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INTEGRATED BUFFER ZONES FOR AGRICULTURAL NITROGEN REMOVAL: A DANISH CASE STUDY

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Introduction

The nutrient load to Danish lakes and coastal waters needs to be reduced in order to improve the ecological status and to meet the requirements of the EU Water Framework Directive. The intensive agriculture on arable land and the livestock production are the primary sources of nutrients. Even though the agriculture has been under regulation since the 1980's, further reduction in nutrient loss is still required. Therefore, a new collective and targeted agro-environmental nutrient regulation has just been implemented. This new regulation implies a shift towards differentiated and regionalized strategies directed towards catchments with the greatest needs for reduction e.g. catchments with low nitrogen (N) retention and vulnerable water bodies.

Subsurface tile drainage of agricultural fields lowers the natural N retention capacity of the land, as the drain water transports N directly to the surface water. The contribution of N from drainage systems to surface waters are considerable, as it has been estimated that 50 % of the Danish agricultural area is drained. Thus, in the intensely drained catchments there is a need for more and new mitigation measures such as integrated buffer zones (IBZs) that can assist in reducing the N loss from drainage systems to surface waters. The primary functionality of IBZs is to intercept the drain flow, which otherwise is led beneath the riparian zone and directly to the surface water.

The IBZ consist of two compartments: the first compartment is a pond with a free water surface, resembling a small wetland (Zak et al., 2018). The second compartment is a vegetated infiltration zone, acting as a saturated riparian zone. Both compartments potentially enhances N removal via denitrification, by supplying carbon from tile drain and vegetation in the pond, increasing hydraulic retention time and creating anaerobic conditions. The aims of this study were to investigate I) if the N removal efficiency and dynamic the between pond and infiltration zone changed with age, II) the factors affecting N removal in the pond.

Method

Study site

The two experimental IBZs (IBZ1 and IBZ2) were located 20 m from Odder stream (55°57'18.0"N, 10°05'29.4"E) and received water from a catchment of approximately 30 ha. A detailed description can be found in Zak et al. (2018). Each IBZ consisted of a pond with free water surface (125 m^2) (POND) and an infiltration zone (125 m^2) planted with Alnus glutinosa (L.) (FILTERBED). The land use in the catchment was mainly Christmas trees (1-2 m high spruce) and arable crops. In IBZ1 the sediment of the pond was primarily clay, while the infiltration zone was sand and gravel with a clay lenses in the top layer and in one meter depth, as recorded during installation of piezometer pipes. In IBZ2 the sediment of the pond and infiltration zone was primarily sand and gravel. The two IBZs were established in July 2014.

Sampling
Water samples (grab) for TN analysis were collected every third to sixth week at the inlet, outlet, POND and piezometer pipes located in the FILTERBED of each IBZ from 7/1/2015 to 6/31/2016 and 7/1/2017 to 6/31/2018. Each inlet and outlet was equipped with an electromagnetic flow-meter (Ø 100 mm; Waterflux 3070, Krohne, Germany) connected with a data logger (Campbell CR10X, Logan, USA) that recorded the flow velocity as a mean every 10 minutes. The water level and temperature of each IBZ were measured using a pressure transducer (Level 2000, Madgetech, Warner, New Hampshire, USA) placed in a piezometer close to the inlet. The water level of the POND was fixed at approximately 70 cm above the bottom in order to prevent an overrun of the IBZ, and to keep the FILTERBED slightly inundated to maintain a high infiltration rate into the FILTERBED.

Water balance calculation
Daily data on precipitation and potential evapotranspiration were obtained from the Danish Meteorological Institute using a weather data grid of 10x10 m and 20x20 m, respectively. Infiltration of water into the FILTERBED ($Q_{seepage}$) was calculated based on the water balance of the IBZ:

$$Q_{seepage} = Q_{in} + P - ET - Q_{out} \pm \Delta S \qquad \text{(Eq. 1)}$$

where Q_{in} is water flow into the IBZ; P is the precipitation; ET is the evapotranspiration; Q_{out} is water flow at the outlet; ΔS is the change of water storage in the POND.

In spring 2017 a preferential flow path appeared just behind the FILTERBED of IBZ1, thus in order to adjust for this new flow path, $Q_{seepage}$ was corrected. This correction was based on the relationship between the water level of the POND and $Q_{seepage}$ before the preferential flow path occurred. Thus from May 2017 the corrected infiltration ($Q_{seepage}$) was predicted using the following equation:

$$Q_{seepage\_corrected}=4E\text{-}69^{(0.0371*WL)/1000} \qquad \text{(Eq. 2)}$$

Where WL is the water level in the pond.

