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Extensive grasslands as an effective measure for nitrate and phosphate reduction from highly polluted subsurface flow – Case studies from Central Poland

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ABSTRACT

Multifunctional ecosystem of narrow grasslands located between croplands and streams slowly disappears from the agricultural landscape in Poland despite its importance to reduce the impact of land-based nutrients on freshwater ecosystems. We studied the effects of five extensive grasslands on nitrate and phosphate reduction in the catchment scale. During our 4-year monitoring, we did not observe the saturation effect in case of the two buffer zones that were receiving high nitrate load via subsurface flow. Highest nitrate concentration exceeded twice the level of 50 mg NO_3/L, which is considered a threshold level of water pollution status by the EU Nitrates Directive. Concentrations above 100 mg NO_3/L were reduced by 68% and 99% passing through the 25 m and 45 m of grassland, respectively. The efficiency of buffer zone to mitigate phosphate losses varied depending on the input load. The results obtained for high concentrations (above 1.5 mg PO_4/L) showed 81% and 76% effectiveness of 45 m and 47 m grassland, respectively. However, the release of phosphates was reported as well and occurred at the buffer zones characterized by low inflow P concentrations when assimilation-decomposition processes dominated ecotone P dynamics. The analysis of nutrient retention in vegetation showed that harvesting of grassland removed 131 kg N/ha/yr and 19.4 kg P/ha/yr. Furthermore, the amount of nitrate and phosphate removed by buffer zones were statistically and positively correlated ($r = 0.62$, $p < 0.05$ and $r = 0.52$, $p < 0.05$, for NO_3 and PO_4 respectively) with the biodiversity (expressed as Shannon index), which underlines the importance of marginal parts of buffer zones.

1. Introduction

Riparian buffer zones (ecotones, and vegetative filter strips) are situated on the main pathways of nutrient cycle between the aquatic and terrestrial ecosystems. Their buffering capacity and ability to control pollution exchange between ecosystems are particularly important when considering the reduction on non-point, agricultural source of pollution, which is well recognized as a direct reason for the degradation of water bodies and coastal zones (Lowrance et al., 1984; Mander et al., 2005; Doskkey et al., 2010; Stutter et al., 2012). Furthermore, the buffer zones play a crucial role in the ecosystems, providing unique habitats for a variety of organisms thus securing the biodiversity and maintaining the energy flow between the ecosystems (Naiman et al., 1989; McCracken et al., 2012). Understanding the cause and effect relationships that regulate the functioning of riparian buffer zone is needed for the optimal formation and management of riparian buffer zones. This knowledge may be used in the regulation of the processes of ecosystems, which according to the theory of ecohydrology (Zalewski et al., 1997; Zalewski, 2014), allows us to increase the capacity, resilience, and ability of flexible reaction of ecosystems on progressive human antropopression and climate change.

The water flux, which drives the exchange of nutrients, reaches the ecotones via surface runoff and subsurface flow (Parn et al., 2012). Soluble phosphates and nitrates, as a mobile fraction of subsurface flow, create an important contribution to the surface water degradation process (Holman et al., 2008; Mittelstet et al., 2011; Robinson, 2015). Subsurface flow efficiency of riparian buffer zones in the reduction of nitrogen is well described in the literature (e.g., Doskkey et al., 2010;

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Young and Briggs, 2005). Mayer et al. (2007) reported mean nitrogen removal effectiveness reaching 76.6% in the meta-analysis performed for 65 individual riparian buffers with different vegetation. However, there is limited data on the efficiency of ecotones for groundwater coming from heavily fertilized cropland (Hefting et al., 2006; Yamada et al., 2007; Balestrini et al., 2011). Most of the research concerning efficiency of buffer zones in phosphorus reduction is primarily focused on the analysis of the role of buffer zone for inhibiting transport of phosphorus compounds from the surface runoff and recognizing sedimentation process (Uusi-Kamppa, 2005; Syversen, 2005; Hoffmann et al., 2009; Dunn et al., 2011). Meanwhile, the effectiveness of buffer zone to reduce phosphate in shallow groundwater is not well documented (Schilling and Jacobson, 2014; Aguiar et al., 2015). Some researchers have suggested that riparian zones are ineffective in removing dissolved phosphorus or even they may release retained phosphorus into water (Carlyle and Hill, 2001; Hoffmann et al., 2006).

Based on the optimistic results of various studies, there are an increasing number of guidelines and also legal regulations toward implementation of buffer zones as an effective and best management practice to buffer aquatic ecosystems against nutrient losses from agricultural landscape (e.g.; FSA, 2010; Holsten et al., 2012). Nevertheless, the widespread use of these buffer zones is still challenged by socio-economic factors (Buckley et al., 2012) mainly because of the agricultural land needed to be transformed back to its natural state. This conflict of interest is well visible in Poland where the transformation of extensive to intensive agriculture is shaping a new type of agricultural landscape. In the times of extensive faming, narrow grasslands located between croplands and streams used to be an important part of agricultural landscape, providing areas for pastures, fodder (e.g. hay) or simply being a communication network. Yet, the currently growing industrialization and intensification of agriculture is putting a great pressure on the remaining ecotones. Firstly, more and more grassland are being transformed and incorporated into the neighboring croplands. Secondly, the intensive animal husbandry is no longer supplied by organic fodder collected from grassy areas of ecotones, therefore there is little interest in preserving ecological structure of those natural buffer zones. However, considering the ecological importance of ecotones, their removal from agricultural landscape, deprives local water bodies from the important, antipollution barriers.

