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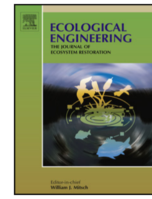

Limitations of stream restoration for nitrogen retention in agricultural headwater streams

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ABSTRACT

High nutrient loading and channelization reduce the nutrient retention capacity of agricultural streams and lead to increases in nutrient downstream transport. The aim of the current study was to study the effects of channel reconfiguration and riparian reforestation on the nitrogen retention capacity of eutrophic agricultural headwater streams. In addition, we investigated the role of stream sediments as a nitrogen sink or source for the stream ecosystem.

We compared two restored reaches with two morphologically pristine and four channelized reaches in an agricultural catchment in the north-east of Austria regarding in-stream ammonium uptake, whole-reach retention of dissolved inorganic nitrogen, potential denitrification enzyme activity, and sedimentary ammonium release.

Restored and pristine reaches exhibited significantly shorter ammonium uptake lengths (330 m) and larger mass transfer coefficients (2.7×10^{-5} m s^{-1}) than channelized reaches (2500 m and 1.1×10^{-5} m s^{-1}, respectively). Increased ammonium uptake was positively correlated with increased transient storage in restored and pristine reaches. Total DIN retention was slightly, though not significantly higher in restored sections (average rates 0.06 g DIN m^{-2} h^{-1}) and showed signs of temporal nitrogen saturation in all reaches. In general, sediments were characterized by small grain sizes (0.04–0.31 mm), high ammonium (60–215 μg g^{-1} DW), and low nitrate concentrations (0.4–5.7 μg g^{-1} DW). Ammonium was released from sediments of all reaches below concentrations of 100 μg NH_4^+-N L^{-1} in the overlying water column which shows the high potential of nutrient-rich sediments to act as an internal ammonium source for the stream ecosystem. Potential denitrification was lowest in sediments of restored reaches and significantly increased after nitrate amendment to 3–26 mg N m^{-2} h^{-1}.

The study reveals that stream sediments, which are loaded with nutrient-rich soil from the agricultural catchment, may limit the effects of stream restoration in agricultural streams. In order to improve the nutrient retention capacity of agricultural streams, reach-scale restoration measures have to be combined with measures in the catchment which reduce nutrient and soil inputs to streams.

1. Introduction

The intensification of agriculture during the last century has impacted the integrity and function of streams considerably (Bernhardt and Palmer, 2011; Dodds and Oakes, 2008; Hancock, 2002; Riseng et al., 2011). An increasing proportion of the landscape has been turned into arable land, thereby altering the vegetation, soil properties, and the hydrologic regime of the catchment and depriving streams of their natural riparian buffer zones (Gordon et al., 2008; Verhoeven et al., 2006). Elevated nutrient concentrations in soils and groundwater, resulting from excessive fertilizer application, decrease the water quality and lead to the eutrophication of agricultural streams (Dodds and Oakes, 2008; Kronvang et al., 2008; Oenema et al., 2005).

Abbreviations: α, transient storage exchange coefficient; *A*, cross-sectional area; As, transient storage zone area; *D*, dispersion coefficient; DIN, dissolved inorganic nitrogen; DEA, denitrification enzyme activity; DO, dissolved oxygen; GPP, gross primary production; ER, ecosystem respiration.

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In addition to changes in the catchment, many agricultural streams have been transformed into straight, trapezoid-shaped channels designed for efficient flood removal. The reduced hydrological and morphological diversity, the deployment of in-stream-structures (e.g. through the removal of debris dams), and enhanced water velocities decrease the water residence time and reduce the contact area with biogeochemically reactive surfaces, thus diminishing in-stream nutrient retention (Baker et al., 2012; Bernot et al., 2006; Bukaveckas, 2007; Ensign and Doyle, 2005; Hancock, 2002; Roberts et al., 2007). The loss of this vital ecosystem service is especially problematic in catchments where streams are already heavily loaded with nutrients (Beaulieu et al., 2009; Gücker and Pusch, 2006; Kronvang et al., 2008; Lefebvre et al., 2007; Oenema et al., 2005; Ranalli and Macalady, 2010; Riseng et al., 2011). As nutrient concentrations in the water column increase, in-stream nutrient uptake approaches saturation (Bernot and Dodds, 2005; Bernot et al., 2006; Dodds et al., 2002; Earl et al., 2006). Thus, elevated nutrient inputs from agricultural catchments amplify the negative effects of channelization on the nutrient retention capacity of agricultural streams.