The water volume leaving the IBZ via the preferential flow path (Q_{pref}) was calculated by:

$$Q_{pref} = Q_{seepage} - Q_{seepage\_corrected} \qquad \text{(Eq. 3)}$$

The daily hydraulic retention time (HRT) of the POND was calculated by dividing the water volume by the inlet flow. The water volume at different water levels in the two IBZs were estimated based on a levelling survey conducted in 24 transects using a RTK GPS (LEICA GNSS NetRower). The survey data was interpolated in ArcGIS 10.2 using a grid approach (1x1 m) interpolation procedure.

Chemical analysis
All water samples for water chemistry analysis were filtered through a 0.45 µm filter (Monta®membrane, Cat No MCEWGS047045, Frisenette, Denmark), and water samples for ion chromatography were additionally filtered through a 0.22 µm nylon membrane filter (SNY2225, Frisenette, Knebel, Denmark). TN were determined from unfiltered samples measured as NO_3^- after wet oxidation with $K_2S_2O_8$ (Quick-Chem method 31-107-04-3-B). The samples were preserved with 2 M H_2SO_4 (100 µl per 5 ml sample).

Nitrogen balance calculations

Daily concentrations of N were calculated using linear interpolation between two subsequent sampling occasions (Kronvang and Bruhn, 1996). The daily load of TN to the IBZ was calculated by multiplying the TN concentration of the inlet water by the total volume of water entering the IBZ:

$$LOAD_{in} = Q_{in} \times C_{in} \qquad \text{(Eq. 4)}$$

where Q_{in} is the water volume entering the IBZ; C_{in} is the concentration of TN at the inlet

The daily loss of TN via the outlet was calculated by:

$$LOSS_{out}=Q_{out} \times C_{out} \qquad \text{(Eq. 5)}$$

Where Q_{out} is the volume of water leaving the IBZ at the outlet; C_{out} is the concentration of the TN at the outlet.

The daily load of N to the FILTERBED was calculated by multiplying the N concentration in the POND by the volume of infiltrating water to the FILTERBED:

$$LOAD_{filter}=Q_{seepage} \times C_{pond} \qquad \text{(Eq. 6)}$$

Where $Q_{seepage}$ is the water volume infiltrating the FILTERBED (see equation 1); C_{pond} is the concentration of the N in the POND.

The daily loss of N from the FILTERBED was calculated by multiplying the N concentration in the piezometers by the volume of outfiltrating water, which we assumed was the same as the infiltrating water. Only dissolved N species were considered, as we assumed that particle transport was negligible in the FILTERBED.

$$LOSS_{filter} =Q_{seepage} \times C_{piezometer} \qquad \text{(Eq. 7)}$$

Where $Q_{seepage}$ is the water volume infiltrating/leaving the FILTERBED (see equation 1); $C_{piezometer}$ is the concentration of N in the percolated piezometers at the end of the FILTERBED.

The absolute N removal of the POND (R_p) was calculated as:

$$R_p = LOAD_{in} – LOSS_{out} – LOAD_{filter} \qquad \text{(Eq. 8)}$$

The absolute N removal of the FILTERBED (R_F) was calculated as:

$$R_F = LOAD_{filter} – LOSS_{filter} \qquad \text{(Eq. 9)}$$

TN removal of each IBZ was calculated by adding R_p and R_f. The annual N load, loss and removal was reported as area specific removal (g m^{-2} d^{-1} , where m^{-2} is the area of the IBZ). The N removal efficiency (%) was obtained by dividing the amount of N retained by the N load. Nitrogen balances were calculated for two years covering 7/1/2015 to 6/31/2016 and 7/1/2017 to 6/31/2018. All calculations were performed in SAS 9.4 (SAS Institute Inc., 2013).

Statistical analysis

Student T-test (SAS Proc Reg; SAS Institute, Inc., Cary, N.C.) was used to test for differences in removal efficiency between years as the data followed a normal distribution. Regression analysis (SAS Proc Reg; SAS Institute, Inc., Cary, N.C.) of the two IBZs was undertaken to develop a regression model describing the removal rate for each IBZ. Sample event-based values were used in the analysis.

Preliminary results

Annual nitrogen and water balance

The hydraulic loading rate (HLR) was higher the first year than the third year after IBZ establishment (Table 1), which corresponded with more precipitation the first year. The fraction of inlet water leaving via the outlet decreased with age at both IBZs (from 24-68 % to 13-24 %). At IBZ1, this was primarily due to a preferential flow path behind the FILTERBED emerging during the spring in 2017. However, at IBZ2 the decrease in outflow was due to an increase in infiltration rate, as the fraction of inlet water infiltrating the FILTERBED increased from 62 to 71% when comparing the first year with the third year. At IBZ1 infiltration decreased from 28 to 21% when comparing the first year with the third.

