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Retention of particles and nutrients in the root zone of a vegetative buffer zone — effect of vegetation and season

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Vegetative buffer zones (BZs) along streams retain particles and nutrients like phosphorus (P) and nitrogen (N), from agricultural runoff. An experiment with drained soil columns was established to study the retention of particles and nutrients from artificial agricultural runoff. The effect of vegetation (grass versus trees, alder versus aspen) and season was examined. The retention of particles and P was significantly higher in columns with trees as compared with that in column with grass. In general this was also the case for organic carbon (C_{org}) and N. Columns with aspen and alder had equal retention efficiency for particles, C_{org} and P, and in most cases also for N. Thus alder and aspen seem to be equally suitable in forest covered BZs. The retention efficiency of nutrients was generally better during spring, summer and early autumn as compared with that during late autumn. Uptake of nutrients in vegetation seemed to be an important retention mechanism.

Introduction

Today the concentration of nitrogen (N) and phosphorus (P) in inland and coastal waters is in many cases so high that many rivers, lakes and estuaries are polluted to such an extent that good ecological quality can no more be achieved (Conley *et al*. 2002, Jeppesen *et al*. 2003). In many areas diffuse pollution from agricultural areas constitutes one of the major anthropogenic sources of N, P and sediment inputs to surface waters (Borgvang and Tjomsland 2001, Kronvang *et al*. 2005). This is due to the increased intensity in modern agriculture combined with removal of small streams, wetlands and vegetative buffer zones (BZs) from the agricultural landscape. Therefore, the objective of reaching good ecological quality in water bodies will require reduction of nutrient and sediment losses from agricultural areas. Responses in the form of best-management practices such as restrictions on manure spreading and reduced tillage during non-growing seasons are necessary but often insufficient measures. In addition there is a widespread reintroduction of buffer systems in the landscape against agricultural nutrient and sediment losses both at source areas and along different pathways. Vegetative BZs along creeks and rivers are one type of buffer system, which is becoming more and more widespread in the modern agricultural landscape. The retention efficiency of BZs depends on local conditions such as climate, soil type and topography. In addition, design criteria such as width and vegetation type affect the retention efficiency (Haycock and Pinay 1993, Syversen 2002a, 2002b, Sabater *et al*. 2003). In BZs several retention processes interact: deposition of sediments and sediment-bound nutrients, infiltration, sorption, uptake in the vegetation and microbial degradation.

Vegetation has a great impact on retention processes in a BZ. Vegetation with a high stem density will increase the hydraulic roughness and thereby reduces the sediment-carrying capacity of the water entering the BZ. Vegetation also changes the soil structure. The structure tends to be better developed in areas with permanent vegetation and this increases the infiltration capacity. Wooded riparian soils have particularly good infiltration capabilities (Lyons *et al*. 2000). Wooded riparian areas with N-fixing trees such as alder are in some cases reported to be sources of N (Lyons *et al*. 2000). Alder is frequently reported to fix large amounts of atmospheric N, and may be a significant source of N in areas with low N levels. With increasing levels of N in the surrounding areas, N fixation is, however, believed to decrease and more N will be taken up by the roots (Vought *et al*. 1994). Mander *et al*. (1996) found a significantly lower atmospheric N_2 fixation in an alder stand at an intensively loaded test site as compared with trees at a less loaded site. The authors conclude that riparian alder forests are effective BZs on stream banks and lake shores (Mander *et al*. 1996). Osborne and Kovacic (1993) compared forested and grass BZ, and found that on an annual basis the forested BZ was more effective in reducing concentrations of nitrate N (NO_3-N) than was the grass BZ, but was less efficient in retaining total and dissolved P. Further it was seen that during the dormant season, both grass and forested BZs released dissolved and total P into the groundwater. The authors conclude that periodic harvesting of plant biomass may reduce the amount of P released during the dormant season (Osborne and Kovacic 1993). In a study from Finland the mean annual total phosphorus (P_{tot}) loss from a grass BZ and a BZ with natural vegetation was 40% lower than the P_{tot} loss from fields without BZs (Uusi Kämmppä 2005). However, the loss of molybdate-reactive P was found to be 70% higher from the BZ with natural vegetation than from the other plots. This was most likely due to P leaching from the soil surface and decaying grass residue during spring (Uusi-Kämppä 2005).

