The role of biogeochemical barriers in protecting aquatic ecosystems against pollution in agricultural environment

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ABSTRACT

This review discusses the importance of ecotones with high plant diversity which are highly effective in retaining pollutants and waste. Biogeochemical barriers play a vital role in eliminating biogenic pollutants, pesticides and heavy metals. Belts of rush plants and meadow vegetation considerably expand the accumulation capacity of water bodies and watercourses. The mechanisms responsible for the protective role of biogeochemical barriers involve various processes such as sorption, sedimentation, denitrification and assimilation, which require the coexistence of plants and microorganisms in aquatic ecosystems. Buffer barriers were presented as one of the ecohydrology tools in agricultural landscapes.

KEY WORDS: buffer zones, water protection, ecohydrology, biological filters, wetlands

Introduction

Due to rising levels of anthropogenic pollution in agricultural areas, there is a growing need for improvement in ecosystems' capacity, resistance to pollution and water quality (Sohel & Ullah 2012). Those goals can be achieved, inter alia by balancing hydrobiological processes in flora and fauna management plans. In line with ecohydrological principles, the creation of buffer zones in environments exposed to high levels of anthropogenic pressure is one of the most effective tools in controlling water pollution (Caracciolo *et al.* 2014). Knowledge of environmental biotechnology combined with hydrotechnical engineering solutions is required to control the levels of biogenic elements and to promote biodiversity by creating habitats for various species of plants and animals (Kędziora 2007, Sohel & Ullah 2012, Zalewski 2013). In areas that are at the greatest risk of diffuse source pollution, aquatic ecosystems can be

managed by preserving or creating retention reservoirs, reclaiming land, creating wetlands, buffer zones with diverse vegetation and barriers that directly protect the banks of water bodies and watercourses (Ryszkowski *et al.* 1999, Sohel & Ullah 2012).

The concepts of buffer zones and biogeochemical barriers are often used interchangeably, and the criteria for distinguishing between them are not clearly identified in the literature (Izydorczyk *et al.* 2013, Sowiński *et al.* 2004, Wysocka-Czubaszek & Banaszuk 2003). In this review, biogeochemical barriers are regarded as an integral part of buffer systems. Solutions of this type can act as marginal filters situated directly in the littoral zone of an aquatic ecosystem, but the resulting biofiltration effects may be low if initial pollutant loads are high (Izydorczyk *et al.* 2013). The area of the buffer zone separating agricultural and urban areas from aquatic ecosystems has to be expanded, and diverse vegetation should be used to effectively prevent degradation of water bodies (Maksimenko *et al.* 2008, Ryszkowski 1999). Buffer zones separating aquatic and terrestrial ecosystems do not have to be static and passive barriers, and they can actively control the flow and transformation of matter and energy to create areas characterized by high levels of biodiversity (Miałdun & Ostrowski 2010).

The role of buffer zones in agricultural landscapes

Buffer zones limit the spread of pollutants or retain them in agricultural habitats (Koc & Szyperek 2004). A buffer zone is a strip of land maintained in permanent vegetation which separates agricultural land from watercourses and water bodies. Buffer zones provide effective physical, biological and chemical protection of water bodies against surface and subsurface contamination (Wasilewski 2012). They support vital processes such as assimilation of inorganic compounds, including nitrogen and phosphorus, by plants and their transformation to biomass, as well as biochemical processes that involve microbial biofilms. Soluble and insoluble phosphorus compounds are absorbed and transported from the surface to deeper soil layers (Błaszczyk 2010, Carluer 2011, Izydorczyk *et al.* 2013).

The effectiveness of natural and artificial barriers should be evaluated in view of various factors. Pollutants are removed by plant and soil filtering mechanisms, therefore, the rate of surface runoffs and the width of the buffer strip should be optimized to increase pollutant and sediment retention (Blanco-Canqui & Lal 2008, Ławniczak & Zbierska 2007, Stachowicz & Nagengast 2013). The selection of plant species is a very important consideration. Tall plants promote the development of microbial biofilms on their aboveground parts, and well-developed root systems improve soil quality. The presence of plants in the buffer zone also stabilizes the shoreline, prevents erosion, reduces runoff rates and improves soil structure, which is of particular importance in terms of surface coverage of grasses (Blanco-Canqui & Lal 2008, Sahu & Gu 2009, Sohel & Ullah 2012). Buffer zones should be created with consideration for vegetation types, the habitat preferences of plants and their ability to adapt to various hydrological conditions. Native plants should be introduced to artificial buffer zones with

