Weight of Land Use for Phosphorus Fertilizer Production in Japan in Terms of Total Material Requirement

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Abstract

The impact of land use for fertilizer production has been evaluated in terms of total material requirement (TMR) with a central focus on phosphorus fertilizers. Three different ammonium phosphates, calcium superphosphate, fused magnesium phosphate, magnesium multi-phosphate and high analysis compound fertilizer were selected as phosphorus fertilizers. For comparison, nitrogen fertilizers such as urea, nitrolime, ammonium sulfate and ammonium chloride, and potassic fertilizers such as potassium sulfate and potassium chloride were chosen as well. Two types of functional units were considered: one was 1 kilogram of the target fertilizer production and the other was 1 kilogram of phosphorus pentoxide (P_2O_5), nitrogen (N), and/or potassium oxide (K_2O). The system boundaries were set from mining to fertilizer production, and all the direct and indirect inputs were considered, along with hidden flows such as tailings and waste rocks. The TMRs of the fertilizers ranged from 5 to 23 kg/kg. It was found that the phosphorus fertilizers, excluding calcium superphosphate and fused magnesium phosphate, showed higher TMR than nitrogen or potassic fertilizers. The annual TMR with respect to fertilizer usage in Japan, which is defined as the product of the estimated TMR and amount of each fertilizer used in Japan in 2012, indicated that phosphorus fertilizers occupy about 69% of the total TMR, with high analysis compound fertilizer and ammonium phosphate in the majority. The TMR and life-cycle carbon dioxide ($LCCO_2$) were found to be different indicators. Case studies were examined in which improvements in phosphoric acid and sulfuric acid production were considered. Improvements in phosphoric acid production were found to be more effective at reducing the TMR of phosphorus fertilizers. Finally, the following equation was proposed for simple estimation of diverse phosphorus, nitrogen and potassium-based fertilizers:

$$TMR = 2 + 0.34\ [\%P_2O_5] + 0.15\ [\%N] + 0.098\ [\%K_2O]$$

Key words: nitrogen fertilizer, phosphoric acid, phosphorus fertilizer, potassic fertilizer, total material requirement

1. Introduction

Boosting crop productivity is an urgent concern for coping with population growth. Therefore, fertilizing to supplement three major nutrients (phosphorus, nitrogen, and potassium) is indispensable in modern day agriculture.

Among various fertilizers, chemical fertilizers are important not only as agricultural materials but also as industrial products. While the use of chemical fertilizers improves crop productivity, at the same time it requires energy and material inputs for its production, leading to various environmental impacts. Thus it is of great importance to sustainable agricultural industry to determine the environmental impacts at each production stage and to consider how to ameliorate them.

Koshino (1992) and Hakamata (1993) carried out life cycle energy (LCE) analyses for fertilizer production and distribution. Kobayashi and Sago (2001) examined LCE and life-cycle CO_2 ($LCCO_2$) analyses. These reports provided basic data for the application of life cycle assessment (LCA) to environmental measures for chemical fertilizers. Recently, by using LCA software such as SimaPro and MiLCA, the global warming potential of fertilizing can be easily evaluated further. Gathered data on inventories informs us that CO_2 emissions from fertilizer production have become dominant in crop production processes (Sonesson *et al.*, 2009; Koga *et al.*, 2006). Specifically, the environmental impacts of ammonia production and sulfuric acid production are high with regard to LCE and $LCCO_2$, respectively (Mitsuhashi *et al*., 2001; Kobayashi & Sago, 2001).

Among the various chemical fertilizers, phosphorus fertilizers have received a great deal of attention. Because the balance between the phosphorus supply and the demand has been delicate recently (Vaccari, 2011; Cordell *et al*., 2011), phosphorus security is globally significant. Phosphate deposits yielding high-grade ore, however, are disappearing, and the available deposits are expected to face exhaustion within the next hundred years (Abelson, 1999; Christen, 2007). In addition, there are essentially no deposits of phosphate ore in Japan or European countries. Therefore, Japan imports its entire phosphate ore reserves from China, South Africa, Morocco and Jordan (Matsubae *et al*., 2011). The USA ceased exporting phosphate ore in 1998. The total amount of phosphate ore imported by Japan halved between 1993 (1,400 kt) and 2008 (774 kt) (Trade Statistics of Japan, 2014).

