Chapter 5

Natural and Restored Wetland Buffers in Reducing Sediment and Nutrient Export from Forested Catchments: Finnish Experiences

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Abstract One of the water quality management practices in forested catchments is to construct wetland buffers between managed areas and recipient water courses. Wetland buffers can be constructed simply by routing runoff from forested areas to natural peatlands and wetlands, or by rewetting lower sections of drained peatlands by filling in or blocking the drainage ditches. The use of natural and restored wetland buffers for reducing nutrient and sediment export from forested catchments, particularly catchments dominated by forestry-drained peatlands, has been studied actively in Finland during the last 15 years. The studies have shown highly variable retention capacity for wetland buffers with different site characteristics and under different environmental conditions. In favorable conditions, high amounts of sediments and adhered mineral elements may be deposited within peat and surface vegetation of the buffer. Dissolved nutrients can be retained biologically into plant

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and microbial biomasses and chemically into peat. In contrast, nitrogen can also be lost into the atmosphere in gaseous form. In this literature review, we summarize the results of the experiments established on natural and restored wetland buffers in forested catchments in Finland to clarify the different processes and factors controlling their nutrient and sediment retention capacity. We also discuss the limitations and possible negative consequences of using wetland buffers for managing water quality in forested catchments.

Keywords Drained peatland • Forestry • Restoration • Retention capacity • Wetland buffer

5.1 Introduction

Nutrient losses from forested catchments are generally low (Kortelainen and Saukkonen 1998; Mattsson et al. 2003), but after forest harvesting (Nieminen 2004), fertilization (Saura et al. 1995), and ditching operations (Joensuu et al. 2002; Nieminen et al. 2010), export of nutrients and sediments may increase. Harvesting of tree stands grown on drained peatlands was shown to increase nitrogen (N) export by over 4 kg ha^{-1} $year^{-1}$ (Uusivuori et al. 2008), and ditch drainage of peatlands and wetlands increased the sediment loading up to several thousands of kilograms per hectare (Hynninen and Sepponen 1983; Ahtiainen and Huttunen 1999). Similarly, forest fertilizations with nitrogen and phosphorus (P) may cause an excess leaching of several kilograms per hectare during the first few years after application (Nieminen and Ahti 1993; Saura et al. 1995). Forestry is typically practiced in headwater catchments where other human influence is insignificant; in these areas forestry is locally the main source of nutrients and sediments in water courses. In order to prevent nutrient and sediment leaching to downstream water courses, the current water protection guidelines in Finland propose that runoff from forested catchments is conveyed to receiving surface waters through wetland buffer areas (Metsätalouden ympäristöopas 2004). Buffer wetlands can be created by simply conducting the discharge waters from forested catchments to pristine mires, or occasionally to paludified mineral soils. However, because most peatlands and wetlands in Finland have been drained, a common practice is to restore sections of drained peatlands by filling in or blocking the drainage ditches. Buffer area size may vary considerably from a few meter-wide buffer zone-type constructions (Liljaniemi et al. 2003) to over hundred meters-long natural mires or restored sections of drained peatlands (Vikman et al. 2010). If only productive forestry land is available for the construction of the buffer, small areas are preferred, and the area then rarely exceeds 1.0–1.5 ha.

In addition to water quality management in forestry areas, wetland buffers or constructed wetlands have been applied to reduce sediment and nutrient loads from peat mining areas and to improve the quality of municipal waste water (e.g., Ronkanen and Kløve 2007, 2008), as well as to reduce loads from agricultural fields (Braskerud 2002) and urban areas (Birch et al. 2004). The quality of runoff from these different land use areas and discharge from waste water treatment plants is different and typically worse compared with runoff from managed forest areas. The retention efficiency in terms of relation between input and output loads tends to be higher for runoff with high pollutant concentrations than runoff with low pollution levels. The functioning of the wetlands for different purposes shares the same mechanisms, and the lessons learned from forest studies have wider implications to all buffer wetlands.

