RIPARIAN BUFFER ZONES AS ECOTECHNOLOGICAL MEASURES TO DECREASE NUTRIENT LOSSES FROM AGRICULTURAL LANDSCAPES

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Abstract

Ecotechnological measures allow to use different natural and seminatural ecosystems to control nutrient losses from intensively used watersheds. The most effective means are buffer strips, buffer zones and constructed wetlands. In southern Estonia a 51 m wide buffer zone of grassland strip, wet meadow and grey alder (Alnus incana) forest removed 86 % nitrogen and 84 % phosphorus, while in a 31 m buffer zone of wet meadow and alder forest 51 % N and 80 % P was retained. Grass vegetation plays an important role in nutrient retention in riparian buffer strips. The phytomass production of the Filipendula ulmaria community was up to 2358 g m⁻², assimilation of N 32.1 and of P 4.9 g m⁻², respectively. This is much higher than the biomass production and N and P uptake of the grey alder community (1730, 20.5 and 1.5 g m⁻², respectively). The outflow of total – N was 4.9 and outflow of total – P was 4.8 lower in well-buffered watershed in comparison to similar watershed with lower buffering ability. Results showed that compared to other seasons the winter performance was not reduced.

Keywords nitrogen removal, non-point pollution, phosphorus reduction, riparian buffer zones, watershed management
INTRODUCTION

Human activities have caused big changes in hydrological regime of rivers and nutrient cycling of river basins. One of the most problematic areas is agricultural watershed where these changes are unpredictable and not so well controllable. Therefore management of watershed is important option to control nutrient outflow from agricultural areas.

Two principle ways exist in the control of non-point pollution from rural catchments: (1) adoption of “Best Environmental Practices” by optimisation of fertilisers use, crop rotation, and soil cultivation methods in a manner that maintains the nutrient equilibrium in the soil; (2) using various mitigation measures as buffering ecosystems (e.g., riparian buffer strips and buffer zones, natural and constructed wetlands, hedgerows, shelterbelts) to intercept and transform nutrient fluxes from agricultural lands to water. These two classes of measures can be classified as ecotechnological measures for pollution control that can be used in certain conditions also for management of point pollution despite of conventional technologies.

Under the term “ecotechnology” (i.e., ecological engineering) we consider the engineering in the sense that it involves the design of this natural environment using quantitative approaches and basing our approaches on basic science; it is technology with the primary tool being self-designing ecosystems (Mitsch and Jørgensen, 1989). According to principles of ecological engineering, the most effective way to reduce pollution load is to decrease pollution at source (often called as “the beginning-of-pipe-principle”, Mitsch and Jørgensen, 1989). This principle is applied in a large variety of organic agricultural systems. However, certain losses of nutrients occur even from the biodynamic farming, the most extremely equilibrium-orientated agricultural system (Granstedt, 1990; Van Mansvelt and Mulder, 1993), which needs measures applied. One of the most ecologically sound solutions to degrease non-point pollution are buffering ecosystems that provide a great interest in terms of controlling the nutrient fluxes (Lowrance et al., 1984; Peterjohn and Correll, 1984; Knauer and Mander, 1989; Haycock and Pinay, 1993; Vought et al., 1994). Riparian buffer strips and buffer zones are multifunctional elements of rural landscapes that have several ecological benefits in addition to the water purification.
Riparian biotopes have the following essential functions:

1. Purifying of polluted overland and subsurface flow from intensively managed adjacent agricultural fields;
2. Protecting banks of water bodies against erosion;
3. Filtering polluted air, especially from local sources (e.g., large farm complexes, agrochemically treated fields);
4. Avoiding intensive growth of aquatic macrophytes by canopy shading;
5. Improving the microclimate in adjacent fields;
6. Creating new habitats in land/inland water ecotones;
7. Creating more connectivity in landscapes due to migration corridors and stepping stones;
8. Providing energy and habitat for in-stream fauna.

Buffer zones can purify overland and subsurface water from suspended solids, organic matter, nitrogen and phosphorus.

Main purification processes are described by Kadlec and Knight, 1996. Suspended solids are purified by:

1. Sedimentation and trapping;
2. Chemical precipitation.

Main purification processes for organic matter are:

1. Microbial decomposition and respiration;
2. Chemical precipitation and sedimentation.

Nitrogen is removed by:

1. Uptake and storage in vegetation;
2. Microbial immobilization and storage in the soil as organic nitrogen;
3. Microbial conversion to gaseous form of nitrogen (denitrification);
4. Ammonia volatilization.

