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Linking terrestrial phosphorus inputs to riverine export across the United States

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ABSTRACT

Humans have greatly accelerated phosphorus (P) flows from land to aquatic ecosystems, causing eutrophication, harmful algal blooms, and hypoxia. A variety of statistical and mechanistic models have been used to explore the relationship between P management on land and P losses to waterways, but our ability to predict P losses from watersheds often relies on small scale catchment studies, where detailed measurements can be made, or global scale models that that are often too coarse-scaled to be used directly in the management decision-making process. Here we constructed spatially explicit datasets of terrestrial P inputs and outputs across the conterminous U.S. (CONUS) for 2012. We use this dataset to improve understanding of P sources and balances at the national scale and to investigate whether well-standardized input data at the continental scale can be used to improve predictions of hydrologic P export from watersheds across the U.S. We estimate that in 2012 agricultural lands received 0.19 Tg more P as fertilizer and confined manure than was harvested in major crops. Approximately 0.06 Tg P was lost to waterways as sewage and detergent nationally based on per capita loads in 2012. We compared two approaches for calculating non-agricultural P waste export to waterways, and found that estimates based on per capita P loads from sewage and detergent were 50% greater than Discharge Monitoring Report Pollutant Loading Tool. This suggests that the tool is likely underestimating P export in waste the CONUS scale. TP and DIP concentrations and TP yields were generally correlated more strongly with runoff than with P inputs or P balances, but even the relationships between runoff and P export were weak. Including P inputs as independent variables increased the predictive capacity of the best-fit models by at least 20%, but together inputs and runoff explained 40% of the variance in P concentration and 46–54% of the variance in P yield. By developing and applying a high-resolution P budget for the CONUS this study confirms that both hydrology and P inputs and sinks play important roles in aquatic P loading across a wide range of environments.

1. Introduction

Human-accelerated phosphorus (P) transport from land to aquatic ecosystems has prompted major concern among scientists and policy makers because of its detrimental effects on water quality (Elser and Bennett, 2011). Although fertilizer use has increased crop yields, export of nutrients from agricultural fields and urban wastewater have also resulted in serious water quality issues. Algal blooms fueled by the excess nutrients can be directly toxic to humans and pets, limit fishing and recreational activities, and contaminate drinking water sources, as well as indirectly affect humans and fisheries by causing hypoxia (Anderson et al., 2002; Michalak et al., 2013; Rabalais et al., 2009). Like much of the rest of the world, United States (U.S.) waters are subject to eutrophication stress[1] and algal blooms, including blooms that produce cyanotoxins (Anderson et al., 2002).

Addressing these challenges will require quantitative understanding of P flows across the landscape and through ecosystems. An improved accounting of terrestrial P flows can also support

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[1] Information on impaired waters in the U.S. available at: https://www.epa.gov/nutrient-policy-data/waters-assessed-impaired-due-nutrient-related-causes.

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effective ecosystem management and help identify opportunities for increased efficiency and recycling in natural, agricultural, urban, and industrial settings (Chowdhury et al., 2014). In the U.S. for example only 8% of P fertilizers used in 2007 were consumed in U.S. diets, and a quarter of mineral P fertilizer use was linked to agricultural exports (MacDonald et al., 2012), pointing to both high losses within the agricultural system (supported by Suh and Yee (2011)) and the importance of trade. In European Union member states, which are all dependent on P rock imports to support their food systems, national P budgets demonstrate that losses are also high in the food production/consumption system, often resulting in long-term soil P accumulation (van Dijk et al., 2016). Trade is also playing an increasing role in EU P flows, potentially because of increasing environmental regulation within the EU (Nesme et al., 2016). Still, there is significant variation among nations. For example although most soils in the EU have accumulated large stocks of P, some countries like Belgium and the Netherlands have continued to accumulate P while others like Slovakia or Austria are mining these soil resources (van Dijk et al., 2016; looking at 2005 annual P budgets). There can also be large variation within a country. For example, France reduced the magnitude of soil P budget surpluses between 1990 and 2006 across most regions, and as such increased its P use efficiency. However agricultural specialization has resulted in an uneven increase in P use efficiency between regions. More specifically animal intensive regions have not seen the same level of increased efficiency as crop-producing areas because of the local reapplication of manure (Senthilkumar et al., 2012). As international and national pressures on agricultural and waste management systems shift (e.g. by changes in fertilizer prices or pollution regulations), it is important to develop up-to-date information on P flows to ascertain what the impacts of such shifts may be on potential opportunities for changes in management (e.g., increased recycling or efficiency in use). In addition, a spatially explicit understanding of these P flows can help identify opportunities and consequences associated with changes (e.g., Metson et al., 2012 at the city scale), especially in a large country like the U.S. with large regional differences (e.g., Metson et al., 2016).

