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Towards the sustainable development of the regional phosphorus resources industry in China: A system dynamics approach

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ABSTRACT

The explosive growth of the phosphorus resources industry in China has led to a series of problems (e.g., resource depletion, market supply and demand imbalances and environmental pollution). It is necessary to analyze the bottleneck in the development of the phosphorus resources industry under traditional modes and to suggest new directions for development. Therefore, this paper presents a system dynamics model based on the state of the regional phosphorus resources industry that focuses on resource, industrial, economic, environmental and social subsystems. Furthermore, by focusing on and quantitatively expressing the tailings recovery and resource reuse module, market regulation and elimination mechanism structures, governmental support and environmental constraints of game structures, and feedback structures between social innovation and industrial production, we construct a transformation mode as a development strategy for the phosphorus resources industry. The results demonstrate that the service life of phosphate rock under the transformation mode can be extended by 31 years. Compared to the 2014 levels, the resource productivity and ecological efficiency levels achieved can be increased by 2-fold and 2.5-fold in 2025, respectively. In addition, the social satisfaction levels can rise by roughly 50% under the transformation mode. Thus, the model can be used to assess the effects of various policies and to support decision making on development and environmental protection strategies.

1. Introduction

Phosphorus plays an extremely important functionality of animal and plant (Soetan et al., 2010). Phosphate rock (PR) is an important strategic resource that can be used for the production of phosphate fertilizers (PFs), detergent additives, feed additives, flame retardants, water treatment chemicals and other chemical products (Corbridge, 2013). Unlike carbon and nitrogen, which undergo biogeochemical cycles, phosphorus is a non-renewable and irreplaceable mineral resource. According to the U.S. Geological Survey (Jewell and Kimball, 2014), by the end of 2012, the global and Chinese PR reserves reached 67 billion tons (Bt) and 3.7 Bt, accounting for 5.5% of Chinese reserves. China's PR is distributed across 27 provinces and autonomous regions, of which Yunnan, Hubei, Guizhou, Sichuan and Hunan serve as phosphate enrichment areas. However, the average grade of Chinese PR is only 17% and high grade PR is scarce (Sun, 2013). Since the 21 st century, China's PF production levels have increased gradually. According to the China Statistical Yearbook (Sheng, 2014), China's PF production levels increased from 1.2062 million tons (Mt) in 2005 to 17.4301 Mt in 2014 (100% P_2O_5). Since 2007, China has become a PF exporter. China's considerable growth in its exploitation of resources and in environmental pollution problems has also been highlighted. Some scholars estimate that China's PR resources will be depleted within the next 50–60 years (Cooper et al., 2011). At present, the sustainable development of the domestic phosphorus resources industry is facing several difficulties (Rawashdeh and Maxwell, 2011), such as shortages of phosphate resources, domestic and international, expansion of international PF production capacities, serious overcapacities within the domestic PF industry and serious environmental pollution problems resulting from industrial development.

Due to pressure from resource depletion and environmental stress, the sustainable development of industry research is very important, such as efficient use of agricultural fertilizers, phosphorus product industry chain extension (Roberts and Johnston, 2015). Scholars have carried out corresponding research at the macro (national), meso (regional) and micro (firm) scales (Chowdhury et al., 2014). It has been noted that different analysis methods should be applied when examining different geographical areas and scales to evaluate phosphorus resource flows and management systems.

At the macro level, studies have focused on the supply of

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phosphorus resources (Ulrich, 2016), on flow metabolism (Scholz et al., 2013), and on soil and river basin deposits (Villalba et al., 2008). For example, Van Vuuren et al. (Van Vuuren et al., 2010) analyzed phosphorus resource demand levels from 1970 to 2100 by simulating a phosphorus consumption scenario. Accordingly, by the end of the century (2100), depletion of the global PR base was predicted to reach 20–35% under the optimal conditions and 40–60% under the pessimistic conditions based on the current resource base in 2008. Ma et al. (Ma et al., 2012) studied the dynamic characteristics of China's phosphorus resource metabolism for 1980–2008, analyzed related effects and put forward corresponding policy suggestions.

At the *meso*-scale, the study focuses on the recovery of phosphorus resources in urban waste (Egle et al., 2015), the flow of phosphorus resources (Wu et al., 2016), phosphorus recovery and utilization in the steel industry slag (Lin et al., 2014). Yokoyama (Matsubae-Yokoyama et al., 2009) studied the Japanese steel industry phosphorus element recycling, with a view to supplement the reserves of phosphorus resources.

At the micro level, studies have paid more attention to the innovation of specific production technologies, enterprise-level product adjustments and production optimizations and integration technologies (Song et al., 2014). Ma et al.'s (Ma et al., 2015b) study of the comprehensive recycling of phosphorus products and of associated resources serves as an example.

At present, the following problems still plague research on phosphorus resources.

