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Capacity of riparian buffer areas to reduce ammonium export originating from ditch network maintenance areas in peatlands drained for forestry

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It is currently recommended to use buffer areas in reducing nutrient export from forested areas to water courses. Nutrient retention in buffer areas has been studied mostly by using artificial nutrient additions, hence information is needed from areas where the increased export originates from an actual forestry practice. We investigated the capacity of riparian buffer areas to reduce the ammonium (NH_4-N) export originating from ditch network maintenance areas on boreal forested peatlands. Our results indicated that buffers are inefficient for reducing loadings that already are close to background levels of forested areas. In such a case, the buffer may even release NH_4-N into through-flow waters. When the loading rate increased high above the background level, efficient reduction in NH_4-N transport became possible. Besides the rate of ammonium loading, a factor behind efficient retention was the sufficient length of the buffer, whereas high volume of runoff decreased retention efficiency. Other buffer characteristics, such as the soil properties (bulk density, CEC), the tree stand structure, and the density of surface vegetation, were insignificant for ammonium retention efficiency.

Introduction

In order to decrease nutrient export from forested areas to watercourses, it is currently recommended in forestry that nutrient-rich drainage waters are conveyed through either natural or restored wetland buffer areas. The use of buffer areas in filtering nitrogen and phosphorus from the waters discharging from forest areas has been actively researched during the last 15 years (Sallantaus *et al*. 1998, Liljaniemi *et al*. 2003, Vasander *et al*. 2003, Silvan *et al*. 2005, Väänänen *et al*. 2006, 2008, Laurén *et al*. 2007, Lundin *et al*. 2008, Vikman *et al*. 2010). The studies indicate efficient nutrient removal, especially by large buffer areas (> 1% of catchment area) and under transient high nutrient loading (Silvan *et al*. 2005, Väänänen *et al*. 2006, Vikman *et al*. 2010). Under low nutrient loading close to the background levels of forested areas, buffer areas have little effect on through-flow nutrient concentrations or they may even act as nutrient sources to recipient waters courses (Liljaniemi *et al*. 2003, Nieminen *et al*. 2005a, Lundin *et al*. 2008). Negative retention capacity is particularly true for newly restored peatland buffers, which may release nutrients to through-flow waters during the first few years after restoration operations, such as ditch blocking and tree stand harvesting (Vasander *et al*. 2003). Low nutrient retention capacity due to saturation of nutrient sinks in soil and vegetation is unlikely to be as important factor in forested catchments as in agricultural areas (Bernot *et al*. 2006, Dorioz *et al*. 2006) and in the buffers used for waste water treatment (Sloey *et al*. 1978, Nichols 1983, Ronkanen and Kløve 2009).

The water purification capacity of buffer areas varies also depending on the rate of hydrological loading entering the buffer area, and soil and vegetation characteristics of the buffer (e.g. Lance 1972, Woltemade 2000). During high flow episodes, water residence time is short and the formation of continuous flow channels across the buffer area decreases retention efficiency (Woltemade 2000, Väänänen *et al*. 2006, 2008). Under low flow conditions, the contact time between through-flowing water and nutrient sinks in soil and vegetation is longer and the retention of soluble nutrients is more effective (Heikkinen *et al*. 1994, Sallantaus *et al*. 1998, Dosskey 2001, Väänänen *et al*. 2008). Dense vegetation cover controls the nutrient retention capacity directly by assimilating nutrients into the above-ground and below-ground parts of plants (Nichols 1983, Huttunen *et al*. 1996, Kallner Bastviken *et al*. 2009), and indirectly by slowing down the water movement. The capacity of soil to retain nutrients in buffer areas varies depending on physical and chemical soil characteristics, such as cation exchange capacity (Heikkinen *et al*. 1994) and phosphate sorption properties (Väänänen *et al*. 2008).

Where the nutrient loading rate is low, artificial addition of nutrient solutions into the water entering buffer areas at a high and steady loading rate during a time period of few days or months is a widely used approach for studying the effect of high loading on retention efficiency and the related processes (e.g. Silvan *et al*. 2005, Väänänen *et al*. 2008, Vikman *et al*. 2010). However, the nutrient addition experiments are unlikely to closely simulate sporadically increased and long-lasting loadings that are shown to occur, e.g., after forest harvesting, fertilization and ditch network maintenance (Binkley *et al*. 1998, Ahtiainen and Huttunen 1999, Joensuu *et al*. 2002). The pattern and duration of nutrient loading may strongly affect nutrient retention efficiency of buffer areas and information is currently needed from areas where the increased loading originates from an actual forestry practice rather than an artificial nutrient addition. The retention of suspended solids in buffer areas receiving increased loading from areas subjected to ditch cleaning was earlier studied by e.g. Nieminen *et al*. (2005b), but soluble nutrient retention in buffer areas under high loading was only studied by using artificial nutrient additions (Silvan *et al*. 2005, Väänänen *et al*. 2008, Vikman *et al*. 2010).

