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Phosphorus footprint in China over the 1961–2050 period: Historical perspective and future prospect

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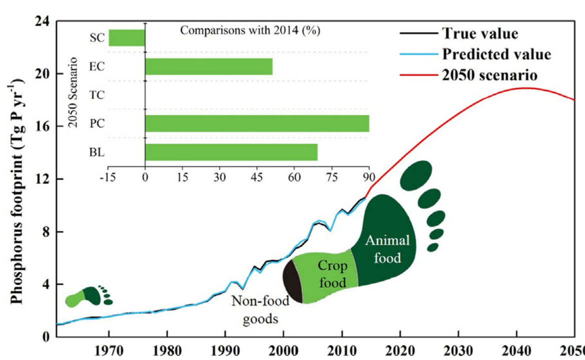
HIGHLIGHTS

- China's phosphorus footprint was estimated to increase from 0.9 to 10.6 Tg between 1961 and 2014.
- Population and urban rate are key factors driving the increasing phosphorus footprint, with contributions of 38% and 33%.
- In the worst case, China's phosphorus footprint would rise to 20.4 Tg and cause depletion of phosphate reserve by 2045.

GRAPHICAL ABSTRACT



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ABSTRACT

The phosphorus footprint (PF) is a novel concept to analyze human burdens on phosphorus resources. However, research on PF approach is still limited, and current several PF studies include incomplete phosphorus sources and have limited quantitative interpretation about the drivers of PF changes, which can help understand future trends of PF. This study develops a more comprehensive PF model by considering crop, livestock and aquatic food, and non-food goods, which covers the mainly phosphorus containing products consumed by human. The model is applied to quantify China's PF from 1961 to 2014, and the results of the model are also used to analyze the factors driving the PF changes and explored China's PF scenarios for 2050 using an econometric analysis model (STIRPAT). The result shows that China's PF increased over 11-fold, from 0.9 to 10.6 Tg between 1961 and 2014. The PF of livestock food dominated China's PF, accounting for 57% of the total in 1961 and 45% in 2014. The key factors driving the increase in China's PF are the increase in population and urbanization rate, with contributions of 38% and 33%, respectively. We showed that in the baseline scenario, China's PF would increase by 70% during 2014–2050 and cause the depletion of China's phosphate reserves in 2045. However, in the best case scenario, China's PF would decrease by 15% in 2050 compared with that in 2014, and it would have 50% of current phosphate reserve remaining by 2050. Several mitigation measures are then proposed by considering China's realities from both production and consumption perspective, which can provide valuable policy insights to other rapid developing countries to mitigate the P footprint.

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1. Introduction

Phosphorus (P) plays an increasingly important role in sustaining food production for an expanding population (Simons et al., 2014). Since World War II, global extraction of phosphate rock increased 15-fold, reaching 223 million tons in 2015 (The United States Geological Survey (USGS), 2016). As global food demand is projected to almost double by 2050 compared with than of 2005 (Tilman et al., 2011), demand for non-renewable phosphate rock will inevitably increase as modern agriculture is more dependent on the availability of chemical P fertilizer (Chen and Graedel, 2016). Therefore, long-term availability of affordable P resources attracts a global concern (van den Berg et al., 2016). China, regarding P resource availability is of particular interest, because of its important role in the global P resource supply-demand network. In 2015, China mined 49% of global phosphate rock extraction, produced 37% of global chemical P fertilizer and consumed 33% of these fertilizer (USGS, 2016; Food and Agriculture Organization of the United Nations (FAO), 2017), because China needs to feed 19% of global population using 7% of the world's arable land (FAO, 2017; World Bank, 2017). However, China only accounts for <6% of global phosphate rock reserves (USGS, 2016), thus it is facing major P resource pressures. Moreover, large anthropogenic P inputs have caused widespread eutrophication of waterbodies in China (Liu et al., 2016), which impairs water quality and damages aquatic ecosystem [Chau and Jiang, 2002; W. Wang et al., 2014]. Accordingly, there is a great urgency to assess the burdens on P resource, especially in China.

