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Eco-Efficiency Assessment of Material Use: The Case of Phosphorus Fertilizer Usage in Japan's Rice Sector

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Abstract: To raise the eco-efficiency of the economy, it is important to not only investigate the eco-efficiency of specific products but also to ascertain whether the resources are used effectively throughout the life cycle. In this paper, we address eco-efficiency of agricultural use of phosphorus in Japan in the years 2005, 2010, and 2011. The increase in revenue from crops due to the use of phosphorus-based fertilizer is considered. The method used allows us to isolate the impact of a single nutrient and to convert this to a monetary value. For impact assessment of P resource use, we combine life-cycle inventory (LCI) data with LIME 2 (Life-cycle Impact Assessment Method based on Endpoint modeling) method. The most significant environment impact of the phosphorus chemical fertilizer life cycle is found to be on climate change by high chemical fertilizer. In 2005, provided service of phosphorus resource use was estimated as the highest while value added service of phosphorus increased, resulting in an uptick in eco-efficiency. During the study period, the lowest eco-efficiency of P resource use resulted in 2011. The results from this study, and the methods used, should be of great interest to industry, the research community, and policy makers concerned with resource efficiency.

Keywords: food; nutrient material flows; life cycle assessment; environmental impacts; fertilizer

1. Introduction

Modern agriculture is heavily dependent on phosphorus-based fertilizers, as phosphorus use improves productivity and contributes to food security. However, the production and use of phosphorus-based fertilizers place a significant burden on the environment, largely through eutrophication of water bodies, as leaching and surface runoff carry the phosphorus from the soil. Phosphorus is derived from phosphate rock, which is a nonrenewable resource. Current global reserves are estimated to have a life of 50–100 years [1]. Depletion and uneven distribution of phosphorus resources have prompted some countries to reconsider their role as a critical raw material. In response to resource constraints, population pressure, and the widespread environmental damage associated with current development patterns, the international community has sought ways of limiting the demand for resources.

Adding phosphorus brought into relation with complex energy transformations in the plant, to soil low in available phosphorus promotes root growth and winter hardiness, stimulates tillering, and often hastens maturity. Experts recommended using phosphorus as a row-applied starter fertilizer for increasing early growth. However, environmental impacts from usage of phosphorus fertilizer could not be negligible. Many studies have addressed environmental performance at a systematic level [2,3]. The resource efficiency and eco-efficiency of phosphorus production by a chemical company have been evaluated in China, which is rich in phosphorus rock [4]. However, it needs to carefully evaluate cosmetic effects of fertilizer application versus increased profits from yield increases from the perspective of environmental impacts by life cycle assessment. Nogi et al. (2016) evaluated the eco-efficiency of phosphorus-based fertilizer using price as a measure [5,6]. However, direct measurement of eco-efficiency using indicators such as crop yield has not yet been attempted at the national level in Japan, which is reliant on imported phosphate. This study focuses on the use of phosphorus and yield effect in rice production in Japan. Phosphorus has unique characteristics, including its essential place in human activities, its strategic role in the production of agricultural products, and its uneven global distribution. Japan has no extractable phosphorus reserves, making its more efficient use a key long-term goal for sustainable development.

In addition, to create a sustainable society, an efficient production and consumption life cycle is needed to reduce environmental impacts and limit resource depletion. Eco-efficiency is an important dimension of this, and is conventionally assessed as a quantitative tradeoff between negative environmental impacts, and in this case, the positive economic value of agricultural products. This relation is expressed as a ratio, facilitating comparison of competing strategies. However, eco-efficiency assessment needs to be extended from its current definition to include direct service indicators such as the service (added value) of each product. In this study, eco-efficiency is analyzed from a life cycle perspective, and the main indicator is defined as follows:

$$\text{Eco-efficiency} = \text{provided service by resource use (added value of resource use)/environmental impact of resource use.}$$

Here, the added value or provided service of the phosphorus resource use in fertilizers is the yield increase. We chose 2000, 2005, and 2011 as the study years since these are the most recent for which data are available. As a first step, we aim to develop an eco-efficiency indicator for the rice sector, as this is both a major crop and food staple in Japan, and is regarded as being at the heart of Japanese life and culture. The study has three main objectives:

(1) To quantify "service provided service by the phosphorus resource" as a chemical fertilizer,
(2) To quantify environmental impacts of chemical fertilizers through the full life cycle, and
(3) To assess the eco-efficiency of the phosphorus resource when used as a fertilizer.

2. Materials and Methods

In the assessment of eco-efficiency, the study followed the five assessment stages of ISO 14045, 2012 [7]: (i) Definition of Goals and Scope (covered by Section 1); (ii) Environmental Assessment; (iii) Value Assessment; (iv) Quantification of Eco-efficiency; and (v) Interpretation. The methodological details of each phase are given in the following sections.