the aim of enhancing the local landscape (Izydorczyk *et al.* 2013). The life span of plants and their ability to propagate, to form dense patches and to eliminate or neutralize pollutants flowing in the direction of water bodies should be evaluated. For buffer zones to effectively purify water, plant communities should have diverse species composition. They should comprise minimum nine plant species (Wasilewski 2012). According to estimates, buffer zones which have a mosaic pattern and incorporate various species of trees, shrubs and grasses are six times more effective in reducing phosphorus flows to water bodies than catchments characterized by homogeneous vegetation (Ryszkowski 1999). Higher levels of organic carbon are found in fields that feature clusters of trees than in intensively fertilized fields. The presence of trees increases the content of humic substances in the soil and contributes to soil porosity and retention capacity (Jaskulska & Hoppe-Wawrzyniak 2013).

The role of various buffer zones in reducing pollution levels in aquatic ecosystems

Buffer zones composed of grasses, sedges and herbaceous plants are highly effective in eliminating nitrogen compounds. According to estimates, a six-metres-wide buffer strip is capable of reducing total nitrogen concentrations by 47%, and this biogenic element is nearly completely eliminated when the width of the buffer zone is extended to 20 m (Wysocka-Czubaszek & Banaszuk 2003). A biogeochemical barrier significantly delays the transport of nitrogen to wetlands in river valleys. Nitrogen levels may be reduced by denitrification and absorption, but they tend to increase in buffer zones over time. The adverse consequences of this process may be minimized by river floods that take place every few years. Plants with shallow root systems may be unable to block the transport of nitrogen into deeper soil layers (Wysocka-Czubaszek & Banaszuk 2003). Nitrophilous plants can be introduced to man-made buffer zones to increase their nitrogen removal capacity. At the end of the growing season, grasses should be cut to reduce nitrogen levels which are very high in plant tissues during that period (Lemkowska *et al*. 2010). Plants of the family Fabaceae are able to form dense patches of vegetation, and they are characterized by a long life span and a long growing season during which nutrients are intensively assimilated for the needs of biomass production and propagation. Plants with a fibrous root system are firmly attached to soil particles, which increases their resistance to powerful surface runoffs (Wasilewski 2012).

The common reed (*Phragmites australis*) is highly capable of accumulating heavy metals, and it can significantly contribute to the effectiveness of biogeochemical barriers in water bodies. The species has low environmental requirements, and it is common in littoral zones. Research has demonstrated that the highest concentrations of heavy metals are found in the roots of reed plants. Lead concentrations were determined at 16.54 $mg \cdot kg^{-1}$ DM in roots, 9.87 $mg \cdot kg^{-1}$ DM in stems and 13.20 $mg \cdot kg^{-1}$ DM in leaves. Zinc levels reached 104.10 $mg \cdot kg^{-1}$ DM in roots and 28.40 $mg \cdot kg^{-1}$ DM in leaves (Bonanno & Giudice 2010). In ecosystems contaminated with metachlor, a popular pesticide, reed plants reduced contamination levels by 28% in comparison with sites where reeds were not present. Other plant species capable of lowering pesticide

levels, *Leersia oryzoides* and *Typha latifolia,* reduced metachlor concentrations by 88% (Vymazal & Březinová 2015). In biogeochemical barriers in littoral zones, pesticides are adsorbed onto sediment particles. Soluble fractions of pesticides such as glyphosate, propiconazole and fenpropimorph were removed in 24–70%, 32–78% and 61–73%, respectively (Syversen & Bechmann 2004).

Riparian forests are highly valuable buffer zones which can significantly lower the loads of biogenic elements. They constitute transitional zones between agricultural land and aquatic ecosystems. According to estimates, a 5–30 m wide buffer zone can reduce pollutant runoffs by more than 30%.

Species diversity also plays a crucial role in buffer zones, and it contributes to the removal of nitrogen and phosphorus compounds (Blanco-Canqui & Lal 2008, Fortier *et al.* 2015). Different types of buffer zones and their efficiency in removing biogenic elements are shown in Table 1. The presented data indicate that zones with diverse vegetation are most effective in minimizing pollution levels. The highest rates of nitrogen and phosphorus removal were noted in a buffer zone overgrown with trees, shrubs and grasses. The presence of tall trees with root systems that stretch several meters away from the littoral zone improves soil drainage (Fortier *et al.* 2015).

