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Analysis

Optimal Phosphorus Abatement Redefined: Insights From Coupled Element Cycles

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ABSTRACT

To successfully combat eutrophication caused by agricultural P loads, we need to understand how various forms of P respond to mitigation measures and thus how they contribute to algal growth. Failure to balance mitigation measures targeting dissolved inorganic P (DIP) and P in eroded soil (PP) may lead to economically inefficient measures at best, and to aggravated eutrophication at worst. We model dynamically optimal eutrophication management in a P-limited and SO_4-containing water body by taking into account the O_2 available and the coupling between the C, Fe, S and P cycles. We show that optimal management would put more weight on mitigating DIP than PP, and that the emphasis on DIP should be particularly strong in eutrophic water bodies. To foster influential and cost-efficient policies, we urge defining water body-specific multipliers to commensurate the main P forms into eutrophying phosphorus, much as greenhouse gases are converted to their CO_2 equivalents.

1. Introduction

Despite efforts to reduce nutrient loading, lakes and coastal waters impacted by agriculture continue to suffer from eutrophication (Diaz and Rosenberg, 2008; Conley et al., 2011; Daloğlu et al., 2012; Michalak et al., 2013). As pressing a need as it is, management of eutrophication must be based on cost-efficiency, which means achieving the highest possible water quality with the resources available. A necessary condition for achieving cost-efficiency is that the effects on the trophic status of the last (i.e. marginal) actions to abate all controllable sources be equal in cost; that is, water quality cannot be improved with the available resources by reallocating abatement efforts from one source to any other. Economically efficient management of eutrophication thus requires that we be able to evaluate how different substances originating from controllable human activities affect the process.

In fresh water ecosystems particularly, eutrophication management has targeted phosphorus (P), as it is considered to be the major driver (Correll, 1998; Schindler et al., 2008; Schindler, 2012; Lewis and Wurtsbaugh, 2008). However, reducing P fluxes to aquatic systems is complicated by the fact that P is present in several forms differing as to where they originate, how they are best mitigated and what biological impact they have. Of the two major forms, dissolved inorganic P (DIP) is fully available to algae, whereas P bound by eroded soil (particulate P, PP) contributes only moderately to bioavailable P in the productive water layers (DePinto et al., 1981; Ekholm and Krogerus, 2003).

Yet, PP may be transformed into DIP long after particles have entered bottom sediments (Lehtoranta et al., 2015). Let us call the contribution of PP to DIP before settling into sediments its short-term bioavailability, and its potential release from sediments its long-term bioavailability. It is often argued that mitigation of PP is beneficial because even though its short-term bioavailability is low, PP stored in sediments may someday be released as DIP, contributing to its long-term bioavailability. While the uncertainty surrounding PP's long-term bioavailability might be an argument for weighting PP and DIP equally, it would be even more judicious to aim for as precise a weighting of DIP and PP as possible: they both contribute to the same problem, that is, eutrophication. What makes proper weighting of DIP and PP extremely important, is that *i)* agriculture is the main source of P to surface waters (Carpenter et al., 1998; Sharpley et al., 2009) *ii)* all main conservation measures in agriculture exhibit strong interactions between PP and DP abatement, with measures targeting PP tending to elevate DIP loading (Dodd and Sharpley, 2016).

Optimal abatement of P from agriculture needs to be defined in terms of eutrophying P, an approach which assigns weights to PP and DIP according to their short- and long-run contributions to algae growth. To this end, we postulate a dynamic bio-economic model that takes into account both the short- and long-term bioavailability of PP. While the phosphorus cycle clearly includes many other forms of P than PP and DIP, we constrain the precision of our model to that

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attainable in agri-environmental management practices. Moreover, our understanding on the effects of various measures on PP and DIP is relatively good (Dodd and Sharpley, 2016), whereas we do not have comprehensive information on how conservation practices affect other phosphorus fractions. On balance, conservation measures can and should be designed and evaluated based on their effect on eutrophying P, calculated as a properly weighted sum of DIP and PP. This should be the next step in improving the precision and efficiency of P abatement.

The long-term bioavailability of sediment phosphorus has been implicitly included in studies such as Tahvonen and Salo (1996), Mäler et al. (2003) and Polasky et al. (2011), which analyze optimal eutrophication management under potential regime shifts. In the case of P, a regime shift involves a change in sedimentary redox conditions resulting in a state in which the ecosystem sustains high concentrations of P, as well as primary production, even if the P load is substantially reduced (Mäler et al., 2003; Carpenter, 2005). However, sediment processes as such are not sensitive to the availability of DIP and PP. Given that P itself is not a redox-sensitive substance, the cycling of P must be coupled to redox-sensitive elements, mainly C, Fe and S in sediments, for a regime shift to occur (Ekholm and Lehtoranta, 2012).

Targeting eutrophying P, rather than total P, in abatement measures would increase economic efficiency of the measures. This paper identifies and analyzes the principles for weighting DIP and PP in efficient P management. The model and application described in what follows highlight the importance of synchronizing the modeling of both DIP and PP at their sources and sinks. We focus on a P-limited and SO_4-rich water body, consider DIP and PP as fractions of external P load and explicitly model the reactive Fe in eroded soils. These choices allow us to maintain a crisp focus in our analysis. The results of coupling the dynamics of P in the system to the cycles of redox-sensitive C, Fe and S suggest that optimal eutrophication management is drastically different from that pursued to date: although DIP and PP both promote eutrophication, society should put substantially more emphasis on DIP abatement.

