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Sustainable Phosphorus Management and the Need for a Long-Term Perspective: The Legacy Hypothesis

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Global food and water security depend upon sustainable phosphorus (P) management.[1] The river catchment scale provides an ideal unit of focus for studying this, and analytical developments in in-field measurements have promoted interest in short-term temporal dynamics (e.g., ref 2). However, we argue that a potentially new and deeper understanding will arise from assessing the historical changes in the P balance at the catchment scale and over many years, with the need for a much longer-term perspective.

In many high-profile cases, intended reductions in catchment P fluxes have not occurred as quickly as expected or desired by catchment managers; this is increasingly recognized to result from the legacy effect, associated with the build-up of P in the topsoil, and the complex release patterns in catchments and their rivers.[3] However, we are currently unable to accurately quantify these effects in response to human intervention at a catchment scale.[4] Here, we attempt to provide a solution, reflecting on some exemplar long-term data to inspire a framework for targeting hypotheses and quantitative research, to help drive the science forward.

Fertilizer use has increased at unprecedented rates following the Second World War (WWII), to meet the food demands of a rapidly growing population, with P is an essential element for agricultural productivity globally. With parallel mechanization and intensification of crop and livestock systems, regional P imbalances have developed, with increasing areas of P surplus above local needs, leading to P-impairment of surface waters, and yet areas of P deficit limiting production. Thus, to get a full understanding of the behavior of P in landscapes and catchments, we need to determine, over the long term, the magnitude of the accumulated P pool in catchments, and, equally, the magnitude of P exports from the catchment. Deriving P flux input and output time-series for extended periods will facilitate calculation of the accumulation or depletion of P within a catchment, from which we can start to estimate, for example, how long it may take, given current rates of P flux export, to draw down the accumulated legacy of P or, conversely, how long it may be before we see enhanced agricultural production in P-deficient areas. From this long-term perspective, we can determine the P sustainability status of catchments. We also need to consider soil-, plant-, and catchment-scale processes in a better evaluation of P balance (e.g., ref 5).

We show some example trajectories in long-term P flux time series for two globally important rivers; the Thames (U.K.) and

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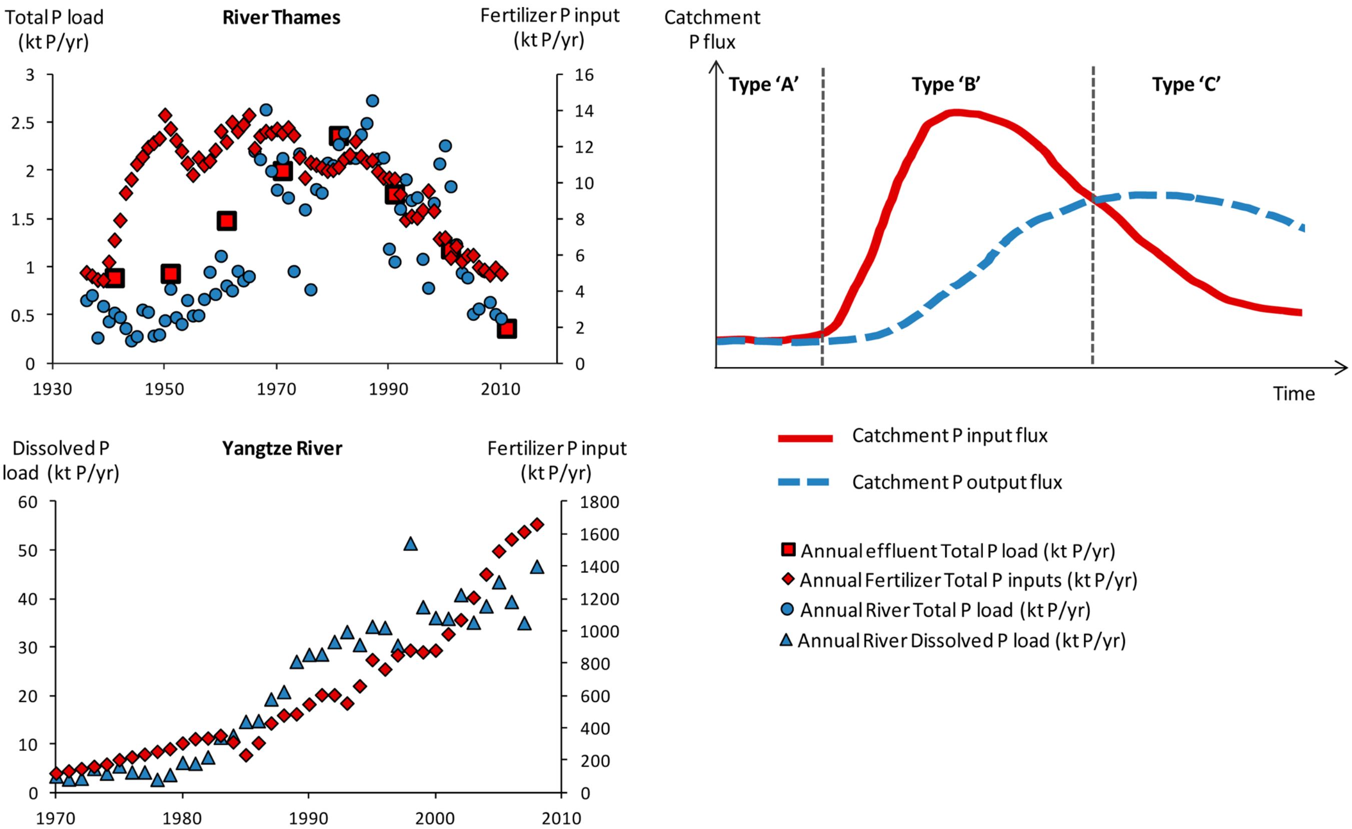