Table 1. Types of buffer zones and their ability to remove biogenic pollutants (Blanco-Canqui & Lal 2008).

Type of buffer zone	Width of buffer zone [m]	Efficiency of nitrogen removal [%]	Efficiency of phosphorus removal [%]
Deciduous forest	10	97	78
Deciduous trees and grasses	75	27	56
Trees, grasses, shrubs	16	94	91
Shrubs and weeds	18	32	30

The white cedar (*Thuja occidentalis*) accumulated 240 kg $N \cdot ha^{-1}$ in roots and 1050 kg $N \cdot ha^{-1}$ in aboveground parts. The species, initially a shrub, eventually develops into a tree, and its accumulation capacity increases with age (Fortier *et al.* 2015). Poplars are a common species of trees that store nitrogen in the form of protein. Poplars reduce biogenic pollution levels, create supportive habitats for forest animals, store nutrients and regulate hydrological conditions in flood zones. Their ability to accumulate carbon increases with age. Traditional buffer zones are being replaced with

systems capable of producing biomass and accumulating significant amounts of biogenic elements: 29–107 t $C \cdot ha^{-1}$, 29–141 kg $P \cdot ha^{-1}$ and 284–1120 kg $N \cdot ha^{-1}$ (Fortier *et al.* 2015).

The location of green belts that act as biogeochemical barriers is equally important. Nitrogen retention can be improved by designing an additional barrier in the middle of a buffer zone rather than directly in the littoral zone. A species that can be effectively used for that purpose is switchgrass (*Panicum virgatum*). A biogeochemical barrier in the littoral zone is capable of eliminating

60–80% of nitrates, and its removal capacity increases to 60–95% when it is located in the middle of the buffer zone (Sahu & Gu 2009).

Small retention reservoirs such as ponds can also act as biogeochemical barriers. Complex systems comprising a body of water, bottom sediments and littoral vegetation are highly effective in accumulating biogenic elements. Bottom sediments and shoreline plants absorb large amounts of pollutants and play a very important role in water purification systems. Pollutants flowing into a pond are filtered by meadow vegetation and rush plants (Koc & Szyperek 2004,

Zieliński & Jekatierynczuk - Rudczyk 2015). A belt of meadow vegetation increases nitrogen retention in the entire system, which is demonstrated by a high rate of accumulation per unit surface area (1.03 kg N·m^{-2}). Bottom sediments are major retention reservoirs of biogenic elements. According to estimates, more than 95% of nitrogen is accumulated in bottom deposits in water bodies devoid of littoral vegetation (Koc & Szyperek 2004). Despite promising research results, ponds should not be regarded as the only effective biogeochemical barriers because they are relatively quickly degraded on account of their small size. Systems with well-developed littoral vegetation are capable of accumulating 1.4 to 344 kg of nitrogen per ha of catchment area (Koc & Szyperek 2004).

Conclusions

Despite differences in their form and structure, buffer zones play a very important role in protecting aquatic ecosystems against pollution. The results of the cited studies demonstrate that buffer zones effectively reduce pollution caused by pesticides, mineral fertilizers

Pollutants can also be retained by naturally occurring geomorphological structures. Ground moraine depressions in the Masurian Lake District are natural filters that capture biogenic elements and accumulate organic matter. Due to a high content of macronutrients and micronutrients, high sorptive capacity and the presence of deposits in the form of loose and relatively narrow slates, ground moraine depressions can be classified as biogeochemical barriers. Their sorptive capacity also determines the rate at which pollutants are retained by acidic meadow soils in agricultural areas (Sowiński et al. 2004, Ryszkowski 1999).

Artificial mechanical barriers can enhance physical and biological processes in plant and soil systems. Barriers formed by sedimentary rocks effectively prevent the leaching of phosphorus compounds. According to estimates, a limestone and dolomite barrier with a width of 1.5 m and a depth of 1.5 m can reduce total phosphorus concentrations by 51.3–63.3% (Izydorczyk et al. 2013).

Regular liming treatments increase the concentrations of magnesium and calcium ions and pose a threat for aquatic ecosystems. Buffer zones can significantly lower the content of ions in runoffs, and they are capable of retaining 20–54% of calcium and 46–72% of magnesium. The highest retention is reported in the first 10–15 m of the buffer zone (Życzyńska-Bałoniak et al. 2005).

and heavy metals. Buffer zones should be preserved and expanded in agricultural areas. The presence of diverse plant species in buffer zones significantly increases their retention efficiency. Buffer zones with a mosaic structure contribute to environmental protection by

creating new habitats and preserving biological diversity. Favorable conditions for the coexistence of various flora and fauna species should be created in ecotones to maximize their self-purification capacity and reduce the risk of ecosystem degradation.