Different studies have shown highly variable nutrient retention efficiency for different wetland buffer areas in managed forest areas. For example, the efficiency of wetland buffers in reducing P load has varied from complete 100 % retention (Kubin et al. 2000) through partial P removal (Silvan et al. 2005a, b; Väänänen et al. 2008) to even increased leaching of phosphate (Liljaniemi et al. 2003; Vasander et al. 2003). Similarly, the retention of ammonium (NH_4-N) in six wetland buffers receiving runoff from upstream ditch-network maintenance areas ranged from clearly negative to complete 100 % retention capacity (Hynninen et al. 2011c). The retention of suspended solids by wetland buffers in seven ditch-network maintenance areas also showed high variation from slightly negative to over 80 % retention capacity (Nieminen et al. 2005a). The varying conditions of the buffer zone areas studied so far, such as their size and shape, vegetation composition and density, soil nutrient retention capacity, management history, life and construction method, environmental and meteorological conditions during the study period, as well as the varying length of the study period, complicate the detection of the common nominators for their nutrient and sediment retention efficiency. In this literature review, we summarize the factors controlling nutrient and sediment retention in wetland buffers used in forested catchments in order to be able to improve their functionality and retention capacity in operational forestry. We also discuss the limitations and possible drawbacks of using wetland buffers in managing water quality in forested catchments.

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5.2 Nutrient Retention Efficiency: Contributing Factors

5.2.1 Buffer Size and Shape

A number of studies indicate that the key factor explaining the nutrient retention efficiency of a wetland buffer is its size, more precisely the size of the buffer relative to the size of the whole upstream catchment area. Nieminen et al. (2005a) showed efficient suspended solid (SS) reduction capacity for the wetland buffers covering >1 % of the catchments area, but no reduction in through-flow SS concentrations for the buffers covering <0.1 %. They conclude the reduction of water flow velocity to be a key factor in the reduction of SS via increasing the time for particles to settle down. Further, as larger buffers (relative to catchment area)

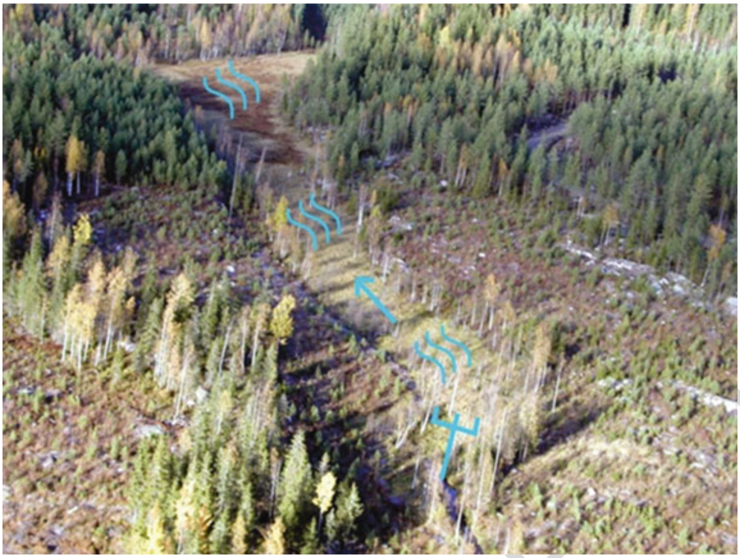

Fig. 5.1 The over 300 m long Kallioneva buffer is highly efficient in retaining the sediments and nutrients discharging from the upstream forested catchment (Photo: Martti Vuollekoski)

slow down water flow velocity more than small buffers, SS removal increases with the relative size.