1) The relationship between government industrial policies and the development of the phosphorus resources industry is weak.
2) Research stresses the leading role of the government and pays less attention to market regulation and elimination mechanisms.
3) Most scholars use single phosphorus elements as the object of study and study the storage and loss of PR reserves and static phosphorus element metabolism from the perspective of environmental management.
4) Research stresses how new technologies can solve environmental pollution problems, yet there is a lack in government support and environmental constraint in terms of forcing industrial transformation and upgrading.
5) Regarding the consumption and application of phosphorus products, studies have paid less attention to downstream market demand forecasting.
6) Existing research lacks a discussion on the structure of feedback between social innovation and industrial production subsystems.

The development of the phosphorus resource industry faces serious challenges. It is thus necessary to re-examine difficulties faced from a comprehensive perspective and to conceptualize future development from a higher starting point. To break through the current development bottleneck, it is necessary to analyze the development and utilization of phosphorus resources in consideration of resources, industries, the environment, society, and so on in a comprehensive and systematic way.

Phosphorus resources industrial system modeling is a complex problem due to the presence of multiple decision makers, complexity of suppliers and consumers' behaviors, feedback processes among module, technological limitations and various kinds of delays. System dynamics (SD) is a suitable approach to model such complexities.

SD is a powerful methodology and modeling technique for understanding and exploring the feedback structure in complex systems. It is based on systems and feedback control theories, computer simulation technologies, simulation study system feedback structures, behaviors and discipline functions (Forrester, 1971). SD involves both qualitative analysis and quantitative expression, focusing on the overall feedback structure of a system. It is suitable for dealing with high-order, multivariable, nonlinear and complex time-varying system problems. It is possible to find the best solution to a problem by simulating system trends and by analyzing simulation results. Even when there is a shortage of real system data and multiple feedback structures change parameters within a controllable range, overall SD trends are not affected (Nordhaus, 1973). The process of SD modeling is illustrated in the Appendix file and the steps are shown in Fig. S1. At present, research on SD is mainly focused on the sustainable development of energy resources (such as coal, oil and natural gas (Hosseini and Shakouri, 2016; Liu et al., 2015b; Wu et al., 2015)) and on regional ecological environment management (such as urban pollution control and construction waste disposal (Marzouk and Azab, 2014; Rehan et al., 2011)). In the phosphorus resource related subject, it has not been reported about studying phosphorus resources at industry linkage level in China based on SD approach.

In this paper, a general SD model is established based on the traditional industrial process system and bottlenecks affecting the development of the phosphorus resources industry (Section 2). Flow directions and interactions between material and information flows are expressed quantitatively based on typical problems of each link in the whole life cycle. In the SD model, we construct a market regulation and elimination mechanism structure, government support and environment restraint game structures, and a feedback structure between social innovation (including the innovation of enterprise, industry and academia, the innovation of support service system and the cultural innovation) and industrial production subsystems. Thereafter, the SD model is applied to Guizhou Province, China (Section 3). By a following comparison of different development paths of traditional and transformation modes, the effects of resources, industries, the economy, the environment and society are then compared in two development modes (Section 4). Finally, some suggestions for the sustainable development of the phosphorus resource industry are put forward (Section 5).

2. System dynamics framework

2.1. System description

2.1.1. Structure analysis of phosphorus resources industry

The phosphorus resources industry chain mainly involves phosphate mining, dressing, processing and post-sale which represented by white blocks in Fig. 1. The material flow between modules is indicated by solid lines. The mutual effects of the subsystems and comprehensive indicators through interactions of information and material flows are shown by dotted line.

The processing industry involves two main processes, namely thermal process phosphoric acid production (TPPAP) and wet process phosphoric acid production (WPPAP). TPPAP mainly involves heating using an electric donkey, blast furnace or kiln to reduce PR levels to obtain yellow phosphorus (YP) and then producing P_2O_5 through YP combustion. Finally, hydration creates phosphoric acid (PA). TPPAP is advantageous because resulting PA purity levels are high and fewer impurities are left. However, high levels of energy are consumed in the development of a unit product, and tail gas emissions generate considerable levels of environmental pollution. The WPPAP mainly involves using sulfuric acid and other inorganic acids to decompose PR into PA and then further purification using a variety of phosphorus chemical products (Afshar et al., 2003). The energy consumption of WPPAP is approximately equal to that of TPPAP at 35%. The method is advantageous in terms of environmental protection and cost efficiency (Afshar et al., 2003). However, resulting product quality levels are not high (containing impurities Fe, Al, Mg, F, Si and S) and purification is required (Monser et al., 1999). Mining and processing processes also generate considerable waste emissions (including solid waste and exhaust gas), leading to environmental pollution. Therefore, the phosphorus resources industry chain is mainly related to resources, industries, the economy, and environment subsystems under traditional modes.

The traditional phosphorus resources industry chain is based on the