The focus in Norway has been on retention processes for P in surface runoff, and the design criteria studied were the width of the BZ and the amount of surface runoff entering the BZ. The effect of vegetation was studied only in two short periods during the summer and autumn (field studies lasting 2 days) (Syversen 2005). More information regarding the effect of vegetation on the retention of nutrients and sediments in cold temperate climate is therefore needed, and a project devoted to this topic is currently being run at two research sites in southeastern Norway. The aim of this work was to study the effect of different types of BZ vegetation in a lysimeter experiment with controlled boundary conditions. The effect of grass *vs*. trees, and aspen *vs*. alder was examined.

Materials and methods

A lysimeter experiment was established at Ås (located about 30 km south of Oslo) in May 2004. Twelve columns, 0.5 m in diameter and 0.5 m deep, were established with topsoil (0–10 cm) from a field site in southeastern Norway (Mørdre, described in Syversen *et al*. 2001) (Fig. 1). The soil was characterized as silty clay with 44% clay, 51% silt, 5% sand and 1.5% organic material. There were 4 columns with dense grass vegetation (length of grass: about 25 cm), 4 columns with aspen and 4 columns with alder. The trees were 2.5- to 3-m-long and about 4 years old when planted in the columns. In the columns with trees, there was one tree per column and no grass vegetation. The columns had free vertical drainage and the water that had passed through the columns was collected (Fig. 1). The site was covered by a roof (Fig. 1).

An experimental run consisted of two different runoff simulations: high runoff (25 mm day^{-1}) with low and high concentrations of nutrients/particles. This equals adding 5 litres each day to every column. The water was added in a single dose using a watering can. The low dose had concentrations of 2 mg N l^{-1}, 0.5 mg P l^{-1} and 500 mg SS l^{-1}, while a high dose had concentrations

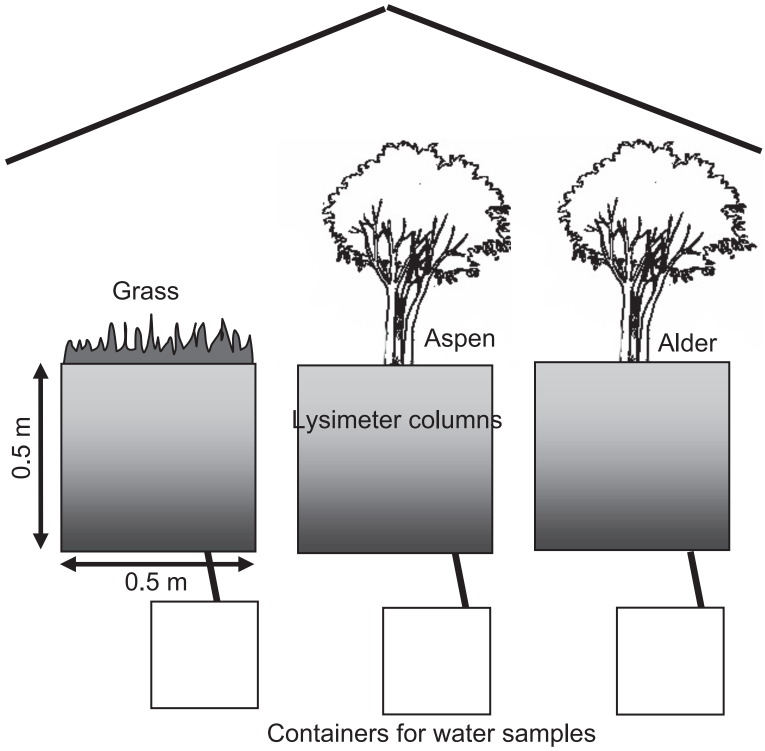

Fig. 1. The lysimeter columns with containers for collection of water samples and a roof above the field site.

of 8 mg N l^{-1}, 2 mg P l^{-1} and 2000 mg SS l^{-1}. This equals 0.05 g N m^{-2}, 0.013 g P m^{-2}, 12.8 g SS m^{-2} and 0.2 g N m^{-2}, 0.05 g P m^{-2}, 51 g SS m^{-2}, for the low and high doses, respectively. Nitrogen was added as KNO_3, while P was added as $KH_2PO_4/NaPO_4 \times 2H_2O$. The suspended solid (SS) consisted of dried and sieved soil from the Mørdre field site.