Figure 1. Long-term phosphorus data from the River Thames and Yangtze River (calculated from many recent references not listed due to limited space, we thank the related references) with a conceptual framework for approaching the long-term sustainable catchment balance.

Yangtze (China). These trajectories reveal differing historical responses to changing anthropogenic inputs, in relation to the changes in agricultural production, population growth, and the effects of nonpoint and point source controls (Figure 1). The River Thames demonstrates how increases in river P fluxes post-WWII responded to population growth and increasing intensity of agricultural production. In contrast, point-source controls from the early 1990s have had a rapid and dramatic impact on reducing river P fluxes. The Yangtze River shows how river P fluxes responded rapidly to increasing population and fertilizer inputs during the 1980s and 1990s, as the catchment underwent urbanization and the drive for food production and intensive agriculture accelerated.

From these analyses, we hypothesize that there are three states that can help provide a framework on the long-term catchment P balance over any given time window: Type A - ***Equilibrium***, where P input and output are equal, over a century-scale time frame; Type B - ***Accumulation***, where P input is greater than P output, such as illustrated for the Thames and in the Yangtze catchment in China; and Type C - ***Depletion***, where output is greater than the input, reflecting a legacy of P export from the system.

The overall aim for sustainable P management should be to achieve an "equilibrium" state at catchment, regional and global scales, that is, supporting agricultural productivity and population growth within catchments, while moving toward closing the P cycle. Achieving P equilibrium will involve balancing P inputs and outputs, to ensure efficient P use, thus minimizing downstream losses and water quality impairment. For example, in accumulating catchments (Type B), strategies should focus on reducing P imports by creating internal P source supplies; in equilibrium catchments (Type A), there will be minimal need for interventions to maintain the sustainable equilibrium state; and in depleting catchments (Type C), strategies would focus on limiting P mobilization and transport to the water body, along with reuse of legacy P. It should be noted, however, that moderately discharging catchments should not be discouraged in places where food demand exceeds supply (e.g., some African nations). This framework may help inspire a global vision of P sustainability that has hitherto been localized, fragmented and, thus, generally ineffective.

By adopting this framework, we hope that more detailed hypotheses relating to P legacy and long-term cycling in catchments can be proposed and tested, and ultimately more effective global and catchment-scale strategies can be developed to help in promoting sustainable P management. There is a pressing need to bring together time series of catchment P inputs and outputs (including livestock, crop and food inputs and outputs from human effluent), and to harmonize and evaluate methodologies for calculating robust catchment P mass balances. The exercise also underlines the importance of long-term catchment monitoring programs. By adopting this framework, this allows us to gain a global perspective on the nature and scale of P accumulation and depletion, helping toward achieving a more sustainable equilibrium P status, which supports food production while protecting water supplies.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Elser, J.; Bennett, E. Phosphorus cycle: A broken biogeochemical cycle. *Nature* **2011**, *478*, 29−31, DOI: 10.1038/478029a.

(2) Haygarth, P. M.; Page, T. J. C.; Beven, K. J.; Freer, J.; Joynes, A.; Butler, P.; Wood, G. A.; Owens, P. N. Scaling up the phosphorus signal from soil hillslopes to headwater catchments. *Freshwater Biol.* **2012**, *57*, 7−25, DOI: 10.1111/j.1365-2427.2012.022748.x.

(3) Sharpley, A. N.; Jarvie, H. P.; Buda, A.; May, L.; Spears, B.; Kleinman, P. Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *J. Environ. Qual.* **2013**, *42*, 1308−1326, DOI: 10.2134/jeq2013.03.0098.

(4) Jarvie, H. P.; Sharpley, A. N.; Spears, B.; Buda, A. R.; May, L.; Kleinman, P. J. A. Water quality remediation faces unprecedented challenges from "legacy phosphorus". *Environ. Sci. Technol.* **2013**, *47*, 8997−8998, DOI: 10.1021/es403160a.

(5) Shen, J.; Yuan, L. X.; Zhang, J. L.; Li, H. G.; Bai, Z. H.; Chen, X. P.; Zhang, W. F.; Zhang, F. Phosphorus dynamics: from soil to plant. *Plant Physiol.* **2011**, *156*, 997−1005.