Footprint analyzes is an effective way to quantitatively describe how human activities impose various burdens on environment and resources (Čuček et al., 2012). In the "family" of footprint tools, ecological footprint, carbon footprint and water footprint are among the most established (Wiedmann and Minx, 2008; Hoekstra, 2009; Galli et al., 2012). These footprint tools have been widely applied to assess sustainability issues, like climate change, water resources and environmental carrying capacity and have garnered a lot of attention (Tom et al., 2016; Venter et al., 2016). The nitrogen (N) footprint is a more recent extension of footprint concept to measure anthropogenic N losses (Leach et al., 2012). Gu et al. (2013) adapted the N footprint tool based on the mass balance approach, and applied it to assess China's N footprint of production and consumption of food, energy and industrial products (Gu et al., 2013). Cui et al. (2016) combined material flow analysis with input-output analysis approach to assess China's N footprint, with a focus on the effects from international trade (Cui et al., 2016). Oita et al. used a more complicated method, by combining a global emissions database, nitrogen cycle model, and input–output database to assess the effects of international trade on N footprint of 188 countries (Oita et al., 2016).

While many publications focus on the N footprint, the P footprint (PF) has still been received little concern. Wang et al. first used the PF concept to measure P demand of China's food chain based on substance flow analysis approach (Wang et al., 2011). Grönman et al. developed a framework to calculate the PF for individual crops from a life cycle perspective (Grönman et al., 2016). However, existing studies consider the PF of partial human activity like food subsystem, and thus cannot help understand the PF of human activities from a social-economic system perspective. Furthermore, these studies have limited quantitative interpretation about the drivers of PF changes, which can help understand future trends of PF.

In this study, we developed a more comprehensive PF model that considers mainly P containing products including crop food, livestock food and aquatic food, and non-food goods. Then, the PF for China from 1961 to 2014 was quantified based on the developed model to measure holistic P demand in China. To facilitate the analysis of the PF result, we also extended the Stochastic Impacts by Regression on Population, affluence, and Technology (STIRPAT) model to quantitatively evaluate the factors driving the changes in China's PF and examined future scenarios of China's PF by 2050. The contribution of this study is providing a more comprehensive PF model to measure the phosphorus demand of an entire economy, which can help to understand human burden on P resources of other countries worldwide. The case study in China can provide valuable policy insights to other rapid developing countries to reduce the P footprint.

2. Materials and methods

2.1. Phosphorus footprint method

The PF in this study is defined as the total P demand as a result of population's consumption, including direct P contained in the products consumed by populations and virtual P of the consumed products (P demand in the production stage). The main types of products considered are crop food, livestock food, aquatic food and non-food goods (Fig. 1a). Analogous to others footprint methods (Ewing et al., 2010), the PF is calculated by the following equation:

$$PF = PF_P + PF_I - PF_E \quad (1)$$

where PF is the holistic PF; PF_P is the PF of the 4 types of products, calculated by Eq. (2); PF_I and PF_E are the PF in imported and exported products. The PF can be expressed in total units of P, or in unit of P per capita for the ease of comparison.

$$PF_P = PF_c + PF_l + PF_a + PF_g \quad (2)$$

where PF_c, PF_l, PF_a and PF_g represent PF of crop food, livestock food, aquatic food and non-food goods, respectively.

The PF of the product type i (c, l, a *and* g) in a certain year is calculated at the sector level based on the mass balance principle (Fig. 1b). As it has been shown in Fig. 1a, the products of a certain sector i consist of two parts: (1) one is transferred to downstream sector; (2) the other is consumed by population. In this study, the PF of the product type i refers to the part consumed by population, which can be expressed by Eq. (3):

$$I_i = O_i + PF_{i\_d} + PF_{i\_v} \quad (3)$$

where I_i is the P inflows to sector i, but excluding the recycled P from wastes, like manure, straws and sludge; O_i is the PF associated with the part transferred to downstream sector; PF_{i_d} is the direct PF of

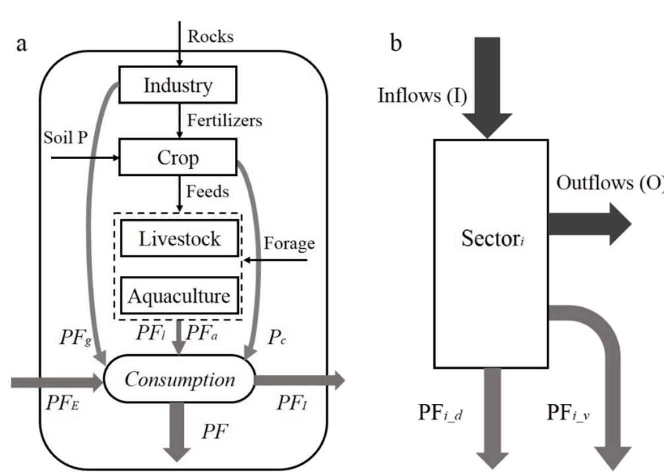

Fig. 1. Schematic of the PF model. (a) Framework of the PF model. (b) Calculation principle of the PF model.

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