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Societal phosphorus metabolism in future coastal environments: Insights from recent trends in Louisiana, USA

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ABSTRACT

Successful adaptation to global environmental change will require confronting multiple unfolding challenges in concert. Coastal regions vulnerable to sea level rise and tropical storms will likely also be influenced by resource limitation in an uncertain future. In this paper, we explore the interrelated dynamics of coastal population migration, economic instability, and anthropogenic phosphorus (P) flows. Accounting for P flows and improving human P use efficiency are critical tasks given the finite global supply of phosphate rock and widespread eutrophication. We use material flow analysis to examine societal P metabolism in the Upper Pontchartrain Basin in coastal Louisiana, USA for two 5-y time periods (2001–2005 and 2006–2010) to capture the effects of fertilizer economics and population growth partially driven by the impact of Hurricane Katrina in the lower basin in 2005. Mass balances encompass human-mediated P fluxes in food production and consumption subsystems across agricultural, developed, and forested landscapes. Drastic reductions in locally purchased inorganic P fertilizer (78% decline between periods) were correlated to increases in fertilizer prices. Total P input to the study region decreased from 5452 to 3268 Mg P y^{-1} between periods. Changes in P flows were primarily driven by fertilizer economics, declining dairy production, and the influx of new residents, which has been characterized by decentralized settlement that limits P recycling. Societal P metabolic efficiency increased from 22% to 32% due largely to reduced fertilizer inputs. Leakage to the Pontchartrain Estuary and the Mississippi River represented 17–23% of total system P input, while the vast majority of P accumulated within soils, wastewater systems, and landfills. We discuss basin trends and management implications. A historic opportunity exists to encourage future coastal development characterized by synergies between local agriculture and human habitation to promote energy efficient nutrient recycling. The effect would be a decreased vulnerability to future fertilizer price spikes, along with the mitigation of current and future eutrophication.

1. Introduction

From a biogeochemistry perspective, heterotrophic life on Earth involves a pursuit of carbon for linkage with other major elements including nitrogen (N) and phosphorus (P) to maintain structure, energetics, and function (Reddy and DeLaune, 2008). As heterotrophs, humans have been incredibly successful at exploiting and affecting global biogeochemical cycles (Smil, 2000; Bennett et al., 2001). Current food production systems largely depend on the availability of affordable fossil fuels and inorganic fertilizers containing N and P to stimulate primary production and feed a global population trending toward over 9 billion by 2050 (Pelletier et al., 2011; Foley et al., 2011; UN, 2013). One result of this global human influence on nutrient cycling has been pervasive eutrophication, or the excessive production of organic matter in water bodies over enriched with N and P (Nixon, 1995).

Recent research has brought attention to the paradox of P: this widespread aquatic contaminant is also a finite mineral resource essential to future human survival for which there is no substitute (Elser, 2012). Industrial inorganic phosphate fertilizer production requires high-quality phosphate rock formed over geologic time scales (Crosby and Baily, 2012). Therefore, even though P is obviously not *disappearing*, the rate of its global, largely one-way *dispersal* from concentrated rock to diffuse concentrations in

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aquatic systems is troubling from a resource management perspective. Cordell et al. (2009) ignited debate on future P availability by suggesting that a peak in global phosphate rock production could occur within decades. An unplanned descent from "peak phosphorus" would have serious implications for global food security. Recently, the reliability of their Hubbert curve analysis has been challenged (Vaccari and Strigul, 2011; Scholz and Wellmer, 2013), longer timelines of resource depletion have been suggested (Van Vuuren et al., 2010), and it has been emphasized that future P availability will be driven by dynamic interactions between supply and demand (Scholz and Wellmer, 2013). However, the debate over the timeline of phosphate rock depletion should not overshadow the more immediate situation of poor resource management (McGill, 2012). Both those concerned about P availability in coming decades and those unconvinced of a near-term P crisis promote improving the efficiency of human P use to achieve sustainable P management and reduce environmental degradation (Childers et al., 2011; Scholz and Wellmer, 2013).

Moving toward more sustainable P management requires an understanding of anthropogenic P fluxes at multiple spatial and temporal scales. A number of recent studies have used material flow analysis (MFA) to foster greater understanding of how P travels through human-dominated landscapes, generating assessments of societal P metabolism. P budgets have been constructed and analyzed for multiple scales (Cordell et al., 2012; Chowdhury et al., 2014), including farm (Öborn et al., 2005), household (Fissore et al., 2011), town/city (Neset et al., 2008; Metson et al., 2012a), watershed (Schussler et al., 2007), regional (Senthilkumar et al., 2012a), national (Senthilkumar et al., 2012b; Cooper and Carliell-Marquet, 2013), and global levels (Cordell et al., 2011). Nutrient budgets often provide a static analysis considering stocks and flows averaged over one time interval. Increasingly, studies are being conducted that examine measured or predicted changes in P dynamics over time scales including decades (Metson et al., 2012b; Ma et al., 2013) and centuries (Neset et al., 2010). These studies better capture the underlying biophysical, economic, and cultural mechanisms that influence societal P metabolism.

