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Effect of organic enrichment and thermal regime on denitrification and dissimilatory nitrate reduction to ammonium (DNRA) in hypolimnetic sediments of two lowland lakes

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ABSTRACT

We analyzed benthic fluxes of inorganic nitrogen, denitrification and dissimilatory nitrate reduction to ammonium (DNRA) rates in hypolimnetic sediments of lowland lakes. Two neighbouring mesotrophic (Ca' Stanga; CS) and hypertrophic (Lago Verde; LV) lakes, which originated from sand and gravel mining, were considered. Lakes are affected by high nitrate loads (0.2–0.7 mM) and different organic loads. Oxygen consumption, dissolved inorganic carbon, methane and nitrogen fluxes, denitrification and DNRA were measured under summer thermal stratification and late winter overturn.

Hypolimnetic sediments of CS were a net sink of dissolved inorganic nitrogen (−3.5 to −4.7 mmol m^{-2} d^{-1}) in both seasons due to high nitrate consumption. On the contrary, LV sediments turned from being a net sink during winter overturn (−3.5 mmol m^{-2} d^{-1}) to a net source of dissolved inorganic nitrogen under summer conditions (8.1 mmol m^{-2} d^{-1}), when significant ammonium regeneration was measured at the water–sediment interface. Benthic denitrification (0.7–4.1 mmol m^{-2} d^{-1}) accounted for up to 84–97% of total NO_3^- reduction and from 2 to 30% of carbon mineralization. It was mainly fuelled by water column nitrate. In CS, denitrification rates were similar in winter and in summer, while in LV summer rates were 4 times lower. DNRA rates were generally low in both lakes (0.07–0.12 mmol m^{-2} d^{-1}). An appreciable contribution of DNRA was only detected in the more reducing sediments of LV in summer (15% of total NO_3^- reduction), while during the same period only 3% of reduced NO_3^- was recycled into ammonium in CS.

Under summer stratification benthic denitrification was mainly nitrate-limited due to nitrate depletion in hypolimnetic waters and parallel oxygen depletion, hampering nitrification. Organic enrichment and reducing conditions in the hypolimnetic sediment shifted nitrate reduction towards more pronounced DNRA, which resulted in the inorganic nitrogen recycling and retention within the bottom waters. The prevalence of DNRA could favour the accumulation of mineral nitrogen with detrimental effects on ecosystem processes and water quality.

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1. Introduction

Transport and fate of nitrogen species across watersheds and inland aquatic ecosystems are critical to determining nitrogen impacts on water quality and ecosystem health (Vitousek et al., 1997; Galloway et al., 2004; Howarth and Marino, 2006; Seitzinger et al., 2006). Denitrification has been widely studied as the main nitrogen sink, although debate is still open on its spatial and temporal variability, controlling factors and cause–effect relationships between loads, processes and transformations (Pina-Ochoa and Alvarez-Cobelas, 2006; Seitzinger et al., 2006; Groffman et al., 2009).

Lakes and wetlands are considered sites in the landscape where excess dissolved nitrogen is temporarily or permanently removed from the water (Saunders and Kalff, 2001a; David et al., 2006; Seitzinger et al., 2006; Schubert et al., 2006; Harrison et al., 2009). In stratified lakes, hypolimnetic nitrogen transformations are mainly controlled by benthic processes mediated by microbial communities. Bacterial ammonification, nitrification, denitrification of dissolved nitrates diffusing from the water column (D_W) or coupled to nitrification (D_N), dissimilatory nitrate reduction to ammonium (DNRA) and anaerobic ammonium oxidation are the main nitrogen pathways (Burgin and Hamilton, 2007). The balance among the different pathways depends on temperature, oxygen, nitrate availability and organic enrichment in the sediment (Saunders and Kalff, 2001b; Pina-Ochoa and Alvarez-Cobelas, 2006; Seitzinger et al., 2006). These in turn are influenced by water stratification and overturn (Mengis et al., 1997; Burgin and Hamilton, 2007; Matthews et al., 2008).

