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Suitability of degraded peat for constructed wetlands — Hydraulic properties and nutrient flushing

Christian Kleimeier [a,*], Ulf Karsten [b], Bernd Lennartz [a]

[a] *University of Rostock, Faculty of Agricultural and Environmental Sciences, Justus-von-Liebig Weg 6, 18059 Rostock, Germany*
[b] *University of Rostock, Institute of Biological Sciences, Albert-Einstein-Strasse 3, 18057 Rostock, Germany*

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ABSTRACT

Nitrate removal from runoff from agricultural land is in general required to reach a “good chemical status” of surface and groundwater bodies according to the European Water Framework Directive. Removing nitrates via heterotrophic denitrification is highly effective but requires stable anoxic environmental conditions as well as available organic carbon as electron donator. Constructed wetlands (CWs), established on peat soils, through which the nitrate-loaded water is routed, may provide denitrification favorable conditions. To study nitrate turnover, hydraulic properties and possible negative side effects of CWs on formerly drained fens, we developed a mesocosm experiment with vertical flow and an open water surface. The first flushing of nitrate during the exchange of the initial pore volume was quantified with 0.58 g NO_3–N kg^{-1} organic substance. Both nitrate and sulfate were released faster and in higher concentrations than DOC and with a ratio corresponding to the composition of the peat. Redox potential measurements revealed that denitrifying conditions established in certain soil depths after roughly 40 days of continuous flux. Transport properties were obtained from analyzing tracer breakthrough curves. It could be demonstrated that the degraded peat had a dual porosity structure. Subjected to nitrate enriched water for two years, the immobile pore water fraction increased from 40 to 80% probably because of physical consolidation processes and microbial activity and subsequent clogging of pores. This was not considered as negative since denitrification processes are believed to preferably operate in immobile, oxygen depleted water regions. We concluded that the first flushing of mineralized nitrate upon rewetting after onset of flux may compromise any positive clean up and nitrate removal effects occurring during long-term operation of peat-wetlands. It is thus advisable to recycle the water during early stages of the establishment of constructed wetlands.

1. Introduction

Decreasing the nitrate concentration in runoff from intensively used agricultural land is often required to achieve the “good chemical status” of surface waters according to the European Water Framework Directive (European Parliament and European Council, 2000). While nitrate is absorbed from the growing vegetation in spring and summer, it is discharged from the soil during winter and early spring through rapid soil water movement. Nitrate possesses a high solubility in water and is transported as mobile anion with the seeping soil water from the nitrate enriched top soil into deeper soil layers. Excess nitrate frequently passes through the artificial drainage system into the surface water, especially at high flow rates, which occur prior to the vegetation period in early spring. For instance, in the northern German lowlands the average discharged amount was found to vary between 3.4 and 21.8 kg N ha^{-1} a^{-1} (Tiemeyer et al., 2008). Especially during peak runoff events the nitrate concentration in the runoff water is not only exceeding the drinking water critical value of 11.3 mg L^{-1} NO_3^-–N, but often falls within the worst water quality class of >20 mg L^{-1} NO_3–N (LAWA, 1998).

Constructed wetlands are engineered to utilize natural degradation processes in a more controlled environment (Vymazal, 2011). They are simple to build and cost effective, blend into the landscape, meet ecologically valuable features and can be operated without substantial effort. However, constructed wetlands, which are designed to foster nitrate reduction, have to meet certain boundary conditions.

Denitrification, the reduction of nitrate to atmospheric nitrogen, is a microbiologically mediated process under reductive and anoxic conditions. These conditions can be established in a constructed wetland by creating permanent waterlogged (saturated) conditions. From a biochemical point of view, denitrification is a bacterial process in which nitrogen oxides (in ionic and gaseous forms) serve as electron acceptors for respiratory electron transport. Electrons are transported from an electron donating substrate (usually organic substances) to a more oxidized N-Form. The resulting free energy is used by the denitrifying organisms to support respiration (Vymazal, 2007). Once

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* Corresponding author.
E-mail address: Christian.kleimeier@uni-rostock.de (C. Kleimeier).

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NO_3^- has been exhausted, first Fe^{3+} and eventually SO_4^{2-} and later organic compounds are used as electron acceptors by different kinds of microorganisms. This series of reductions is set in a redox sequence that is related to the decreasing thermodynamic and metabolic effectiveness of the mineralization as the Eh of the environment becomes lower. Therefore, processes such as denitrification and iron and sulfate reduction occur sequentially in time and space (Garcia-Gil and Golterman, 1993). According to Sigg (2000) redox potentials above +500 mV reflect oxic metabolic processes, followed directly by nitrate reduction. Metabolic iron reduction occurs at redox potentials below +150 mV and sulfate reduction appears underneath redox potentials of −100 mV. In mineral soils and other natural systems denitrification is often limited by the availability of organic components, while it is found to be NO_3^- limited in a rewetted degraded fen (Davidsson et al., 2002).

Potential sites for constructed wetlands are located where drainage water ditches pass through lowland fens. These sites can be turned into a constructed wetland by controlled rewetting and adjustment of the hydraulic conditions. Degraded fens have, by nature, the potential to provide the necessary boundary conditions to support denitrification. The degraded peat serves as substrate for denitrification, offering both the permeable bed medium as well as the source of organic carbon. Studies showed that rewetting of peat lands did not decrease the further decomposition of the peat (van Dijk et al., 2004). Especially the uppermost, highly decomposed peat layer is responsible for the high mobilization of organic compounds (Zak and Gelbrecht, 2007).