2. Materials and Methods

2.1. The Model

Our schematic model includes three interlinked state variables: (i) DIP, (ii) potentially mobile P in sediments (M) and (iii) reactive Fe in sediments (F) (Fig. 1). The changes in the variables from one period to another are driven by their current state, associated inputs and the within-system exchange between sediment and water, this last depending on the availability of O_2.

The stock of DIP in the water body develops according to Eq. (1). It is increased by DIP load (p_t), the DIP desorbed from PP before sedimentation ($\eta_1 e_t$) and the benthic release of P that reaches the euphotic zone (q_t). A share of DIP (γ) is taken up biologically by algae and removed from the water by sedimentation. During each period, a fraction (δ_P) of the DIP is exported from the system with the outflow.

The stock M (Eq. (2)) increases with the settling of organic matter containing P (γP_t) and the settling of PP ($\eta_2 e_t$). Each period, a fraction (δ_M) of M is permanently retained. M also decreases with the release of benthic P (q_t). The stock of reactive Fe in sediments (F) increases with the supply of Fe oxides in eroded soil ($\eta_3 e_t$) and decreases with the formation of solid Fe sulfides. The amount of Fe sulfides is denoted by s_t and the proportion of Fe in it by parameter ξ_4. F is buried permanently at the rate of (δ_F).

Benthic P release, jointly driven by all three state variables, is a focal mechanism in our model. The sedimentation of algae and debris

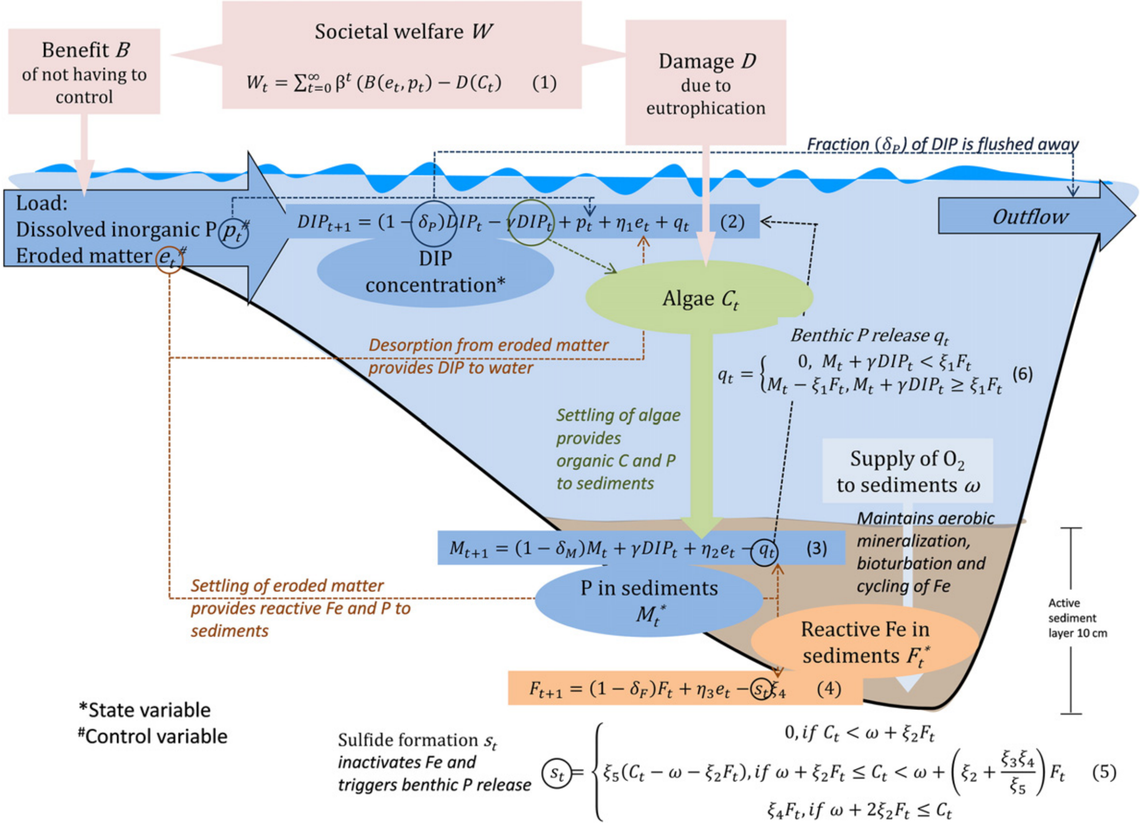

Fig. 1. Schematic model of the system. The arrows depict in- and outflows, ellipses the state variables and algae, and boxes at the top the economic variables: benefits from averted abatement costs and damage from eutrophication. The model works as follows: i) each period, DIP and erosion loading enter the system, increasing some or all of the stocks (2), (3) and (4) ii) DIP stock prompts algae growth iii) decaying algae consumes TEAs and provides organic P to sediments iv) P and Fe in sediments, TEA demand and supply of oxygen jointly determine the benthic release of P as given in Eqs. (3)–(6). Benthic release adds to DIP stock.