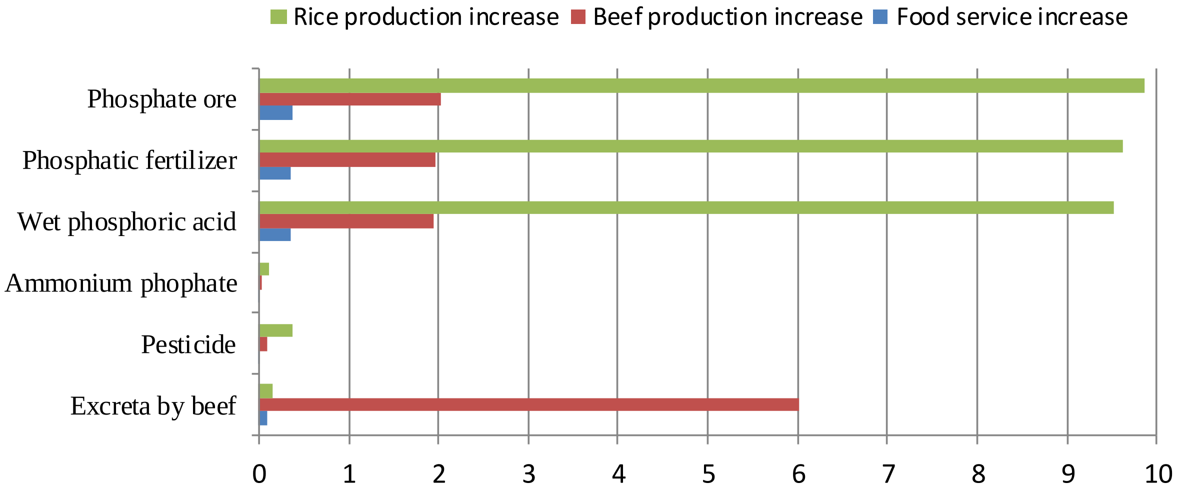

Fig. 2 Phosphorus demand associated with food demand (Unit: kg-P)

Fig.3 shows the amounts of phosphorus, estimated using C_{MP}, which are contained in products corresponding to production amounts of one million yen, as well as the amounts of the demand for phosphorus as material. Here, material refers to wet phosphoric acid, dry phosphoric acid and yellow phosphorus. The results show that one million yen of rice and beef contain 1.71kg and 0.02kg of phosphorus, respectively, and that a domestic demand for 10.08kg and 2.10kg of phosphorus arises in order to produce the fertilizer, feed and agricultural chemicals required for their production. Food services corresponding to one million yen contain 0.05kg of phosphorus, and a demand for 0.41kg of phosphorus arises in order to supply it. In the demand for phosphorus in food services, in addition to the demand of food origin there is also influx in the form of detergents and food additives. Although the demand arising in these three sectors is mainly for wet phosphorus acid required for fertilizer production, it is expected that the proportion of dry phosphoric acid would be greater in phosphorus supporting the demand in industrial sectors.