Phosphorus is removed by:

1. Sedimentation of particulate phosphorus and chemical precipitation;
2. Soil sorption;
3. Removal of dissolved inorganic phosphorus by plant uptake;
(4) microbial immobilization and storage in the soil as organic phosphorus.

This paper describes purification efficiency of two riparian buffer zones in Estonia and the effect of buffer zones on the water quality on the watershed scale.

MATERIAL AND METHODS

Site Description. To study buffer zone efficiency we established two transects in south Estonia with similar physico-geographical conditions. The transects are situated on slopes adjacent to streams and follow surface water flow across agricultural fields and different riparian plant communities.

The Viiratsi transect (Figure 1) is situated in the Sakala heights (Varep, 1964) consisting of moraine hills and undulated plains with variety of glacial deposits. The transect is located on the moraine plain in the vicinity of the pig farm (about 30 000 pigs during the study). Almost all the slurry from the pig farm is spread on the neighbouring fields and whole area is heavily impacted by pig slurry. The transect crosses following plant communities: a cultivated field on planosols and podzoluvisols where slurry was spread in autumn 1994; an 11 m wide strip of grassland (Elytrigia repens-Urtica dioica) and young alder (Alnus incana) trees on colluvial podzoluviol; a 12 m wide wet grassland (Filipendula ulmaria) on gleysol and a 28 m wide grey alder (Alnus incana) forest on podzoluvic gleysol.

The Porijõgi site (Figure 3) is situated in the watershed of Porijõgi River in the plain of south-east Estonia (Varep, 1964). The elevation of the moraine plateau is 30 to 60 m above m.s.l., with undulated relief (slopes are usually 5-6%) and the landscape is dissected by primeval valleys. A more detailed description of the study area is given in an earlier study (Mander et al., 1995). The Porijõgi transect is located on the slope of a primeval valley where agricultural activities stopped in 1992, two years before we began our study. The Porijõgi transect crosses several plant communities: abandoned field (last cultivated in 1992) on planosols and podzoluvisols; abandoned cultivated grassland (last mowed in 1993) on colluvial podzoluvisol (dominated by Dactylis glomerata and Alopecurus pratensis); an 11 m wide wet grassland on gleysol (two parallel communities, one dominated by Filipendula ulmaria, another by Aegopodium podagraria); and a 20 m wide grey alder stand (Alnus incana) on gleysol.
**Water Sampling and Analysing.** Shallow ground water samples from upper aquifer of buffer zone transects were collected once to twice a month from piezometers installed on the borders of plant communities. The piezometers on the borders of riparian communities were installed with 3 replicates in 20 (Pori) to 30 (Viiratsi) meters wide zone. The depth of ground water varied 1-2m in the field sampling points and 10-100cm in riparian communities. Samples were taken from July 1994 to December 1995.

Stream discharge was measured and water samples were taken for analysing in laboratory once per month from closing weirs of 3 subwatersheds of Porijõgi River watershed in 1987-1990. Filtered water samples were analysed for NH$_4^+$-N, NO$_2^-$-N, NO$_3^-$-N, total Kjeldahl-N, PO$_4^{3-}$-P, total-P, SO$_4^{2-}$, Fe, Ca$^{2+}$ in the laboratory of Estonian Agricultural University following standard methods for examination of water and wastewater quality (APHA, 1989).

**Soil Sampling.** Complex soil samples were taken in three replicates from two depth (0-10 cm and 10-20 cm) from all plant communities toposequent through the riparian buffer zones. Sampling was done twice a year: in spring (May) and autumn (October). The hand-held 4-cm diameter corer was used to collect samples. Soil pH value, organic matter (loss of ignition), and N and P content were analysed using standard methods (APHA, 1989).