Ditch network maintenance (ditch cleaning and complementary ditching) is a widely used practice in Finnish forestry in order to maintain the drainage efficiency and the good growth and productivity of tree stands on drained peatlands (Paavilainen and Päivänen 1995). However, it may have significant harmful effects on water quality of recipient streams and lakes (Joensuu *et al*. 2002, Nieminen *et al*. 2010). The most pronounced change after ditching is the increase in suspended sediment export (Joensuu *et al*. 2002, Nieminen *et al*. 2010). On the other hand, exports of phosphate and nitrate are generally not changed after ditch network maintenance and the exports of dissolved organic carbon and organic nitrogen may even decrease (Joensuu *et al*. 2002, Nieminen *et al*. 2010). However, ammonium export typically shows a clear increasing trend due to ditch network maintenance (Manninen *et al* 1998, Joensuu *et al*. 2002). In undisturbed forest areas, the concentrations of ammonium in surface waters are naturally low and increased export due to ditch network maintenance may increase eutrophication.

The aim of the present study was to investigate the capacity of riparian buffer areas in forested catchments to reduce ammonium export originating from ditch network maintenance areas in peatlands drained for forestry purposes.

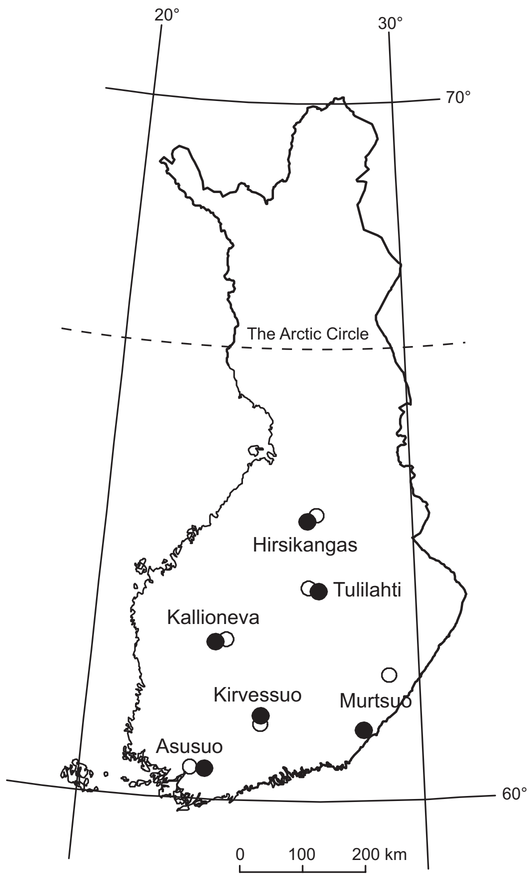

Fig. 1. Location of the study sites (dots) in southern and central Finland, and location of the nearby small catchments (circles) of the Finnish Environment Institute used as reference data for monthly runoff. For information about the network of small catchments, *see* Hyvärinen and Korhonen (2003).

Based on earlier artificial addition experiments, we hypothesized that buffer areas are efficient for retaining ammonium from through-flow waters. We further hypotheitzed the retention efficiency to be related to the soil characteristics (e.g. CEC and peat bulk density), vegetation composition and the size and shape of the buffer, the water flow into buffer area and the level of ammonium export. However, due to the different duration and pattern of NH_4-N loading caused by ditch network maintenance, we expected overall retention efficiency and the significance of the contributing factors differ from that found in artificial addition experiments.

Material and methods

Study sites and sampling

The study was carried out at six watershed areas in south-central Finland (Fig. 1). At each watershed there was an old forested peatland drainage area, where the ditch network was maintained and a buffer area was constructed downstream from the outlet of the drainage network (Table 1). The description of catchments and construction of buffer areas are presented in detail in Nieminen *et al*. (2005a, 2005b), and only a brief outline of the sites is presented here. Four of the six buffer areas (Asusuo, Murtsuo, Kirvessuo and Hirsikangas) were constructed by filling in the main outlet ditch of the upstream drainage area and conducting its discharge to a downstream undisturbed and flat mire area. No active buffer area construction operations were needed at the remaining two areas (Kallioneva and Tulilahti), where the outlet ditches from the drainage areas ended in undrained areas through which the waters had been flowing long before the monitoring in the present study was started. The sizes of buffers varied from 0.09 to 1.03 hectares, accounting for 0.09% to 4.88% of the catchment areas, respectively.