The relative size of wetland buffers also explains much of the dissolved nutrient retention. The large size itself is a contributing factor because the vegetation and soil sinks are correspondingly larger, which results in lower relative nutrient load and lower probability of saturation of these sinks. The large relative size also enables longer water residence time and thus a longer contact time between the chemical and biological nutrient sinks and nutrient-rich through-flow waters (Fig. 5.1). In the very small buffer areas, the nutrient retention is poor, particularly if the flow is channelized to form continuous flow channels across the buffer area. In such channels, flow velocity is high and contact time between vegetation and soil sinks and through-flow water nutrients short; both of these factors are disadvantageous for high nutrient retention capacity (Väänänen et al. 2006). Thus, the study by Liljaniemi et al. (2003) showed negligible nutrient retention for the 2–8 m wide buffer strips, and they concluded that wider buffer areas with extensive overland flow areas are needed to efficiently control diffuse pollution from forested areas. In an artificial N addition experiment by Vikman et al. (2010) on six wetland buffers with the relative buffer size between 0.1 and 4.9 %, the correlation between NO_3-N retention (% of added) and relative buffer size was 0.75 ($p = 0.008$), but only 0.42 (n.s.) for NH_4-N. Their results actually indicated that the buffer length may be an even more important factor for buffer N retention efficiency than buffer size. The correlations between NH_4-N and NO_3-N retention and buffer length were 0.65 ($p = 0.03$) and 0.92 ($p < 0.001$), respectively. The effect of buffer length was interpreted to be because the probability of the formation of continuous flow channels across buffer area is lower for long buffers than short and wide buffers of the same size. The best-performing (NO_3-N retention 93.3–99.9 %) three wetland buffers in the study by Vikman et al. (2010) were all >100 m long and with no visible flow channels, while the 30 m long Asusuo buffer with a continuous flow channel across the buffer area had a NO_3-N retention capacity of <16 %. As the P retention capacity of the Asusuo buffer was also poor (Väänänen et al. 2008), Hynninen et al. (2010) question the rationale of constructing such small and short buffers.

5.2.2 *Nutrient and Hydrological Loading*

Although the size and shape of the buffer are important in sediment and nutrient retention, the results indicate that other factors also exist. The hydrological loading entering the buffer area and its temporal variability are considered to be one of the key factors (Väänänen et al. 2008). During high-flow episodes, the water residence time is short and the short contact time between nutrient sinks and through-flow water nutrients, as well as the formation of flow channels across the buffer, decreases the retention efficiency (Fig. 5.2). In an artificial nutrient addition experiment by Vikman et al. (2010), the correlation between NO_3-N retention and hydrological loading during 5 days after starting the N addition was −0.73 ($p < 0.010$), and −0.42 (n.s.) for NH_4-N. The study by Hynninen et al. (2011c), where they investigated the efficiency of buffer areas to reduce the ammonium export originating from ditch-network maintenance areas, also indicated that runoff during the study duration is a significant factor explaining the nutrient retention efficiency of buffer areas. As annual runoff increases toward northern latitudes, Hynninen et al. (2010) pointed out that larger buffer areas are needed in northern Finland to achieve similar retention efficiency as in southern Finland.

Although the hydrological loading and the buffer length were significant in explaining the NH_4-N retention originating from ditch-network maintenance areas in the study by Hynninen et al. (2011c), the contribution of these factors was minor compared with the strong influence of NH_4-N loading, i.e., the higher the NH_4-N loading into the buffer area was, the better the retention efficiency was. While the buffer length and the hydrological loading each explained about 5 % of the variation in ammonium retention, the rate of NH_4-N loading into the buffer areas was responsible for about 68 % of the variation. Hynninen et al. (2011c) argued that their results likely overestimate the effect of NH_4-N loading on retention efficiency and underestimate the contributions of other factors, such as buffer size, as the largest buffer areas with potentially high retention efficiency would probably have been able to retain much more ammonium from a higher loading than the buffers actually received after the ditch-network maintenance. Nevertheless, their results showed that the extent and pattern of nutrient loading may be a significant factor explaining the nutrient retention efficiency by wetland buffers. Also, Nieminen et al. (2005a) showed a strong positive correlation between

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Fig. 5.2 Channelization of water flow, particularly in small wetland buffers during high snowmelt flow periods, significantly decreases the nutrient retention capacity (Photo: Anu Hynninen)

sediment retention efficiency by wetland buffers and inflow water sediment concentrations.