Each simulation lasted 2 × 5 days. The first 5 days, all columns received 5 litres a day with a low dose and the following 5 days all columns received 5 litres a day with a high dose. For each 5-day period, the drainage water from the first 2 days was discarded, while samples were collected from the columns from the last 3 days. For each type of vegetation, water samples from 3 out of the 4 columns (randomly picked) were collected. This was due to economical reasons. Thus for each 5-day period and vegetation type, 9 samples were analysed (3 columns × 3 days). The amount of percolated water was measured and the samples analysed for suspended solids (SS), loss on ignition (LOI: C_{org}), total nitrogen (N_{tot}), nitrate (NO_3-N), ammonium (NH_4-N), total phosphorus (P_{tot}) and phosphate (PO_4-P). The water samples were analysed according to Norwegian standards (NS): SS and LOI (NS 4733), P_{tot} (NS 4725), PO_4-P (NS 4724), N_{tot} (NS 4743), NO_3-N and NH_4-N (Traacs auto analyser).

To examine retention during different seasons, simulations were performed in late September 2004, in late June 2005, in the beginning of November 2005 (no leaves left on the trees) and in the beginning of April (no leaves on the trees). Due to economical reasons, only a simulation with a high dose was performed in April. Between the experimental simulations, the columns were only given water (approximately 5 liters 3 times a week), except during the winter period when they received neither nutrients nor water.

Statistical analyses (*t*-test, ANOVA and Tukey-Kramer at $P < 0.05$) were carried out. The *t*-test was used to find significant differences in the removal efficiency of the various chemical parameters with regard to dose (low/high concentration). ANOVA and Tukey-Kramer were used to find significant differences in the removal efficiency of the various chemical parameters with regard to season and type of vegetation. The

Table 1. Average retention efficiency (%) for the various chemical parameters for the different vegetation types and seasons (only data from simulations with high doses). Negative numbers indicate release from the columns.

	Grass				Aspen				Alder			
	summer	early autumn	late autumn	spring	summer	early autumn	late autumn	spring	summer	early autumn	late autumn	spring
SS	76^{A}	88^{A}	82^{A}	80^{A}	95^{AB}	99^{A}	92^{B}	98^{A}	94^{B}	99^{A}	94^{B}	99^{A}
C_{Org}	73^{A}	87^{A}	80^{A}	82^{A}	95^{A}	96^{A}	88^{B}	98^{A}	94^{A}	98^{A}	88^{B}	99^{A}
N_{tot}	39^{B}	60^{A}	7^{C}	24^{BC}	81^{A}	88^{A}	58^{B}	88^{A}	92^{A}	81^{B}	55^{C}	78^{B}
NO_3-N	40^{B}	64^{A}	22^{B}	21^{B}	84^{A}	93^{A}	77^{A}	95^{A}	93^{A}	84^{B}	81^{B}	82^{B}
NH_4-N	13^{A}	-60^{A}	24^{A}	-208^{B}	65^{A}	-6^{A}	42^{A}	-29^{A}	87^{A}	65^{AB}	38^{C}	40^{BC}
P_{tot}	52^{B}	75^{A}	40^{B}	79^{A}	90^{B}	93^{AB}	83^{C}	96^{A}	96^{A}	96^{A}	92^{B}	98^{A}
PO_4-P	52^{B}	74^{A}	42^{B}	79^{A}	90^{B}	91^{AB}	84^{C}	96^{A}	97^{A}	95^{AB}	93^{B}	99^{A}

Different letters indicate significantly (ANOVA and Tukey-Kramer tests) different retention efficiencies during the four seasons regarding one vegetation type and one chemical parameter. Similar letters indicate no significantly different retention efficiency.

statistical program used was JMP 5 (The Statistical Discovery Software, SAS Institute Inc., USA).