Based on these points, Matsubae *et al*. proposed the concept of "virtual phosphorus ore" and evaluated the amount of phosphorus ore required for food production in Japan (Matsubae *et al*., 2011). The concept of virtual phosphorus ore is important because it can quantify the impact, unlike $LCCO_2$ analysis. Total material requirement (TMR) can be thought of as an extended concept of virtual phosphorus ore in terms of land use, since TMR includes not only the direct and indirect material flows upstream of the process, but also hidden material flows, such as overburden and waste rock (Wuppertal Institute, 2014; Adriaanse *et al*., 1997). For instance, for most phosphoric acid production, phosphate ore and sulfuric acid are used as primary inputs. The amount of land use relating to phosphate ore mining, which is regarded as a hidden flow, is equivalent to about 8.7 times the amount as phosphate ore itself (Kobayashi & Sago, 2001). Further, for the production of sulfuric acid, sulfur from crude oil desulfurization processes or as a by-product from copper smelting is generally used, indicating that both forms of sulfur production induce some hidden flows with regard to these mining activities. Thus TMR measures the physical basis of inputs in terms of primary materials and provides additional information on the environmental pressure associated with the land use. In other words, TMR relates the use of natural resources to the capacity of the environment to provide those materials by considering entire inputs (Adriaanse *et al*., 1997).

Although biomass materials are sometimes regarded as almost or completely "carbon neutral," based on current $LCCO_2$ evaluation criteria, the impact of deforestation or soil loss should not be ignored. Since many of the fertilizers consist of mineral components, they probably account for a great deal of land use, but no quantitative evaluation has been reported thus far.

Thus, the aims of the present study are to estimate TMRs of fertilizer production with a central focus on phosphorus fertilizers, and to evaluate the impact of fertilizer production on land use, differences among fertilizers, and their relationship with $LCCO_2$ analyses.

2. Methodology

2.1 Target fertilizers, system boundaries, and functional units

The target fertilizers in this study are listed in Table 1. As phosphorus fertilizers, three ammonium phosphates (12–50, 18–46, 19–42, [%N]–[%P_2O_5]), calcium superphosphate, fused magnesium phosphate, magnesium multi-phosphate and high analysis compound fertilizer (15–15–12, [%N]–[%P_2O_5] – [%K_2O]) were selected. For comparison, urea, nitrolime, ammonium sulfate and ammonium chloride as nitrogen fertilizers, and potassium sulfate and potassium chloride as potassic fertilizers were chosen as well. The above-mentioned phosphorus fertilizers accounted for 92.4% of the entire phosphorus fertilizer demand, by mass, in 2000 in Japan. The selected nitrogen and potassic fertilizers accounted for 88% and 87% of domestic demand, by mass, in 2007, respectively (Association of Agriculture-Forestry Statistics, 2013).

The functional unit was 1 kg of target fertilizer production. The system boundaries were set to include mining to fertilizer production with all the direct and indirect inputs, and hidden flows such as tailings and waste rocks were considered, while any treatments of tailings such as detoxification were regarded as being beyond the system boundaries. This is in accordance with the definition of

Table 1 Target fertilizers in this study.

	N (%)	P_2O_5 (%)	K_2O (%)	Annual productoin (t/y)
Ammonium phosphate (12-50)	12.0	50.0		391020
Ammonium phosphate (18-46)	18.0	46.0		
Ammonium phosphate (19-42)	19.0	42.0		
Calcium super-phosphate		17.0		65341
Fused magnesium phosphate		20.1		56938
Magnesium multi-phosphate		35.0		95322
High analysis compound fertilizer	15.0	15.0	12.0	789502
Urea	46.0			385541
Nitrolime	21.0			43146
Ammonium sulfate	21.1			590245
Ammonium chloride	25.0			71997
Potassium sulfate			54.1	86308
Potassium chloride			63.2	363676

material intensity by the Wuppertal Institute (2014), TMR by Halada (2012), and natural-ore TMR (NO−TMR) by the present study's authors (Yamasue *et al.*, 2009a; Yamasue *et al.*, 2009b; Yamasue *et al.*, 2013a; Yamasue *et al.*, 2013b). Where certain by-products were expected to be produced, shared inputs were allocated by the monetary ratio of those products.

Most chemical fertilizers consist of phosphorus, nitrogen and potassium, and their reduced contents P_2O_5, N and K_2O are involved in fertilizing. Therefore, as an additional functional unit, 1 kg of P_2O_5, N and K_2O were also considered. For multicomponent fertilizers, the weight ratio of each component was used for simple allocation, although fertilizer response depends on the existence of certain forms of phosphorus, nitrogen and potassium.

2.2 Detailed estimation methods and usage data

Figure 1 gives a fertilizer production process schematic with a central focus on phosphorus fertilizers. It should be noted that not all material inputs, energy inputs, detailed processes or by-products are shown. Nevertheless, the various processes have been found to be complexly interrelated.