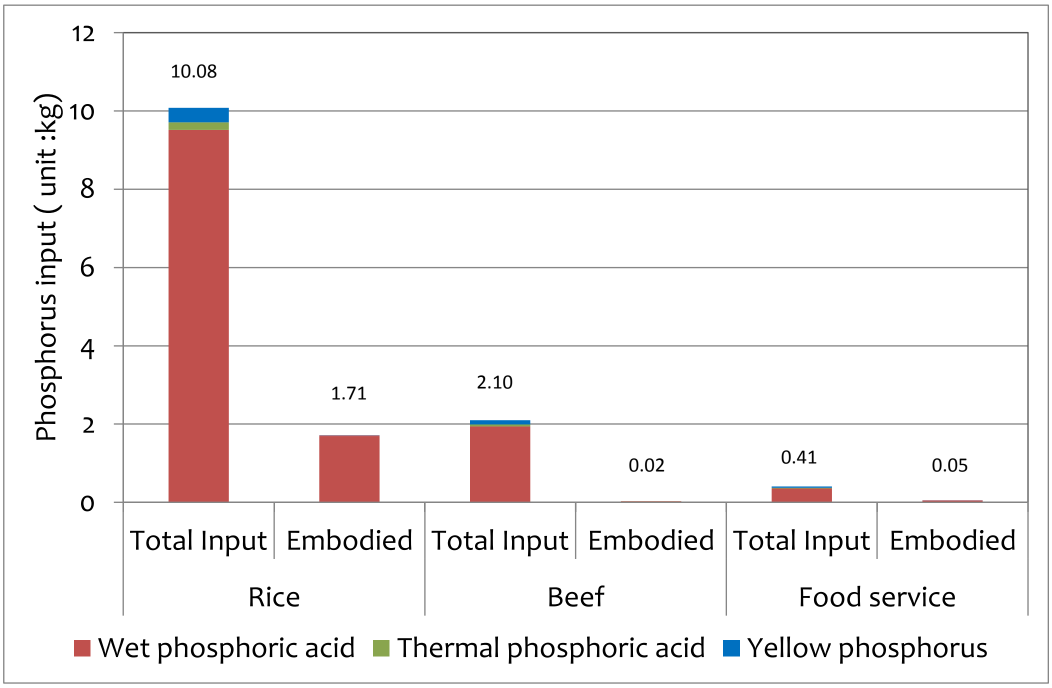

Fig. 3 The amount of input and embodied phosphorus demand associated with food demand (Unit: kg-P)

3.2 Scenarios

The following four scenarios considered to be technically feasible were prepared as presumed recycling uses of phosphorus, based on the amounts of each of the potential secondary resources obtained from the results of material flow analysis and on the recovery technologies which have been devised at present (Table 4).

Table 4 Scenarios

Scenario		Recovery source	Substitute
1	Carbonization of poultry manure	poultry manure	Fertilizer
2	Phosphorus recovery from waste water by HAP method	Waste water	Fertilizer
3	Phosphorus recovery from sewage sludge by Heatphos method	Sewage sludge	Fertilizer
4	Yellow phosphorus recovery from incineration ash of sewage sludge	Incineration ash of sewage sludge	Yellow phosphorus

3.2.1 Carbonization of poultry manure

The reuse of phosphorus as fertilizer by carbonization of poultry manure has been devised, and such fertilizer has actually been commercialized. Thus, in this scenario, of the 222.8kt of phosphorus in livestock excreta, 21.2kt, which is half of the 42.3kt in poultry manure of broilers, was presumed to be subject to carbonization treatment for reuse as fertilizer.

The estimated results were that the amount of phosphorus recovered from 21.2kt of phosphorus in poultry manure is 14.7kt, that the cost of electric power required for the recovery is 3688 million yen, that the cost of drugs is 323 million yen, that the cost of fuel is 2436 million yen and that other raw material costs (water bill) are 158 million yen. Further, by reusing 14.7kt of phosphorus in poultry manure as fertilizer, phosphorus in poultry manure which had previously been directly reduced to soil, such as in ranches, to be used for growing feed, such as pasturage, decreases by 14.7kt and, at the same time, phosphorus originating from imported ammonium phosphate and wet phosphoric acid, which is used in fertilizer production, decreases by 14.7kt.

3.2.2. Phosphorus recovery from waste water by the HAP method

The amount of phosphorus contained in waste water discharged from human life activity is 57.4kt. Of this amount, 38.8kt of phosphorus is dispersed into the waters after water treatment, and 18.5kt of phosphorus is concentrated as sewage sludge. In this scenario, 10kt of phosphorus is recovered by the HAP method from the wastewater that was previously dispersed into the waters.

In order to recover 10kt of phosphorus from wastewater, it is necessary to treat 12.5kt of wastewater containing phosphorus by the HAP method, and 580 million yen of electric power and 2190 million yen of drugs are required for the recovery. On the other hand, by reusing 10kt of phosphorus recovered from wastewater as sewage sludge fertilizer, the demand for phosphorus in compound fertilizers which had been produced in the industrial sector decreases by 10kt.

3.2.3. Phosphorus recovery from sewage sludge by the Heatphos method

The amount of phosphorus which is input into sewage sludge by wastewater treatment is 18.5kt, of which 10.2kt is currently utilized as sludge fertilizer. However, because it is possible to recover phosphorus in a form called bio-phosphorus ore, in high concentrations as well as with characteristics quite similar to phosphorus ore, in this scenario, rather than reusing the recovered phosphorus as fertilizer, it is finally utilized as bio-phosphorus ore in products with high added value such as industrial dry phosphoric acid and various phosphorus compounds, in distinction to the conventional reuse as fertilizer, which is tolerant with respect to the concentrations of phosphorus and of contaminants.