References

Blanco-Canqui, H. & Lal, R. 2008. Buffer strips. In: Principles of soil conservation and management, pp. 223–257, Springer Netherlands.

Błaszczyk, M.K. 2010. Samooczyszczanie się zbiorników wodnych. In: Mikrobiologia środowisk, pp. 244–246. Wydawnictwo Naukowe PWN, Warszawa.

Bonanno, G. & Giudice, R.L. 2010. Heavy metal bioaccumulation by the orgaus of *Phragmites australis* (common reed) and their potential use as contamination indicators. Ecological Indicators, 10: 639–645.

Caracciolo, D., Nato, L.V., Istanbulluoglu, E., Fatichi, S. & Zohu, X. 2014. Climate change and ecotone boundaries: Insights from a celluar automata ecohydrology model in a Mediterranean catchment with topography controlled vegetation patterns. Advances in Water Resources, 73: 159–175.

Carluer, N., Tournebize, J., Gouy, V., Margoum, C., Vincent, B. & Gril, J.J. 2011. Role of buffer zones in controlling pesticides fluxes to surfance waters. Procedia Environmental Sciences, 9: 21–26.

Fortier, J., Truax, B., Gagnou, D. & Lambert, F. 2015. Biomass carbon, nitrogen and phosphorus stock in hybrid poplar buffers, herbaceous buffers and natural woodlots in the riparian zone on agricultural land. Journal of Environmental Management, 154: 333–345.

Izydorczyk, K. Frątczak, W. Drobniewska, A., Cichowicz, E., Michalska-Hejduk, D., Gross, R. & Zalewski, M. 2013. A biogeochemical barrier to enhance a buffer zone for reducing diffuse phosphorus pollution - preliminary result. Ecohydrology & Hydrobiology, 13: 104–112.

Jaskulska, R. & Hoppe-Wawrzyniak, A. 2013. Właściwości fizykochemiczne i wodne gleb płowych pól uprawnych i sąsiadujących z nimi zadrzewień śródpolnych. Journal of Research and Applications in Agricultural Engineering, 58(3): 235–239.

Kędziora, A. 2007. Przyrodnicze podstawy ochrony ekosystemów rolniczych. Fragmenta Agronomica, 3(95): 213–223.

Koc, J. & Szyperek, U. 2004. Skuteczność barier biogeochemicznych w ograniczaniu spływu azotu w środowisku rolniczym. Annales UMCS, 59 (1): 93–100.

Lemkowska, B., Sowiński, P. & Pożarski, K. 2010. Zmiany warunków glebowo-troficznych rezerwatu Ustnik jako element zagrożeń jego funkcji przyrodniczych. Woda - Środowisko - Obszary wiejskie, 10, 1(29): 73–87.

Ławniczak, A.E. & Zbierska, J. 2007. Wpływ sposobu użytkowania strefy przybrzeżnej jeziora na jakość wód gruntowych. Fragmenta Agronomica, 3(95): 283–291.

Maksimenko, S.Y., Zemskaya, T.I., Pavolova, O.N., Ivanov, V.G. & Buryukhaer, S.P. 2008. Microbial community of the water column of the Selenga river-lake Baikal biogeochemical barierr. Microbiology, 77 (5): 587–594.

Miałdun, J. & Ostrowski, M. 2010. Wymiar fraktalny fragmentów zdjęć lotniczych strefy przybrzeżnej jeziora Mikołajskiego, Śniardw i Łukajno. Archiwum Fotogrametrii, Kartografii i Teledetekcji, 21: 267–279.

Ryszkowski, L. Bartoszewicz, A. & Kędziora, A. 1999. Management of matter fluxes by biogeochemical barriers at the agricultural landscape level. Landscape Ecology, 14: 479–492.

Sahu, M. & Gu, R.R. 2009. Modeling the effects of riparian buffer zone and contour strips on stream water quality. Ecological Engineering, 35: 1167–1177.

Sohel, S. J. & Ullah, H. 2012. Ecohydrology: A framework for overcoming the environmental impacts of shrimp aquaculture on the costal zone of Bangladesh. Ocean & Coastal Management, 63: 67–78.

