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Historical pattern of phosphorus loading to Lake Erie watersheds

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ABSTRACT

Phosphorus (P) applied to croplands in excess of crop requirements has resulted in large-scale accumulation of P in soils worldwide, leading to freshwater eutrophication from river runoff that may extend well into the future. However, several studies have reported declines in surplus P inputs to the land in recent decades. To quantify trends in P loading to Lake Erie (LE) watersheds, we estimated net anthropogenic phosphorus inputs (NAPI) to 18 LE watersheds for agricultural census years from 1935 to 2007. NAPI quantifies anthropogenic inputs of P from fertilizer use, atmospheric deposition and detergents, as well as the net exchange in P related to trade in food and feed. Over this 70-year period, NAPI increased to peak values in the 1970s and subsequently declined in 2007 to a level last experienced in 1935. This rise and fall was the result of two trends: a dramatic increase in fertilizer use, which peaked in the 1970s and then declined to about two-thirds of maximum values; and a steady increase in P exported as crops destined for animal feed and energy production. During 1974–2007, riverine phosphorus loads fluctuated, and were correlated with inter-annual variation in water discharge. However, riverine P export did not show consistent temporal trends, nor correlate with temporal trends in NAPI or fertilizer use. The fraction of P inputs exported by rivers appeared to increase sharply after the 1990s, but the cause is unknown. Thus estimates of phosphorus inputs to watersheds provide insight into changing source quantities but may be weak predictors of riverine export.

Introduction

Prior to European settlement, the Laurentian Great Lakes varied from the highly oligotrophic Lake Superior to naturally eutrophic Lake Erie. However, cultural eutrophication became apparent in all five Great Lakes as settlement progressed, and most severely in Lakes Erie, Ontario and Michigan (Stoermer et al., 1993). By the late 1960s, Lake Erie was experiencing severe cultural eutrophication, evidenced by hypoxia, loss of benthic invertebrates, and proliferation of *Cladophora* and noxious cyanobacteria such as *Microcystis* (Rosa and Burns, 1987). Although these symptoms have ameliorated, recent years have seen a return of hypoxia (Hawley et al., 2006) and nuisance algae (Vincent et al., 2004). The causes of nutrient enrichment have varied over time, and include a European settlement and deforestation period marked by pulsed nutrient loading from 1850 until 1940; a period of urbanization, phosphorus (P) detergent use and intensive agriculture with dramatic increases in phosphorous loading from 1940 until 1970; and a nutrient abatement period from 1970 to the present (Baker and Richards, 2002; Richards et al., 2009). Following the 1972 Great Lakes Water Quality Agreement (IJC, 1972), external phosphorus loads to Lake Erie have significantly decreased, due to stricter effluent standards for wastewater treatment plants, the banning of some P-based detergents and efforts to reduce non-point source P inputs through a variety of erosion control measures (Baker and Richards, 2002; Richards et al., 2002). In addition, sales of P fertilizer increased until about 1980 and then declined, reflecting evolution in nutrient management and environmental awareness (Ohio EPA, 2010).

An assessment of historic trends in P loading to watersheds can provide insights into the relative magnitude of inputs, variation among watersheds and trends over time. Clearly the increased use of commercial fertilizers to improve agricultural yields has played a major role in improving crop yields and allowing for the geographic separation of crop and animal production because farmers no longer needed to rely on manure to supply nutrients to crops (Lanyon, 2000). P applied to croplands in excess of crop requirements has resulted in large-scale accumulation of P in soils worldwide (Bennett et al., 2001), increasing the likelihood of P runoff to nearby aquatic systems for decades into the future (Carpenter, 2005).

Nonetheless, the annual P surplus and thus rate of accumulation of soil P appear to be decreasing in developed countries, and this is

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borne out by studies of individual watersheds. The Neuse River watershed of North Carolina (Stow et al., 2001), the state of Illinois (David and Gentry, 2000), the Maumee and Sandusky watersheds draining to Lake Erie (Baker and Richards, 2002) and watersheds of the St Lawrence River Basin (MacDonald and Bennett, 2009) are similar in documenting substantial increases in cropland applications of inorganic phosphorus from roughly the 1940s through the 1980s, followed by declines to 50–75% of peak values over the past few decades. In counties of the state of Pennsylvania, P fertilizer use generally increased from 1939 to 1978 and then decreased from 1978 to 2002, and nearly always showed a positive balance (Lanyon et al., 2006). Tributary watersheds of the St Lawrence evidenced the largest overall P surplus in 1981, and in 2001 the balance had declined to pre-1951 levels as a result of increases in P crop removal and decreases in fertilizer P inputs (MacDonald and Bennett, 2009).

Nutrient budgets provide a full accounting of all anthropogenic inputs to a watershed, allowing analysis of the contributions of different sources and the potential to match trends in inputs with trends in river export. The net anthropogenic nitrogen input (NANI) method, which estimates the contribution of N-fixing crops, fossil fuel combustion, inorganic fertilizer and net trade in crops and animal products, has been widely used to compare anthropogenic N sources across watersheds (Boyer et al., 2002; Howarth et al., 1996) and also over time. In an analysis of 25 individual watersheds that comprise nearly all of Lake Michigan's drainage, anthropogenic N was apparent as early as 1880, rose most rapidly after about 1960, and then slowed to an apparent plateau by the mid-1980s (Han and Allan, 2011). Inorganic fertilizer was responsible for most of the increase as well as its timing, and increased crop export also strongly influenced N net inputs.