The efficiency of buffer areas to retain nutrients and sediments is generally expressed as a load reduction percentage from the load input to the buffer. As significant reduction is not likely to occur from the inflow water with already low nutrient concentrations close to background levels of forested areas, it is not surprising that particularly poor retention efficiencies were reported when the performance of wetland buffers was assessed under such conditions (Vasander et al. 2003; Nieminen et al. 2005b). It is also to be noted that the very high retention efficiencies that are often reported after artificial nutrient additions (Silvan et al. 2005a, b; Väänänen et al. 2008; Vikman et al. 2010) may partly be explained by the fact that the high transient and steady loadings of artificial additions are retained more efficiently than the sporadically increased and long-lasting loadings typical for forested catchments after management options, such as harvesting (Nieminen 2004), ditch-network maintenance (Joensuu et al. 2002), and fertilization (Nieminen and Ahti 1993). In a nutrient addition experiment by Vikman et al. (2010), large and long buffers were able to retain almost all of the 25 kg of ammonium added during four days, but the model simulations by Hynninen et al. (2011c) indicated that only about half of the ammonium would be retained by similar long buffers from an equal annual loading caused by ditch-network maintenance.

Collectively, the previous results from forested catchments indicate that the wetland buffers have little effect on nutrient transport when the loadings are already near the background levels of forested catchments and that the pattern and duration of loading is a significant factor explaining nutrient retention efficiency under increased loadings. It is also to be noted here that the saturation of nutrient sinks in vegetation and soil due to chronic high loadings, as often occur in agricultural catchments and waste water treatment wetlands, may not be a common problem in forested catchments, where increased nutrient loadings due to forest management (harvesting, fertilization, ditch drainage) only occur 2–3 times during the tree rotation (80–100 years) and where the overall nutrient input into buffer areas is significantly lower.

5.2.3 Vegetation and Soil Processes

It is generally accepted that dense vegetation is important in nutrient retention, not only through nutrient accumulation in plant biomass but also because a dense vegetation cover forms a hydraulically rough surface and slows down the water flow velocity through the buffer area. A common argument supporting the importance of soil is the high cation exchange capacity (CEC) of peat in wetland buffers that enables a considerable potential to the retention NH_4-N, while the low P adsorption capacity of peat (Nieminen and Jarva 1996) may not enable much chemical retention of phosphate. Although vegetation has been found superior over microbes in compaction of N (Silvan et al. 2005a, b), the microbial communities are likely to thrive under high N inflow into buffer areas (Silvan et al. 2002; Hynninen et al. 2011a). A significant amount of N can be immobilized through an increase in the size and N concentrations of the microbial biomass. Despite these arguments, there are very few studies that attempted to quantify the roles of vegetation and soil processes in nutrient retention in wetland buffers in forested catchments.

Especially the role of different plant species in nutrient retention is weakly known. One aspect in the role of vegetation to be accounted for is the changing vegetation composition due to restoration succession promoted by increased water level in restored buffers. Species turnover might be further impacted by increased availability of nutrients that give competition advantage to opportunistic species such as cotton grass (Silvan et al. 2004).

