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# Persistent and widespread long-term phosphorus declines in Boreal lakes in Sweden

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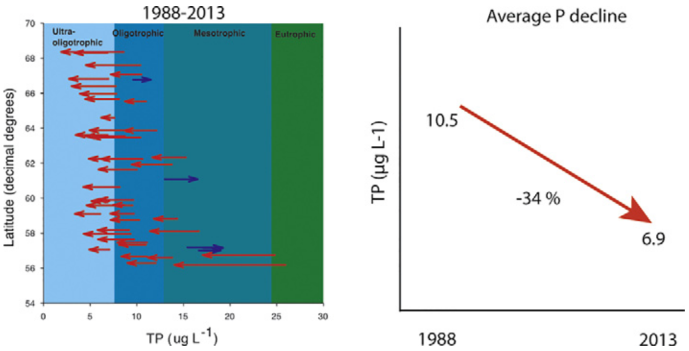
## HIGHLIGHTS

- Substantial, long-term declines in TP were detected in boreal lakes across Sweden.
- Lake trophic status has changed in many lakes to ultra-oligotrophic.
- Increased reliance on forest biomass and hydropower will likely exacerbate P declines.
- Legislation is poorly equipped to handle impairments caused by oligotrophication.

## GRAPHICAL ABSTRACT



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## ABSTRACT

We present an analysis of long-term (1988–2013; 26 years) total phosphorus (TP) concentration trends in 81 Swedish boreal lakes subject to minimal anthropogenic disturbance. Near universal increases in dissolved organic carbon (DOC) concentrations and a widespread but hitherto unexplained decline in TP were observed. Over 50% of the lakes ($n = 42$) had significant declining TP trends over the past quarter century (Sen's slope = 2.5% $y^{-1}$). These declines were linked to catchment processes related to changes in climate, recovery from acidification, and catchment soil properties, but were unrelated to trends in P deposition. Increasing DOC concentrations appear to be masking in-lake TP declines. When the effect of increasing DOC was removed, the small number of positive TP trends ($N = 5$) turned negative and the average decline in TP increased to 3.9% $y^{-1}$. The greatest relative TP declines occurred in already nutrient poor, oligotrophic systems and TP concentrations have reached the analytical detection limit (1 µg $L^{-1}$) in some lakes. In addition, ongoing oligotrophication may be exacerbated by increased reliance on renewable energy from forest biomass and hydropower. It is a cause of significant concern that potential impairments to lake ecosystem functioning associated with oligotrophication are not well handled by a management paradigm focused exclusively on the negative consequences of increasing phosphorus concentrations.

## 1. Introduction

Freshwater productivity can be limited by a number of factors including nutrients (nitrogen, phosphorous, carbon) and light. Phosphorus (P), often the limiting nutrient in lakes, is regulated by atmospheric inputs,

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point and diffuse sources, and processes occurring in the lake and surrounding catchment. Human activity has altered freshwater P availability for centuries; however, most concern has focused on increasing anthropogenic P inputs and subsequent problems associated with eutrophication (Smith and Schindler, 2009). While the prevailing scientific and management paradigm has been that less P is better, studies have shown the deleterious effects of P declines (oligotrophication) on freshwater ecosystems, e.g. reservoirs (Stockner et al., 2000). This is a concern as widespread oligotrophication, which cannot be ascribed to direct anthropogenic pressures, is occurring in lakes and streams across the northern hemisphere (Arvola et al., 2011; Eimers et al., 2009; Hu and Huser, 2014; Stammler et al., 2017; Yan et al., 2008).

There are many anthropogenic and natural factors in the lake and surrounding catchment that can influence in-lake total phosphorus (TP) concentrations (Eq. (1)). These can be broken down into processes operating in the catchment that affect external P loads ($L_{Ext}$; g yr$^{-1}$), in lake processes regulating internal loading ($L_{Int}$: g yr$^{-1}$), in-lake retention ($R_S$; proportion as sedimentation), and climate-related and in-catchment processes controlling runoff (Q: m$^3$ yr$^{-1}$) (Nurnberg, 1984).

$$\mathrm{TP}=\frac{L_{Ext}+L_{Int}}{Q}(1-R_S) \tag{1}$$

As can be seen from Eq. (1), declines in P concentration consistent with oligotrophication can occur due to a decline in loading from internal and/or external sources, an increase in retention, an increase in runoff, or some combination of these factors. Oligotrophication may occur when external loads are reduced as a result of in-catchment processes including e.g. declining deposition, alterations in land management, increased uptake by terrestrial vegetation, or changes in P solubility. In-lake processes (e.g. thermal stratification) can alter sedimentation rates and geochemical factors controlling internal loading and retention. Changes in the timing and amount or runoff will also affect in-lake TP concentrations by influencing both delivery and flushing rates. These factors and the mechanisms by which they may lead to oligotrophication are summarized in Table 1.