The Asusuo, Hirsikangas and Kallioneva buffer areas were nearly pristine, undrained mires. The Hirsikangas and Kallioneva buffer areas were treeless mires, while the Asusuo area was covered by a dense downy birch stand (*Betula pubescens*) with an average tree height of 10 m. The Murtsuo and Kirvessuo buffer areas were drained peatlands, where the surface vegetation had undergone compositional changes from the pristine state as a result of drainage. The Murtsuo buffer area was dominated by a dense downy birch stand and the Kirvessuo buffer area was characterized by a mixed Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*) and downy birch stand. The Tulilahti buffer area was a paludified mineral soil forest of the *Vaccinium vitis-idaea* type (Cajander 1926) and it had been cut in a seed tree position five years before the start of the study. The depth of the peat layer was > 1 m at all five peatland-dominated buffer areas. The total coverage of bottom layer vegetation in the five peat covered buffer areas varied between 3% and 69%, and that of field layer vegetation from 4% to 43% (Table 1). The most common bottom and field layer species in the five peatland dominated buffer areas are given in Väänänen *et al*. (2008). Soil bulk density in the five peatland dominated buffer areas varied from 0.08 to 0.36 g dm^{-3} and CEC from 90 to 422 mmol kg^{-1}. The sparse vegetation cover at Murtsuo was a result of the dense downy birch stand and the sediment that had eroded from the upstream drainage network and deposited in the buffer area. The high bulk density of soil at Asusuo was also because of the high content of mineral sediments.

The lowest parts of the Tulilahti buffer area were characterized by a number of big rocks and waters from the upstream drainage area mostly travelled as channel flow between these rocks and bulk soil (silty till). Most of the water flow at the other buffer areas occurred as an overland flow (or a sheet flow) across the relatively flat buffer areas. Contribution of the channel flow to the total surface flow was largely related to the size of the buffer, i.e. the channel flow was considerable in small areas, but almost totally absent in Hirsikangas and Kallioneva.

In each buffer area, sampling of inflow and outflow waters was started as soon as the buffer construction operations were finished, namely in summer 1995 at Murtsuo and Asusuo, in summer 1996 at Kirvessuo, in winter 1996 at Tulilahti, and in spring 1998 at Kallioneva and Hirsikangas. The sampling continued until the end of 2000 in Tulilahti and until the end of 2001 at all other sites. Sampling was started during snowmelt in spring and continued untill the freezing of waters in late autumn. The sampling interval was twice a week during spring and from weekly to biweekly during other seasons. The inflow samples were taken either from the overflow of a V-notched weir (Asusuo, Murtsuo, Kallioneva) or directly from flowing water in the inlet ditch. Outflow water sampling also occurred at a V-notched weir (Kallioneva and Hirsikangas)

Table 1. Background information of the studied buffer areas (BAs).

	Asusuo	Kirvessuo	Tulilahti	Murtsuo	Hirsikangas	Kallioneva
Location	60°26´N, 23°38´E	61°14´N, 25°16´E	63°01´N, 26°59´E	61°01´N, 28°19´E	64°04´N, 26°40´E	62°16´N, 23°48´E
BA (ha)	0.20	0.12	0.09	0.16	1.01	1.03
Watershed area (ha)	87	133	50	107	90	21
BA (% of watershed area)	0.23	0.09	0.18	0.20	1.12	4.88
Length of BA[1] (m)	30	55	90	50	100	320
Site description	Undrained mire	Drained peatland	Paludified mineral soil	Drained peatland	Undrained mire	Undrained mire
Site type[2]	Tall-sedge spruce swamp	Herb-rich type	*Vaccinium vitis idaea* type	*Vaccinium myrtillus* type	Low-sedge bog	Tall-sedge fen
Stand description	*Betula pubescens* dominated	*P. abies*, *P. sylvestris*, *B. pubescens* dominated	*Pinus sylvestris* dominated	*Betula pubescens* dominated	Treeless	Treeless
Stand volume (m^3 ha^{-1})	80	100	30	80	0	0
Peat depth (m)	> 1	> 1	< 0.1	> 1	> 1	> 1
Bulk density (g cm^{-3})	0.35 ± 0.07	0.14 ± 0.03	–	0.19 ± 0.01	0.13 ± 0.03	0.07 ± 0.01
CEC[3] (mmol kg^{-1})	90 ± 23	422 ± 46	–	290 ± 9	129 ± 30	253 ± 23
Vegetation coverage[4] (%)						
Field layer	15	43	–	4	11	29
Bottom layer	69	24	–	3	43	90