The conversion of a fen into a constructed wetland, however, may possess further, negative side effects and environmental constraints. Thus, large field experiments converting a fen into a vertical flow constructed wetland have not been conducted so far. Nevertheless, several studies based on small and large scale incubation experiments reported potentially high denitrification rates of up to 75% total N removal in peat (Amha and Bohne, 2011; Cabezas et al., 2012). Conversely, compared to stagnant incubation experiments, constructed wetlands are systems with dynamic flow conditions and hence a short water retention time. Since nitrate possesses a high mobility in soil, solute transport may have a large impact on its turnover.

Peat is an organic substrate with a dynamic structure as compared to mineral soils. It can be hypothesized that the pore structure and related transport properties of peat used as a medium for (microorganism controlled) nitrate turnover processes will change in time. Studies reporting the temporal dynamic of soil hydraulic properties related to microbial activity are scarce. Rühle et al. (2013) as well as Seifert and Engesgaard (2007) observed bio-clogging of pores in half-year long column experiments. Likewise, Brovelli et al. (2009) deemed bio-clogging of pores responsible for changes in solute transport properties. They found a fractionating of the soil water into mobile and immobile phases upon an increasing microbial biomass. However, all available studies were performed using mineral soil. Up to date it is unknown to which extent the pore structure of a peat soil and the resulting flow and transport properties are affected by a constant flow and possible microbial activity.

Consequently, we were aiming at characterizing the transport properties of peat by evaluating tracer breakthrough curves employing the concept of mobile and immobile water fractions. We were interested in possible changes of the transport characteristics over time as resulting from a continuous (nitrate loaded) water flux just as it would be expected in a low lying fen used as a constructed wetland. Furthermore, we wanted to know if degraded peat is in general suitable as a substrate for denitrification purposes as tested under dynamic flux conditions. In order to obtain results that allow conclusions for the field situation, we developed a comparable large container set-up mimicking the conditions in a vertical flow-through constructed wetland.

2. Material and methods

The excavation and sampling of the peat took place in late summer 2010. The soil profile was characterized by horizons of degraded peat. Due to the artificial drainage of the site, the water table drops below the gyttia layer (below 80 cm) underlying the peat during summer. The top horizon (0–20 cm) of the peat can be described as highly degraded peat and has a crumb structure with aggregates smaller than 5 mm. The underlying horizon showed shrinkage cracks which continued into the gyttia layer. This peat horizon can be described as highly decomposed. The fen was classified as sapric histosol. The experimental soil material was collected from the upper soil horizon. The soil substrate was manually homogenized but not sieved to receive equally sized and stable aggregates. Coarse plant roots were removed and the medium was transported to the laboratory in black polyethylene bags.

2.1. Experimental set-up

A 0.15 m^3 polyethylene box served as experimental vessel (100 cm length × 30 cm width × 50 cm height and 2 cm wall thickness). The container was packed using disturbed, field-moist top-soil material. The bulk density was adjusted according to field conditions. Since the top-soil was subjected to regular plowing, it is believed that the disturbed peat material as used in the experiments still reflects field conditions. The total soil volume of the mesocosm was 0.12 m^3. The pore volume of the experimental vessel was 0.083 m^3 as calculated from the porosity (Table 1). The inflow-device, as well as the outlet, was installed prior to packing the container (Fig. 1). Redox probes were installed vertically from the top during the packing. After packing, the mesocosm was slowly saturated with tap water from the bottom to allow the shrunken peat to swell. The redox probes were enclosed firmly by the resulting pressure. Before applying any flux, the surface was leveled and a central cavity of 20 by 40 cm, serving as the water inlet, was formed by packing peat along the vessel walls. In this way, any preferential flow along the vessel walls was avoided. The water supply was established and the system was checked for proper functioning.

2.2. Inflow

The water surface served as hydraulic potential reference and was kept constant using an overflow outlet (Fig. 1). The height difference between the free water surface and the fixed position of the outlet hose in conjunction with the transport distance formed the hydraulic gradient and imposed a homogeneous, predominantly one dimensional vertical flow through the filter medium. The flow was adjusted manually by regulating the hydraulic pressure head, i.e. the level of the outlet. The water table was adjusted to 2–3 cm above the peat surface to ensure the saturation of the filter system. The constant water saturation guaranteed an anaerobic environment within the peat. The supplied water was reused and circulated constantly from the collecting tank (200 L) using an aquarium pump (Compact 1000, EHEIM GmbH & Co. KG, Deizisau, Germany) with a rate of 150 L h^{-1}.

2.3. Outflow

The bottom layer (4–5 cm) of the mesocosm was formed of gravel, which allowed the water to flow freely towards the outlet hose. The

Table 1
Properties of the top horizon (0–15 cm) used for the experiment, estimated from core samples taken from the set-up after dismantling.

Soil type (WRB)	Sapric histosol
Loss on ignition	54.9
Dry bulk density (ρ)	0.44 g cm^{-3}
Porosity	69.4 vol.%
Saturated hydraulic conductivity	1.06 m d^{-1}
Total soil volume of experimental set-up	0.120 m^3
Total pore volume of experimental set-up (PV)	0.0832 m^3
Total carbon	33.0% of dry matter
Total nitrogen	2.0% of dry matter
Total Sulfur	7.1 mg/g