The lack of information on the roles of vegetation and soil processes in nutrient retention may be due to experimental difficulties. The study by Silvan (2003) quantified the retention of P in soil and vegetation using the samples collected before and after an artificial P addition. The retention of P in peat was estimated to be 43 % of the added P, but then only the volumetric concentrations (mg cm^{-3}) indicated any P retention, while the gravimetric P concentrations (mg g^{-1}) remained unchanged. This reveals a possible experimental error in this type of approach; as the soil and vegetation samples collected before and after nutrient loading cannot be from exactly the same position, the different characteristics between the pre- and post-load sampling positions introduce error in the results. Thus, the higher volumetric concentrations in the post-addition samples in the study by Silvan (2003) may simply be because the samples were from more humified sampling positions than the pre-addition samples. Some of the error involved in pre- and post-load sampling could be decreased by increasing the number of sampling positions, but as the number already was high, e.g., in Silvan (2003), this would make the estimation very laborious, with no possibility to foresee any improvements in estimation accuracy. An additional problem with this type of approach is that, as the N and P stores in peat and vegetation may be large already before increased N and P loading or artificial addition, the changes in stores will easily remain too small for reliable estimation.

Experimental difficulties may also explain some of the very high variation in P and N retention estimates between the different studies. While Silvan (2003) estimated the retention of added N and P in vegetation biomass to be 70 and 25 %, respectively, Huttunen et al. (1996) in their study on a wetland buffer below a peat extraction area found more release than accumulation of P and only a slight retention of N (4 % of N input). The variation in nutrient retention estimates between the different studies may also be because soil and vegetation may not be permanent nutrient sinks, and while some of the nutrients are released after first being retained, the length of the study period affects the retention estimates. Some fraction of the nutrients are released from vegetation during the senescence and decay of the litter in the end and after the growing season, and also the nutrients retained in labile forms in the soil may be released when the nutrient concentrations in soil solution return to the levels before the increased nutrient loading. The only permanent nutrient "sink" in wetland buffers can actually be argued to be the loss of N_2 and N_2O into the atmosphere. If the nutrients retained in the vegetation and soil of wetland buffers eventually end up as structural components of the constantly accumulating dead biomass, i.e., peat, then nearly permanent retention in terms of unforeseen future is also possible.

The use of labeled isotopes could be a more powerful tool in the estimation of N and P retention in plant biomass and peat than the comparison of pre- and post-loading samples, but only the study by Väänänen et al. (2006) has utilized the labeled isotope approach in a forested catchment. They estimated that the recovery of added ^{32}P in a natural mesotrophic fen used as a wetland buffer was 16 % of added P, of which 92 % was in surface peat and 3 % in vascular plants and mosses. They interpreted that the low overall recovery and low accumulation in vegetation were because the addition experiment was realized in early spring, when snowmelt in the upslope areas still contributed to the high hydrological loading and plant photosynthesis and P assimilation had not yet recovered after a winter period. Thus, besides the extent of nutrient loading (see Sect. 5.2.2), the timing of loading may be a significant factor behind wetland buffer retention efficiency. In areas with a distinct winter period with snow accumulation-melting cycles and ground freezing, significant retention is improbable, when the highest loadings occur during the snowmelt periods with sparse vegetation cover.

A major problem in using labeled P in retention studies is that only short-term experiments are possible, as the degradation of ^{32}P to ^{31}P with a half-life of 14.3 days rapidly lowers the radioactivity level below reliable detection limits.

The problem in using ^{15}N isotope in N retention studies is its price; one kg of ^{15}N labeled ammonium nitrate costs still several thousands of euros in 2013. Thus, only laboratory-scale estimations are thus so far feasible.

Collectively, the previous results from wetland buffers indicate that roles of vegetation and soil processes in nutrient retention are difficult to quantify reliably and that it is possible that the highly variable results between the different studies are, at least partly, due to these experimental difficulties. Indirect information on the roles of vegetation and soil in nutrient retention may also be achieved by using vegetation and soil factors (e.g., bottom or field layer vegetation coverage (%), soil CEC (mmol kg^{-1}), soil phosphate adsorption capacity) as explanatory variables in the experimental models explaining the buffer retention efficiency. However, their effects are easily hidden behind the factors that are more significant for the retention capacity, such as the buffer size and the nutrient and hydrological loading. This was also the case in the study by Hynninen et al. (2011c), where the ammonium retention efficiency of wetland buffers was modeled using buffer size, buffer length, the coverage of buffer bottom and field layer vegetation, tree stand volume, soil bulk density, soil CEC, hydrological loading, and ammonium loading as explanatory factors. Only ammonium loading, buffer length, and hydrological loading were significant in explaining the ammonium retention efficiency by six wetland buffers.