Here, the scenario is presumed, with regard to the 18.5kt of phosphorus which is contained in the sludge, that the entire amount, including the phosphorus in the sludge which is currently being reused as fertilizer, is input to the process of recovery as bio-phosphorus ore by the Heatphos method. Presuming that using the recovered bio-phosphorus ore by blending with phosphorus ore which is conventionally used gives exactly the same performance as the phosphorus ore, dry phosphoric acid is considered to be produced by using phosphor ore blended with bio-phosphorus ore.

It is possible to recover 6.5kt of phosphorus from sewage sludge containing 18.5kg of phosphorus, and 1679 million yen of electric power and 3585 million yen of drugs are required for the recovery. By blending 6.5kt of phosphorus in bio-phosphorus ore with natural phosphorus ore to input to the production of wet phosphoric acid, the demand for phosphorus ore decreases by an amount corresponding to 6.5kt of phosphorus.

3.2.4. Yellow phosphorus recovery from incineration ash of sewage sludge

The scenario is presumed in which phosphorus is recovered in a state of high purity called yellow phosphorus by subjecting the entire 18.5kt of phosphorus in sewage sludge to the technique of incineration ash melting for utilization in the chemical industry sector. In actuality, not the entire amount of phosphorus contained in sewage sludge is transferred to incineration ash, but here it is assumed that the entire 18.5kt of phosphorus in sewage sludge is transferred and input to the incineration ash melting process.

It is possible to recover 12.6kt of yellow phosphorus from incineration ash of sewage sludge containing 18.5kg of phosphorus, and 3400 million yen of electric power and 435 million yen of fuel are required for the recovery. On the other hand, by inputting the recovered 12.6kt of yellow phosphorus into the chemical industry sector, the amount of input of other yellow phosphorus, that is the amount of import, decreases by an amount corresponding to 12.6kt of phosphorus.

3.3 Results

It was found that, by introducing the scenarios of carbonization of poultry manure and of treatment of waste water by the HAP method, the amount of import of phosphorus ore can be reduced by 6.3% (6.4t-P) and 4.3% (4.3t-P), respectively, when phosphorus is recovered and reused as raw material for fertilizer.

In recent years technologies have been developed for the recovery of high concentrations of phosphorus as bio-phosphorus ore and yellow phosphorus from sewage sludge, and their reuse in industrial fields as phosphorus products with high added value is expected. As a result of an analysis of the scenario, it was found that by recovering bio-phosphorus from sewage sludge using the Heatphos method, although the amount of import of phosphorus ore is reduced by 6.4% (6.5kt- P), the amount of production in the entire domestic industry by the introduction of the scenario increases by 7575 million yen, compared to the amount of 972 million yen which corresponds to the reduction in import of phosphorus ore.

With the scenario of recovering yellow phosphorus by melting and reduction of incineration ash from sewage sludge, the amount of import of yellow phosphorus can be reduced by 40% (12.6kt-P), the direct and indirect cost such as of electric power accompanying the recovery of yellow phosphorus is 3836 million yen and the amount of production in the entire domestic industry is 5991 million yen, and thus it may be said to be a very useful recovery technology and recycling scenario in view of the possibility of improvements in the recovery technology and the rise in prices of phosphorus resources.

Table Summary of the results

	Unit：t-P, million yen	Scenario 1	Scenario 2	Scenario 3	Scenario 4
		Carbonization of manure	HAP method	Heatphos method	Reduction and melting of ash
Phosphate rock	t-P	-6420.8	-4349.5	-6468.4	0.1
Phospatic fertilizer	t-P	-3.6	2.3	8.7	0.1
Compound fertilizer	t-P	-4.9	3.2	12.0	0.2
Wet phosphoric acid	t-P	-6240.3	-4227.2	8.6	0.1
Yellow phosphorus	t-P	0.0	0.0	0.1	-12584.5
Ammonium phosphate	t-P	-71.9	-48.7	0.1	0.0
Sewage/Sludge	t-P	0.0	10000.0	-3728.7	2378.4
Other inorganic chemistry product	t-P	153.8	1644.4	2766.9	0.9
Petroleum products	t-P	2238.8	55.1	185.4	524.5
Utility electricity	million yen	3835.6	625.1	1825.8	3555.6
Water supply	million yen	186.4	2.4	8.4	5.1
Industrial water	million yen	-1.9	2.0	7.3	0.4
Sewer	million yen	-0.7	1.8	6.7	1.4