[1] Distance between water inlet and outlet of a buffer.
[2] Site types for pristine mires and drained peatlands according to Heikurainen and Pakarinen (1982), for mineral soils according to Cajander (1926).
[3] Measured with $BaCl_2$ extraction, ICP/IRIS.
[4] According to Väänänen *et al.* (2008).

or at a natural flow channel. In the laboratory, the water samples were filtered through 1.0 μm fibre-glass filters and the filtrates were analyzed for NH_4-N with a Tecaton FIA analyser according to Jarva and Tervahauta (1993).

To increase the export of ammonium flowing into the buffer areas, ditch network maintenance operations (ditch cleaning and/or complementary ditching) were performed at the drainage areas above each buffer area. The maintenance operations were performed three years after the buffer construction at Kirvessuo and one year after the construction at the remaining five areas. The ditch network maintenance area accounted for about 16% of the catchment area at Murtsuo, 25% at Asusuo, 39% at Kirvessuo, 29% at Kallioneva, 32% at Tulilahti, and 65% at Hirsikangas.

Calculations of the retention of NH_4 in the buffer areas

The statistical significance of the measured changes in the NH_4-N concentrations before and after ditch network maintenance and between the inlet and outlet of the buffer area were calculated using a non-parametric Mann-Whitney-Wilcoxon test. It tests whether the median values of two populations differ. The significance level was set at 0.05.

To investigate the efficiency of buffer areas in reducing the NH_4-N export (kg a^{-1}), we first calculated the annual NH_4-N export (kg a^{-1}) above and below each buffer area. The annual NH_4-N export was computed in the following way. First, available NH_4-N concentration measurements were used to produce monthly mean concentration in ditch water above and below each buffer area. Concentration values for the months with no observations were interpolated from the closest available monthly values. Second, the monthly concentration was multiplied by monthly runoff, which was obtained using the data from the nearby research catchments of the Finnish Environment Institute (Fig. 1). Finally, the monthly exports were summed up to yield the annual export and the efficiency of the buffer areas in retaining NH_4-N was calculated by subtracting the annual ammonium export below the buffer area from the export above the buffer area.

In the computation of the NH_4-N export, runoff was assumed to be unaffected by ditch network maintenance. The effect of ditch network maintenance on runoff is reported to be negligible in a number of earlier papers (e.g. Åström *et al*. 2001a, 2001b, 2002, Koivusalo *et al*. 2008) and many earlier sediment and nutrient export studies adopted this assumption in the estimation of export values in kg ha^{-1} a^{-1} (e.g., Joensuu *et al*. 2002, Nieminen *et al*. 2010).

The factors behind the variation in the annual NH_4-N retention efficiency were analyzed by a linear regression model. The mixed model approach was used in the model construction in order to account for autocorrelation between repeated measurements (McCulloch and Searle 2001). We identified two hierarchical levels of variation in the datasets: (a) between the buffer areas, and (b) within the buffer areas between the measurement occasions. The two hierarchical levels were used as the random variables in the models. The tested explanatory variables were the buffer size (ha), the relative buffer size (% of catchment area), the buffer length (m) (Table 1), the coverage of buffer bottom and field layer vegetation (%), the volume of buffer tree stand (m^3 ha^{-1}), the soil bulk density (g cm^{-3}), the soil CEC (mmol kg^{-1}), the water flow (m^3 a^{-1}) and the NH_4-N loading (kg a^{-1}) to the buffer area. If the relationship of the explanatory variable against the dependent variable was nonlinear, the variables were linearized using the natural logarithm. When testing the effects of vegetation coverage and surface soil characteristics on the retention efficiency, only the five peatland dominated riparian buffers were included, i.e. the Tulilahti paludified mineral soil site was excluded.

The mixed model was constructed as follows:

$$y_{ijl} = \alpha_{ij} + b_1 x_{1ij} + b_2 x_{2ij} + \ldots + b_n x_{nij} + u_j + e_{ij} \quad (1)$$

where y_{ijl} is the annual NH_4-N retention (kg a^{-1}) in year i in buffer area j, α is the intercept, $b_1 \ldots b_n$ are the model parameters, $x_{1ij} \ldots x_{nij}$ are the explanatory variables, u_j is the random effect of the buffer area j, and e_{ij} is the random error that accounts for the within-buffer area variation among the NH_4-N observations. The underlying assumption is that the random variables u_j and e_{ij} are uncorrelated and follow normal distributions with zero means.

