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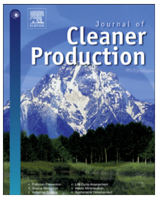

A review of phosphorus management through the food system: identifying the roadmap to ecological agriculture

Huijun Wu [a], Yongliang Zhang [b], Zengwei Yuan [c, *], Liangmin Gao [a]

[a] School of Earth and Environment, Anhui University of Science and Technology, Huainan 232001, PR China
[b] Policy Research Center for Environment and Economy, Ministry of Environmental Protection, Beijing 100029, PR China
[c] State Key Laboratory of Pollution Control and Resource Reuse, School of the Environment, Nanjing University, Nanjing 210023, PR China

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ABSTRACT

The possibility of future phosphorus (P) scarcity and the requirement to improve the environment quality necessitates P management for achieving ecological agriculture. The study reviews different methods of analyzing P flows through the food system including the human activities of fertilizer manufacturing, crop cultivation, crop processing, livestock breeding, resident consumption, etc. to identify the priority management. It is revealed early studies analyzed P flows mainly based on monitoring and geography information system, or combined with the soil erosion and P loss formula, which calculated the P loads but could not be used to trace the sources of these flows. Then the mass-balance or the input–output balance method was applied based on the mass balance principle, tracking and analyzing P utilization and transformation ineffectively, and likely leading to ineffective P management. A substance flow analysis of P was suggested to do such an inquiry. Apart from substance flow analysis, there are also several studies assessing the environmental impacts with P use in the food system based on life cycle assessment. These studies have focused mainly on quantifying P discharge from the systems and identifying the key sources and paths of pollution, while often ignored the P management or just analyzed from only ecological point. For achieving the ecological agriculture, P management has to face more challenges, such as the appreciate method from the life cycle aspects, more comprehensive system defined, adequate and high-quality data, more time-and-spatial scale, etc.

1. Introduction

Phosphorus (P) exists in the earth's crust in the form of phosphate rock containing around 5-10 × 10^8 Mt of P, and it is only through the processes of weathering and leaching that P is mobilized into terrestrial systems (Brunner, 2010; Suh and Yee, 2011). The most abundant of the phosphate minerals is apatite, which is the most common naturally occurring P containing mineral in the Earth's crust (over 95% of P) (Jahnke, 1992; Smil, 2000). Microbes and plants play an important role in assimilation, decomposition and mineralization of P. In the pre-industrial era, the main source of P to the biological cycle was P weathering from soil. Phosphorus use exploded in the 1940s and 1950s, supported by the development of the modern phosphate industry.

It has only been over the last 50 years that the human mobilization of P increased dramatically in order to cope with the unprecedented increase in the demand for food by rapidly growing global population (Newman, 1997; Tilman et al., 2002). Worldwide P is extracted from phosphate rock mining operations for conversion and application as fertilizer, and the remained for other purposes. It is estimated that around 90% of the P derived from phosphate rock is used in agriculture as fertilizer or feed (Brunner, 2010). Approximately 60% of the P applied to cropland comes from this non-renewable resource (Cordell, 2010; Liu et al., 2008; Smil, 2000; Smit et al., 2009), with the remainder from recycled P in organic residues such as manure, crop residues and human excreta. Without this supply humanity cannot sustain agricultural productivity and present food production output.

As one of the essential nutrients for plant growth, P input is necessary to maintain profitable crop productivity (Lin et al., 2009). In agriculture, this nutrient has been applied in increasing quantities in chemical fertilizers since the early 20th century (Neset et al., 2008). When P fertilization exceeds the removal of P by the crop,

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* Corresponding author. Tel.: +86 025 89680532.
E-mail address: yuanzw@nju.edu.cn (Z. Yuan).

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most of the surplus P will remain in the soil to add to the P reserve (Hooda et al., 2001). About 90% of the mined phosphate is used for food, only about 17% makes it into the human food supply (Cordell et al., 2009). Meanwhile, most of what does reach our food is subsequently disposed of without recycling (Vaccari and Strigul, 2011). Excessive soil P levels have been linked to high P losses in runoff and may increase the potential eutrophication of surface waters (Elliott et al., 2002; McDowell and Trudgill, 2000; Sims et al., 2000).

Obviously, P cannot be extracted out of finite mineral deposits forever to compensate for use losses. In recent years, the modern agriculture relies heavily on chemical fertilizers derived from phosphate rock, while the reserves of phosphate rock for mining are limited. The main global source of P (mined phosphate rock) is becoming increasingly scarce and expensive. Cooper et al. (2011) indicated that 70% of global production is currently produced from reserves that will be depleted within 100 years. Cordell et al. (2009) also estimated the reserves of phosphate rock worth mining are limited, and suggested that production of phosphate rock will peak before 2050. In addition, P prices rose in 2007 and particularly sharply in 2008 (AEA, 2010), although they have now peaked and declined somewhat. The price variations have been driven mainly by changes in agricultural production, driven in turn partly by ill-considered policy in Europe and the US promoting biofuel crops (Clift and Mulugetta, 2007). By mid 19th century, chemists attempted to improve agricultural production by applying calcium phosphate derived from animal bones, e.g. guano (van Sittert and Crawford, 2002; Clark and Forster, 2009; Snyders, 2011). Guano refers to P resources originating in vertebrate excrements, feathers and bones, with the P content usually between 2% and 21%, and also containing other important nutrients such as fixed N in varying amounts. There are also layers of calcium phosphate originating in the reaction between phosphate leached from guano and limestone and old guano deposits (Hutchinson, 1950). However, these measures couldn't afford the increasing consumption of the resource. In the nineteenth and early 20th century, available P became to be perceived as a limiting factor to agricultural production (Clark and Forster, 2009; Snyders, 2011; Melillo, 2012).

