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論 文 内 容 要 旨

The potential for advances to be made with regard to phosphorus resource efficiency in Asia has been evaluated by the close examination of the international trade in phosphorus, the virtual phosphorus demand in the China, India and Japan, and by careful consideration of how the phosphorus in the steelmaking slags of these countries can contribute to phosphorus resource efficiency. While the trend in recent years has been to focus on the risk humanity faces as phosphate rock goes into a cycle of depletion and to debate whether or not this is actually an imminent threat, this study takes the view that recovering and recycling phosphorus in the waste stream allows for better nutrient management, and makes good sense over the long term, regardless of the state of the reserves.

Whereas phosphorus came to be seen mostly as a pollutant in the mid-to-late twentieth century, it is now being given the attention it deserves, as a valuable resource which needs to be managed well to avoid unnecessary losses and reduce dependency on imports of phosphorus to nourish the crops which sustain the population. As the phosphorus content of iron ore inevitably increases, and because modern steelworks

include a dephosphorization step, a unique opportunity is presented to countries which produce steel to recover and recycle that phosphorus. The potential of this recovered phosphorus to contribute to the phosphorus demand in China, India and Japan is examined in this thesis, in the light of the phosphorus dependency for all Asian countries, and the changing diets and populations of those three countries as we approach 2030.

The task of phosphorus sustainability has been taken up in earnest in Europe, North America and Australia in particular, while there are comparatively few initiatives in Asia, Latin America, the Middle East and Africa. As much as 80% of the phosphate rock suitable for exploitation is found in just five countries, and the geopolitical risks associated with dependency on supply from these countries are considerable. Considering that phosphorus was the secret ingredient of the Green Revolution, which has given us confidence that we can feed the world's population as it soars towards the 10 billion mark, the importance of ensuring that each and every country has a ready supply of phosphorus to produce the crops which sustain humanity cannot be underscored. In this study, the concept of virtual phosphorus is used to extrapolate the demand for phosphorus to provide food for the populations of China, India and Japan, considering the likelihood of continued change in the diets of the two emerging countries as their people become more affluent.

The enormous demand for steel in emerging countries to construct the infrastructure and feed the building boom means that emerging countries inevitably establish their own steelworks to meet that demand. In this thesis, the potential for those steelworks to be producers of steel and also phosphorus is considered closely. With high-grade iron ore in depletion, the amount of phosphorus in the ore is increasing, and removal of this phosphorus is standard practice in modern steelmaking procedures. By employing a dephosphorization step, the steelmakers are producing a slag rich in P2O5 which can be separated and recycled in the chemical and fertilizer industries. Another benefit is that the ferric residue can be fed back into the iron-making process, reducing the

demand for iron ore. The technologies for phosphorus separation are developing to the extent that the day when steelmakers produce both steel for infrastructure and the phosphorus vital for food production is eagerly anticipated. This would break dependency on imports and contribute to industry's role in realizing a fully recycling society. This will contribute to a lessening of waste and pollution, and to sustainability in industry.

In Chapter 2, the extent to which the various nations of Asia depend on imports to meet their domestic demand for phosphorus is examined closely. A material flow analysis tracing the path that phosphorus travels once leaving its source, whether as phosphate rock, yellow phosphorus, iron ore, or as phosphate fertilizer, is carried out to determine the risks in the supply chain. The extent of dependency on one or just a few sources of phosphorus was determined, and the risks associated with that dependency are discussed. Considering the potential for instability in the countries with sizeable phosphate reserves, the geopolitical risks of depending on imports of phosphate rock are discussed along with other risks which may compromise the ability to secure the phosphorus the nation needs to meet domestic demand. In Asia, the risk that China will cease its exports of phosphate rock and engage only in the export of fertilizer equate to higher prices borne, ultimately, by the general public. Rising food prices present a significant risk of instability, as discussed in the light of the 2008 food riots which followed the commodity price hike, where phosphate rock commodity prices saw a fivefold increase.

