Science of the Total Environment 624 (2018) 845–858

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Trends and seasonality of river nutrients in agricultural catchments: 18 years of weekly citizen science in France

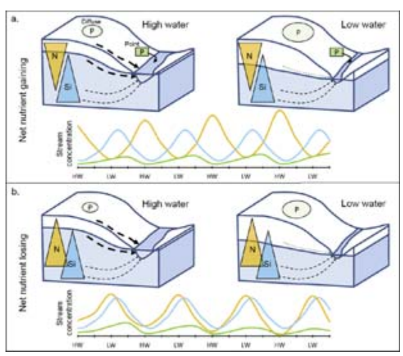
Benjamin W. Abbott [a,b,*], Florentina Moatar [c], Olivier Gauthier [d,e], Ophélie Fovet [f], Virginie Antoine [d], Olivier Ragueneau [d]

[a] Brigham Young University, Department of Plant and Wildlife Sciences, Provo, USA
[b] ECOBIO, OSUR, CNRS, Université de Rennes 1, 35045 Rennes, France
[c] University François-Rabelais Tours, EA 6293 Géo-Hydrosystèmes Continentaux, Parc de Grandmont, 37 200 Tours, France
[d] Laboratoire des Sciences de l'Environnement Marin (LEMAR UMR 6539 CNRS UBO IRD IFREMER), Institut Universitaire Européen de la Mer, Université de Bretagne Occidentale, 29280 Plouzané, France
[e] Observatoire Marin (UMS 3113 CNRS), Institut Universitaire Européen de la Mer, Université de Bretagne Occidentale, 29280 Plouzané, France
[f] UMR SAS, AGROCAMPUS OUEST, INRA, 35000 Rennes, France

HIGHLIGHTS

- High schools measured NO_3^-, PO_4^{3-}, and silica weekly in 13 rivers for 18 years.
- Large decreases of NO_3^- and PO_4^{3-} primarily due to elimination of point sources
- Despite decline, nutrient seasonality did not change for most catchments.
- Concentrations remain high and future improvements may be slower than initial gains.
- Citizen science can produce long-term, medium-frequency water quality data.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 15 August 2017
Received in revised form 29 November 2017
Accepted 16 December 2017
Available online xxxx

Editor: Daniel Wunderlin

Keywords:
Eutrophication
Nitrogen
Phosphorus
Silica
Time series analysis
Citizen science

ABSTRACT

Agriculture and urbanization have disturbed three-quarters of global ice-free land surface, delivering huge amounts of nitrogen and phosphorus to freshwater ecosystems. These excess nutrients degrade habitat and threaten human food and water security at a global scale. Because most catchments are either currently subjected to, or recovering from anthropogenic nutrient loading, understanding the short- and long-term responses of river nutrients to changes in land use is essential for effective management. We analyzed a never-published, 18-year time series of anthropogenic (NO_3^- and PO_4^{3-}) and naturally derived (dissolved silica) riverine nutrients in 13 catchments recovering from agricultural pollution in western France. In a citizen science initiative, high-school students sampled catchments weekly, which ranged from 26 to 1489 km^2. Nutrient concentrations decreased substantially over the period of record (19 to 50% for NO_3^- and 14 to 80% for PO_4^{3-}), attributable to regional, national, and international investment and regulation, which started immediately prior to monitoring. For the majority of catchments, water quality during the summer low-flow period improved faster than during winter high-flow conditions, and annual minimum concentrations improved relatively faster than annual maximum concentrations. These patterns suggest that water-quality improvements were primarily due to elimination of discrete nutrient sources with seasonally-constant discharge (e.g. human and livestock wastewater), agreeing with available land-use and municipal records. Surprisingly, long-term nutrient decreases were not accompanied by

* Corresponding author at: Brigham Young University, Department of Plant and Wildlife Sciences, Provo, USA.
E-mail address: benabbott@byu.edu (B.W. Abbott).

https://doi.org/10.1016/j.scitotenv.2017.12.176

changes in nutrient seasonality in most catchments, attributable to persistent, diffuse nutrient stocks. Despite decreases, nutrient concentrations in almost all catchments remained well above eutrophication thresholds, and because additional improvements will depend on decreasing diffuse nutrient sources, future gains may be much slower than initial rate of recovery. These findings demonstrate the value of citizen science initiatives in quantifying long-term and seasonal consequences of changes in land management, which are necessary to identify sustainable limits and predict recovery timeframes.