The fixed and random parameters of the model were estimated simultaneously with the restricted iterative generalized least-square (RIGLS) method — which has been recommended for small samples — using the MLwiN software (Rasbash *et al*. 2001). The standard error of the parameter estimates was used to determine the significance of the parameter. A parameter was determined to be significant when its absolute value was two times greater than the estimate of the standard error. The value of –2(log-likelihood) was used to compare the overall goodness-of-fit of the models of increasing number of explanatory variables. The model was constructed by adding one variable after another until there was no significant improvement in the likelihood measure, or one or more of the explanatory variables became non-significant. The Akaike Information Criterion (AIC) was used as the test criterion when assessing the model improvement after adding one explanatory variable and finding the best-performing model. The performance of the model was evaluated by calculating the systematic error (Bias) and the explained variance of the total variation in the data (EV%).

Results

Before ditch network maintenance, the NH_4-N concentrations in inflow and outflow waters of the buffer areas were low (< 0.07 mg l^{-1}) in Kirvessuo, Tulilahti and Asusuo, but sporadic high concentrations were observed in the inflow of Kallioneva and in the inflow and outflow of Hirsikangas and Murtsuo (Fig. 2). The average concentrations in Kallioneva after ditch network maintenance were 0.063 mg l^{-1} in the inflow and 0.004 mg l^{-1} in the outflow water. The inflow and outflow concentrations, respectively, after ditching from the other areas were: 0.005 and 0.006 mg l^{-1} in Asusuo, 0.048 and 0.022 mg l^{-1} in Hirsikangas, 0.094 and 0.047 mg l^{-1} in Tulilahti, 0.273 and 0.187 mg l^{-1} in Murtsuo; and 0.093 and 0.048 mg l^{-1} in Kirvessuo. According to the Mann-Whitney-Wilcoxon test, significantly higher NH_4-N concentrations in the inflow to the buffer area occurred after ditch network maintenance than during pre-maintenance period in Murtsuo, Kirvessuo, Tulilahti, and Hirsikangas buffer areas. At Asusuo and Kallioneva, the ammonium concentrations in the inflow waters to buffer areas did not increase significantly by ditch network maintenance.

Before ditch network maintenance, the export of NH_4-N in kg a^{-1} was higher in the outflow than in the inflow in Asusuo, Murtsuo, Tulilahti and Hirsikangas (Table 2). After ditch network maintenance, all buffer areas except for Asusuo had higher NH_4-N export above the buffer area than below it. The annual retention efficiency of NH_4-N at Kallioneva varied between 2.8 and 7.3 kg a^{-1} during three years following ditch network maintenance, and from 6.1 to 7.4 kg a^{-1} at Tulilahti (Table 2). Corresponding variations during two years following ditch network maintenance were from 12.2 to 21.5 kg a^{-1} at Kirvessuo, and from 4.0 to 7.9 kg a^{-1} at Hirsikangas. The retention of NH_4-N at Murtsuo was from 6.1 to 17.1 kg a^{-1} and from –1.4 to 0.5 kg a^{-1} at Asusuo during four years after ditch-network maintenance.

According to the mixed model, the variation in NH_4-N retention was mostly explained by the rate of NH_4-N loading into the buffer area, responsible alone for about 68% of the variation in NH_4-N retention efficiency (EV%, Table 3). Adding the buffer length or the water flow as explanatory variables into the model increased goodness-of-fit of the model, and their effects on the model performance were rather similar. EV% after adding the second, new variable was about 73% (Table 3). The bias of the model predictions was small, slightly overestimating the retention (Table 3). The buffer area bottom layer or field layer vegetation coverage, the buffer tree stand volume, the pristine or restored state of buffer, or the buffer soil characteristics (bulk density, CEC) tested as explanatory variables did not increase goodness-of-fit of the models.

The model simulations showed that the retention of NH_4-N was non-linearly and positively related to the buffer length and negatively to the volume of water discharging to the area (Figs. 3 and 4). Even more NH_4-N was released than retained in the buffer areas, when NH_4-N loading