Chapter 3 highlights the importance of ensuring a ready supply of phosphorus is available to each and every country to produce the food necessary to feed the populations of those countries. By focusing on the diets of China, India and Japan, the consumption of phosphorus in the food supply is calculated over a period of time and then extrapolated to 2050. It was assumed that the diets of the populations in China and India will continue to change over time with increasing affluence, but not exceed the dietary behavior of the Japanese during the 1980s and 1990s with regard to

demand for animal protein. The amount of phosphorus required to produce the food consumed was calculated using the concept of "virtual phosphorus". This data is then extrapolated to provide a realistic projection of how much phosphorus will be required to produce food to feed the populations in these three countries. The importance of securing sufficient phosphorus for use on croplands to food security is highlighted in this study. Also, the disproportionate requirement for phosphorus to produce animal-based foods is highlighted, with India's largely vegetarian population requiring significantly less phosphorus per capita than their Chinese and Japanese counterparts.

In Chapter 4, the potential for the phosphorus in the steelmaking slags to contribute to a nation's phosphorus portfolio was examined. The amount of phosphorus that has been wasted in the steelmaking slags in China, India and Japan was calculated considering the amount of steel output in each country over a period of 32 years, from 1980 to 2012. The potential for the phosphorus in the waste stream of the steel industry to be recovered and recycled domestically was presented from the perspective of the technology for phosphorus recovery which has been presented in the academic literature. The strengths and weaknesses of the technologies developed to date are presented considering the effectiveness of the technique, the cost of establishing the necessary infrastructure, the energy costs, and the issue of waste. The necessity of for further developments in technology capable for use in large-scale steel producing facilities is highlighted. The opportunity for steelmakers to reduce waste, and engage in practices that would provide the nation with a domestic supply of phosphorus, and thus reduce the risk associated with phosphate rock imports, is clear from the analysis in Chapter 4. At a more detailed level, the potential for the steelmaking industry to contribute significantly to the virtual phosphorus demand for producing plant based foods, as determined in Chapter 3, is estimated. These results indicate that the steelmakers of China, India and Japan have the potential to contribute a large percentage of the phosphorus required for crop production in those countries. In China this would lessen any concern that phosphate rock has to be preserved for domestic consumption, and in India and Japan, which have no phosphate reserves and

are entirely dependent on phosphorus imports, a ready domestic supply of phosphorus would be provided for use in domestic industry, and ultimately in the production of food. The lessening of dependence evaluated in Chapter 2 would strengthen the nations' security profile by lessening the potential impact of disruptions to supply from phosphorus exporting countries.

In Chapter 5, the anticipated concerns of the stakeholders and how they can be addressed is discussed. While this chapter is focused largely on the concerns of the stakeholders in Japan, the lessons and considerations are considered likely to apply to China and India, and to any other future emerging economy that would be presented with the opportunity to produce phosphorus for domestic consumption as a byproduct of the production of steel. The steelmaking industry, the fertilizer industry, the farmers and the general public, as the consumers of agricultural produce, all would foreseeably hesitate before accepting a change from the business-as-usual phosphors supply system to a system which utilizes domestically recovered phosphorus from steelmaking slag. The stakeholder interests and concerns are discussed in light of an investigation into the stakeholder concerns and the bottlenecks to dissipating the phosphorus recovered from the Japanese wastewater industry. This analysis provides insight into how phosphorus recovered from the steelmaking industry might be received by the various stakeholders, how to address their concerns, and how to ensure the recovered phosphorus is effectively recycled. The importance of establishing nutrient platform and to implement an industry-wide requirement for the recovery and recycling of phosphorus in the waste stream is presented. The importance of regulations, infrastructure, new standards, transparency, and education is also highlighted for the change from the business-as-usual model to one where a domestic supply of phosphorus is provided by the recovery of phosphorus from steelmaking slag.