2.1. Environmental Assessment

The environmental impact of phosphorus resource use in chemical fertilizers (JPY/kg P) was quantified using Multiple Interface Life Cycle Assessment (MiLCA), which is a life cycle assessment (LCA) support system which enables the researcher to make the basic calculation required for basic LCA, including inventory analysis and impact assessment. In addition, the inventory database for environmental analysis (IDEA) is included as a standard equipment. Original data source in MiLCA LCA software are made from Japanese and global statistics modeling of attributional approach of production process and industry associations. Final emission results are GHGs (Greenhouse Gas emissions) and about 50 elementary flows by using approximately embedded 3000 datasets [8].

The process by which environmental impacts were analyzed and the system boundaries are shown in Figure 1. When establishing the appropriate system boundaries for LCA, a "cradle-to-grave" approach was taken, starting from the extraction of the primary resource, phosphorus, to the point where the products leave the agricultural system. Figure 1 shows the upstream mining and production steps of phosphorus resource use and the downstream usage and outflow. The upstream environmental impacts of production of phosphorus fertilizer and the downstream impacts of phosphorus runoff to the hydrosphere must be summed to give the total impact. In this research, for evaluating environmental impacts, MiLCA software is mainly used. However, that software could not access downstream parts. Thus, handling downstream and upstream parts by respective detail methodologies is extremely important. Details will be explained in the following sections.

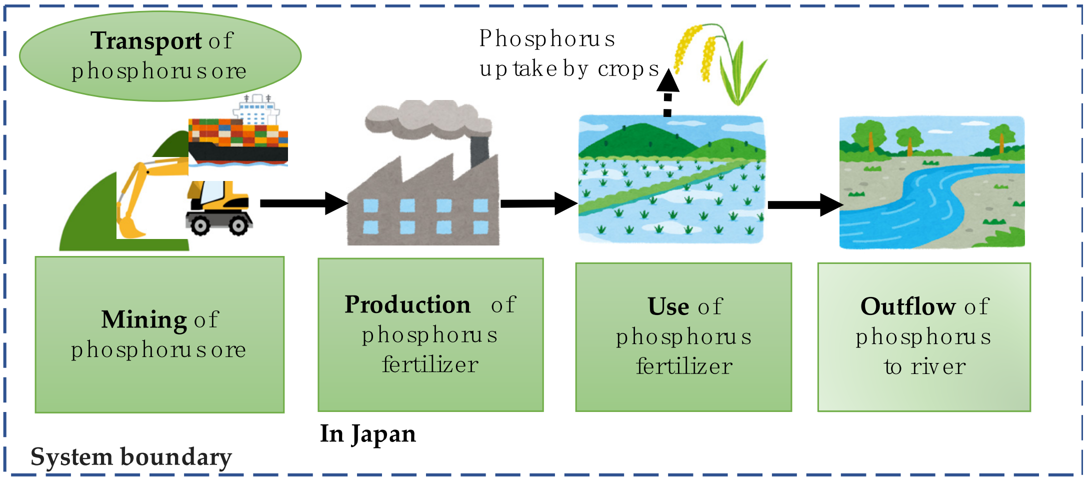

Figure 1. System boundary of life cycle of phosphorus resource used for chemical fertilizer.

2.1.1. Environmental Impact of Phosphorus Resource Use up to the Production Stage of Phosphorus Fertilizer

To take account of ore transport to Japan, the total travel distance from the main trading partners (China, Morocco, and South Africa) was weighted by the amount imported, using the following equation.

$$D_{i,j} = D_{actual\ distance,j} \times r_{i,j} \quad (1)$$

Here, $D_{i,j}$ is the total distance weighted by the imported quantity; $D_{actual\ distance,j}$ is the transport distance/sea route from country j to Japan, calculated using the Ecological Transport Information Tool for Worldwide Transports [9]; and $r_{i,j}$ is the ratio of phosphate ore imported to Japan [10]. The port locations in the exporting countries and in Japan were identified using a range of data sources including the World Port Rankings [11] and the Trade Statistics for Japan, broken down by prefecture [10]. More details on the distance calculations can be found in S note 1 in the Supporting Information: Final import and distance data for phosphate ore. The total calculated distance (7729 km) was entered into the MiLCA software to derive the environmental impact of producing 1 kg of phosphorus fertilizer (EP_e unit in JPY/kg P). This gave the environmental impact of phosphorus resource use up to the production stage of phosphorus fertilizer. Although in these calculations, more recent data were sometimes available (for example, the 2015 World Port Rankings), we used only 2010 data, for consistency with the base data of MiLCA.