**Phytomass Sampling and Analysing.** The phytomass (i.e., standing crop) samples were collected from all riparian plant communities during the maximum flowering time of the dominant plant species (2$^{nd}$ and 3$^{rd}$ week in July; see Milner and Hughes, 1968). Sampling plots (six in Porijõgi and three in Viiratsi) were installed in typical areas of the community. The above ground phytomass was collected from three replicate quadrates (1x1 m) in each community. Below ground phytomass was collected from soil cores taken by auger (diameter 158 mm) to a depth of 40-50 cm in three replicates from each location. Roots were washed of soil and from the dried roots and above ground phytomass, dry weight was measured and N and P content was analysed in the laboratory of Estonian Agricultural University. To estimate the above ground phytomass and productivity of grey alder forests, dimension-analysis techniques (Bormann and Gordon, 1984; Rytter, 1989; Huss-Danell and Ohlsson, 1992) were used. At both test sites (age 14 in Porijõgi transect and 40 years in Viiratsi transect) 17 and 5 sample trees per plot, respectively, were felled to collect data on the following tree components: stem (wood and bark), secondary branch growth (wood and
bark), primary branch growth, leaves, generative organs (Lõhmus et al., 1996). The relative increments of the wood and bark of an over-bark fraction were assumed to be equal. Root systems for 6 and 3 out of the sampled 17 and 5 trees, respectively, were excavated. The dried weight of all tree components was measured and N and P content in dried phytomass were analysed in laboratory of Estonian Agricultural University.

**Efficiency and buffering percentage calculations.** Removal efficiency E (%) of N and P in buffer communities was estimated as:

\[
E = 100 \% \times \frac{(Q_{in}C_{in} - Q_{out}C_{out})}{(Q_{in}C_{in})} \tag{1}
\]

\(Q_{in}\) and \(Q_{out}\) = inflow and outflow values (m³ d⁻¹), respectively; \(C_{in}\) and \(C_{out}\) = concentration values (mg l⁻¹), respectively.

The percentage of buffered stream banks was calculated as follows:

\[
B = \frac{l_b}{\Sigma l_t} \times 100\% \tag{2}
\]

\(l_b\) = length of all stream banks in the catchment (m), having buffer zone or strip between field and stream.

\(\Sigma l_t\) = total length of stream banks in the catchment (m).

The percentage of unbuffered stream banks was calculated as follows:

\[
U = \frac{l_u}{\Sigma l_t} \times 100\% \tag{3}
\]

\(l_u\) = length of all stream banks in the catchment (m), having agricultural fields up to the bank of stream.

The percentage of stream banks with natural communities was calculated as follows:

\[
N = \frac{l_n}{\Sigma l_t} \times 100\% \tag{4}
\]

\(l_n\) = length of all stream banks in the catchment (m), bordering with natural plant communities.
RESULTS AND DISCUSSION

**Nutrient dynamics in buffer zones.** The investigated buffers showed good removal efficiency. The 51 m wide Viiratsi transect removed 87% of total nitrogen and 84% of total phosphorus (Figures 1 and 2), while the 31 m wide Porijõgi transect showed 50% and 78% removal (Figures 3 and 4), respectively (Kuusemets and Mander, 1999). The lower N removal efficiency in the Porijõgi transect can be explained by lower incoming nitrogen load in soil water (average for study period 3.0 mg N l⁻¹). In Viiratsi the same value was 23 mg N l⁻¹. In both cases the most intensive retention and transformation was taken place already in the first part of the buffer. In the Porijõgi transect all phosphorus and major part of nitrogen was retained and transformed within the first 11 m wide *Filipendula-Aegopodium* wet meadow strip. Likewise, in the heavily polluted Viiratsi buffer zone first 11 m wide *Elytrigia repens*-grassland and 12 m wide *Filipendula-Aegopodium* wet meadow retained all phosphorus and main part of nitrogen entering the buffer. In the Viiratsi transect grey alder stand (*Alnus incana*) did leach out some phosphorus. However, the concentrations of out flowing ground water were very low (0.07 mg l⁻¹) for such heavily polluted area and were comparable with outflow from less polluted Porijõgi River transect (0.06 mg l⁻¹). The increase of phosphorus in lower part of Viiratsi transect can be caused due to the saturation in buffer zone.