Results

In general the amount of particles, C_{org} and nutrients in the outlet were lower than the input values. In some cases an increase from the inlet to the outlet was observed for NH_4-N, resulting in negative retentions (Fig. 2). The average retention efficiencies (± SD) for all simulations were 88% ± 13%, 83% ± 17%, 58% ± 27%, 72% ± 26%, 4% ± 112%, 76% ± 22% and 77% ± 21% for SS, C_{org}, N_{tot}, NO_3-N, NH_4-N, P_{tot} and PO_4-P, respectively.

Retention of SS, P_{tot} and PO_4-P was significantly higher in the columns with trees as compared with that in the columns with grass. This was in general the case for the other parameters with some exceptions (Fig. 2). The difference between trees and grass was in general more pronounced for the nutrients (40% ± 13%) than for the particles and C_{org} (17% ± 7%). For SS, C_{org} and P_{tot}, retention was equal in columns with aspen and alder. This was generally the case for the other parameters, however, with some exceptions.

When simulations with low and high doses were compared, it was seen that the retention efficiency was either equal for low and high doses, or higher for the simulations with high dose. This was valid for all chemical parameters and seasons, with only three exceptions: N_{tot} in the column with aspen during summer and NO_3-N in the columns with grass and aspen during summer.

The difference in retention efficiency between, on one hand, the summer and early autumn with a rapid growth of the vegetation, and on the other hand, late autumn and spring with no leaves on the trees varied depending on the parameter measured (Table 1). For SS and C_{org} in columns with grass, the retention was equal regardless of the season. For SS and C_{org} in columns with aspen and alder, the retention was in general higher during spring, summer and early autumn than during late autumn. For N and P the results varied more. In general the retention was better during