4. Discussions and conclusions

Here we present the analytical tool to describe phosphorus flows and its requirement for our economic activities. The P flows and its cycle is not well known to the public and to policy makers. Furthermore, because of the complexity of the issue there is only limited knowledge about how to optimize the increasing need for food and energy crops. IPCIO was presented as a first step to describe how P flows and where we are wasting P resources. IPCIO can helps scientists, policy makers and decision makers in P contained waste treatment sectors better understand the complex manner in which P flows through our societies.

This paper clarified the P requirement of goods and services, and the effects of introduction of phosphorus recovery technology. One million yen of rice and beef production requires 5.89 and 115 times as much as its contained amount of phosphorus. Compared with P recycling scenarios, yellow phosphorus recovery from incineration ash of sewage sludge can reduce 40% of yellow phosphorus import while almost same amount of electricity is required as much as carbonization of poultry manure. In Japan, 100% of yellow phosphorus is imported and no facility to produce it, while yellow phosphorus could be used as a material of chemical compounds rather than fertilizer. For the diversity of resource procurement, this technology might be worthy of consideration.

Finally, we will have to collect data of phosphorus flows and inventory data for phosphorus recovery technology with higher accuracy. We selected the best scientific knowledge to provide the IPCIO database. However, several further developments are required in this direction, which will be addressed in future works.

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References

Goodlass, G., N. Halberg, et al. (2003). "Input output accounting systems in the European community - an appraisal of their usefulness in raising awareness of environmental problems." European Journal of Agronomy **20**(1-2): 17-24.

Li, B. X., Y. Z. He, et al. (2007). "Simultaneous determination of three organophosphorus pesticides residues in vegetables using continuous-flow chemiluminescence with artificial neural network calibration." Talanta **72**(1): 223-230.

Liu, Y., G. Villalba, et al. (2008). "Global phosphorus flows and environmental impacts from a consumption perspective." Journal of Industrial Ecology **12**(2): 229-247.

Matsubae-Yokoyama, K., H. Kubo, et al. (2010). "Recycling Effects of Residual Slag after Magnetic Separation for Phosphorus Recovery from Hot Metal Dephosphorization Slag." Isij International **50**(1): 65-70.

Matsubae-Yokoyama, K., H. Kubo, et al. (2009). "A Material Flow Analysis of Phosphorus in Japan." Journal of Industrial Ecology **13**(5): 687-705.

Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2008, Directory of fertilizer [hiryou youran][In Japanese]

Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2009a, Consumption and a safe office agricultural production safety control division, Pocket fertilizer survey, 2008, Association of Agriculture and Foresty Statistics

Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2009b, The food security division, Food balance sheet, 2008, Association of Agriculture and Foresty Statistics

Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF), 2009c, Statistics Department, Livestock raising, 2009, Association of Agriculture and Foresty Statistics

Ministry of Education, Culture, Sports, Science and Technology (MEXT), Food Composition Database, Tokyo, 2005 [In Japanese].

Ministry of Environment of Japan (MOE) <http://www.env.go.jp/recycle/waste_tech/ippan/index.html>, (17.8.2010)

Ministry of Internal Affairs and Communications (MIC), 2009, Input Output Table

Nakamura, S., K. Nakajima, et al. (2007). "The waste input-output approach to materials flow analysis - Concepts and application to base metals." Journal of Industrial Ecology **11**(4): 50-63.

Neset, T. S. S., H. P. Bader, et al. (2008). "The flow of phosphorus in food production and consumption - Linkoping, Sweden, 1870-2000." Science of the Total Environment **396**(2-3): 111-120.

US Geological Survey, (USGS) <http://minerals.usgs.gov/minerals/pubs/commodity/phosphate_rock/>, (Accessed 17.8.2010)

Vaccari, D. A. (2009). "Phosphorus: A Looming Crisis." Scientific American **300**(6): 54-59.