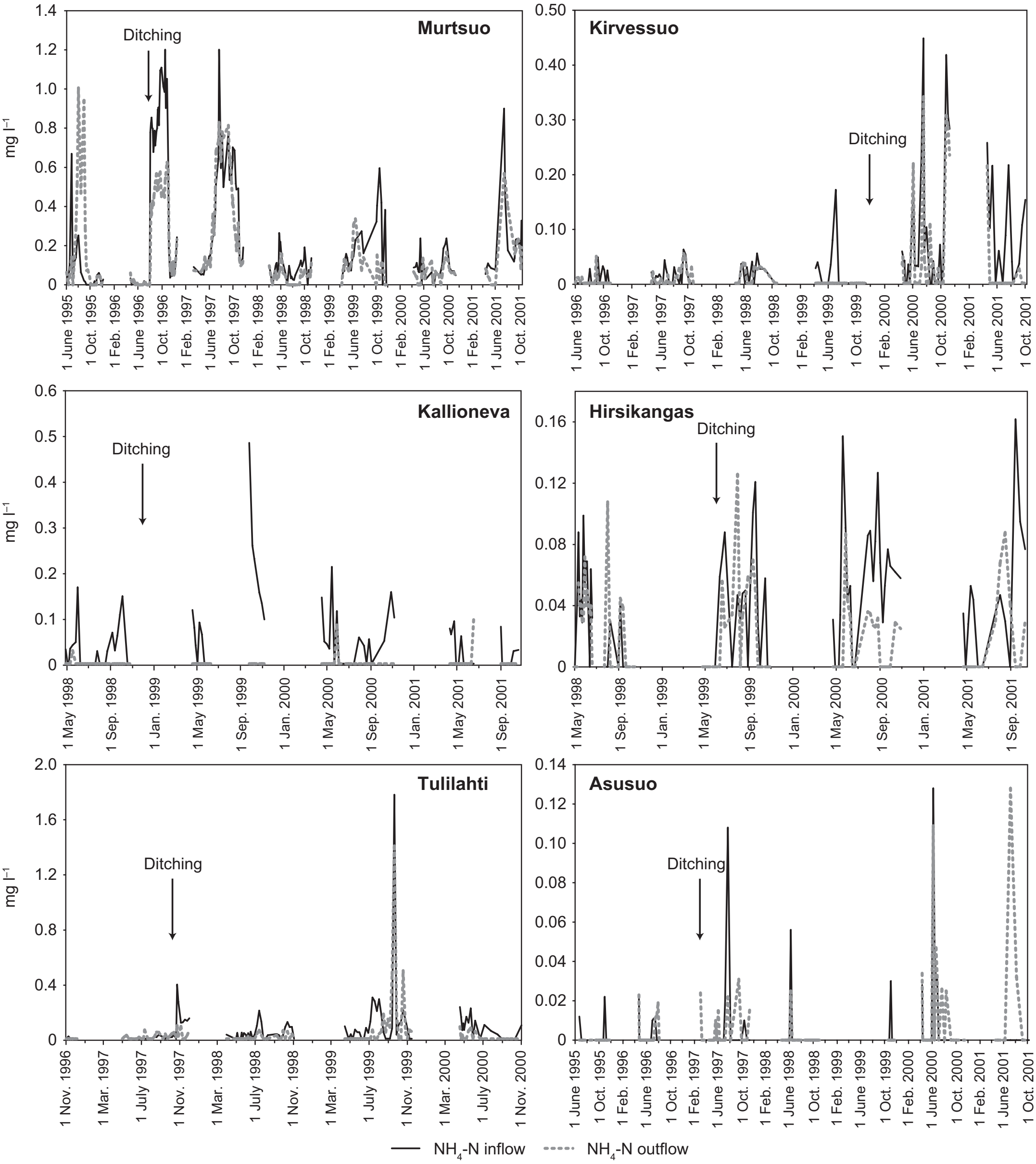

Fig. 2. Ammonium (NH_4-N) concentrations in inflow and outflow waters of the buffer areas before and after ditch network maintenance.

was low. According to model simulations, the retention was near zero or negative, if the annual NH_4-N loading was 1 kg a^{-1} and the annual water discharge to the buffer area more than 300 000 m^3 a^{-1} (Fig. 3). Negligible or negative retention occurred also under such conditions, where the NH_4-N loading was below 10 kg a^{-1} and the length of the buffer area less than 40 m (Fig. 4).

Discussion

We studied for the first time the nutrient retention efficiency of buffer areas in forested catchments under high loading that, instead of being caused by artificial nutrient addition, was due to actual forestry operation. However, our results were in agreement with the earlier artificial nutrient

Table 2. Mean water flow and NH_4-N loading into buffer areas before and after ditch network maintenance (DNM) and NH_4-N retention efficiency of the studied buffer areas.