2.1.2. Environmental Impacts of Phosphorus Runoff

For the third stage, the impact of the phosphorus fertilizer used in the field was estimated using Equation (2).

$$Q_{Pf} = EP_e \times Qu_{Pf} \quad (2)$$

Here, Q_{pf} is the quantity of phosphorus fertilizer used in the field, EP_e is the environmental impact from producing 1 kg of phosphorus fertilizer (JPY/kgP), and Qu_{Pf} is the quantity of phosphorus fertilizer used per kilogram of rice produced (kg P_f/kg Rice), obtained from the Inventory Database for Environmental Analysis (IDEA), which is the standard database for use with MiLCA LCA software [8].

When addressing the post-use system, an important question arose: How much phosphorus leaches from the soil from the input of a unit of phosphorus? Equation (3) was used to quantify the phosphorus run-off Q_{Pr} (kg P_r/kg P_f).

$$Q_{Pr} = \partial \times Q_{Pf} \times \frac{kg\ rice}{kg\ P_f} \quad (3)$$

where Q_{pf} stands for quantity of P-fertilizer used in the field (unit in kg Pf/kg Rice) and ∂ is a coefficient showing the share of phosphorus fertilizer applied to the field that will runoff to the environment. This is given as a percentage, but was calculated in kg P_r/kg P_f. Q_{Pf} was derived from Equation (2). The final parameter is the rice produced by application of 1 kg of phosphorus fertilizer (kg Rice/kg P_f) and was also derived from Equation (2).

The ∂ coefficient (ratio of phosphorus runoff from the field to the hydrosphere) was derived using the balance method of FAO [12]. Figure 2 is a diagram of substance flow and water flow in a paddy field. The input flows included phosphorus fertilizer, irrigation water, and rainwater, and the outflows included the phosphorus fertilizer taken up by the crops, surface water, and percolation water.

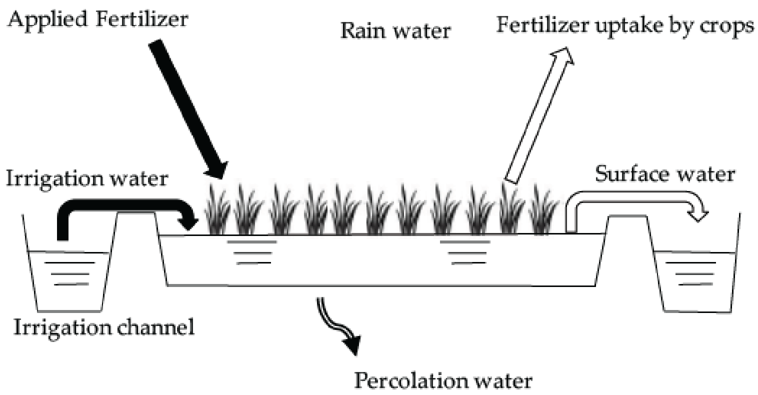

Figure 2. Substance and water flow in a paddy field (adapted from [13]).

For the final, post-use stage, the important question concerned the amount of phosphorus leachate produced by the input of a unit of phosphorus (kg P/ha). Phosphorus is one of the most important mineral nutrients used in agriculture, and as farming systems have increased, the concomitant increase in losses of phosphorus from agriculture land has had serious detrimental effects on water quality and the environment. However, after phosphorus is added to the soil in the form of fertilizer or manure, the large residue buildup may increase crop yields for a number of years. After taking this residual phosphorus into account, the amount of phosphorus in the runoff water was estimated using Equations (4)–(6). The data used in these equations were taken from a series of previous studies [13–18] to reflect Japanese agricultural practices and soil characteristics.

$$\partial = \frac{P_{outflow\ from\ the\ field\ to\ hydrosphere}}{P_{applied\ in\ the\ field}} \quad (4)$$

Here, $P_{outflow\ from\ the\ field\ to\ hydrosphere}$ is the total amount of outflow of phosphorus in surface water and percolation water to the hydrosphere (kg $P_{outflow}$/ha), and $P_{applied\ in\ the\ field}$ is the amount of phosphorous applied as chemical fertilizer in the field (kg $P_{fertilizer}$/ha).

$$P_{outflow\ from\ the\ field\ to\ hydrosphere} = P_{outflow\ of\ freshly\ applied\ P} - P_{outflow\ of\ residual\ P\ in\ the\ soil} \quad (5)$$

Here, $P_{outflow\ of\ freshly\ applied\ p}$ is the outflow from conventional application of phosphorus as chemical fertilizer in the field to the hydrosphere (kg $P_{outflow}$/ha), and $P_{outflow\ of\ residual\ p\ in\ the\ soil}$ is the outflow of residual phosphorus from the soil to the hydrosphere (kg $P_{outflow}$/ha).

$$P_{applied\ in\ the\ field} = P_{freshly\ applied} - P_{residual\ P\ in\ the\ soil} \tag{6}$$

Here, $P_{freshly\ applied}$ is the amount phosphorus in the chemical fertilizer applied in the field (kg $P_{fertilzier}$/ha) and $P_{residual\ P\ in\ the\ soil}$ is the amount of phosphorus accumulated in the soil (kg $P_{fertilzier}$/ha). In all of the above equations, a value of $\partial = 0.48\,\%$ is used. The derivation of this ratio is described in S_note 2 in the Supporting Information: Ratio of phosphorus runoff from the field to the hydrosphere.