While this study was limited to Asia, the implications extend to all steelmaking nations, both present and future, which incorporate a dephosphorization step in the steelmaking process. By engaging in good industry practice and recovering and

recycling the phosphorus in steelmaking slag, steelmakers will add a new dimension to the issue of how to close the phosphorus loop in countries with steelmaking facilities. The development of technologies which make it possible to separate the phosphorus from dephosphorization slag presents an opportunity for steelmaking nations to radically improve their phosphorus resource use efficiency by the establishment of a domestic phosphorus supply. In establishing this domestic phosphorus supply, these nations can either completely eliminate or significantly reduce the risks associated with the dependency of foreign imports of phosphorus, whether as phosphate rock or fertilizer. This, then, provides the steelmakers with the opportunity to contribute to national security. With the domestic supply of phosphorus, the nation can engage in the business of producing food for its populations without the risk of not being able to secure this vital resource in the global marketplace.

Whether the depletion of phosphate rock reserves is a short term or long term issue, the reality is that by mining a finite supply, the day will come when the resource will no longer be considered abundant. Considering the absolute necessity for a ready supply of phosphorus to nourish the crops which sustain life, ensuring a long term supply of phosphorus by recovering it from the waste stream in industry makes good long term sense. The gravity of the risks involved in not being able to secure phosphorus in the global marketplace cannot be overstated. As populations increase and the demand for phosphorus increases in all countries, and with increasing fossil fuel prices and depleting phosphate rock reserves, it is reasonable to presume that commodity prices will go up and securing supply will become increasingly difficult. The steelmaking nations have an opportunity to offset, or even obviate, the risks. Government, industry and the general public need to be aware of the risks which confront them with regard to phosphorus supply and fully understand the consequences to the nation. The implementation of the necessary changes will ensure that steelmaking nations can feed their people regardless of what eventuates in the international market.

論文審査結果の要旨

リン資源の需要は、経済発展、人口増加を背景に今後ますます増大する一方、環境制約、地政学的リスク等の要因から一次資源供給は困難になるものと予想される。特にアジアはリン資源の需要・供給面から重要な地域であり、持続可能なリン資源管理において、循環資源の利用促進が不可欠と考えられる。本博士論文は、このような背景に鑑み、以下の視点から解析と考察を行っている。

第一に、現在ならびに将来の経済発展、人口増大に伴うリン資源需要の増大が予想されるアジア地域に着目し、231 カ国・地域×231 カ国・地域の国際貿易に伴うリンの詳細なマテリアルフロー解析を行った。工業用途において重要な位置を占め、資源・材料戦略上重要な製品である黄リンに関しては、輸入財市場の外国依存度について HHI（Herfindahl-Hirschman Index）を用いた解析を行い、中国への依存度が極めて高いことを定量的に示した。

第二に、食糧供給に着目し、インド、中国、日本の食糧消費を支えるリン資源量について VP(バーチャルリン)指標を導入し、LCA（ライフサイクル分析）の視点から定量解析を行った。世界のリン消費量に対するインド、中国への食糧供給のために必要なリンの量の比率が極めて大きいこと、特に食肉消費の増大がリン消費量の増加に大きな影響をもたらすこと等を明らかにした。

最後に、インド、中国、日本における鉄鋼生産に伴い副生するスラグ中のリンに着目し、循環利用の可能性を定量的に推計するとともに、スラグ中リンの回収技術に関する詳細なサーベイを行った。

上記の視点に基づき、リンを含む循環資源を利用する際のボトルネックと障壁、ならびに産業、政府、消費者など各ステークホルダーの役割と課題を示し、持続可能なリン資源管理のための政策提言を行った。

以上、本博士論文は定量的な解析に基づき、アジアにおけるリン資源ガバナンスをより強く進める重要性について論じており、さらにマルチステークホルダーガバナンスを実現するために乗り越えるべき障壁を明らかにし、将来志向すべきベストケースシナリオの提案を行っている。特にアジアに着目したリンのマテリアルフローの詳細な解析はこれまでに無い新たな知見を示したものであり、高く評価できる。

また、本研究に関しては、Science of the Total Environment を含め、筆頭著者、共著者として 5 本の査読つき学術雑誌にすでに掲載されている。マテリアルフロー分析を行うにあたり、データ入手の困難性から、いくつかの制約的な仮定に基づくものもあり、それらについては将来的に改善　の余地が指摘できるものの、本博士論文の価値を大きく損ねるものではないと判断される。

よって、審査員一同、本論文は博士(環境科学)の学位論文として合格と評価した。