Thus, it has been suggested that the conservation and recycling of P could help sustain crop production and reduce the pollution of surface waters (Carpenter, 2008). P is added to cropland in mineral fertilizers and organic waste; then, P flows to animal production in feed and to household consumption as food (Ma et al., 2010; Neset et al., 2008). Accordingly, a growing number of studies have become concerned with efforts towards the more efficient and effective use of P, reducing waste and losses along the P lifecycle of the food system. The formation of the Global Phosphorus Research Initiative (GPRI) and the declaration on global P security (Bondre, 2011; GPRI, 2009) has attracted particular attention. There are also a growing number of researchers, initiatives, and governments beginning to concern with the more efficient and effective use of P, reducing waste and losses along the P lifecycle, and recycling, which were mainly studied on the national (ESPC, 2013) and global levels (GPRI, 2009; Scholz et al., 2013; Syers et al., 2011; Ulrich et al., 2013). To achieve an ecological agriculture, it will require an integrated set of policy options and technical measures that ensure efficient management of this vital resource. Formulation of better policy and management response requires a better understanding of the nature and magnitude of P flows though the food system. The P processes or cycle are as following: phosphate rock is mined, and the resulting chemical fertilizers are applied regularly to cultivation fields combined with organic fertilizers. The crops consume a fraction of the applied fertilizers with the remaining fertilizer flowing into the environment or accumulating in the soil. The crops are harvested and processed leaving crop residues and loss. Then the processed crops and livestock products (meat, eggs, and milk) are consumed by the residents ending up in solid wastes and wastewater, part of which are disposed in waste management (Cordell et al., 2013; Ma et al., 2010; Neset et al., 2008). Therefore, the food system affecting P management is mainly comprised of the processes of fertilizer manufacturing, crop cultivation, crop processing, livestock breeding, and resident consumption. Thus, to improve the P management, there is a need to trace and quantify P flows and P use efficiencies (PUEs) in these processes.

Although a considerable number of P management have already been conducted with different methods, we are unaware of any systematic review of the available knowledge to provide a more integrated and effective approach to the management of the P cycle in the food system. This approach could be very useful to identify specific priority P flows, and interpret the environment–anthropogenic interactions, which in turn a requisite for making more effective P management decisions. Through a systematic and in-depth review of recent analyses of P management in the food system, we attempt to construct a more appropriate approach to suggest the P management. The study reviews existing P flows and management, and assesses their scope and key findings in the food system consisting of the processes of fertilizer manufacturing, crop cultivation, crop processing, livestock breeding, and resident consumption. The study also aims to identify the knowledge gaps in the available P management literature and discuss optimized and integrated research for making better P management.

2. Assessment of P management methods

Considering the main methods of P management, P loss evaluation, P mass balance, P substance flow analysis (SFA), and P life cycle assessment (LCA) are selected to be assessed according to the development of these methods. From the assessment, generations, knowledge gaps and implications of every method are stressed, including the potential for sustainable new P management that can respond to the P management challenge.

2.1. P loss evaluation

To improve P management, an indispensable first step is to trace and quantify the P flows in these agriculture processes. There are studies focused on evaluating the P loss to reflect the field vulnerability and proposing measures to prevent erosion (Smith et al., 1999; Childers et al., 2011; Simpson et al., 2011). An approach has been adopted to reflect the field vulnerability of P loss, one type of P flow (Lemunyon and Gilbert, 1993; Hughes et al., 2005). While the weight and P loss rating of each source seemed to more qualitatively lead to the only P loss ranks of the crops. Thus, it is important to analyze the P flows with a quantitative method. There are also other studies quantifying P loads or concentrations in lakes or reservoirs that are based mainly on monitoring (Bechmann et al., 2005; McDowell and Trudgill, 2000; McDowell et al., 2001) and Geographic Information Systems (GIS) (Eastman et al., 2010) or are combined with soil erosion and P loss formulas (Ekholm et al., 2005; Leone et al., 2008). These approaches calculated the P loads but could not be used to trace the sources of these flows because their results could not interpret complex environment–anthropogenic interactions. Therefore, this approach satisfied the management requirement of a ‘simple and easy-to-apply’ method. However, this approach is neither able to interpret complexity nor the effectiveness of the best management practice choice in the specific context, but the balance between the input and output served as a performance indicator for P management. Attaining a proper nutrient balance while producing optimum crop

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