Finally, the environmental impact associated with phosphorus runoff (EP_r in unit of JPY/kgP) is estimated using Equation (7).

$$EP_r = EuP_r \times QP_r \tag{7}$$

Here, EuP_r is the environmental impact produced by each kilogram of phosphorus runoff, and is obtained using LIME2, the impact assessment method associated with the IDEA database in the MiLCA LCA software (JPY/kg Pr) and QP_r is derived from Equation (3).

2.1.3. Environmental Impact of Phosphorus Resource Use in Chemicals

As described above, the goal is to estimate the total environmental impact of upstream phosphorus fertilizer production and downstream phosphorus runoff to the hydrosphere. Equation (8) was used to derive the total impact EP (JPY/kg-P).

$$EP = EP_e + EP_r \tag{8}$$

This research addressed the phosphorus content of four chemical fertilizers used in rice production: (A) calcium superphosphate; (B) fused phosphate fertilizer; (C) low chemical fertilizer, and (D) high chemical fertilizer. The A and B types contain mainly phosphorus (P), whereas the C and D types also contain calcium (K) and nitrogen (N). The amount of content of nutrients (%) in each type of fertilizer is shown in Table 1 [19].

Table 1. Amount of nutrient (%) in each type of fertilizer.

Nutrient Names		N	P_2O_5	K_2O
Chemical fertilizer	(A) Calcium super phosphate	-	17%	-
	(B) Fused phosphate fertilizer	-	20%	-
	(C) Low chemical fertilizer	8%	8%	5%
	(D)High chemical fertilizer	15%	15%	15%

Note: P_2O_5 stands for phosphorus pentoxide. This research focused only on P. Therefore, all data related to P_2O_5 were carefully converted by multiplying a conversion factor of 0.4364 to estimate % of P content in P_2O_5.

The environmental impacts from the four types were coded as EP_A, EP_B, EP_C, and EP_D, and their respective values were derived using Equations (1)–(8). The total environmental impact of phosphorus in the four types (JPY) was then estimated using Equation (9).

$$EP_P = \sum_{i=A}^{D} (EP_i \times A_i) \tag{9}$$

Here, A_i is the amount of fertilizer of type i consumed, given by the amount applied per hectare (kg P/ha) and the area of rice plantation (ha).

2.2. Value Assessment

The economic benefit of phosphorus resource use was derived using the total value added (TVA) or total provided service (JPY). This is the economic value added by applying phosphorus fertilizer and corresponds to the addition to net cash flow of all the different factors across the rice production sector. It was calculated using Equation (10).

$$TP_{rv}S = P_{rv}S \times P \tag{10}$$

Here, $P_{rv}S$ is the monetary value of the marginal increase in rice production from one unit of phosphorus (JPY/kg P), and is given by Equation (11).

P: Amount of phosphorus fertilizer for rice production sector (kg P) [19]

$$P = P_{ha} \times A \tag{11}$$

where P_{ha} is the amount of phosphorus fertilizer applied per hectare (kg P/ha) and A is the rice plantation area (ha). The $P_{rv}S$ (JPY/kg P) was derived from the increase in rice yield per unit of phosphorus ΔQ (kg rice/kg P) and the gross added value of the rice production sector V (JPY/kg rice), and was given by Equation (12).

$$PrvS = \Delta Q \times V \tag{12}$$

ΔQ: Increase in rice yield of by one unit of phosphorus (kg rice/kg P).

Based on previous studies [20–23], the increase in rice yield (ΔQ) was derived from the agronomic efficiency of the applied phosphorus nutrient, using Equation (13). In deriving the yield *(YN,P,K − YO/P)/FP*, $Y_{N,P,K}$ and $Y_{O/P}$ are the crop yields with and without the nutrient phosphorus, and F_P is the amount of phosphorus applied per field, all in kg ha^{-1}.

$$\Delta \mathrm{Q} = \frac{Y_P}{FP} = \frac{Y_{N,P,K} - Y_{O/P}}{FP} \tag{13}$$

More details on ΔQ can be found in S note 3 in the Supporting Information: Share of soil type by paddy field in Japan in 2007. In this paper, yield increase effect is taken as a direct service indicator of phosphorus resource use in the rice sector. Then, ΔQ is calculated by Equation (13). In this case, ΔQ value is calculated based on experimental results of literature reviews thinking of the same condition of agro-ecological resources (soil texture, terrain, and climate) but neglecting of making categories of varieties of rice.

Parameter V in Equation (12) is the gross value added per unit of rice produced (JPY/kg rice). This is the gross value added by Japan's rice sector, and was taken from the input/output tables of the Ministry of Internal Affairs and Communications [24].

