Resources, Conservation and Recycling 122 (2017) 94–105

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

The implications of allocation scenarios for global phosphorus flow from agriculture and wastewater

Cherry Myo Lwin*, Mari Murakami, Seiji Hashimoto

Ritsumeikan Global Innovation Research Organization (R-GIRO), Ritusmeikan University, 1-1-1 Nojihigashi, Kusatsu 525-8577, Shiga, Japan

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 24 January 2017
Accepted 28 January 2017
Available online 17 February 2017

Keywords:
Eutrophication
Phosphorus ore depletion
Fertilizer
Sewage
Shared Socioeconomic Pathways (SSPs)

ABSTRACT

The world's population growth has driven the increase of phosphorus fertilizer use in agricultural activities and domestic wastewater containing phosphorus (P). Actually, P used for cultivation and that contained in wastewater flowing into the hydrosphere contributes to severe environmental damage from eutrophication. Related concerns have arisen about the rapid depletion of P resources. Therefore, elucidating the amount of global P flow into bodies of water is extremely important to ascertain its environmental effects and to formulate methods for the sustainable management of P resources. This study was conducted future trends (2010–2100) of global P flows from agriculture and domestic wastewater based on scenarios of numerous parameters that include economic development, population, livestock demand, harvested areas, P removal ratios in sewage treatment facilities, etc. in 26 countries and 27 EU member countries as one combined country group (27 study countries). Results reveal that global P flows from agriculture to the hydrosphere occurred at an annual rate of between 5.7 Tg P yr^{-1} and 6.1 Tg P yr^{-1} in 2010, but they are expected to double by 2100. P flows from domestic wastewater occurred at an annual rate of 1.3 Tg P to 2.3 Tg P during the studied period. By 2100, the amount of P flowing from agriculture and domestic wastewater in India is expected to rank first in the world, followed in order by China, Brazil, and the United States. Those countries have the largest populations and intensive agricultural activities. According to most results of our scenarios, total P flows are expected to exceed planetary limits during the study period, indicating that marked reduction of fertilizer use is necessary. Recovery of P from sewage sludge can substitute for a small share of fertilizer use. This global research provides a core for the appraisal of P utilization and facilitates determination of important objectives for sustainable P management.

1. Introduction

Phosphorus (P), a necessary element for living organisms, is specifically applied for agriculture. Crop growth and food production rely mainly on fertilizers, which typically include three main nutrients: nitrogen, phosphorus, and potassium. Population growth, changes in lifestyles and living standards, acceleration of industrialization and urbanization, food demand, and more diverse contemporary uses of P products all continue to raise fertilizer demand and requirements. According to current world fertilizer trends, the world demand for fertilizer nutrients in 2016 was 194 million tonnes (Mt) (FAO, 2012). According to the USGS (2016), the world's consumption of P_2O_5 is included in fertilizers. Phosphorus is used not only in agriculture but also in industry. Industrial uses were projected to increase gradually from 43.7 million tons in 2015 to 48.2 million tons in 2019. Concerns of worsening phosphate ore depletion are attributable to the worldwide range of applications relying on limited natural resources. The total phosphate rock reserve in the world is 69 Gt. The three countries with the largest phosphate rock reserves are China (3.7 Gt), the United States (1.1 Gt), and Morocco and Western Sahara (50 Gt). Most of the world's phosphate rock reserves are concentrated in a handful of countries. Some studies have shown that phosphate rock reserves might be depleted within 50–100 years (Cordell, 2010; De Haes et al., 2009). Contrary to those projections, some reports describe that phosphate rock reserves will be extended in the future (Van Kauwenbergh, 2010; Van Vuuren et al., 2010). Whatever the timeline, individual countries must not only increase process efficiencies and technology development. Nations must also seek a new management paradigm that includes effective use and reuse of P, which might reduce reliance on imported P and decrease

* Corresponding author.
E-mail addresses: cml-11@fc.ritsumei.ac.jp, cherrymyoolwin@gmail.com (C.M. Lwin).

http://dx.doi.org/10.1016/j.resconrec.2017.01.017
0921-3449/

the individual country's resource scarcity. For instance, reduction of phosphate rock consumption might be accomplished through recovery and reuse of the P that flows into the hydrosphere.

In many forms after human use, discarded P passes through soil via leaching, runoff, and erosion, eventually leading to the hydrosphere, and consequently exacerbating water quality problems such as eutrophication. Results of future expansion of population and farmland in individual countries might strongly affect the environment on a global scale.

Studies of material flow and substance flow analysis of P, both globally and in individual countries, have been conducted by researchers around the world (Cordell et al., 2009; Matsubae-Yokoyama et al., 2009; Ma et al., 2013; van Dijk et al., 2015; Chen and Graedel, 2016). However, those studies were completed by estimation of past conditions and current target timing of P flows. Furthermore, those studies did not provide estimates for the future. Because P is a resource that will be consumed worldwide and because it will pass eventually into freshwater by erosion, runoff, and leaching of P in soil, elucidating the amount of global P flow into water bodies is extremely important to ascertain its environmental effects and to formulate methods for sustainable management of P resources and a more secure basis for global P management in the future.