For the estimation, two data sources were referred to basically for the required energy and material inputs, the Association of Agriculture-Forestry Statistics (2013) and Research Center for Life Cycle Assessment *et al.* (2014). The latter uses the IDEA ver. 1.1.0 database with MiLCA ver. 1.1.2.50 software. Price data for the allocation also utilized MiLCA. The details of material and energy inputs are shown in Table 2. Although this table shows only direct inputs for phosphorus fertilizer production, as many direct and indirect inputs and hidden flows as obtainable were actually considered. For instance, in the case of ammonium phosphate production, phosphoric acid is used as one of the direct inputs, and both phosphate rock and sulfuric acid are required for phosphoric acid production. They are regarded as indirect inputs for ammonium phosphate production. For the evaluation, the amount of waste rock behind phosphate ore mining activity was considered as a hidden flow.

The specific TMRs for electric power, heavy oil, crude oil, city gas and natural gas are reported to be 1.9 kg/kWh, 8.1 kg/L, 7.7 kg/L, 2.5 kg/Nm^3 and 1.3 kg/Nm^3, respectively (Nakajima *et al.*, 2006). Regarding phosphoric acid production, the authors reported a specific TMR value assuming that the total amount of hidden flow mined (overburden plus ore) was almost twice that of phosphate ore mined (Yamasue *et al.*, 2013a). From Kobayashi and Sago (2001), however, we realized that this value should be changed from 2 to 8.7. In addition, in our previous report, only the desulfurization process was considered for sulfuric acid production.

Thus, in this study, by-product sulfurous acid gas was also considered for sulfuric acid production, as described later. As a result, the specific TMR value of phosphoric acid was recalculated to be 29 kg/kg. It should be noted that this value assumes a phosphogypsum by-product. Hereafter, the estimation methods for specific TMRs of certain important raw materials will be described briefly.

For sulfuric acid production, only the contact process is currently used in Japan. As sources of sulfur, desulfurization of crude ore and sulfurous acid gas from copper and lead smelting are used. As a result, the specific TMR of sulfur from desulfurization processes (Research Center for Life Cycle Assessment *et al.*, 2007) was estimated to be 2.1 kg/kg and that of sulfurous acid gas from copper smelting (Narita *et al.*, 2001a, 2001b) was 13.5 kg/kg. In 2013, Japan produced about 6.35 million tons (t) of sulfuric acid, of which 78.6%, 18.8% and 2.5% were made from sulfurous acid gas, sulfur by desulfurization processes and other processes, respectively (Sulfuric Acid Association of Japan, 2014). By considering the weight

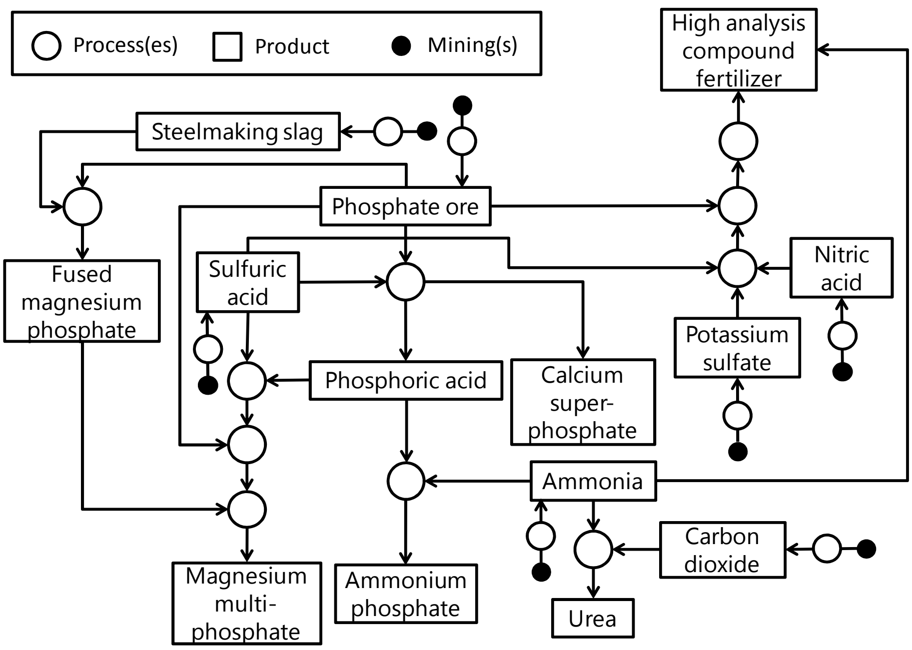

Fig. 1 Schematic diagram of the process flow for phosphate fertilizer production.

