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Low phosphorus release but high nitrogen removal in two restored riparian wetlands inundated with agricultural drainage water

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ABSTRACT

Re-established riparian wetlands used to mitigate nitrogen (N) loss from agricultural soils to surface water may lose phosphorus (P) from the top soils that often have received fertilizers. This could lead to eutrophication of lakes and estuaries. For a 2-year period we established mass balances of N and P in two restored riparian wetlands of ~0.6 ha situated on mineral soil. Monitoring began 5 years after restoration. Both wetlands received drainage water from upland agricultural fields rich in nitrate (1.5–12.3 mgN L^{-1}) and low in total P (TP) (0.016–0.04 mg P L^{-1}). Water balances were reasonably accounted for (15% imbalance at most). Water passed the wetlands as sheet flow without exchange with groundwater because of clay horizons in sub-soils, and sheet pilings along the stream banks allowed continuous measurements of inflow and outflow. The Egeskov riparian wetland (wetland:upland ratio 0.13) removed 121 and 28 kg N ha^{-1} yr^{-1} (43 and 75% of the load) and retained 0.08 kg P ha^{-1} (6% of the load) in year one and had a net release of 0.15 kg P ha^{-1} (25% of the load) in year two. The Stor Å riparian wetland (wetland:upland ratio 0.02) removed 229 and 158 kg N ha^{-1} yr^{-1} (32 and 26%). Net releases of P were 0.33 and 0.90 kg P ha^{-1} yr^{-1} (22 and 127%). Nitrogen removal rates are on par with published rates for similar wetlands, while the P release rates appear surprisingly low. Phosphate outlet concentrations resembled the equilibrium concentrations (EPC_0) where no phosphate exchange occurred between top soils and drainage water, suggesting that P release or retention was controlled by phosphate adsorption. This value was 0.015 mg P L^{-1} for Egeskov and 0.047 mg P L^{-1} for Stor Å. The high phosphate affinity was probably governed by high ratios between oxidized iron and iron-bound P. The top soils (10 cm) contained 87 and 201 kg P ha^{-1} as iron-bound P and herbaceous vegetation accumulated 10.7 and 16.5 kg P ha^{-1} yr^{-1}. These figures are 55–136 and 8–11 times higher than the annual P-load to the wetlands, and we suggest that annual harvest of vegetation could maintain or even improve the P retention capacity of these wetlands.

1. Introduction

In Western Europe diffuse losses of nutrients from agricultural watersheds constitute a major threat to the water quality in lakes, estuaries, and coastal seas. In Denmark and other countries where rivers discharge to restricted water bodies, such as the Baltic Sea or the Kattegat estuary, much effort has been dedicated to reducing the nitrogen (N) run-off because external N loading has been identified as the major cause of nuisance phytoplankton blooms in open waters (e.g. Boesch et al., 2006). In coastal waters, N may also limit algae production, but in spring and early summer phosphorus (P) is likely to be the key limiting nutrient (Conley, 1999;

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Kronvang et al., 2005a). For inland lakes it is well established that increasing external P loading accelerates eutrophication (e.g. Wetzel, 2001), and a P loading reduction is therefore needed before implementing lake restoration measures (e.g. Jeppesen et al., 2009). Since natural wetlands most often retain nutrients from passing water (e.g. Fisher and Acreman, 2004), re-establishment of wetlands or of semi-natural wetlands on low-lying fields has become an increasingly popular method to mitigate nutrient run-off from non-point sources to inland and coastal waters (Leonardson et al., 1994; Tanner et al., 2010; Hoffmann et al., 2011; Schoumans et al., 2011). In Denmark, where 62% of the area is used for agriculture, re-establishment of riparian wetlands has been included in several action plans since 1998 with the aim to decrease N loading to coastal waters, and so far ∼10.000 ha of wetlands have been established in Denmark (Hoffmann and Baattrup-Pedersen, 2007). Meanwhile, experiences from Germany have shown that rewetting of former wetlands (i.e. peaty fens) may lead to mobilization of P from the flooded soil (Zak and Gelbrecht, 2007). Similarly, in a review by Fisher and Acreman (2004) it was found that retention of P in wetlands is more variable than that of N, and some wetlands may even show net P release. Thus, in Denmark, the re-established riparian wetlands on former agricultural low-lying fields, with the objective of N removal, may pose a threat to inland water bodies and estuaries as the flooded soils may contain large amounts of P in the plough layer due to excessive spreading of manure and chemical fertilizers (Hoffmann et al., 2009).

One of the methods applied to re-create riparian wetlands is to intercept drain pipes at the border of a low-lying field so that it becomes inundated with the agricultural drainage water that would otherwise run under the field and directly into the stream (e.g. Voight et al., 1994). This practice to reduce diffuse N run-off is considered one of the key measures for reaching the goals for good water quality in surface waters set by the EU Water Framework Directive (EU Commission, 2000). However, experience with the performance of re-established semi-natural wetlands in the treatment of agricultural drainage water seems to be scarce. A few studies (Kovacic et al., 2000; Jordan et al., 2003; Beutel et al., 2009; Tanner and Sukias, 2011) have shown that N removal in such semi-natural wetlands generally is high (246–424 kg N ha^{-1} yr^{-1}), while retention of P is low (Kovacic et al., 2000) or varies from year to year often with net loss of P from the wetland (Jordan et al., 2003; Koskiaho et al., 2003; Tanner and Sukias, 2011).