Plant nutrient assimilation in the Viiratsi transect was higher in the wet meadow *Filipendula ulmaria* association (sampling plot 3, Figures 1 and 2), where an average of 21.1 g N m⁻² yr⁻¹ and 4.8 g P m⁻² yr⁻¹ was assimilated in grass. This was higher than the nutrient assimilation in the alder stand (14.0 and 1.1 g m⁻² yr⁻¹, respectively, sampling plot 4). In the Porijõgi transect the assimilation of nutrients was also highest in the wet meadow where the *Filipendula ulmaria* association (sampling plot 5, Figures 3 and 4) assimilated 21.3 and 3.0 g m⁻² yr⁻¹ of N and P, respectively. This was higher than annual N and P assimilation by alder forest: 20.5 and 1.5 g m⁻², respectively (sampling plot 6). Nutrient assimilation in 1994 reached 32.1 g N m⁻² in the Porijõgi transect (sampling plot 5) and 5.5 g P m⁻² yr⁻¹ in the Viiratsi transect (sampling plot 3).
Figure 1: N variation in Viiratsi transect

Figure 2: P variation in Viiratsi transect
The nutrient assimilation in plants indicates that grass communities play as important role in nutrient retention as grey alder forest. The average N and P content in herbal shoots in the wet meadows were 10.6 and 2.3 g m\(^{-2}\), respectively in the Viiratsi transect and 11.6 and 1.6 g m\(^{-2}\), respectively in the Porijõgi transect. These high values give good opportunity to remove portion of nutrients by grass mowing and hay removing while felling of trees can be done with intervals of decades. Cutting should be done during the maximum flowering period of the dominant species when the nutrient content in the shoot phytomass is highest (Deinum, 1966). The mowed herbs should be removed after mowing to avoid rapid nutrient loss from hay (Schaffers et al., 1998).

The N and P contents in soil increase in wet meadow riparian communities. The N content in the Viiratsi topsoil layer increased from 2.16 to 9.87 mg g\(^{-1}\) (sampling points 2 and 4, Figure 1) and the P content from 0.49 to 0.94 mg g\(^{-1}\) (Figure 2). In Porijõgi transect the increase of nitrogen and phosphorus was from 2.02 to 10.74 and from 0.45 to 1.02 mg g\(^{-1}\), respectively (sampling points 3 and 6, Figures 3 an 4). The highest values were in the alder *Alnus incana* communities.

Despite the increase of N and P content in soil in *Alnus incana* community the content of nutrients in groundwater is decreasing. The average outflow values from both buffer zones were lower than 3.1 and 0.07 mg l\(^{-1}\) of total-N and total-P in Viiratsi, respectively and 1.5 and 0.06 mg l\(^{-1}\) in Porijõgi, respectively. This indicates that the increased N and P content in soil are not affecting the water quality directly. The increased nutrient content in soil in *Alnus incana* community can be explained by very high nutrient content in litter of alder (Mikola, 1958).

The results show that complex buffer zones of grass and forest strips are very effective in N and P retention, which agrees with previous research (Schultz et al., 1995; Lowrance, 1991). This kind of complex can be recommended for buffer strip design where grass strips considered as sediment traps but also as important mechanism for dissolved N and P removal. Both features provide the opportunity to remove part of the nutrients from the system. In addition to efficient nutrient purification potential, forest buffer strips have many other environmentally important functions such as protection against soil erosion, filtering polluted air, canopy shading, and increasing biological and landscape diversity.
The impact of buffer zones in watershed level. The impact of buffer zones to water quality in the watershed level was analysed in Vända, Sipe and Porijõgi upper subcatchments of Porijõgi River watershed (Kuusemets and Mander, 1999). The subcatchments of Vända and Sipe have similar physico-geographical conditions, situating in central part of Porijõgi River catchment. Currently, 68% of Vända (Figure 5) and 58% of Sipe (Figure 6) subcatchments are used as agricultural land (Table 1).
The Porijõgi upper subcatchment has only 6.4% agricultural land (Figure 7), 79% of the subcatchment is covered by forest. This subcatchment can be used as control area to describe natural outflow rate in the region.