The total value added by each of the four fertilizer types was derived using Equations (10)–(13) and the total provided value of phosphorus in the chemical fertilizers (JPY) using Equation (14).

$$(TPrvV)_P = \sum_{i=A}^{D} (TPrvV)_i \tag{14}$$

2.3. Eco-Efficiency Indicators

Eco-efficiency is the ratio between the value of the goods produced and the environmental impacts. The eco-efficiency of phosphorus resource use in the rice production sector (*Ecoeff.P_{rice}*) was estimated using Equation (15).

$$Ecoeff.P_{rice} = \frac{(TPrvV)_P}{EP_P} \tag{15}$$

3. Results and Discussion

3.1. Environmental Impacts of Phosphorus Production (JPY/kg P)

To quantify the environmental impacts of phosphorus resource use in fertilizers, we consider the impacts from the material inputs and those associated with energy use. Figure 3 shows the total environmental impacts for each type of fertilizer derived from MiLCA LCA software. Although Figure 3 identified seventeen categories of environmental impact as shown, it includes some small impacts which could be negligible since their environmental impacts are less than 0.001 JPY/kg-fertilizer: (1) Ozone depletion, (2) Ecotoxicity, water (3) Ecotoxicity, ground, (4) Indoor air pollution, (5) Human toxicity, water (6) Human toxicity, ground and (7) Noise.

As can be seen, the biggest environment impact category resulted by using four types of fertilizer is urban air pollution throughout the chemical fertilizer life cycle. The most significant environmental impact of the phosphorus chemical fertilizer life cycle is found to be on climate change by high chemical fertilizer.

As we described before, although Figure 3 shows 17 categories of environmental impact, out of this, seven categories give small impacts on environments. So, to be certain of the results in the most distinguished categories and to provide more details of the upstream and downstream parts of environmental impacts, Table 2 is provided. It can be seen clearly that urban air pollution following impacts on climate change and resources is the most important environmental impact resulted from the upstream part of phosphorus resource use and eutrophication is the most severe from the downstream part.

As basic data only exists for 2010 in the MiLCA database, the impact of phosphorus resource use is assumed to be the same in each of our study years (2000, 2005, and 2010). While the historical trend is important, this cannot be addressed using the MiLCA software, which is unable to process time-series data.

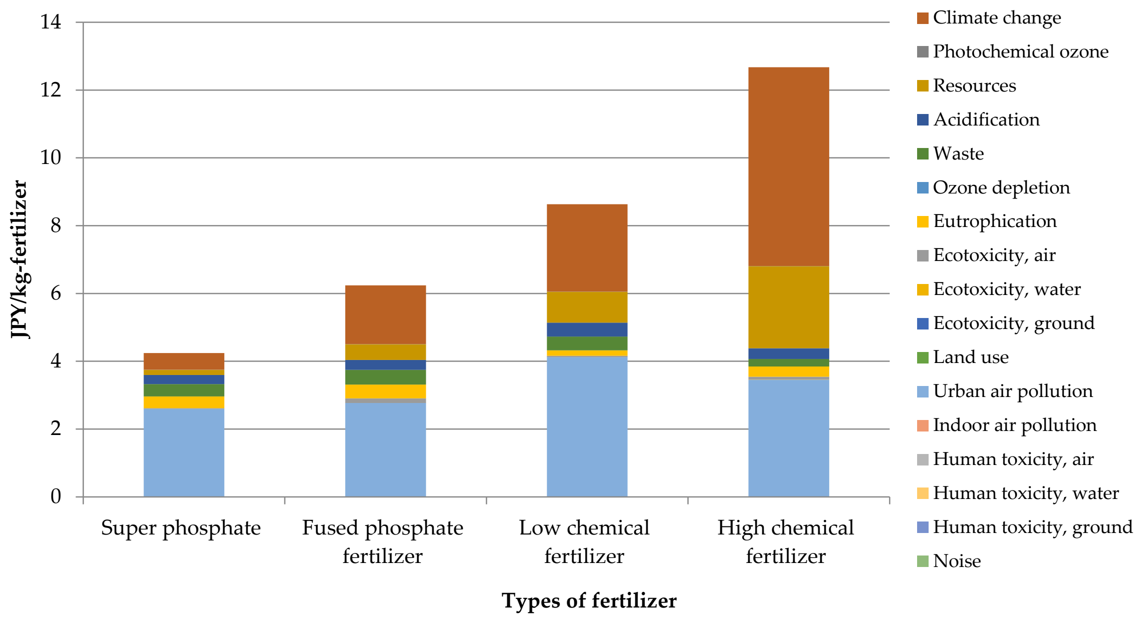

Figure 3. Environmental impacts of phosphorus resource use for each fertilizer type.

Table 2. Categories of environmental impacts of phosphorus resource use.