Due to the lack of buffer zones, large amounts of nutrients enter the stream in form of eroded soil particles via overland flow (Birgand et al., 2007; Hamilton, 2012; Hancock, 2002). Accumulations of organic-rich soil in the stream channel alter the sediment structure, restrict the hyporheic water exchange, and lead to oxygen depletion in the sediments, thereby changing the nitrogen cycling in the hyporheic zone (Gordon et al., 2008; Hancock, 2002; Lefebvre et al., 2004; Teufl et al., 2012). In the absence of oxygen, mineralization and nitrification becomes restricted, while denitrification and dissimilatory reduction of nitrate to ammonium may be enhanced (Arango et al., 2007; Harrison et al., 2012). Due to high organic matter contents and small grain sizes, sediments of agricultural streams have the potential to remove substantial amounts of stream water nitrate via denitrification, if the surface water is in contact with denitrifying sites in the sediments (Arango et al., 2007; Birgand et al., 2007; Lefebvre et al., 2004). In contrast to nitrate, ammonium is usually accumulated in the anaerobic sediments of agricultural streams (Lefebvre et al., 2004; Teufl et al., 2012) and may be released into the water column through diffusion, bioturbation, or sediment mobilization (Birgand et al., 2007; O'Brien et al., 2012). Sediments of agricultural streams may hence act as sinks or sources for different nitrogen species, depending on concentration gradients at the water–sediment interface, sediment structure, and the duration and frequency of contact between stream water and sediment particles (Birgand et al., 2007). As the last two factors are determined largely by the hydrology and morphology of the stream, channelization and channel reconfiguration may affect the sink-source function of sediments for nitrogen considerably (Hancock, 2002; Harrison et al., 2012; Lefebvre et al., 2004).

During the last decades, channel reconfiguration has been increasingly used to reverse stream degradation, restore the morphological and hydrological heterogeneity, re-connect streams with their riparian zones, and initiate the rehabilitation of stream functions and ecosystem services (Baker et al., 2012; Bernhardt and Palmer, 2011; Bukaveckas, 2007; Craig et al., 2008). Particularly in headwater streams, channel reconfiguration is also expected to restore the natural capacity of in-stream nitrogen uptake and storage (Craig et al., 2008). However, in agricultural catchments, land-cover conversion and the on-going intensive agricultural land use may significantly restrict the effectiveness of channel reconfiguration to improve in-stream nitrogen retention (Bernhardt and Palmer, 2011). Legacies in groundwater and soils may hold nutrient background concentrations at an elevated level for decades, thereby protracting an effective reduction of nutrient inputs to stream channels (Gordon et al., 2008; Hamilton, 2012; Oenema et al., 2005; Verhoeven et al., 2006). Considering the continued nutrient loading of surface and subsurface waters, the effects of channel reconfiguration on nitrogen spiralling and in-stream nitrogen uptake is a key question for the management of agricultural streams (Baker et al., 2012; Ranalli and Macalady, 2010). In the present study, we investigated the potential of stream restoration to increase the nitrogen retention capacity of eutrophic agricultural headwater streams. Restoration measures included channel reconfiguration and riparian reforestation. In specific, we aimed to answer the following questions:

(1) What is the effect of stream restoration on nitrogen uptake at the reach scale?
(2) Does restoration affect the denitrification potential and net ammonium flux in stream sediments?

For that purpose, we compared two restored headwater reaches with two morphologically pristine and four channelized reaches within an intensively used agricultural catchment in the north-east of Austria. In stream uptake of nitrogen was measured via short-term additions of ammonium, which is readily taken up by the biota (Birgand et al., 2007; Gücker and Pusch, 2006). Whole-reach nitrogen retention capacity was estimated via the net export of dissolved inorganic nitrogen during low water level. We also measured denitrification potential and potential ammonium flux from sediments of different reaches exposed to a gradient of nitrate and ammonium concentrations.

The study was based on the following hypotheses:

(1) Due to increased hydrologic retention, restored and morphologically pristine meandering reaches will exhibit increased in-stream ammonium uptake compared to channelized reaches, showing shorter uptake lengths and higher uptake velocities.
(2) As a result of increased nitrogen uptake, restored and morphologically pristine reaches will show a reduced net export of dissolved inorganic nitrogen during low water level compared to channelized reaches.
(3) Sediments of restored and morphologically pristine reaches will show lower potential ammonium release rates than those of channelized reaches due to coarser grain sizes and lower sedimentary ammonium contents. Ammonium release will increase with decreasing stream water concentrations.
(4) Due to coarser grain sizes, sediments of restored and morphologically pristine reaches will also show a lower denitrification potential than channelized reaches. The denitrification potential will increase with increased stream water nitrate concentrations.

2. Study area

The Weinviertel in the north east of Austria is one of the most productive agricultural regions of the country. Intensive agriculture prevails the catchment with cultivation of grain (wheat, barley, rye), wine, and sugar beet (Weigelhofer et al., 2012). The study area belongs to the Molasse Zone and the Vienna Basin, characterized by gravel, sand, clay, and marly siltstone. Average annual precipitation is between 500 and 600 mm.

Until the 18th and 19th centuries, the Weinviertel was predominantly marshland with small, meandering, and often intermittent streams. With the intensification of agriculture, large parts of the original landscape were transformed into arable land. Most headwater streams were excavated and straightened, turning them into deeply incised channels designed for a fast removal of surface water