Buffer area	Years from DNM	Water flow (m^3 a^{-1})	NH_4-N loading (kg a^{-1})	NH_4-N retention	
				(kg a^{-1})	(% of NH_4-N loading)
Asusuo	–1	309190	0.8	–0.5	–54.5
	+1	286370	0.7	–1.4	–196
	+2	306670	0.2	–0.0	–11.9
	+3	346650	1.0	0.5	50.0
	+4	358240	1.2	–0.5	–41.7
Kirvessuo	–3	264590	2.3	0.6	26.1
	–2	443470	5.7	1.8	31.6
	–1	350050	8.1	7.5	92.6
	+1	394300	57.7	12.2	21.1
	+2	300030	54.2	21.5	39.7
Tulilahti	–1	130020	0.6	–0.5	–83.3
	+1	141510	8.2	6.1	74.4
	+2	125690	10.9	6.4	58.7
	+3	109410	9.8	7.4	75.5
Murtsuo	–1	207850	2.6	–2.2	–84.6
	+1	242670	39.5	4.1	10.4
	+2	244610	30.3	10.3	34.0
	+3	434990	34.5	6.7	19.4
	+4	268400	33.2	19.2	57.8
Hirsikangas	–1	266730	2.6	–0.3	–11.5
	+1	238460	5.1	4.0	78.4
	+2	254160	11.3	7.9	69.9
Kallioneva	–1	83400	2.1	1.9	90.5
	+1	55430	6.3	6.3	100
	+2	76460	7.6	7.3	96.1
	+3	80910	3.2	2.8	87.5

Table 3. Regression models for the annual retention of NH_4-N in the buffer areas (kg a^{-1}). NH_4-N inflow = ammonium load (kg a^{-1}) into the buffer area; W_{inflow} = water inflow into the buffer area (m^3 a^{-1}); BL = length of the buffer area (m). u_j = random effect of buffer area *j*; e_{ij} = random effect of the observation (i.e. the annual sum or the average value of the given explanatory variable) *i* in buffer area *j* (random error); SEM = standard error of mean, Bias = absolute bias (kg), EV% = explained proportion of the total variance.

Explanatory variable	Model 1		Model 2		Model 3	
	Parameter	SEM	Parameter	SEM	Parameter	SEM
Fixed part						
α	1.203	(0.816)	29.825	12.229	–6.307	3.375
NH_4–N inflow	0.298	(0.042)	0.317	0.038	0.306	0.038
$\ln(W_{inflow})$			–2.363	1.007		
ln(BL)					1.719	0.757
Random part						
u_j	0.631	(1.734)	0		0	
e_{ij}	8.922	(2.887)	7.907	2.233	8.008	2.262
Bias	–0.318	–0.316	–0.274			
EV%	68.3	73.8	73.2			

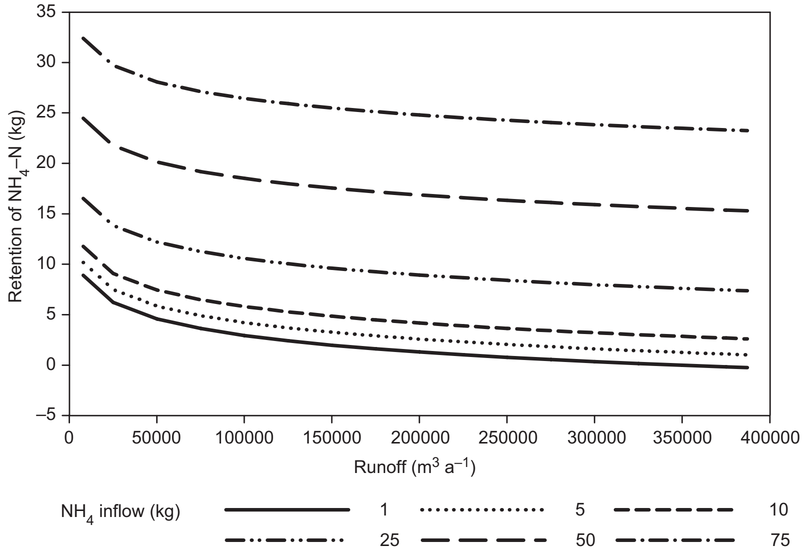

Fig. 3. The simulated annual NH_4-N retentions (kg a^{-1}) in the buffer areas in relation to the annual water inflow (m^3 a^{-1}) with different annual NH_4-N loadings. The simulations are performed by applying the model 2 presented in Table 3.