The objective of the present study was to examine historical trends in phosphorus inputs to Lake Erie (LE) watersheds for comparison with P export by rivers. We constructed P budgets for 18 watersheds at eleven time intervals from 1935 to 2007 to determine how total annual inputs of anthropogenic P and the contributions of different P sources have changed over time and space. We report that after a period of increasing P inputs, fertilizer use has declined and crop exports have risen over the past three decades, resulting in a decline in nutrient imbalances, although inputs continue to exceed outputs. In addition, P export by rivers since the 1980s has varied mainly with river discharge, and since the 1990s the fractional export of P by rivers, relative to watershed inputs, appears to have increased.

Methods

Because data availability from U.S. agricultural censuses used to construct P budgets and also from monitoring of river P exports varied among years and watersheds, we used two different watershed boundaries for different goals, as shown in Fig. 1. First, to obtain the longest record of historical trends in anthropogenic P loadings to land, we selected 18 LE watersheds with available agricultural census data (Fig. 1 and Table 1). All are within the U.S. for ease of data access and data consistency. The boundaries of all watersheds within the U.S. portion of the Lake Erie Basin (LEB) were delineated based on hydrological classifications of the United States Geological Survey (USGS). These 18 watersheds comprise 54,114 km^2 (70% of the entire LEB) and drain directly to LE or enter Lake St Clair and the Detroit River before reaching LE. Individual watersheds range in size from 662 km^2 (Lake St. Clair) to 17,052 km^2 (Maumee) (Fig. 1 and Table 1). For some analyses we grouped these 18 watersheds into three regions based on geography and land cover: 1) upper western region (UWR) including five watersheds from Lake St Clair to the Huron of Michigan; 2) lower western region (LWR) including six watersheds from the Ottawa-Stony to the Huron-Vermilion; and 3) central and eastern region (CER) consisting of seven watersheds from the Black-Rocky to Buffalo-Eighteenmile.

The second watershed boundary delineation was based on locations of discharge monitoring stations. For this analysis we delineated watershed boundaries upstream of the lower-most USGS gaging station using 30-meter National Elevation Dataset (Fig. 1), as described in Han et al. (2011). Availability of historical data for river export of P limited our investigation of the relationship between anthropogenic P inputs and river P exports to six U.S. watersheds, with a total area of 28,037 km^2 (51% of the U.S. LEB).

The combined landscapes of the 18 watersheds are 66% agricultural, 20% forest, 3% wetland and 9% urban, based on the 1992 National Land Cover Database (NLCD) (MRLC, 1995). Agricultural land is greatest (>84%) in the two western regions of LEB, and more variable in the CER where some watersheds are much more forested (30–55%). The most urbanized watersheds include Lake St. Clair (38%), Detroit (59%), and Cuyahoga (25%) (Table 1). The six watersheds used to examine the relationship between P inputs and riverine TP export were highly agricultural (>77%), with smaller amounts of forest (15%), wetland (3%) and urban land (4%).

Soils of the lower western and central region (from Maumee to the Grand of Ohio) are dominated by clayey till, while the remaining three CER watersheds (from Chautauqua-Conneaut to Buffalo-Eighteenmile)

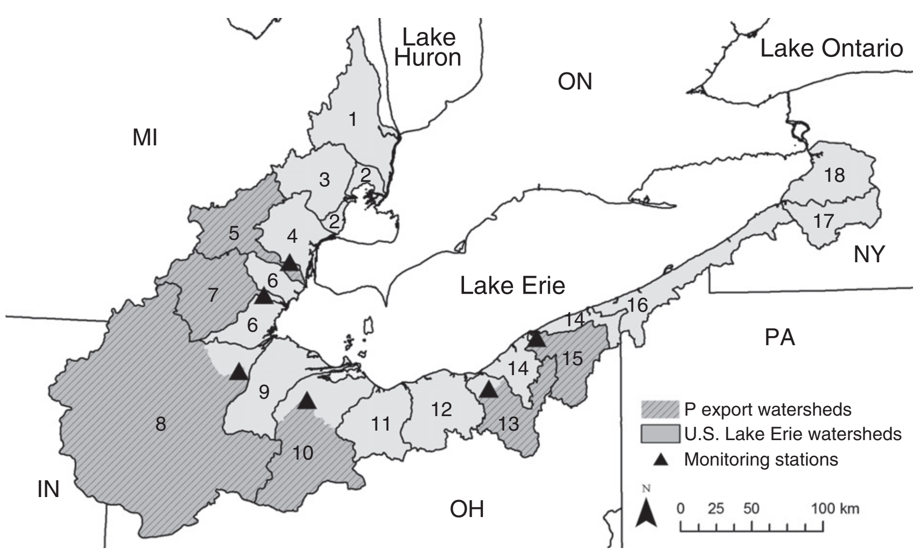

Fig. 1. Location of the eighteen U.S. watersheds for which net anthropogenic P inputs were estimated. See Table 1 for watershed names and characteristics. Triangles denote USGS gage stations where river P export was estimated for six watersheds, and shaded portion of those watersheds corresponds to area used for P input–export comparisons.