Terrestrial nutrient budgets are useful, but if we aim to target terrestrial sources to improve water quality, budgets must be paired with understanding of the relationship between sources of P and losses to waterways. A variety of statistical and mechanistic models have been used to better understand the relationship between terrestrial P management and losses to waterways. For example, at the regional scale the SPAtially Referenced Regression On Watershed attributes (SPARROW) model can account for 87% of the variance in TP loads and 68% of the variance in yields across the Mississippi River Basin (MRB), but requires 16 input parameters to achieve this level of predictive skill (Alexander et al., 2008). In contrast, a recently developed, uncalibrated, spatially-explicit, process-based global model, the Integrated Model to Assess the Global Environment—Global Nutrient Model (IMAGE-GNM), systematically underestimates Mississippi River P concentrations at 11 stations (with a root mean squared error of 51% (Beusen et al., 2015)). On the other hand smaller scale models such as the Soil and Water Assessment Tool (SWAT) (Douglas-Mankin et al., 2010; Gassman et al., 2007), the field-scale Erosion Policy Impact Climate (EPIC) model, and the multi-field extension version called Agricultural Policy Environmental eXtender (APEX, Gassman et al., 2004) have been used to predict P loading when using fine-scale location-specific data (e.g. Tripathi et al., 2003). In addition to these more complex mechanistic or statistical models, simple soil and water net budgets (e.g., Sobota et al., 2011) and net system budgets (also referred to as a mass balance approach), such as the net anthropogenic phosphorus inputs (NAPI, Russell et al., 2008; Hong et al., 2012) methods have be calculated at a variety of scales and geographical contexts and linked to water quality statistically. These budgeting approaches usually require fewer (and often more widely available) data inputs than the global or field-scale models, giving them a strong advantage in comparative work. Although there exist comparisons of such regional terrestrial budgets to riverine P, most studies focus on only one or two specific geographic areas. For example, Han et al. (2011) examined 24 watersheds around Lake Erie and Lake Michigan. Jacobson et al. (2011) looked at 113 watersheds in the MRB, while Hale et al. (2015) 42 watersheds in the North Eastern US,. In summary, although mechanistic models provide essential insights on the drivers of P riverine losses, simpler statistical models linking terrestrial budgets and riverine P are more easily implementable for comparison and targeting reductions at regional or large watershed scales.

With all of this as context we developed an updated (year 2012), spatially continuous P flux database for the entire conterminous U.S. (CONUS), and used this dataset to investigate continental-scale P dynamics. We then applied this dataset, in combination with a separate dataset containing river P export estimates from 72 watersheds distributed throughout the CONUS, to explore relationships between watershed characteristics (including P sources, sinks) and aquatic P loading across a wide range of environments. Importantly this exploration uses the same datasets across these regions as opposed to comparing previous works to eachother where methods, target years, and data-sources can confound the patterns that are identified between regions.

2. Methods

2.1. Overview

In order to explore the relationship between anthropogenic terrestrial P sources, landscape characteristics, and water quality we quantified aquatic P fluxes as well as landscape and climate variables that have been shown to mediate the loss of P to waterways in other studies (Harrison et al., 2010, Jacobson et al., 2011, see Table 1 and supplemental information (SI)). For each of these landscape and climate characteristics a mean value for each watershed was extracted from gridded data using the “Zonal Statistics by Table” tool in ArcGIS 10.2 (ESRI, 2013), using watershed area polygons. We applied similar methods to those used in regional N studies (Boyer et al., 2002; Schaefer and Alber, 2007; Schaefer et al., 2009; Sobota et al., 2009) and one regional P study (Sobota et al., 2011) across the U.S., utilizing simple linear regressions between water quality variables: concentrations, yields, and TP fractional export (TP yield/nutrient inputs, see Eq. (6)), and potential explanatory variables. Water quantity and quality information were obtained from the USGS National Water Information System through the R dataRetrieval package (Hirsch et al., 2015) and processed with LOADEST (Runkel et al., 2004).

2.2. Anthropogenic phosphorus sources

2.2.1. Agricultural system

P inputs considered included inorganic P fertilizers and manure P from confined livestock. P removal in harvested crops was also considered. For each of these P flows, data were obtained from two main sources to ensure consistency. We used phosphorus fertilizer sales, P produced by animals in confined feeding operations, and P removed in crop harvest compiled by the International Plant Nutrition Institute (IPNI, 2012) at the county level, following methods described by Kellogg et al. (2000) for manure. County level P fluxes were spatially disaggregated by assuming that fertilizer and manure P were applied to NWALT (U.S. National wall-to-