5.2.4 *Other Factors*

One likely factor behind sediment retention in wetland buffers is also the type of sediment particles. Light organic particles and fine-textured mineral soil particles are probably retained less efficiently than heavy and high-density mineral particles, but the effect of this factor on sediment retention in wetland buffers has not been studied. Water protection constructions based on the sedimentation of SS, such as sedimentation ponds, have been shown to be inefficient in reducing the transport of light organic particles and fine-textured mineral soil particles (Joensuu et al. 1999). As the increase in fine-textured mineral soil particles, in particular, may be substantial after ditching operations and ditching-induced sediment transport is regarded as the most harmful water quality impact of forestry in Finland (Joensuu et al. 2002), the contribution of wetland buffers to the reduction of fine-textured sediment transport is an important future research subject.

Also the age of the buffer has been shown to be a factor behind nutrient retention efficiency, particularly the retention of phosphate (Vasander et al. 2003). The wetlands recently restored for use as buffer areas may release more phosphate than accumulate it, probably because the redox-sensitive phosphate compounds in peat are released along with filling in or blocking the ditches and consequent rewetting and water table rising. If the restoration also involves harvesting of the tree stand from the buffer area, the harvest residues left on site also form a possible source of phosphate and other nutrients from the buffer area into receiving water courses. However, although enhanced export of P would occur during peatland restoration for use as a buffer area, and perhaps a few years after restoration (Vasander et al. 2003), Liljaniemi et al. (2003) and Nieminen et al. (2005a) pointed out that all wetland buffers are likely to turn into nutrient-accumulating systems in the long term. As the enhanced release of P due to rewetting may only last for 2–3 years (Vasander et al. 2003), relatively newly restored wetland buffers may already be efficient in retaining the nutrients released from the upstream forest area as a consequence of forest management operations. It should also be noted that only some of the peat soils appear to contain significant amounts of redox-sensitive P (Kaila et al. 2012), but the current level of understanding does not support the identification of sites with high risk for increased P release upon rewetting. As pointed out earlier, the aging of buffer areas in forested catchments is unlikely to result in decreased nutrient retention capacity (i.e., saturation of nutrient sinks), as may be true for the buffers in agricultural areas and the waste water treatment buffers, because the nutrient loadings into wetland buffers in forested areas are significantly lower.

5.3 Limitations and Possible Drawbacks

Blocking or filling in the ditches in the area planned to be used as a buffer results in water table rising not only in the buffer area itself but also in the upstream area. The size of the affected area and the rate of water table rising depend on the local land topography, soil depths, and soil hydraulic properties. In a sloping land, the rewetted area above the buffer area may be just a few meters or tens of meters long, but in the very flat lowlands, the rewetted area may extend to several hundreds of meters from the buffer area. This causes a major limitation in the use of wetland buffers in operational forestry. In the coastal area of western Finland, in particular, the lands are flat and constructing wetland buffers there could mean significant water table rising and decrease in the vitality and growth of trees in the large productive forestland areas above the buffer area. Thus, even if the use of wetland buffers is currently recommended as the most efficient means of decreasing diffuse pollution in forested catchments, their use in operational forestry is restricted to areas where sloping land facilitates the construction of the buffer without severely disturbing tree growth in the upstream productive forestland. In the very flat areas, typically consisting of drained peatland forests, use of the recently developed peak runoff control method (Marttila and Klöve 2010) is recommended to decrease ditch erosion and the export of suspended sediments and adhered mineral elements. Instead, the use of sedimentation ponds as the only water quality protection method should be avoided due to their very limited capacity for decreasing sediment export (Joensuu et al. 1999).