Table 2 Input energy and materials for phosphorous fertilizer production.

Calcium superphosphate					
Item	Material	Input	Unit	Output	Unit
Raw material	Sulfuric acid	360	kg		
	Phosphate ore	570	kg		
Product	Calcium super-phosphate			1000	kg
By-product	Sodium silicofluoride			4	kg

Fused magnesium phosphate (MiLCA)					
Item	Material	Input	Unit	Output	Unit
Raw material	Energy	3500	MJ/kg		
	Phosphate ore	500	kg		
	Steelmaking slag	500	kg		
Product	Fused magnesium phosphate			1000	kg

Ammonium phosphate (Pocket Hiryo Yoran)					
Item	Material	Input	Unit	Output	Unit
Raw material	Phosphoric acid	525	kg		
	Ammonia	165	kg		
Product	Ammonium phosphate (12-50)			690	kg

Ammonium phosphate (Pocket Hiryo Yoran)					
Item	Material	Input	Unit	Output	Unit
Raw material	Phosphoric acid	475	kg		
	Ammonia	240	kg		
Product	Ammonium phosphate (18-46)			715	kg

Ammonium phosphate (MiLCA)					
Item	Material	Input	Unit	Output	Unit
Raw material	Ammonia	0.244	kg		
	Sulfuric acid	0.102	kg		
	Hydrofluoric acid (50 %)	0.573	kg		
	Electricity	0.03	kWh		
	Crude oil	0.26	kg		
Product	Ammonium phosphate (19-42)			1	kg

Magnesium multi-phosphate					
Item	Material	Input	Unit	Output	Unit
Raw mamterial	Sulfuric acid	35	kg		
	Phosphate ore	135	kg		
	Phosphoric acid	240	kg		
	Fused magnesium phosphate	220	kg		
	Magnesia-based minerals (olivine, etc)	250	kg		
	Heavy oil	18	L		
Product	Magnesium multi-phosphate			1000	kg

Fused magnesium phosphate (Pocket Hiryo Yoran 2009)					
Item	Material	Input	Unit	Output	Unit
Raw material	Electricity	1000	kWh		
	Phosphate ore	650	kg		
	Steelmaking slag	530			
Product	Fused magnesium phosphate			1000	kg

Fused magnesium phosphate (Pocket Hiryo Yoran 2009)					
Item	Material	Input	Unit	Output	Unit
Raw material	Heavy oil	180	L		
	Phosphate ore	650	kg		
	Steelmaking slag	530			
Product	Fused magnesium phosphate			1000	kg

High analysis compound fertilizer (15-15-12)					
Item	Material	Input	Unit	Output	Unit
Raw mamterial	Potassium sulfate	260	kg		
	Sulfuric acid	80	kg		
	Nitric acid	465	kg		
	Phosphate ore	470	kg		
	Ammonia	80	kg		
	High analysis compound fertilizer			1000	kg
	Gypsum			350	kg

ratio of each process (except for the "other processes"), the specific TMR of sulfuric acid was estimated to be 4.8 kg/kg.

Although sulfurous acid gas is also produced from lead and other nonferrous metal smelting processes, only copper smelting was considered in this study.

The Haber–Bosch process is generally used to produce ammonia from nitrogen in the air. In this study, JEMAI-LCA Pro, Option data pack (Research Center for Life Cycle Assessment *et al*., 2007), MiLCA, Pocket Hiryo Yoran (Association of Agriculture-Forestry Statistics, 2013) and a report by Kobayashi and Sago (2001) were used as data sources. As a result, the specific TMR of ammonia ranged from 3.0 to 4.5 kg/kg, and we employed 4.5 kg/kg in this study.

The database from MiLCA is available for the estimation of urea, which is produced from ammonia and the carbon dioxide by-product from ammonia production. The specific TMR of the carbon dioxide by-product was estimated to be 1.8 kg/kg and the specific TMR of urea was estimated to be 4.8 kg/kg.

3. Results

Figure 2 shows the estimated TMRs of various fertilizers, with the functional unit considered to be 1 kg of fertilizer production. The estimated TMR values vary widely. The phosphorus fertilizers, excluding calcium superphosphate and fused magnesium phosphate, show higher TMRs than nitrogen and potassic fertilizers.