The aim of the research was to prove the utility of extensive grasslands as an effective barrier to intercept the lost agricultural nutrients transported through the shallow groundwater streams into water bodies. We monitored five buffer zones that consist of a grassland strip with tall herb fringe or swamp non-forest communities directly adjacent to streams at the temperate, lowland Pilica River catchment in Central Poland. The effectiveness in nitrate and phosphorus reduction from shallow subsurface flow were analyzed based on 4 years monitoring results. The analysis of species composition was included in the study to determine whether biodiversity of ecotones affects their effectiveness in reducing pollution. The primary objective of this study was to demonstrate the usage of buffer zones as an effective tool to reduce the transfer of non-point pollution and to place it in the catalog of actions aimed at improving water quality in the Pilica River catchment and preventing further eutrophication of Sulejów reservoir (Frątczak and Izydorczyk, 2015).

2. Materials and methods

2.1. Site description

The following five case studies located within the Pilica River Catchment in Central Poland were chosen to best represent the biological and geological characteristic of the region (Fig. 1): Radonia (two sites: R and D), Kłudzice (L), Tresta (T), and Kałek (K). The width of buffer zones varied from 8 m to 77 m depending on the location (Table 1).

The sampling sites covered the buffer zone between the cropland and first-order streams or small drainage ditch (L site). The chosen grasslands were established more than 15 years ago. Previously they were regularly fertilized and mowed or grazed. Before establishing the sampling sites, local surveys and observation were carried out to obtain the information about the past and present use of the ecotones. Currently only the biomass was regularly removed from grasslands, 2–3 times a year. No additional agricultural activities were reported to take place on the monitoring sites. Additionally, all buffer zones included a narrow marginal part located in the immediate vicinity of the watercourse excluded from the agricultural management and composed of tall forbs or swamp non-forest communities. Neighboring croplands were used in the cultivation of plants (barley, rye, oat, corn, or triticale). According to the farmers' declarations, the croplands were mostly fertilized with mineral fertilizers (mainly nitrogen fertilizers − 150 kg/ha) and occasionally with cattle manure (40 tons/ha). Nevertheless, over our 4-year research duration, the discharge of poultry litter, slurry, and domestic sewage was also noted.

The hydrogeological, and morphological characteristic was presented in Table 1. Geological cross-sections of four out of five research sites showed little variation. Typically, at the crop field borders, the first layer with a thickness of 0.3–0.5 m is made of soil, which can be found above a uniform layer of permeable tracks (fine sands, grits, and coarse sand). Additionally, peat layers have been found close to the streams at K and T sites. Only D site is characterized by the presence of clay and silt lenses occurring between layer of soil and permeable tracks (fine sands). The groundwater level in inlet sections fluctuated between 0.25 m and 1.97 m below ground level (BGL), while in outlet sections: 0.15–1.73 m BGL.

The region receives an average annual rainfall of about 600 mm (Szcześniak and Piniewski, 2015). In 2011–2014, the values of total annual rain or snow precipitation reached 563 mm, 480 mm, 592 mm, and 818 mm, respectively. The mean annual temperature reaches 8.6 °C. Typically, the snow cover would last for $<$ 2 months (50 days on an average).

2.2. Groundwater monitoring

The piezometers paired (cropland/buffer) for groundwater monitoring were installed in January 2011 by professional company specialized in hydrogeological research. At first the topographic analysis and geological boreholes were done for preliminary assessment of groundwater flow patterns. The piezometers were made of high-density polyethylene pipes (Ø50 mm; Eijkelkamp) and installed in holes drilled using a machine auger fixed on a lightweight trolley. The piezometers length ranged from 2.1 to 3.0 m and they were perforated throughout 1 m from the bottom. Finally piezometers were leveled. Additionally, lithology (granulometric estimation and thickness) was determined by visual inspection of soil material collected by auger during installation. Based on this geological cross-sections were done.

Groundwater samples were collected monthly from February 2011 until September 2014 (within 44 months). During each sampling, at first the water level was manually measured, using electric contact meter (KLL-Mini, SEBA Hydrometrie). Next, 3 well volumes were pumped out with the electric groundwater pump (Gigant-WHALE 12 VDC) to removed standing water prior to collection of the water samples. Immediately after piezometers had fully recharged, the water samples were taken and temperature, conductivity, and pH were measured *in situ* (YSI Professional Plus, model 10E1744 and model Pro10102030). Water samples were transported to the laboratory in 250 mL bottles in ice boxes and were filtered immediately after arrival through Whatman GF/C filters. Analysis of dissolved forms of nitrogen and phosphorus was performed with use of ion chromatography (Dionex ICS-1000) which enable the quality and quantity analysis of cations with Ion Pac CS15 column (NH_4^+) and anions with the Ion Pac AS14A column (NO_2^-, NO_3^{2-}, PO_4^{3-}). The method detection limit was