Relationships between denitrification and DNRA with ecosystem properties are of particular interest to quantify actual rates of nitrogen removal and recycling and thereby to understand how ecosystem modification can alter the nitrogen cycle. To date, however, only few studies have assessed the ability of lakes to sequester or eliminate nitrogen relative to ecosystem properties (Mengis et al., 1997; Saunders and Kalff, 2001b; David et al., 2006; Seitzinger et al., 2006; Weyhenmeyer et al., 2007). Few studies have directly quantified denitrification in hypolimnetic lake sediments, while nitrogen losses were mainly inferred from mass balances or model simulations at different spatial scales (Harrison et al., 2009). In addition, DNRA rates in aquatic sediments have been measured only in a few occasions with parallel measurements of denitrification and DNRA (Burgin and Hamilton, 2007). These studies have mainly been performed in coastal marine environments (Christensen et al., 2000; An and Gardner, 2002; Nizzoli et al., 2006).

Lakes and reservoirs in the agricultural landscape are subject to increasing inputs of nitrates and organic matter. Here, under thermal stratification, persistent hypoxia or even anoxia can establish, with the onset of anaerobic processes and reducing (sulphidic) conditions. To some extent, these conditions are favourable to nitrate removal by denitrification. However, there is evidence suggesting that under highly reduced conditions, DNRA can prevail over denitrification (Brunet and Garcia-Gil, 1996; Burgin and Hamilton, 2007). Under these conditions DNRA could induce a feedback loop, keeping high concentrations of mineral nitrogen within the lake.

The main goal of this study was to analyze how organic enrichment and hypolimnetic conditions influence the benthic metabolism and the fate of reactive nitrogen in sediments of lowland lakes. In particular we: (1) quantified denitrification and DNRA rates and their relative importance; (2) evaluated the role of denitrification as a mineralization pathway; and (3) analyzed to what extent organic load, oxygen depletion and reducing conditions affect reactive nitrogen recycling and retention within lakes.

We measured benthic oxygen fluxes, organic matter mineralization rates, inorganic nitrogen fluxes, denitrification and DNRA rates in hypolimnetic sediments of two neighbouring artificial lakes with different trophic status and hypolimnetic conditions. Measurements were made under summer thermal stratification and late winter overturn to represent critical times of nitrogen cycling. We also measured depth profiles of temperature, oxygen and dissolved inorganic nitrogen throughout the year, to provide context for rate measurements. Both lakes are fed by the same nitrate rich groundwater, which makes them suitable for a comparative study of lowland freshwater ecosystems with a similar nitrogen contamination but with different organic loads and oxygen availability.

2. Materials and methods

2.1. Study area

The study was conducted in two neighbouring lakes (distance < 2 km), formed by sand and gravel mining. These are close to the main course of the Po River near Piacenza (Northern Italy). The main features of the lakes are reported in Table 1. In lake Ca' Stanga (CS), sand extraction ceased in April 2004. Afterwards the littoral zone was restored and the ecosystem protected against possible direct pollution. Lake Verde (LV) is about 30 years old and is exploited for fish farming and for recreational angling. CS is mesotrophic and LV hypertrophic (Tavernini et al., 2009). Both lakes had no discrete inlets or outlets. Water inputs were only from direct precipitation, groundwater and overland runoff. During the study period lakes were not subjected to significant fluctuations of the water level.

Table 1 – Ca' Stanga and Lake Verde morphometric data.

	CS	LV
Latitude N	45° 03′ 15″	45° 03′ 33″
Longitude E	09° 47′ 47″	09° 46′ 15″
Maximum length (m)	423	350
Maximum width (m)	319	165
Surface area (m^2)	113,535	32,033
Volume (m^3)	1,018,935	180,595
Maximum depth (m)	17	12.7
Mean depth (m)	9	5.6
Perimeter (m)	1441	845