1. Introduction

Nutrient pollution of freshwater and estuarine water bodies is degrading ecological functioning and ecosystem services at a global scale. Economic damage from nitrate (NO_3^-) contamination alone is estimated to cost 0.2 to 2.3 trillion USD annually—up to 3% of the global gross domestic product (Bodirsky et al., 2014; Sutton and UNEP, 2013). In the past 50 years, global fertilizer use increased by over 500% (Foley et al., 2011), and nitrogen and phosphorus pollution are expected to keep pace with population growth and meat consumption, increasing until the middle of the century (Canfield et al., 2010; Seitzinger et al., 2010). At the same time, human activity, primarily agriculture, has disturbed approximately three-quarters of the Earth's ice-free land surface (Ellis et al., 2010), reducing the capacity of ecosystems to buffer and process nutrient inputs (Pinay et al., 2015; Seitzinger et al., 2006; Thomas et al., 2016a). The resulting nutrient excess has contaminated groundwater aquifers (Aquilina et al., 2012; Ben Maamar et al., 2015; Jasechko et al., 2017) and increased the flux of nutrients through river systems to the sea, creating eutrophic dead zones in many lakes and estuaries, and altering biogeochemistry throughout the ocean (Diaz and Rosenberg, 2008; Howarth, 2008; Reed and Harrison, 2016). In response to this accelerating environmental crisis, governments have funded a broad range of programs to monitor and improve water quality (Andreen, 2004; Hering et al., 2010; Liu and Yang, 2012; Withers and Haygarth, 2007), but results of interventions have been mixed (Jarvie et al., 2013; Jenny et al., 2016; Wilcock et al., 2013). In many developed countries, phosphorus concentration and flux from large catchments have decreased over the last two decades, mostly due to treatment of point sources (e.g. waste water treatment plants), but NO_3^-, which is highly mobile and has many diffuse sources, has showed little change (Minaudo et al., 2015; Moatar et al., 2017). Furthermore, in small to medium catchments, where the bulk of terrestrial nutrient loading occurs (Abbott et al., 2017a; Alexander et al., 2007), trends are even less clear, with nutrient fluxes differing substantially among apparently similar catchments (Aubert et al., 2013b; Burt and Pinay, 2005; Stålnacke et al., 2003).

Two primary factors complicate the quantification of water-quality trends in small catchments. First, nutrient concentrations and fluxes through river networks vary strongly at event, seasonal, and interannual timescales (Gascuel-Odoux et al., 2010; Moatar et al., 2013; Thomas et al., 2016a), meaning that repeat measurements are necessary to characterize the overall nutrient condition of a catchment. Second, because nutrient residence times can be on the order of decades in soil, unsaturated zone, and groundwater (Howden et al., 2011; Kolbe et al., 2016; Meter et al., 2016; Sebilo et al., 2013), substantial time lags can exist before changes in management practice are reflected in water quality. Consequently, quantifying the effectiveness of changes in land management requires both long-term (Abbott et al., 2017a; Burt et al., 2011) and high-frequency monitoring (Abbott et al., 2016; Aubert et al., 2013a; McDonald et al., 2016; Vilmin et al., 2016). One approach to achieving this ambitious goal is to involve non-professional community members in sample collection (Bonney et al., 2014). Citizen science has been used both as a tool to extend ecological observation and a mechanism to improve the general public's engagement with science (Bonney et al., 2014; Cohn, 2008; Silvertown, 2009). Though not without limitations in data reliability and acceptance by researchers (Conrad and Hilchey, 2011), citizen science has successfully been used for a variety of projects including mapping the distribution of species, quantifying anthropogenic impacts, analyzing visual data, and monitoring water quality (Breuer et al., 2015; Gardiner et al., 2012; Kyba et al., 2013; Savage, 2012).

In this context, we analyzed a never-published, 18-year time series of riverine nutrient concentrations in 13 catchments recovering from agricultural pollution in western France. Samples collected weekly from 1998 to 2016 by volunteer high school students were analyzed for NO_3^-, phosphate (PO_4^{3-}), and dissolved silica (DSi). We analyzed long-term trends and changes in seasonality, i.e. periodicity of cycles, timing of maximum and minimum concentrations, and relationships between discharge and concentration. We hypothesized generally that seasonal fluctuations in stream nutrient concentrations would depend on interactions between three factors (Fig. 1): 1. vertical and horizontal location of nutrient sources, which is a function of current and past land use and land cover, 2. seasonal changes in water flowpath and associated residence time, and 3. seasonal and long-term changes in biogeochemical nutrient retention and removal (e.g. denitrification or uptake by plants and microorganisms). Based on this hypothesis, we predicted that discharge and concentration would fluctuate asynchronously for nutrients that increase with depth (e.g. DSi, which is primarily geogenic, or NO_3^- in catchments with a legacy of groundwater pollution) and synchronously for those that decrease with depth (e.g. NO_3^- in a catchment with current excess nitrogen input; Fig. 1a). We also hypothesized that decreases in diffuse-source nutrients would more rapidly improve stream concentrations during the high-water period when shallow flowpaths with shorter residence times contribute a larger portion of discharge, but that elimination of seasonally-constant point sources (e.g. waste water effluents) would result in relatively faster nutrient decreases during low flows (Fig. 1b). We tested these predictions with a variance-partitioning approach, comparing the magnitude of seasonal, annual, and interannual changes in nutrient concentrations.

2. Methods

2.1. Land-use history in far western France

The peninsula of Brittany is part of the Armorican Massif, which is underlain by crystalline bedrock and overlain by Quaternary loess and alluvial and colluvial deposits (Kolbe et al., 2016). Silty loam is the dominant soil texture. Brittany has a maritime climate with monthly average temperatures ranging from 17.5 °C in July to 5 °C in December and mean annual precipitation of around 1000 mm, roughly evenly distributed through the year (Thomas et al., 2016a). While the peninsula's many coastal catchments have relatively homogeneous climate and lithology, there is a great diversity of current and past land use, providing an ideal template to test the impact of agriculture on water quality. For example, annual NO_3^- fluxes vary from 9 to 89 kg N ha^{-1} y^{-1} among catchments (Gascuel-Odoux et al., 2010), and phosphorus fluxes vary from 0.1 to 1.4 kg P ha^{-1} yr^{-1} (Delmas et al., 2015; Dupas et al., 2015), covering most of the range observed throughout western Europe (Dupas et al., 2013; Poisvert et al., 2017).

The western tip of Brittany, where our 13 study catchments are located, has a long history of intensive animal husbandry and row-crop agriculture (Fig. 2). Brittany represents only 7% of French agricultural