The N loading to the IBZs were highest in the first year (Fig. 1), which was due to a higher HLR in the first year (Table 1), however the TN concentration in the inlet water was also significantly lower the third year (n=37, DF=35, t=6.41, $p<0.001$). In the first year the TN concentration of the inlet water was 6.5± 1.4 mg L^{-1} and in the third year it was 3.9 ±1.0 mg L^{-1}. Despite this, both the absolute and relative removal efficiency were highest in the third year. For IBZ1 the absolute removal efficiency increased from 210 to 220 g m^{-2} yr^{-1}, and for IBZ1 it increased from 101 to 104 g m^{-2} yr^{-1}. For IBZ1 this corresponded to an increase of the percentage N removal efficiency from 32 to 61%, while for IBZ2 it increased from 19 to 32 %.

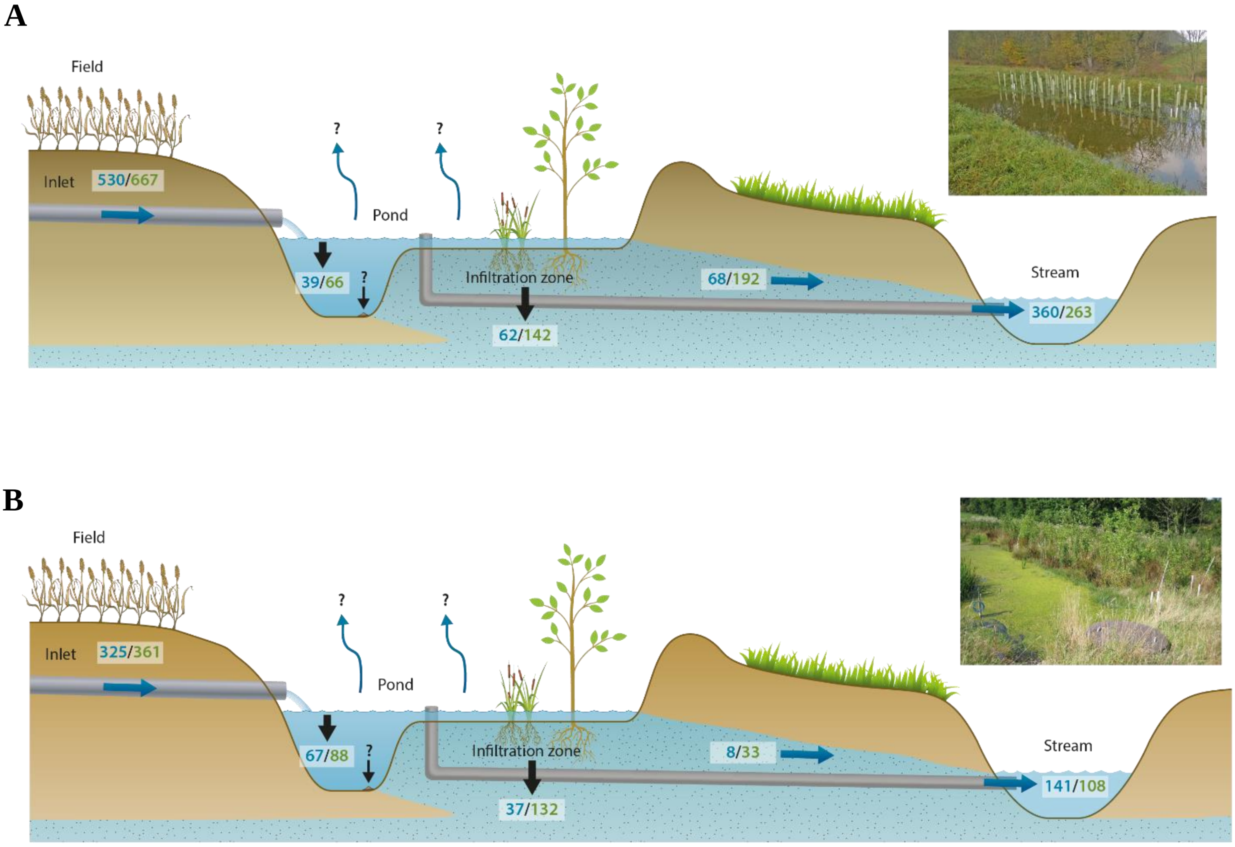

Figure 1. N balance (g m^{-2} yr^{-1}) for **IBZ1** and **IBZ2** in the first (2015/16) (**A**) and third (2017/18) (**B**) year after establishment.

Table 1. Water balance for IBZ1 and IBZ2 for the first (2015/16) and third (2017/18) after establishment.