Another major limitation in the use of buffer areas arises from the need to conserve endangered wetland site types. Use of these sites as buffer areas may induce unwanted changes in the plant species composition. According to Hynninen et al. (2011b), grasses, sedges, as well as herbs are generally favored in wetland

Fig. 5.3 The vegetation in the Hirsikangas during the time of buffer construction (Photo: Jorma Issakainen)

buffers, and the changes are more apparent in the upstream parts of buffers than the lower parts (Fig. 5.3). Also, the vegetation growing in the lawn-level surfaces changes more than the hummock vegetation. To protect endangered mire site types, such sites should be left aside from buffer use to avoid significant changes in vegetation composition (Hynninen et al. 2011b) (Fig. 5.4). AU4

It should be noted that wetland buffers may be efficient in mostly reducing inorganic nutrient export, while much of the nutrient export from forestland occurs in organic forms. For example, while the increased export of inorganic N following harvesting of drained spruce mires was only a few hundred grams per hectare, the increase in dissolved organic N export was several kilograms per hectare (Nieminen 2004). Forest clear-felling may also result in substantially enhanced dissolved organic carbon (DOC) export (Nieminen 2004), but because organic soils, including wetland buffers, typically act as sources rather than sinks of DOC, wetland buffers may not be used as efficient means for decreasing DOC export. The efficiency of wetland buffers in reducing DOC and organic nutrient transport has not been assessed in forested catchments, but the studies from peat extraction areas showed that wetland buffers in those areas were not efficient in reducing dissolved carbon export (Klöve et al. 2012). The fate of DOC and organic nutrients in wetland buffers in forested catchments still needs to be assessed, but the hypothesis is that their retention may not be particularly efficient.

The use of buffer areas to filter high loads of N could change the dynamics of N cycling, including the production of greenhouse gas N_2O. However, the study by Hynninen et al. (2011a) indicated low emissions even when the artificial N addition

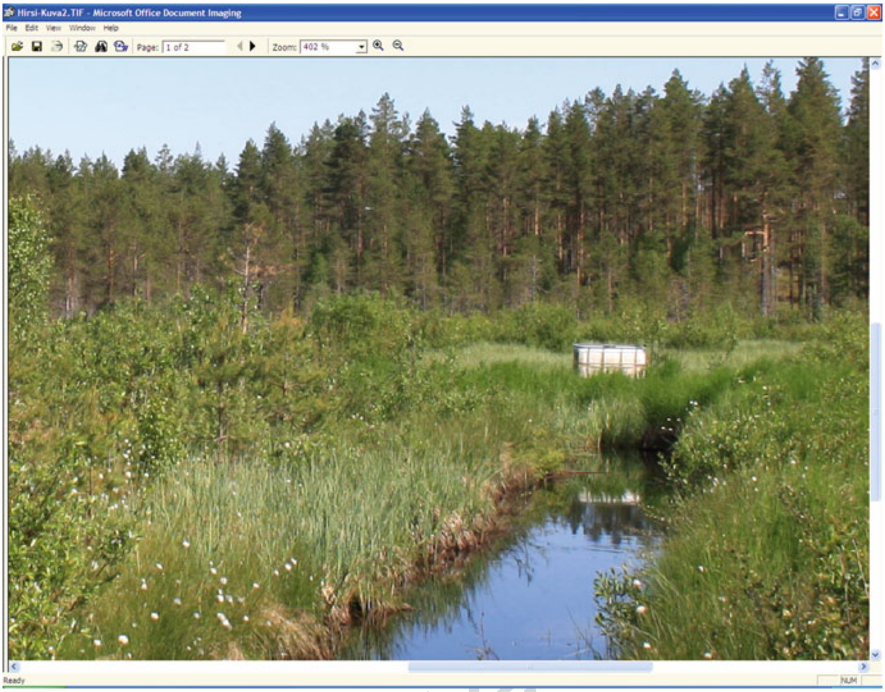

Fig. 5.4 The vegetation in the Hirsikangas buffer 11 years after buffer construction (Photo: Anu Hynninen)