TOTAL Environmental Impacts of Phosphorus Resource Use (Unit in JPY/kg-Fertilizer)	Type of Fertilizer	All Impact Categories	Climate Change	Photo-Chemical Ozone	Resources	Acidification	Waste	Eutro-Phication	Eco-Toxicity, Air	Eco-Toxicity, Water	Urban Air Pollution	Human Toxicity, Air
Chemical P-fertilizer	Super phosphate	4.240	0.491	0.001	0.154	0.267	0.366	0.345	0.015	0.000	2.600	0.001
	Fused phosphate fertilizer	6.240	1.730	0.008	0.459	0.293	0.438	0.405	0.135	0.001	2.760	0.010
	Low chemical fertilizer	8.630	2.580	0.002	0.912	0.413	0.403	0.162	0.039	0.000	4.120	0.003
	High chemical fertilizer	12.700	5.860	0.005	2.420	0.319	0.223	0.300	0.088	0.000	3.450	0.007
Environmental impacts (Upstream part, unit in JPY/kg-fertilizer)												
Chemical P-fertilizer	Super phosphate	3.890	0.491	0.001	0.154	0.267	0.366	0.000	0.015	0.000	2.600	0.001
	Fused phosphate fertilizer	5.830	1.730	0.008	0.459	0.293	0.438	0.000	0.135	0.001	2.760	0.010
	Low chemical fertilizer	8.468	2.580	0.002	0.912	0.413	0.403	0.000	0.039	0.000	4.120	0.003
	High chemical fertilizer	12.400	5.860	0.005	2.420	0.319	0.223	0.000	0.088	0.000	3.450	0.007
Environmental impacts (Downstream part, unit in JPY/kg-fertilizer)												
Chemical P-fertilizer	Super phosphate	0.350	0.000	0.000	0.000	0.000	0.000	0.345	0.000	0.000	0.000	0.000
	Fused phosphate fertilizer	0.410	0.000	0.000	0.000	0.000	0.000	0.405	0.000	0.000	0.000	0.000
	Low chemical fertilizer	0.162	0.000	0.000	0.000	0.000	0.000	0.162	0.000	0.000	0.000	0.000
	High chemical fertilizer	0.300	0.000	0.000	0.000	0.000	0.000	0.300	0.000	0.000	0.000	0.000

3.2. Value of Phosphorus Resource Use (JPY/kg-P)

Figure 4 shows the added value of phosphorus use (monetary value of marginal increase in rice production from one unit of phosphorus by type of fertilizer). Assuming the rice yield to be constant unless increased by the addition of phosphorus, the marginal value of phosphorus resource use in the target years was highest in 2005. This can be interpreted as indicating that the gross value added for the rice sector (V in Equation (12)) was highest in 2005. This is discussed in the next section. In summary, the increase in rice yield from a unit of phosphorus in a chemical fertilizer is estimated to be in a linear relation with the gross added value of rice production.

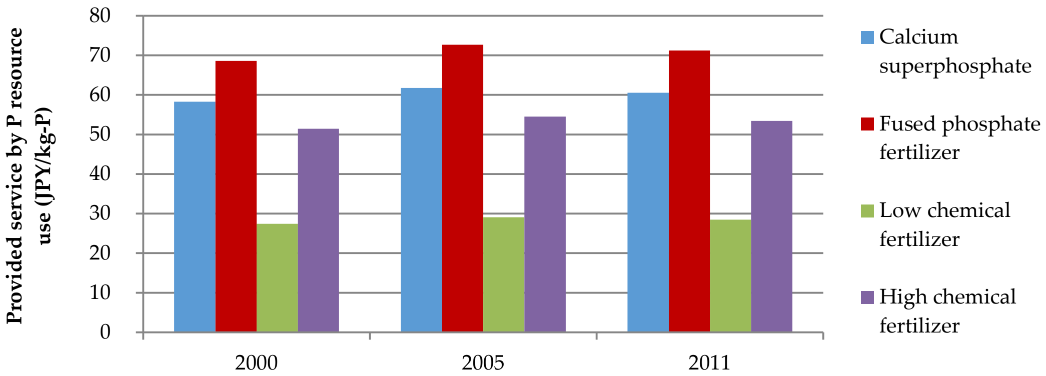

Figure 4. Provided service of phosphorus resource use in each type of fertilizer.

3.3. Eco-Efficiency of Phosphorus Resource Use

Figure 5 shows the eco-efficiency of phosphorus resource use. Assuming that the environmental impact does not change in the targeted years, this will reflect fluctuations in the gross added value per unit of rice and consumption of each chemical fertilizer in the rice sector. As the gross added value per unit of rice in the rice industry was significantly higher in 2005, as shown in Figure 4, the calculated eco-efficiency was also highest in that year.