Nitrate is the dominant N form in drainage water and removal of nitrate in wetlands takes place through the denitrification process (e.g. Reddy and Delaune, 2008), although uptake of N in plants may temporarily immobilize 83.0–146.1 kg N ha^{-1} yr^{-1} of the plant biomass (Hefting et al., 2005; Hoffmann et al., 2006a), which at the same time contributes with electron donors to denitrification upon decay (Tanner et al., 1995; Fennessy and Cronk, 1997; Reddy and Delaune, 2008). Phosphorus retention in wetlands dominated by surface water flow is controlled by physical, geochemical and biological processes such as deposition of suspended solids, sorption and precipitation, reduction and oxidation processes, plant uptake, and biological mineralization-immobilization dynamics (Hill, 1996; Sabater et al., 2003; Hoffmann et al., 2009). Especially, the abiotic regulation of P release and retention may include a series of parameters such as pH, redox potential, soil content of iron, aluminum and calcium as well as organic matter content, soil P content and P-loading (e.g. Reddy and Delaune, 2008). Overall, Fisher and Acreman (2004) found that re-established riparian wetlands are less efficient in retaining nutrients than natural wetlands and also that net P release is observed more often when measurements of water and nutrient balances have been conducted with high sampling frequency. They ascribe this observation to the fact that most of the annual P transport occurs during peak-flow incidents and is therefore only captured in the mass balance if sampling is undertaken sufficiently frequent.

The objective of this study was to examine if two restored riparian wetlands, re-established for N removal, would exhibit net release of P due to mobilization of primarily iron-bound P from the formerly fertilized soil. We compared and quantified the retention or release of N and P in two re-established surface flow wetlands receiving agricultural drainage water under varying hydraulic conditions, identified parameters responsible for P sorption and desorption, quantified P pools in the top soil, and estimated temporal immobilization of N and P in the aboveground biomass. To obtain good nutrient mass balances we monitored water fluxes by continuous measurement of inflowing and outflowing surface water during two consecutive discharge seasons (6–9 months from autumn to spring when water was running in the inlet drain pipes) and undertook high frequency sampling of water for nutrient analyses (every 3 h) using automated sampling equipment.

2. Study areas and methods

The study was carried out at two restored riparian wetland sites situated 60 km apart on the island of Funen, Denmark. The study was undertaken 5 years after re-establishment of the two riparian wetlands in order to overcome the potentially unrealistically high nutrient uptake rates occurring in the restored wetlands in the initial and thus transitional stage (e.g. Beutel et al., 2009). Also, changes in redox conditions just after re-establishment may bias the monitoring results. Average annual precipitation is 740 mm and annual mean temperature is 8.2 °C at both sites. Both sites are situated immediately next to a stream, and both have been used for cereal production for more than 50 years. The restored riparian wetlands are semi-natural and inundated with drainage water from adjacent upland fields, but no attempts have been made to improve certain wetland functions such as hydraulic efficiency and nutrient retention by shaping. Thus, the two riparian wetlands were restored with the sole purpose of retaining N leached from the fields through tile drainage systems. Study site Egeskov (10°30′E; 55°09′N) located 3 km from Egeskov Castle is 6200 m^2 and receives drainage water from an upland agricultural field with an area of 4.5 ha (wetland:upland ratio 13.7%). Two drainage pipes were disconnected at the border between the field and the wetland, thereby allowing drainage water to inundate the wetland. The wetland was created in 2001 and is part of a bigger 65 ha wetland restoration project in Karlsmosen (see Hoffmann and Baattrup-Pedersen, 2007). The soil profile is a typical gley with a gray matrix and iron oxide in larger pores. The upper 60 cm is very clayey with low hydraulic conductivity. Study site Stor Å is located close to the village of Brenderup (9°59′E; 55°29′N) and has an area of 5870 m^2. The wetland receives tile drainages water from a 24 ha agricultural field (wetland:upland ratio 2.4%). It was created in 1990 by the County of Funen. The soil profile is clayey and a 20–30 cm clay layer is located at ∼1 m depth under most of the wetland.

2.1. Field set-up at Egeskov

The restored riparian wetland Egeskov is hydrologically isolated from the remaining re-established wetland due to topography and soil texture. The two inlet drainpipes to the riparian wetland were mounted with electromagnetic flow meters (Krohne, Germany). Both inlets were measured continuously and data were stored on a data logger (Campbell, CR10x, Shepshed, England). Due to the topography water ran as sheet flow across the wetland to the nearby stream, Hågerup Å. To establish a water balance for the wetland a sheet piling was established at the river bank, and at the