In this paper, we present the first study to the best of our knowledge that focuses on dynamic societal P metabolism in a coastal region over a decade. The study region is a 7-parish portion of the Upper Pontchartrain Basin in coastal Louisiana, USA. We have specifically aimed to capture the short-term influence of economic instability (i.e., the 2008 fertilizer price spike) and human population growth on P dynamics to better understand drivers of change. Fertilizer cost is a key parameter influencing demand for P. In 2008 as the financial crisis of 2007–2008 grew into the Great Recession, rapid increases in sulfur, phosphate rock, and ammonia prices drove the prices of inorganic phosphate fertilizers to historic highs (Huang, 2009). Fertilizer prices are influenced by a complex array of supply and demand factors including energy costs, raw material costs (e.g., phosphate rock), currency value, the strength of export fertilizer associations, the increasing concentration of fertilizer industries, global population, economic growth, dietary preferences, and foreign trade policies (e.g., China imposed an increased export tariff on phosphate in 2008) (Huang, 2009; Metson et al., 2012c). The 2008 spike in P fertilizer prices offers an opportunity to assess economic influences on human-mediated P fluxes.

Human population centers result in the concentration and intensification of biogeochemical cycles in urban and agricultural portions of the landscape (Fissore et al., 2011). Coastal zones less than 10 m above sea level cover 2% of Earth's land area, but contain 10% of the total global population and 13% of the global urban population. Many of these coastal zones are at risk to future environmental hazards including sea level rise and tropical storms (McGranahan et al., 2007). The Mississippi Delta in coastal Louisiana provides an example of a coastal human population facing environmental hazards associated with high rates of land loss and relative sea level rise, large amounts of land below 1.0 m elevation, and the impacts of tropical storms like Hurricane Katrina (Thieler and Hammar-Klose, 2000; DeLaune and White, 2012; State of Louisiana, 2012; Fig. 1). The Pontchartrain Basin lies within this dynamic landscape and is home to over 40% of Louisiana residents, making it an ideal setting to examine changes in anthropogenic P cycling in a coastal zone.

Our main objective in this study was to determine the effects of P fertilizer price volatility and population migration on human-mediated P cycling within a vulnerable coastal Louisiana basin. Specific tasks to meet this objective were as follows: (1) identify trends in P fertilizer economics and investigate the correlation of fertilizer purchases in the study region with prices; (2) identify trends in human population in the Pontchartrain basin, including the impact of Hurricane Katrina in 2005; (3) construct budgets representing human-mediated P fluxes in the study region of the Upper Pontchartrain Basin for two time intervals (2001–2005 and 2006–2010); (4) identify major drivers of change in P fluxes between the two periods; (5) assess dynamics in societal P metabolism between periods; and (6) identify opportunities for moving toward more sustainable P management in coastal basins.

2. Materials and methods

2.1. Study region

The Upper Pontchartrain Basin encompasses portions of southeastern Louisiana and southwestern Mississippi in the US, covering a total area of 12,476 km^2 (Roy et al., 2013). Here, we focus on a 9320 km^2 region within the watershed that includes land in five hydrologic cataloging units of the Upper Pontchartrain Basin (Amite – 08070202, Tickfaw – 08070203, Lake Maurepas – 08070204, Tangipahoa – 08070205, and Liberty Bayou-Tchefuncte – 08090201) and seven Louisiana parishes (Ascension, East Baton Rouge, East Feliciana, Livingston, St. Helena, St. Tammany, and Tangipahoa) (Fig. 1). The study region includes portions of the Baton Rouge Metropolitan Area; the region along the northern coast of Lake Pontchartrain including the cities of Hammond, Covington, Mandeville, and Slidell; and rural upland areas extending northwards to the Mississippi border. Wetlands cover approximately 33% of the region. Other land coverage categories include forested (18–20%), shrub/scrub (11–13%), agricultural (pasture + cropland) (17–18%), and urban/developed (11–13%) (Homer et al., 2007; Fry et al., 2011).

Runoff in the study region eventually enters the Lake Pontchartrain Estuary, a shallow (mean depth = 3.7 m), oligohaline estuary with a surface area of 1637 km^2 (Turner et al., 2002;Fig. 1). Water column P availability in Lake Pontchartrain can influence eutrophication dynamics including harmful blooms of cyanobacteria (Roy et al., 2013). Tributaries entering and draining the study region are the primary source of external P loading to Lake Pontchartrain during most years (McCorquodale et al., 2009). Sediments in the estuary contain a legacy of past external P loading and provide a significant internal source of P to the water column (Roy et al., 2012), as is the case in other coastal systems including the Baltic Sea (Vahtera et al., 2007).

2.2. System design

The conceptual design of P flows in the study region was divided into agricultural, forested/wetland, and urban/developed landscapes (Fig. 2). Societal P metabolism was assessed based on two