Although the amount of phosphorus-based fertilizer used in rice production in Japan decreased, the value added by fertilizer increased between 2000 and 2005. This increased the eco-efficiency because the denominator is the monetized environmental impact, and this could not be varied due to the limitations of the MiLCA software. However, in 2011, the gross value added for the rice sector decreased slightly and the production of rice also decreased. As the decline in the gross value was much greater than that in rice production, eco-efficiency was lower in 2011.

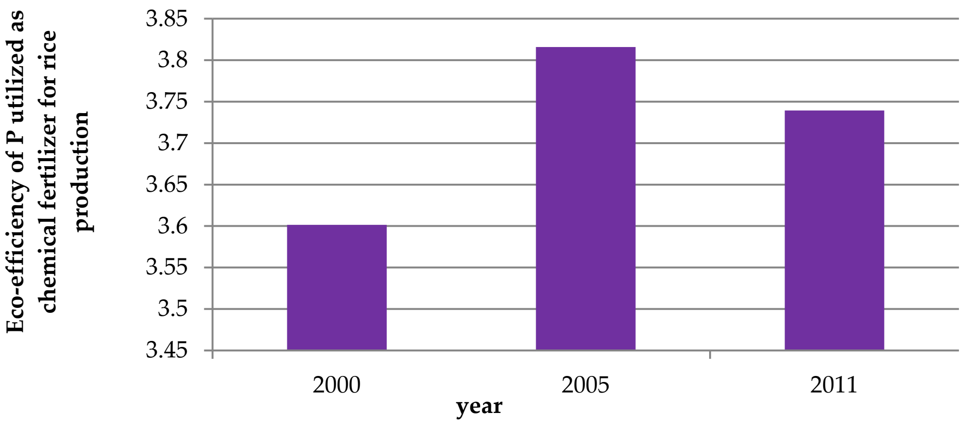

Figure 5. Eco-efficiency of phosphorus resource use in rice production.

3.4. Overall Eco-Efficiency

Eco-efficiency is affected by both the value of the rice produced and the consumption of phosphorus fertilizer. The added value (JPY/kg P) was associated with ΔQ (kg rice/kg P), V (gross value added per unit of rice production (JPY/kg rice), and consumption of phosphorus fertilizer (kg P/ha). ΔQ (change in rice yield by use of phosphorus) was constant in the targeted year. The two main factors that contributed to the decrease in eco-efficiency were as follows:

(1) Gross value added per unit of rice production (JPY/kg rice) and
(2) Consumption of phosphorus fertilizer (kg P/kg rice).

Figure 6a shows the provided service by phosphorus used in rice production. Here, $(TPrvV)_P$ (unit in JPY) is the total provided value from the phosphorus fertilizer applied per hectare (kg P/ha) and the area of rice planation (ha). Figure 6b shows the environmental impact of phosphorus use. Here, $(EP)_p$ is the total environmental impact of phosphorus fertilizer (JPY), based on the amount applied per hectare (kg P/ha) and the rice plantation area (ha).

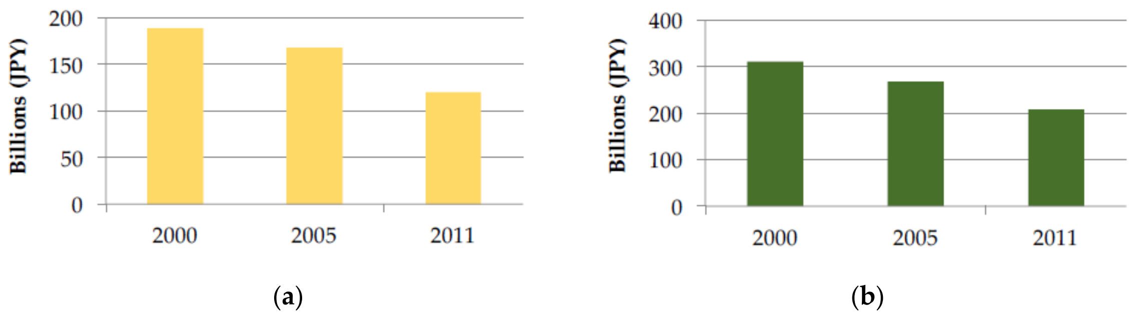

Figure 6. Provided service and environmental impact of phosphorus resource use. (**a**) Provided service by phosphorus resource use (JPY); (**b**) Environmental impact of phosphorus resource use (JPY).

The decline in the provided service was greater than that in the environmental impact. The decline in total value reflected a decrease in both the consumption of fertilizer and the gross value added for the rice sector in the target year. The decline in environmental impact reflected a decrease in the consumption of fertilizer in the target year.

3.5. Promoting Eco-Efficiency in Agriculture

Eco-efficiency can be promoted by decreasing the use of chemical fertilizer. One way of doing this is to speed-up the introduction of organic fertilizers. These are produced from organic waste using natural processes such as composting or vermicomposting. In Japan, organic fertilizers can be classified by their derivation from animal matter (fish meal, bone meal, dried blood, and other meal), vegetable matter (rape seed meal and soybean meal), organic waste (dried microbes and sewage sludge), and composting materials (cattle manure, swine manure, poultry manure, bark, sewage sludge, and urban refuse).