Sowiński, P., Smólczyński, S. & Orzechowski, M. 2004. Gleby obniżeń śródmorenowych jako bariery biogeochemiczne w krajobrazie rolniczym Pojezierza Mazurskiego. Annales UMCS, Sec. E 59(3): 1057–1064.

Stachowicz, W. & Nagengast, B. 2013. Roślinność strefy przybrzeżnej mezotroficznego jeziora Powidzkiego w warunkach wzrastającej presji osadniczej i rekreacyjnej: stan aktualny oraz ocena wartości dla ochrony przyrody. Badania Fizjograficzne, R I. Seria B Botanika (B59): 7–42.

Syversen, N. & Bechmann, M. 2004. Vegetative buffer zones as pesticide filters for siumulated

surface runoff. Ecological Engineering, 22: 175–184.

Wasilewski, Z. 2012. Dobór gatunków traw i roślin bobowatych na strefy buforowe oraz zasady ich zakładania i pielęgnowania, 12, 1(37): 219–227.

Wysocka-Czubaszek, A. & Banaszuk, P. 2003. Migracja składników azotowych i bariery biogeochemiczne w zalewowych dolinach rzecznych na przykładzie doliny górnej Narwi. Acta Agrophysica, 1(2): 349–354.

Vymazal, J. & Březinová, T. 2015. The use of constructed wetlands for removal of pesticides from agricultural runoff and drainage: A review. Environmental International, 75:11–20.

Zalewski, M. 2013. Ecohydrology: process-oriented thinking towards sustainable river basin. Ecohydrology & Hydrobiology, 13: 97–103.

Zieliński, P. & Jekatierynczuk- Rudczyk, E. 2015. Comparison of mineral and organic phosphours froms in regulated and restored section of small lowland river (NE Poland). Ecohydrology & Hydrobiology (In press).

Życzyńska – Bałoniak, I., Szajdak, L. & Jaskulska, R. 2005. Impact of biogeochemical barriers on the migration of chemical compounds with the water of agricultural landscape. Polish Journal of Environmental Studies, 14 (5): 671–676.

Streszczenie

Bariery biogeochemiczne stanowią obszary o potencjalnie dużej zdolności do ograniczania przedostawania się metali ciężkich, pestycydów oraz związków biogenicznych do środowiska wodnego. Zastosowanie rozwiązań ekohydrologicznych pozwala na regulację nadwyżki pierwiastków biogenicznych oraz przyczynia się do wzrostu bioróżnorodności, dzięki wytworzeniu siedlisk dla licznych gatunków roślin i zwierząt. W niniejszym opracowaniu włączono bariery biogeochemiczne w ogół układów buforowych. Rozwiązania tego typu mogą być traktowane, jako filtry marginalne umiejscowione bezpośrednio w strefie przybrzeżnej ekosystemu wodnego, co w przypadku wysokiego wstępnego obciążenia spływu powierzchniowego może okazać się nie wystarczające dla osiągnięcia dobrych efektów biofiltracji. Aby w sposób skuteczny przeciwdziałać degradacji ekosystemów wodnych na obszarach rolniczych, konieczne jest zwiększenie powierzchni strefy oddzielającej je od wód oraz wykorzystanie zróżnicowanej roślinności. W obrębie stref buforowych wyróżnia się asymilację związków nieorganicznych, w tym azotu i fosforu przez rośliny, co umożliwia ich transformację w biomasę, a także procesy biogeochemiczne realizowane dzięki aktywności drobnoustrojów występujących w postaci biofilmów. Ponadto proces sorpcji i transportu rozpuszczalnych oraz nierozpuszczalnych związków fosforu realizowany jest w glebie, gdzie odpływ krąży w jej wierzchniej warstwie. Skuteczne działanie stref buforowych powinno obejmować preferencje siedlisk, określone rodzaje roślinności i ich tolerancję dla różnych warunków hydrologicznych. Przytoczone badania zwracają uwagę na konieczność zachowania zróżnicowanych gatunków w obrębie stref buforowych. Obecność na obszarze jednego siedliska zarówno drzew, krzewów i traw zapewnia ponad 90% efektywność w usuwaniu związków biogenicznych. Zapewnienie odpowiednich warunków dla współistnienia wielu organizmów w obrębie jednego ekotonu pozwala na skuteczne działanie procesów samooczyszczania i redukuje ryzyko degradacji ekosystemu.