		Inlet	**Outlet**	**EA**	**Precip**	**Infiltration**	**Pref. flow**
		m^{-3}	m^{-3}	m^{-3}	m^{-3}	m^{-3}	m^{-3}
IBZ1	*2015/16*	20072	14273	148	264	5872	-
	2017/18	19106	8896	157	183	3995	6255
IBZ2	*2015/16*	27744	10511	150	265	17258	-
	2017/18	21556	6384	157	183	15297	-

Removal dynamics in pond and infiltration zone

In the POND of IBZ1 the N removal increased significantly from in average 17 to 28 % when comparing the first year with the third year ($p < 0.0001$, DF 682, T = –6.7). In the IBZ2 POND the average removal efficiency increased from 15 to 38 % ($p < 0.0001$, DF 687, T = –10.9). In the FILTERBED of IBZ1 the average removal efficiency increased from 43 to 73 % ($p < 0.0001$, DF 717, T = –27.9) when comparing the first year with the third year. While at IBZ2 the removal efficiency of FILTERBED increased from 52 to 80 % ($p < 0.0001$, DF 653, T = –22.2).

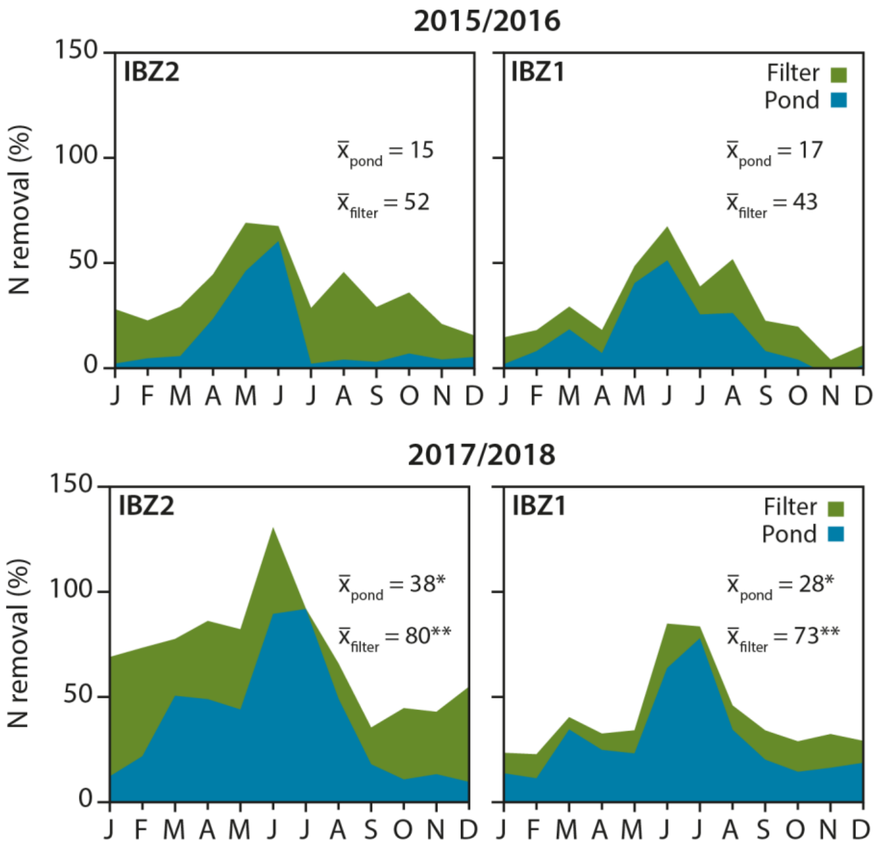

Figure 2. Monthly N removal efficiency of the POND and FILTERBED of IBZ1-2 in first (2015/16) and third (2017/18) year after IBZ establishment.

Factors controlling N removal

The preliminary results showed that inlet TN concentration and ln(HRT) explained 64 and 43 % of N removal in the POND of the IBZ1 and IBZ2, respectively (Table 2). Ln(HRT) alone explained 58 and 28 % of the N removal in the POND of the IBZ1 and IBZ2, respectively.

Table 2. Parameter estimates from regression analysis for IBZ1 and IBZ2.

	Parameter	**Unit**	**N**	**DF**	**Parameter Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
IBZ1	LN(HRT)	*hours*	42	1	20.6	2.8	7.3	<.0001
	Inlet TN	*mg* L^{-1}	42	1	-2.8	1.2	-2.4	0.021
IBZ2	LN(HRT)	*hours*	42	1	15.0	5.0	3.0	0.005
	Inlet TN	*mg* L^{-1}	42	1	-5.9	1.8	-3.2	0.003

Conclusions

The IBZs are valuable enhancement of dry riparian buffer zones in order to mitigate N losses from tile drained agricultural fields. The absolute TN reduction varied between 101 to 220 g m^{-2} yr^{-1}.

The IBZs showed an increase in its ability to reduce N with age, as the percentage removal efficiency increased from 19-32 % to 34-61 % when comparing the first year with the third year after establishment. The N removal efficiency (% of N load) of the IBZs were controlled by HRT and inlet N-concentration.

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