of 150 kg of NH_4NO_3 per buffer area increased the N loading to considerably higher levels than is likely to occur under actual conditions in managed forested catchments. The emissions (0.15 kg N_2O ha^{-1}) were substantially lower than the annual emissions reported for drained minerotrophic peatland forests by Martikainen et al. (1995) (0.4–1.4 kg N_2O $year^{-1}$), or for peat soils drained for agricultural purposes (Regina et al. 2004); (0.3–19 kg N_2O ha^{-1} $year^{-1}$). Saari et al. (2013) also showed low N_2O emissions for a wetland buffer receiving water flows from a drained peatland forest, and they concluded the low inflow N concentrations to be the main reason for low emissions.

The restoration of drained peatlands for use as wetland buffers has also raised a concern of increased methane emissions. However, Juottonen et al. (2012) showed negligible methane emission from the wetland buffers rewetted >10 years earlier compared with corresponding natural wetland buffers. The emission from natural wetland buffers was similar as reported for the natural peatlands that are not used as buffer areas. The analysis of methanotrophic and methanogenic populations by Juottonen et al. (2012) indicated that, rather than enhanced methane oxidation, the reason behind low methane emissions was that the time after rewetting was still too short for the restoration of methanogen populations. The methanogenic populations in the three restored wetland buffers differed significantly from the populations in three natural wetland buffers sharing very identical populations.

5.4 Summary

We summarize the results of the experiments established on wetland buffers in forested catchments in Finland as follows.

The over 100 m long buffer areas with a relative size of over 1 % from the upstream catchment are generally highly efficient in reducing sediment and dissolved nutrient transport, while the short and small buffer zone-type constructions covering <0.1–0.2 % may be inefficient in retaining the nutrients released from upstream forest areas as a consequence of forest management operations.

High hydrological loadings decrease the buffer nutrient retention efficiency, and in areas with a distinct winter period, such as Finland, buffer areas may not be particularly efficient, if the highest nutrient loadings occur during high snowmelt flow periods with still sparse vegetation cover. As runoff increases toward northern latitudes, larger buffers are needed in northern Finland to achieve similar retention capacity as in southern Finland.

When the nutrient loadings into buffer areas are already low and near the background levels of forested catchments, wetland buffers may have little effect on nutrient transport. The timing, pattern, and duration of nutrient loading are significant factors explaining the nutrient retention efficiency under the increased loadings caused by forest management operations.

The roles of vegetation and soil processes in nutrient retention in wetland buffers are difficult to quantify reliably. The highly variable retention estimates for soil and vegetation between the different studies may, at least partly, be because of these experimental difficulties.

The major limitation in the use of wetland buffers in operational forestry is that their use is restricted to areas where sloping land enables the construction of the buffer without leading to the rising of water table in the upstream productive forestland. Another major limitation is that wetland buffers may not be particularly efficient in decreasing the transport of DOC and dissolved organic nutrients. It should also be noted that as the vegetation in natural mires used as wetland buffers is likely to undergo significant changes, endangered mire site types in their pristine state should not be used as buffer areas.

Even if the area of wetland buffers increased significantly from the present state, the emissions of greenhouse gases N_2O and CH_4 from wetland buffers are unlikely to increase to levels causing problems from the viewpoint of global warming. The low CH_4 emissions from restored wetland buffers, even after >10 years after restoration, make them promising candidates for buffer areas to take advantage of their nutrient retention capacity without simultaneously causing high methane fluxes.

Future research should clarify the contribution of sediment type (organic vs. mineral, fine textured vs. coarse) to sediment retention efficiency by wetland buffers, as well as the retention of DOC and dissolved organic nutrients in different types of wetland buffers. An important future research topic is also to provide tools to identify the sites that are likely to release redox-sensitive P into drainage waters, when drained peat soils are restored and rewetted for use as a buffer area.

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