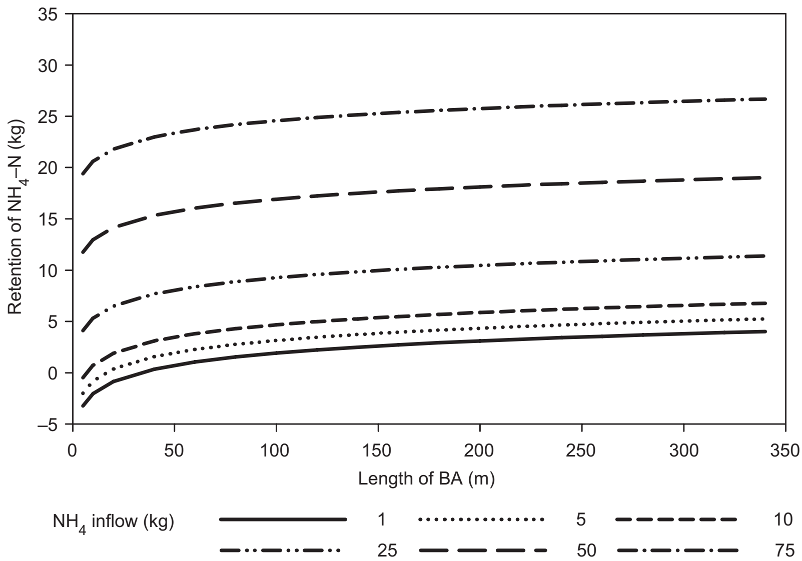

Fig. 4. The simulated annual NH_4-N retentions (kg a^{-1}) in the buffer areas in relation to the length of the buffer area (m) with different annual NH_4-N loadings. The simulations have been performed by applying the model 3 presented in Table 3.

addition experiments and supported the finding that the key factors contributing to the retention efficiency were the nutrient loading and water flow into buffer area, and the size and shape of the buffer area (e.g. Väänänen *et al*. 2006, Väänänen *et al*. 2008, Vikman *et al*. 2010).

As compared with that in the earlier artificial nutrient addition experiments, however, the NH_4-N retention efficiency in the present study was lower. 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 NH_4-N added during four days. According to the model simulations (Model 3, Fig. 4) in the present study, the retention efficiency for long buffers with similar annual NH_4-N loading would be less than half of the loading. Although the results of artificial nutrient addition experiments are not directly comparable with those of this study, it should be noted that the two largest buffers in the present study received relatively low loadings. As large buffers probably have potential to efficiently retain NH_4-N from higher loadings as here, the results of this study could probably overestimate the effect of NH_4-N loading on retention efficiency and the effects of other contributing factors, such as buffer size, may partly be hidden by the strong correlation between NH_4-N loading and retention efficiency. However, as the Asusuo buffer received low NH_4-N loading, the correlation between buffer size and NH_4-N loading was not particularly strong, indicating that the rate of NH_4-N loading may, after all, be the key factor for efficient NH_4-N reduction also for large buffers. Nevertheless, future studies should quantify the retention efficiency of large buffers under higher loadings as in the present study.

Although buffer vegetation and soil are the most probable sinks for ammonium, soil and vegetation characteristics were not significant in explaining ammonium retention efficiency. Again, this is most probable because their effects were hidden by the factors that, in this data set, were more significant for retention capacity.

The decrease in retention efficiency under high water flow as shown in the present study is probably caused by the fact that the contact time between through-flow water and soil and vegetation of the buffer is shorter in high flow than in low flow situations (Väänänen *et al*. 2008, Vikman *et al*. 2010). The formation of continuous flow channels across the buffer area during high flow episodes also greatly decreases the contact between nutrients in through-flow water and vegetative and soil sinks of the nutrients. The relationship between the buffer length and the retention efficiency is probably explained by the fact that the probability of the formation of continuous flow channels across the buffer area is lower for long buffers than short and wide buffers of the same size (Vikman *et al*. 2010). The models showed that the NH_4-N retention increased most sharply when the buffer length was < 50 m. In larger lengths, the retention levelled-out and the net retention was controlled more by the NH_4-N loading than buffer length (Fig. 4).

In conclusion, we showed that buffer areas can be used to decrease NH_4-N transport from forested catchments, not only under transient high N loading as in earlier papers, but also during sporadically increased and long-lasting loading, which is typical for forestry areas after, e.g., forest harvesting or ditch network maintenance. Our results supported the earlier investigations, where buffer areas were found to be inefficient for reducing nutrient loading that already is close to background levels of forested areas. In such a case, the buffer may even release nutrients into through-flow waters. When the loading rate increases high above the background level, efficient reduction in nutrient transport becomes possible by using peatland buffer areas. Besides the rate of nutrient loading, a factor behind efficient retention was the sufficient length of the buffer, whereas high volume of runoff decreased retention efficiency. The other buffer characteristics, such as the soil properties, the tree stand structure and the density of surface vegetation, were insignificant for ammonium retention efficiency.

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