This study was conducted to estimate possible changes of P flows from agriculture and domestic wastewater during 2010–2100 as results of different scenarios related to population, agricultural land area, livestock demand, etc. within individual countries and on the global level.

Three main objectives are pursued for this research.

1. Estimation of P flow from agriculture to the hydrosphere for the world and individual countries.
2. Estimation of effects of efficient or less-efficient fertilizer use and sewage systems on the flows of P to the hydrosphere.
3. Assessment of possible P recovery.

This report is organized as presented below.

- Following this section presenting the *Introduction* and the *Aims* and *Objectives*, we present Section 2 for P flow from agriculture (from fertilizer and from livestock) and domestic wastewater (from human excreta and from gray water) to hydrosphere along with treatment of the three objectives above.
- Results obtained for global and national analyses are summarized and presented in Section 3.
- The final section presents conclusions, followed by horizons for future research.

2. Methods and data

2.1. Outflow path to the system boundary and hydrosphere

Our research scope of the P flow framework is presented in Fig. 1. Broken lines in this research flow show topics that are excluded from our research. Moreover, the figure shows a system boundary of global P flow from agriculture and domestic wastewater flows to water bodies for all scenarios for 2010–2100. Therefore, although many P flows exist from production of phosphate ore in mining, resource flows from other uses such as food production are not examined. We divide P flows into two main components: agriculture (outflow route to the hydrosphere through soil from farmland and pasture) and domestic wastewater (outflow route from human excreta and gray water usages to the hydrosphere). Some absorption of P into soil in some countries can be accomplished through the re-use of gray water from households for watering of gardens, parks or other open space planting, fire-fighting, snow melting, and other processes. Nevertheless, we assume for this study that all P flows of any form through domestic wastewater usage will flow into the hydrosphere eventually. Future agriculture land and livestock demand through varieties of scenarios are taken from Tamura et al. (2015) and Tamura (2016). Moreover, other estimated data related to future demand such as population, gross domestic product (at purchasing power parity) per capita [GDP/cap (In$/cap)], and rural and urban shares of the population, are taken from some parts of Shared Socioeconomic Pathways Scenario 3 (SSP3) provided by the International Institute for Applied Systems Analysis (IIASA): SSP3 denotes "fragmentation," whereby high population growth and low economic growth occur.

2.2. Estimation period and target countries

The study period is set to every 10 years during 2010–2100. The target countries are 27 nations (26 countries and EU-27 member countries as one combined group) based on data availability. Targeted countries are presented below.

The 26 countries: Argentina, Australia, Bangladesh, Belarus, Brazil, Canada, Chile, China, Egypt, India, Indonesia, Iran, Japan, Malaysia, Mexico, Morocco, Pakistan, the Philippines, Russia, South Africa, Thailand, Turkey, Ukraine, the United States, Uzbekistan, Vietnam.

[One combined country] The 27 EU member countries: Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, the United Kingdom

2.3. Phosphorus flow from agriculture

Estimated P flows from agriculture to hydrosphere mainly include two components: estimation of P flow from fertilizer (PF_f) and estimation of P flow from livestock manure (PF_m). By summarizing of PF_f and PF_m, total P flow from agriculture can be obtained. The following sections will present a discussion of how to estimate these two parameters (PF_f and PF_m).

2.3.1. Phosphorus flow from fertilizer (PF$_f$)

The annual P flow derived from fertilizer (PF_f unit in teragrams of phosphorus per year: Tg P yr^{-1}) to water bodies can be calculated using the following Eq. (1).

$$PF_f = \left(\sum_i (P_{CROPi} \times HA_i) + (P_{ls} \times R_{ls}) + (P_e \times R_e)\right) \times R \quad (1)$$

In that equation, the following variables are used: P_{CROPi} stands for the amount of P in mineral fertilizer to be applied per unit harvested area of crop i (tonnes/ha); HA_i signifies the harvested area of crop i (ha); P_{ls} is the amount of annual P amount contained in livestock manure (tonnes/yr); R_{ls} denotes the ratio of P return to farm from livestock manure (%); P_e represents the amount of annual P contained in the human excrement (tonnes/yr); R_e is the ratio of P contained in the societal excrement back to the farmland (%); and R denotes the ratio of outflow to water from farms (%).

Harvested area data for each targeted crop for 2010 were obtained from the FAOSTAT web site. The total amounts of P fertilizer applied to crops of each type were referred from IFA data (Heffer, 2013). Furthermore, the estimated harvested areas during 2020–2100 were referred from a report by Tamura et al. (2015) and Tamura (2016). However, for some crops, although harvested area data were available from FAO, the amounts of P used in fertilizer data are missing in IFA. Sometimes, the opposite is true. For example, for oil palms in Bangladesh, data do not exist for the harvested