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Review

Phosphorus recovery and recycling with ecological engineering: A review

Eric D. Roy

Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, VT 05405, United States

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ABSTRACT

Phosphorus is essential to life on Earth and frequently limits the productivity of ecosystems, including agroecosystems. Currently, a substantial portion of the global human population relies on finite phosphate rock resources used for chemical fertilizer production. Concern over poor management of these vital resources and continued efforts to enhance soil fertility and food security have stimulated interest in phosphorus recovery and recycling. Existing heterogeneity in phosphorus waste flows, agricultural phosphorus needs, the availability of resources, and spatial patterns of land use calls for a diverse array of phosphorus recycling strategies. Ecological engineers working on phosphorus management have most commonly aimed to create phosphorus sinks on the landscape to help mitigate eutrophication. There is a growing need for ecological engineering approaches that go beyond phosphorus retention to create pathways for phosphorus recovery and recycling, supporting both eutrophication control and food security. This review includes a brief overview of human impacts on the global phosphorus cycle and a survey of existing ecological engineering techniques for phosphorus recovery and recycling discussed in the literature. A systems approach for design and feasibility assessment of phosphorus recycling with eco-technology is outlined, along with several key challenges. The importance of an interdisciplinary, multiple element, and multiple resource approach to phosphorus recycling is emphasized.

Contents

E-mail address: eroy4@uvm.edu

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1. Introduction

Phosphorus (P) is an element essential to life, and thus to global food security (Elser, 2012; Chen and Graedel, 2016). The global P cycle has no significant gaseous component, a unique feature among the major biogeochemical elements (Schlesinger and Bernhardt, 2013). Natural P mobilization is part of the geotectonic denudation-uplift cycle that unfolds over millions of years, and the low solubility of phosphates and their fast conversion to insoluble forms leads to P commonly being the growth-limiting nutrient in ecosystems, including both agroecosystems and aquatic ecosystems (Smil, 2000). Humanity's mining of vast amounts of phosphate rock (mostly sedimentary rocks of marine origin) provides the raw material for chemical P fertilizers and has helped supercharge global food production (Schlesinger and Bernhardt, 2013). There tends to be little recycling of P within human food and waste management systems. Instead massive P losses to water bodies and landfills occur (Chen and Graedel, 2016).

One result of human alteration of the P cycle has been widespread eutrophication, defined as the excessive production of organic matter in water bodies over-enriched with nutrients (Nixon, 1995; Carpenter et al., 1998). Researchers and practitioners in multiple fields, including ecological engineering, have responded with numerous strategies to reduce P loading to aquatic ecosystems in an era of eutrophication control. Despite these efforts, which have led to some success stories (Schindler et al., 2016), eutrophication remains a widespread water quality problem globally (Schindler and Vallentyne, 2008).

P has challenged ecological engineers working in watersheds to mitigate eutrophication. The common aim is to retain excess P upstream through processes including assimilation by vegetation, periphyton, and microorganisms; sorption and exchange reactions with soils, sediments, and other media; chemical precipitation in the water column; and sedimentation (Reddy et al., 1999). The longevity of P retention in ecologically engineered systems can be compromised by high loading rates. Many of these systems act as P sinks upon construction and for multiple years after, but then eventually become sources of bioavailable P to downstream environments as their capacities for P assimilation and retention are exceeded (e.g., Hoffmann et al., 2009). Additionally, ecosystem restoration in watersheds, wetlands, and lakes can be impeded by the P legacy resulting from decades of high inputs (Reddy et al., 2011; Roy et al., 2012; Sharpley et al., 2014).

Eutrophication control is very likely to remain a priority in environmental management due to the critical importance of clean drinking water and healthy aquatic ecosystems. Research continues on ways to improve P retention in ecologically engineered systems and landscapes to reduce eutrophication. However, there is a broader role that ecological engineering can play that supports a circular P economy (Nesme and Withers, 2016). P management strategies focused more prominently on recovery, recycling, and upstream source reduction will provide greater leverage for needed systemic change than those strategies where downstream retention is the primary goal (Fig. 1).

In this review, I highlight several efforts already underway in the field of ecological engineering to move beyond P retention and toward P recovery and recycling in the pursuit of clean water and productive food systems. These practices aim to serve human needs in a manner that is sustainable in times of decreasing resource availability through the design and restoration of ecosystems (Mitsch, 1993). This is especially relevant today given the finite nature of P resources, recent P fertilizer price instability, potential for future turbulence in energy and fertilizer markets, and pervasive eutrophication (Schindler and Vallentyne, 2008; Elser et al., 2014; Hall et al., 2014; Mew, 2016). This review includes the following: (1) a brief overview of P resource dynamics and sustainability concerns, (2) a survey of ecological engineering approaches being investigated for P recovery and recycling, (3) discussion of key challenges inherent to these P recovery and recycling strategies, and (4) a systems framework for future research.

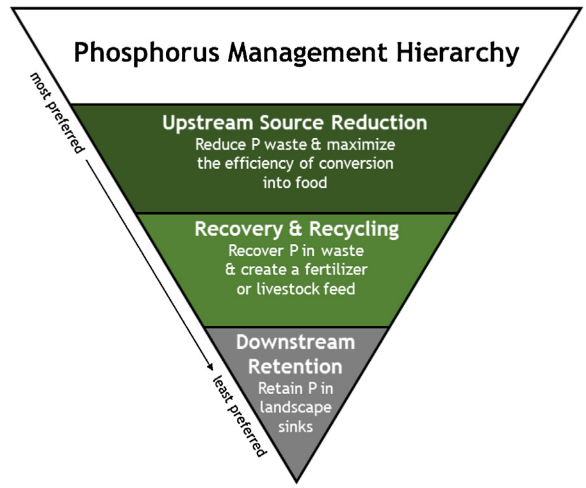

Fig. 1. Proposed hierarchy of management approaches to reduce watershed phosphorus (P) loading to aquatic ecosystems. This schematic is inspired by the U.S. EPA's food recovery hierarchy (US EPA, 2016). Preference in the P management hierarchy is a function of potential total benefits to the environment, society, and economy. However, all three categories have a vital role to play in comprehensive P management. Which P recovery and recycling strategies are more preferred than others in a given context can be determined using the process described in Fig. 4.

2. Phosphorus resource dynamics and sustainability concerns

Many nations appear to be in the very early stages of a transition from an era of eutrophication control where nutrient *retention* or *removal* has been prioritized to a new era with increased focus on nutrient *recycling* for food production (Ashley et al., 2011). In the case of P, this has been stimulated by concerns over future phosphate rock availability. A debate is under way concerning the estimated timeline of phosphate rock resource depletion (Cordell et al., 2009; Scholz and Wellmer, 2013; Cordell and White, 2014; Ulrich and Frossard, 2014). However, this debate should not distract from the immediate effects of poor resource management. There are several reasons to be concerned now about the future of P, regardless of the exact timetable of global resource depletion (Table 1). Critically, lack of access to affordable P fertilizer still constrains agricultural productivity in many regions of the world (Nziguheba et al., 2016).

Closing the human P cycle by harvesting nutrients in waste streams is an emerging area of intensive inquiry (Childers et al., 2011; Karunanithi et al., 2015; Mayer et al., 2016). Possible techniques for P recovery include a wide spectrum of technologies (Cordell et al., 2011; Mayer et al., 2016). At one end, there has been a growing focus in the literature on engineering approaches such as