The three ammonium phosphates with different compositions show the highest TMRs among all the fertilizers. Although there are two methods for producing fused magnesium phosphate, the electric furnace method and fuel method, the estimated TMRs were similar: 8.1 kg/kg and 7.7 kg/kg, respectively. In the figure, the mean value of 7.9 kg/kg was used. Among nitrogen fertilizers, the TMR of nitrolime was remarkably high.

The TMRs of fertilizers range from 5 to 23 kg/kg, which are close to TMRs of common metals such as steel (8 kg/kg), lead (30 kg/kg), zinc (40 kg/kg), and aluminum (50 kg/kg) (Halada, 2012). Phosphorus, nitrogen and potassium are relatively common elements and, therefore, the TMRs of these fertilizers accordingly have similar values to those of common metals.

Figure 3 shows the results of changing the functional unit to 1 kg of P_2O_5, N and/or K_2O. Excluding nitrolime, the TMRs of phosphorus fertilizers are higher compared to other fertilizers. Interestingly, the variation among TMRs of phosphorus fertilizers is only slight as compared to that of nitrogen fertilizers. This could be due to the TMR of phosphate ore being dominant for all phosphorus fertilizer. The higher value of nitrolime is due not only to lime and coke with higher specific TMRs, but also the large amount of electric power input.

Figure 4 presents the product of estimated TMR and each amount of fertilizer used in Japan in 2012. The total value (2.8×10^7 TMR-t) can be regarded as the annual TMR with respect to fertilizer usage in Japan. It should be noted that although not all fertilizers used in Japan are produced in Japan, all of those fertilizers are assumed to be produced in Japan. These data suggest that phosphorus fertilizers, including compound fertilizers, occupy about 69% of the total TMR, with high analysis compound fertilizer and ammonium phosphate in the majority. The annual TMR per capita is calculated to be 220 TMR-kg.

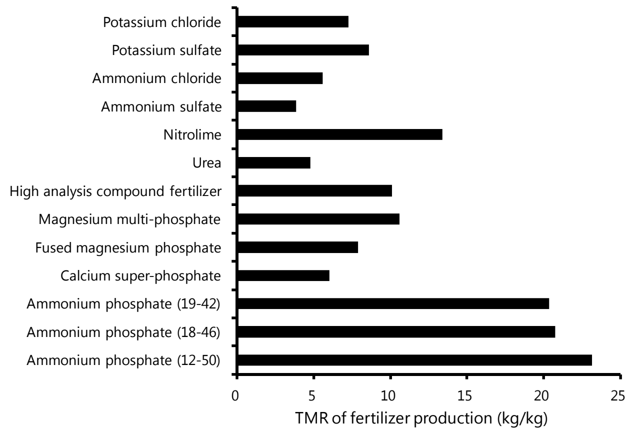

Fig. 2 TMRs for 1 kg of fertilizer production.

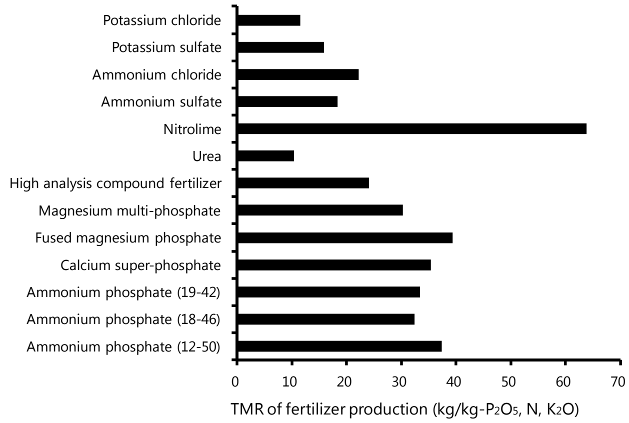

Fig. 3 TMRs of fertilizer production per kg of P_2O_5, N or K_2O.

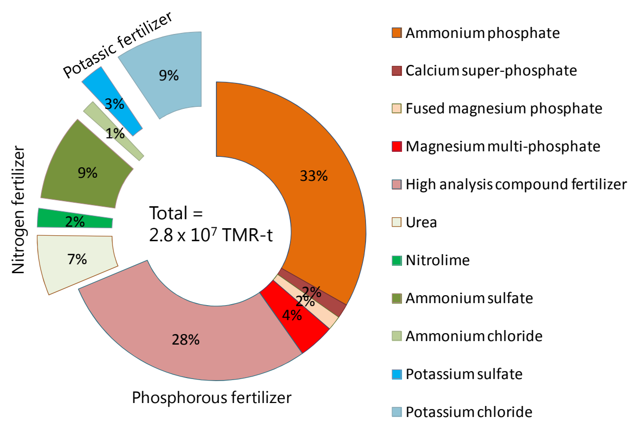

Fig. 4 Annual TMR of fertilizer production in Japan in 2012.