Japan is the country with the greatest use of chemicals in agriculture. A 2004 OECD survey reported that Japan's farmers use almost 16 kg of chemicals per hectare, whereas U.S. farmers use only 2 kg in rice plantations [25]. However, the Japanese government now sets strict limits on the use of fertilizers and pesticides, and organic produce is becoming more widespread. The use of organic fertilizers can improve the environment by making locally grown produce available to consumers and reducing the demand for imports of agricultural produce and the precursors of chemical fertilizers.

There are more than 30 million hectares of certified organic fields in the world. In Japan, the total area was less than 10,000 Ha in 2010, or 0.2% of the total arable land. In the same year, total production of organic foods in Japan was less than 60,000 tons, including 31,000 tons of vegetables and 11,000 tons of rice [26]. Clearly, Japan is unable to meet the demand for organic products, and promotion of organic farming is expected to increase eco-efficiency, while establishing more sustainable agriculture. However, the use of organic fertilizers will increase costs and the total provided service ($TP_{rv}S$) of organic fertilizers and their environmental impacts should be investigated. Due to limitations of time and data, this is left for future research.

One more possible method to reduce chemical fertilizer usage in agriculture sector is usage of bio-fertilizers or bio-organic fertilizers avoiding environmental pollution resulting from build-up of agrochemicals in soil and water and low nutrient uptake efficiency. This could allow farmers to use cheaper and more environmentally friendly fertilizers. Currently in Japan, bio-fertilizer is used mostly in Hokkaido but country wide usage is still in progress using bio-fertilizer projects and research. Although it is certain that the use of bio-fertilizer will reduce costs, evaluation of the total provided service ($TP_{rv}S$) of bio-fertilizers and systematic study of their environmental impacts could not be completed in this study due to time and data limitation. This has to be put aside as one of the possible scenarios for future study to promote eco-efficiency in agriculture for specific crops.

4. Conclusions

In this study, we evaluated the eco-efficiency of phosphorus resource use by considering the total value added based on crop yield and the life cycle environmental impacts. We concluded that the biggest environmental impact category was climate change through phosphorus resource use in fertilizer throughout the life cycle due to high chemical fertilizer. As an overall result, urban air pollution is the most severe of the environmental impacts due to four types of fertilizers in the upstream part of phosphorus resource use, and eutrophication is the worst impact in the downstream part. The total provided service in monetary value by phosphorus use in chemical fertilizers was highest in 2005 and the highest eco-efficiency was also found in that year. The main factors accounting for the decrease in eco-efficiency over the study period were a decrease in the gross value added by the rice sector and a fall in the consumption of phosphorus fertilizer.

This research aims to evaluate eco-efficiency for phosphorus resource use. That means that environmental impacts of phosphorus resource use only need to be explored. However, for production of phosphorus fertilizer, we need other resources such as fossil fuels and machinery (such as iron, steel, copper, etc.). Our current evaluated environmental impacts of phosphorus resource use in chemical fertilizer are combined with those of other resources used for producing the phosphorus in chemical fertilizer. In other words, our estimated results are environmental loads mixed with other resource use in the supply chain. As a future study, methodology for allocating environmental impacts produced by only phosphorus resource use should be developed although it will be a complex and challenging task.

There are many parameters used in this research playing specific and important roles. Since this is pioneer research, respective data are rare. Thus, we handle literature reviews for estimation of parameter values carefully, trying to avoid uncertainty as much as we could. However, even in MiLCA LCA software, uncertainty depends on the dataset. It is described that each dataset is evaluated by modified pedigree matrix. Thus, in future research, researchers must evaluate the factors driving eco-efficiency by using decomposition analysis. Sensitivity analysis should also be followed for the most sensitive parameters that are derived from decomposition analysis results. In addition, further research is needed to estimate the impacts of phosphorus accumulation in the soil in specific study years. The current study considered only four fertilizer types, due to limitations in data availability. In future research, this will be extended to cover all fertilizer types used in Japan. In addition, the environmental impacts of chemical fertilizers and organic fertilizers will be compared. The methods used in this will be applied to other nutrients, such as K and N, and research will also be extended to a wider range of crops.

Our results can support product development and improvement, strategic planning (budgeting and investment analysis), public policy making, marketing, green purchasing, and awareness raising. As an ultimate goal, the research is aimed to go to the level of eco-efficiency assessment of phosphorus resource use for all types of products and the method proposed in this paper can be applied to other resources by supporting policy analysis and allowing for an evaluation of measures such as optimizing the use of phosphorus resources, increasing the value of phosphorus use, and reducing the environmental impacts of phosphorus.

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