Recovery from acidification can alter external and internal loading rates as well as retention, primarily through pH-mediated changes to fluxes of aluminum (Al) to lakes and sediments and dissolved organic matter (DOM) solubility (Huser and Rydin, 2005; Kopáček et al., 2008). Increased DOM fluxes may lead to increased external P loading as dissolved organic phosphorus (DOP) is a component of DOM. Declines in sulfate deposition since the 1980s may increase available soil P-binding sites due to less anionic competition (Geelhoed et al., 1997). However, recovery from acidification may also reduce external P loading because soils recovering from anthropogenic acidification may display increased P binding to (oxyhydroxide) metals (Gustafsson et al., 2012) and clay minerals (Gérard, 2016) that can limit P mobility in the watershed and subsequent transfer to lakes.

Climate change can affect external and internal loading, runoff, and potentially retention (Brantley et al., 2011). Warmer temperatures and a longer growing season can lead to increased P uptake by catchment vegetation (Jonard et al., 2015), changes in catchment hydrology caused by increased evapotranspiration (Crossman et al., 2016), and increases in internal loading (Jensen and Andersen, 1992). If warmer temperatures promote increased in-lake productivity, retention may also increase due to increased rates of sedimentation.

Finally, declining atmospheric P deposition may contribute to oligotrophication through a reduction in external loading (Zhai et al., 2009). Combustion-related sources of atmospheric P deposition related to combustion have decreased over Europe since the 1980s (Wang et al., 2015b); however, few long-term trends for total (natural plus anthropogenic) P deposition have been detected (Tipping et al., 2014) and none were detected at Canadian sites where surface water P declines have occurred (Eimers et al., 2009).

In boreal lakes, most water column P is present in organic forms, most of which are associated with DOM (Palviainen et al., 2016). Brownification, related to increasing surface water dissolved organic carbon (DOC) concentrations (a proxy for DOM), has been reported across much of the northern hemisphere and has been ascribed to recovery from acidification (Monteith et al., 2007) and a changing climate (Haaland et al., 2010; Hongve et al., 2004). If there are no changes in hydrology or DOM stoichiometry, increasing DOM fluxes from watersheds to lakes should also increase rates of external loading and in-lake P concentrations (Eq. (1)), but this has clearly not been the case in other studies (Arvola et al., 2011; Eimers et al., 2009; Hu and Huser, 2014; Yan et al., 2008).

Furthermore, darker conditions associated with increased DOC concentrations can alter the energy budget of lakes. Increasing DOC concentrations limit light penetration, enhance thermal stability, and as a result can lead to cooler bottom-water temperatures during the summer (Tanentzap et al., 2008). Reduced light can potentially lower rates of primary productivity (Thrane et al., 2014) and shift aquatic ecosystems from nutrient to light limitation (Karlsson et al., 2009). Stronger and longer thermal stratification can effectively isolate bottom waters from the atmosphere. This may lead to increased bottom water anoxia and internal P loading (Spears et al., 2017). While there is a body of work documenting plausible drivers of temporal P trends (summarized in Table 1), none of the aforementioned mechanisms have been directly linked to the widespread surface water oligotrophication that has been observed across the northern hemisphere.

In this study we assessed long-term (1988–2013) changes to total P (TP) concentrations in a large ($N = 81$) dataset of Boreal lakes across Sweden. All lakes had minimal, direct anthropogenic disturbance in the watershed (e.g. point sources, urbanization or agriculture) or to the lake itself (e.g. liming). Multiple linear regression models were developed to relate TP trends to factors including land-use, catchment soil properties, climate, deposition and in-lake processes. Policy-related implications of declining P concentrations are discussed, and potential exacerbating factors e.g. hydropower and forest harvesting are examined as well.

## 2. Methods

### 2.1. Data collection and handling

To quantify temporal variation in lake water chemistry and assess possible correlates of declining TP in surface waters, we used long-term (1988–2013) Swedish national monitoring program data. The data set originally included 110 lakes (trend lakes covering latitudes 56–68 °N) with no point sources of pollution. All lake data were collected as part of the Swedish national monitoring program (Folster et al., 2014) and analyzed at the water chemistry laboratory (accredited by the Swedish Board for Accreditation and Conformity Assessment) at the Department of Aquatic Sciences and Assessment at the Swedish University of Agricultural Sciences. Epilimnetic samples (0.5 m water column depth) were collected four times per year (spring, summer, fall, winter) and analyzed for a suite of parameters (Table 2). Further details on methods, detection limits, and quality control can be found at the following website: http://www.slu.se/en/departments/aquatic-sciences-assessment/laboratories/geochemical-laboratory/water-chemical-analyses/. The dataset, at least to the authors' knowledge, is unprecedented for its temporal duration, spatial extent (covering nearly the entire latitude range for the Boreal ecosystem) and internal consistency of laboratory methods. Only lakes minimally affected by urbanization (<1% watershed area) or agriculture (< 5% watershed area) were included in the analysis, reducing the original dataset to 81 lakes. Outliers in water quality time series were identified by log transforming all data and excluding any values outside ± 3 standard deviations from subsequent analysis. DOC was determined as total organic carbon (TOC). This was considered acceptable because