4. Discussion

4.1 Effects of data accuracy and variation

In the literature from Pocket Hiryo Yoran (Association of Agriculture-Forestry Statistics, 2013), energy consumption for ore pulverization and concentration, and plant environmental conditions such as air conditioning and illumination were not mentioned for some fertilizers. Energy and fuel consumption other than raw material production and heating processes for ammonium sulfate production, however, occupy about 4% in terms of TMR. In the cases of urea and ammonium phosphate, we found them to be 9% and 1%, respectively. Thus, it can be said that such underestimation does not influence the essence of this discussion.

As described previously, the specific TMR for ammonia varied from 3.0–4.5 kg/kg, and we employed 4.5 kg/kg in this study. Ammonia is also an important raw material for phosphorus fertilizers. When 3.0 kg/kg is used as the specific TMR of ammonia, the TMR of ammonium chloride shows the highest difference (–8%) and those of other fertilizers are −2%–0%. Thus, the variation in TMR for ammonia does not have a significant influence on the outcome either.

4.2 Comparison with $LCCO_2$ analysis

In this section, the relationship between the land use evaluation in terms of TMR in this study and the evaluation in terms of $LCCO_2$ will be discussed. Mitsuhashi *et al.* carried out $LCCO_2$ for various fertilizers using the same system boundary as this study (Mitsuhashi *et al.*, 2001). Figures 5 and 6 compare the results when the functional unit is 1 kg of fertilizer production and 1 kg of P_2O_5, N, and/or K_2O, respectively.

Compound fertilizers are also regarded as phosphorus fertilizers in these figures. Since no compositional information for ammonium phosphate was mentioned in the report, we use the same value for the three ammonium phosphates. It should also be noted that no allocation manner was mentioned in their report either.

No significant relationship can be seen between the results of TMR and $LCCO_2$. Although there might be a rough linearity in Fig. 6, when we look at phosphorus, nitrogen and potassic group separately, there seems to be no interrelation. The reason may be that the effect of land use is greater than energy for fertilizer production, although TMR considers not only land use but also energy consumption. In the case of ammonium phosphate (19–42), the TMR ascribed to energy consumption for heating in the production stage accounts for about 10% of the total. In the cases of fused magnesium phosphate and magnesium multiphosphate, the ratios are 20%–25% and 1%, respectively, indicating that energy factors are not dominant. Further, the direct energy inputs for the production of sulfuric acid and phosphoric acid are approximately 1%. In the case of ammonia, the ratio was somewhat higher, *i.e.*, 30%. Thus, TMR and $LCCO_2$ are essentially different indicators and should be evaluated individually.

4.3 Effective fertilizer production in terms of TMR

Based on the above understanding, this section will discuss effective fertilizer production in terms of TMR. Mitsuhashi *et al*. clarified that the impact of sulfuric acid production is high in terms of $LCCO_2$, and therefore the reduction in CO_2 from sulfuric acid production would be a key issue for the entire chemical fertilizer industry (Mitsuhashi *et al*., 2001). On the other hand, it is clear that phosphorus fertilizers show higher TMRs than the others and this is because the specific TMR of phosphoric acid (29 kg/kg) used in many phosphorus fertilizer is considerably higher than those of other raw materials such as ammonia (3.0–4.5 kg/kg) and sulfuric acid (4.8 kg/kg). In our previous report, steelmaking slag had sufficient potential as an alternative source of phosphorus products (Yamasue *et al*., 2013a). Based on this report, the specific TMR of phosphoric acid production can be reduced from 29 to 13.2 kg/kg by just using steelmaking slag alternatively as the phosphorus source. Further, for the production of phosphoric acid, a large amount of sulfuric acid is required. Thus, reduction of the specific TMR of sulfuric acid indirectly contributes to the reduction of the specific TMR of phosphoric acid. When all the sulfuric acid is assumed to be produced using only sulfur from the crude oil desulfurization process, the specific TMR of sulfuric acid is reduced to 2.9 kg/kg and consequently, the specific TMR of phosphoric acid is 26.8 kg/kg. Therefore, the following four cases are considered:

- Case 1: Current phosphoric acid and sulfuric acid production (default case).
- Case 2: Phosphoric acid produced from steelmaking slag (the specific TMR of phosphoric acid is reduced from 29 to 13.2 kg/kg).
- Case 3: Improvements in sulfuric acid production (the specific TMR of sulfuric acid is reduced from 4.8 to 2.9 kg and that of phosphoric acid production from 29 to 26.8 kg/kg).
- Case 4: Combination of cases 2 and 3 (the specific TMR of sulfuric acid is reduced from 4.8 to 2.9 kg and that of phosphoric acid production from 29 to 10 kg/kg)

Since calcium superphosphate and fused magnesium phosphate production do not use phosphoric acid but make direct use of phosphate ore, it is assumed that an equivalent amount of steelmaking slag with P_2O_5 in phosphate ore is used.