In Estonia, the most intensive use of agricultural lands took place at the end of Soviet period, from 1985 to 1990 (Mander and Palang, 1994). For instance, in 1987 the average fertilisation intensity was 150 kg N ha\(^{-1}\) and 60 kg P ha\(^{-1}\). Since 1990 the use of fertilisers dropped and constituted in 1994 only 2.3% N and 0.8% P of the level in 1987. In the Porijõgi catchment, the fertilisation intensity followed the tendency for the whole Estonia. In our study, outflow values for N and P are calculated as average for 1987-90 (Table 1). The results show very high outflow of nitrogen (24.4 kg ha\(^{-1}\) yr\(^{-1}\)) and phosphorus (0.67 kg ha\(^{-1}\) yr\(^{-1}\)) from the Vända subcatchment. It is 9.0 and 7.4 times higher than the outflow from the natural Porijõgi upper subcatchment, respectively. At the same time, from Sipe subcatchment with similar intensity of agricultural use, the outflow of nitrogen and phosphorus were only 1.9 and 1.6 times higher than in the natural subcatchment, correspondingly. Although Sipe stream has 51% percentage of unbuffered stream banks, the outflow of N and P is much lower than that in the Vända subcatchment with 63% unbuffered stream banks. One of the explanations is more complex landscape pattern in Sipe subcatchment that shows better buffering capacity (see Figures 5 and 6). Here in addition to buffer zone complex structure of landscape plays important role (45% of the 6.6 km long main stream is buffered), the main stream has meandering valley with a well-developed hyporheic zone. The Vända stream is completely straightened, has no meandering parts and only very short fragment of it has buffer zone on both banks that constitutes 7% of the total length (4.8 km) of the stream.

Table 1. Riparian buffer zones, natural communities adjacent to streams, and outflow of N and P (kg ha\(^{-1}\) yr\(^{-1}\)) from three subcatchments of the Porijõgi River.

<table>
<thead>
<tr>
<th>Subcatchment (stream)</th>
<th>Total area (ha)</th>
<th>Area of agricultural land (ha)</th>
<th>(B)</th>
<th>(U)</th>
<th>(N)</th>
<th>Outflow of total - N (kg ha(^{-1}) yr(^{-1}))</th>
<th>Outflow of total - P (kg ha(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vända</td>
<td>220</td>
<td>150</td>
<td>6</td>
<td>63</td>
<td>31</td>
<td>24.4</td>
<td>0.67</td>
</tr>
<tr>
<td>Sipe</td>
<td>900</td>
<td>518</td>
<td>32</td>
<td>51</td>
<td>17</td>
<td>5.0</td>
<td>0.14</td>
</tr>
<tr>
<td>Porijõgi upper</td>
<td>1230</td>
<td>79</td>
<td>6</td>
<td>1</td>
<td>93</td>
<td>2.7</td>
<td>0.09</td>
</tr>
</tbody>
</table>

B - Percentage of buffered stream banks (Formula 2)  
U - Percentage of unbuffered stream banks (Formula 3)  
N - Percentage of stream banks with natural communities (Formula 4)
**Watershed management.** Establishment and dimensioning of buffer zones needs proper analysis of whole catchment area. Watershed management should be carried out for the reduction of nutrient leaching from agricultural areas and application of mitigation measures. It needs detailed assessment of possible critical source areas, where the potential of nutrient leaching is higher (Kuusemets and Mander, 2001). The need of buffer zones depends mostly on soil and relief conditions. More sandy soils and steeper slope cause higher risk for erosion and nutrient outflow. Also, thalwegs of slopes and flow pathways must be considered for positioning of buffer zones. The width of the buffer zones can be calculated by special formulas (Mander *et al.*, 1997). The landscape structure and landcover must be taken into consideration as well to decrease nutrient leaching and to improve ecological network of the area. The mitigation measures should be used in the areas with higher pollution risk to receive higher ecological and economical efficiency.

**CONCLUSION**

Ecotechnological measures give good possibilities for controlling nutrient fluxes in watersheds. The most attractive multi-functional mitigation element for watershed management will be creation of buffer zones and buffer strips along ditches, channels and riverbanks. Buffer zones and buffer strips have number of positive functions. Some are important to reduce the negative environmental impacts to the water others are beneficial to the landscape and biodiversity. Buffer strips and zones allow stopping pollution at the source where it arises and reducing expenses of measures for improvement water quality in the stream. The most effective are complex buffer zones that consist of different buffer strips with different plant communities. For instance, a heavily loaded complex buffer zone consisting of grass and forest strips showed relatively low output concentrations for total-N and total-P that are comparable with the output values from the unloaded buffer zone with natural conditions. Buffer zones are very suitable for using in low-income countries like China as low cost tools for nutrient leaching reduction. In addition to the economical benefits buffer zones have several ecological advantages. They are also very suitable in the areas with high erosion risk. They can save remarkable part of humus layer at the same time decreasing the nutrient especially phosphorus outflow.
When planning and designing buffer zones, the role of grass buffer strips and wet meadows should be considered. Management of grasslands and forests can significantly decrease outflow from complex buffer zones.

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