Figure 7 shows the results of our estimation. Notable reduction is seen for ammonium phosphates and magne-

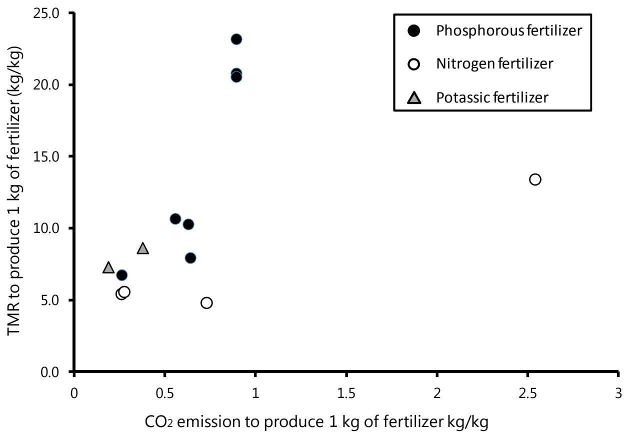

Fig. 5 The relationship between the TMR per kg of fertilizer produced and the CO_2 emissions per kg of fertilizer produced.

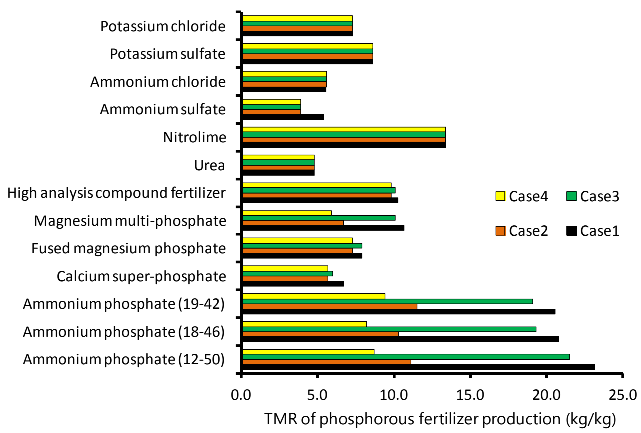

Fig. 7 Reduction in TMR when improvements in phosphoric acid and sulfuric acid are considered.

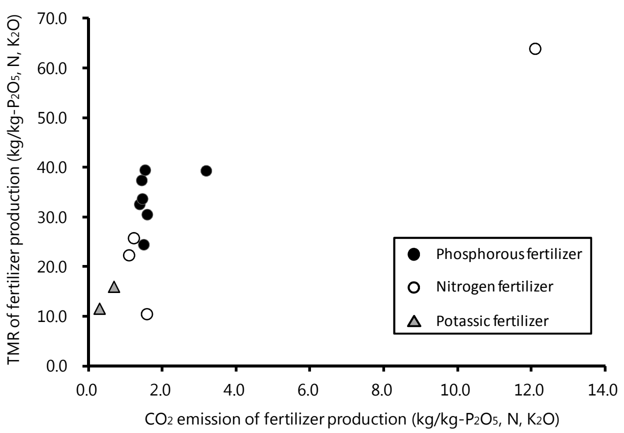

Fig. 6 The relationship between fertilizer production TMRs for 1 kg of P_2O_5, N and/or K_2O and their CO_2 emissions.

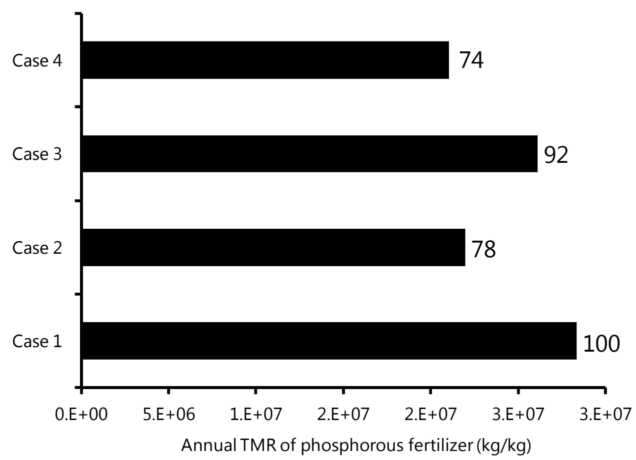

Fig. 8 Effect of improvements in phosphoric acid and sulfuric acid on the annual TMR.

sium multiphosphate because they use phosphoric acid directly in production. Although the improvement in sulfuric acid production is also effective, that in phosphoric acid production is more effective. Figure 8 shows the annual TMR for each case using the same method as in Fig. 4. Improvements in phosphoric acid production and sulfuric acid production, and their combination reduce the annual TMR by 22%, 8%, and 26%, respectively, compared with the default case.

As can be easily guessed, certain assumptions were made in estimating the specific TMR of phosphoric acid production from steelmaking slag (Yamasue *et al.*, 2013a). The value of 13.2 kg/kg used in the previous discussion was estimated assuming that phosphogypsum and phosphoric acid were recycled from the slag. If the only thing being recycled were phosphoric acid or if the residue remaining after the recycling of phosphogypsum and phosphoric acid were also originally being recycled by recharging it into a blast furnace, the values would increase to 29.4 kg/kg or 7.6 kg/kg, respectively. In the former case, no significant effect would be seen even using steelmaking slag and in the latter case, further effect could be attained.

Besides steelmaking slag, other phosphorus containing waste materials, including incinerator sludge ash or MBM (meat and bone meal) ash could provide a potential alternative as secondary phosphorus resources. Some of these biological resources have been recycled and their technological and economic feasibilities are well known. It should be noted, however, that steelmaking slag could provide good properties as a secondary phosphorus resource in that it is free of naturally occurring radioactive materials (NORMs) and heavy metals. Comparison of these secondary phosphorus resources is also important and will be an issue for future study.

4.4 Estimation of TMR from P_2O_5, N and K_2O content

Various chemical fertilizers are used in addition to the above-mentioned fertilizers. It is not realistic to estimate the TMR for each. Therefore, a simplified estimation method from P_2O_5, N, and K_2O contents will be considered in this section. Using the estimated TMR in this study, a multiple regression analysis was applied, where the contents of P_2O_5, N and K_2O were used as explanatory variables. As a result, the following equation was obtained with a 0.78 coefficient of determination (R^2).

$$\mathrm{TMR} = 2 + 0.34\,[P_2O_5] + 0.15\,[N] + 0.098\,[K_2O]$$

A comparison between the TMR calculated from this equation and the estimated TMR is shown in Fig. 9. A rough linearity is seen ($R^2 = 0.75$). A larger deviation downwards is seen for nitrolime. This is because, although nitrolime contains calcium as a valuable component, which requires larger amounts of materials and energy inputs, the above equation considers only P_2O_5, N, and K_2O. Thus, the above equation is applicable to phosphorus, nitrogen, and potassium-based fertilizers.

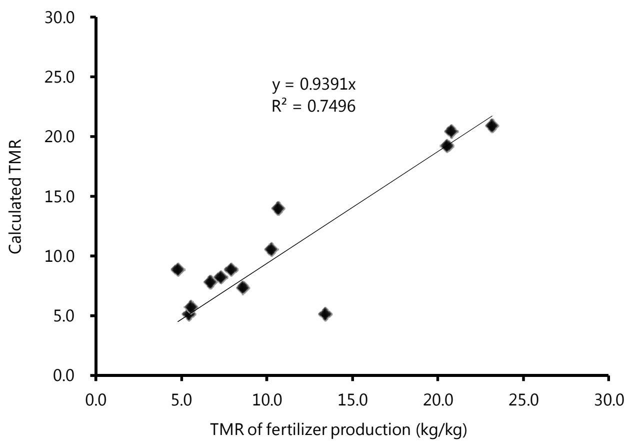

Fig. 9 The relationship between the calculated TMR using the proposed equation and the estimated TMR.

5. Conclusion

In this study, the TMRs for the production of phosphorus, nitrogen and potassic fertilizers were estimated to evaluate the land use of fertilizer production. From the results presented here, one of the key issues for phosphorus fertilizer production is reduction of the TMR of phosphoric acid production. A possible solution is to utilize steelmaking slag instead of phosphate ore. Further factors, such as the impact of imported fertilizer, utilization of organic fertilizers like compost and reaction efficiency in fertilizer production, must also be considered, and this will be addressed in future research.

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