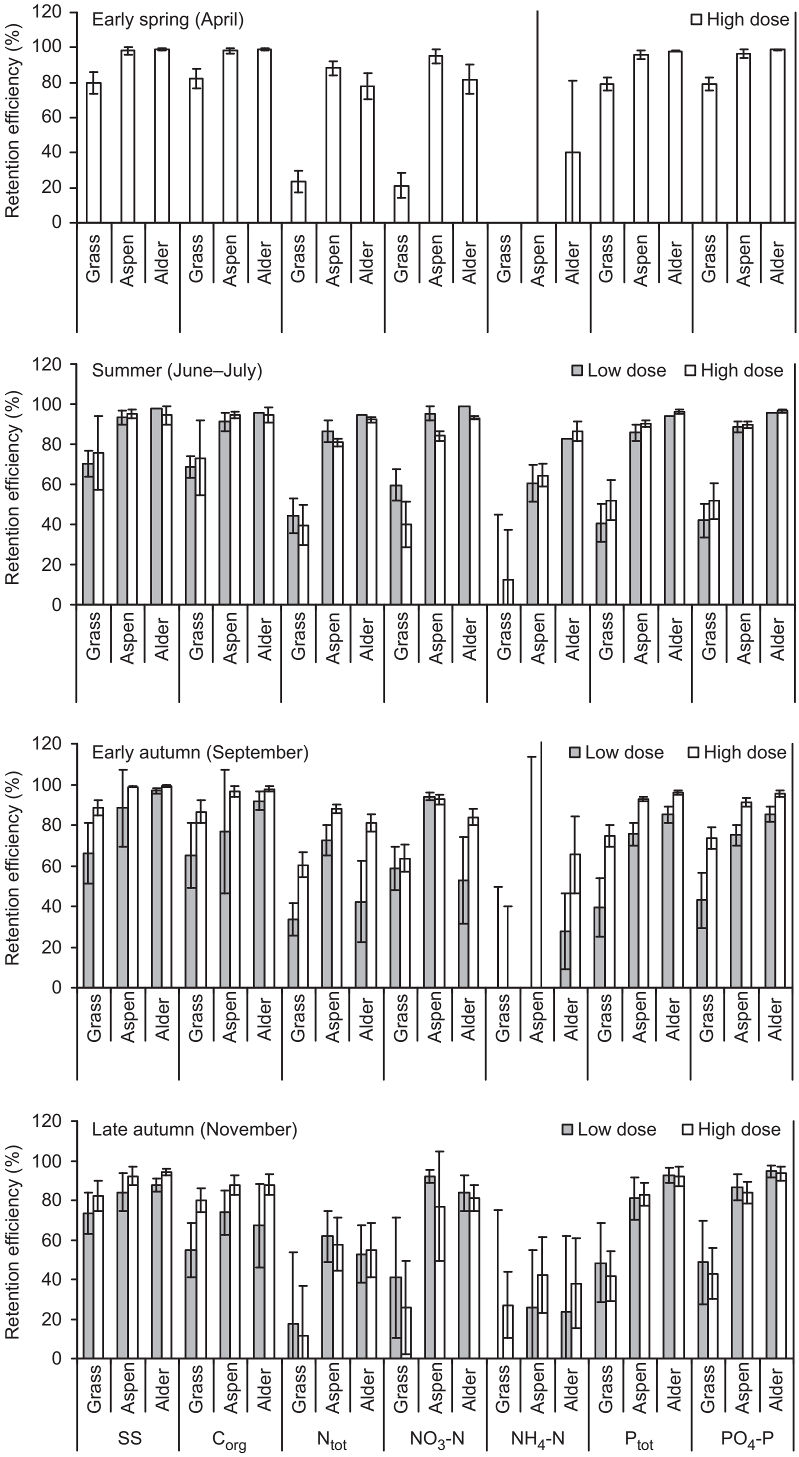

Fig. 2. Mean and standard deviation (n = 9) of the percentage retention efficiency (%) of suspended solids (SS), organic C (C_{org}), total N (N_{tot}), NO_3-N, NH_4-N, total phosphorus (P_{tot}) and PO_4-P depending on the vegetation (grass, aspen and alder), season (spring, summer, early and late autumn) and dose. Only positive retention efficiencies are shown, however, for NH_4-N, negative average retentions were observed (early spring, grass, high dose: –208 ± 86; early spring, aspen, high dose: –29 ± 155; summer, grass, low dose: –4 ± 50; early autumn, grass, low dose: –181 ± 231; early autumn, grass, high dose: –60 ± 100; early autumn, aspen, low dose: –4 ± 118; early autumn, aspen, high dose: –6 ± 214; late autumn, grass, low dose: –67 ± 143).

spring, summer and early autumn compared to late autumn (Table 1).

When the retention of the various chemical parameters was compared in all simulations, it was seen that in most cases, the retention followed the pattern: $SS/C_{org} > P > N$.

Discussion

Surface runoff as well as subsurface inputs from terrestrial areas, are major sources of water, sediments and nutrients to streams. The major reason for constructing vegetative BZs is to slow down and filter these terrestrial inputs. The lysimeter experiment in this study with water added at the top of the soil columns may partly be regarded as a surface flow experiment (the processes affecting sediment deposition on the surface area are operative) and partly as an unsaturated subsurface flow experiment (the retention efficiency of the root zone is studied).

In our study the columns with trees had in general better retention efficiency than the columns with grass. The only exceptions were during early autumn (low dose), when the columns with alder and grass had equal retention for N_{tot} and NO_3-N. Denitrification is taking place in anaerobic soil. As the soil in the columns in this study was drained, the soil is thought to be mainly aerobic. Denitrification may still take place in small anaerobic sites within soil aggregates. Still, we assume a larger uptake of NO_3-N in the trees as compared with that in the grass to be the reason for the observed differences. Results from studies regarding retention efficiency of N in BZs with different vegetation types (forest versus herbaceous) are not consistent (Hefting *et al*. 2005). In accordance with the results of this study, some authors report better performance of forest-covered BZs as compared with that of a grass-covered zones (Vought *et al*. 1991, Haycock and Pinay 1993, Osborne and Kovacic 1993). This has partly been attributed to a higher total biomass, (semi-)permanent storage of nutrients and a deeper root system. Plant uptake of nutrients is, however, not regarded as the main retention mechanism for N. The microbial process denitrification, which permanently removes N from the water, is thought to be more important. Vegetation plays, however, a vital role regarding this process, as the root system of trees produces more biomass at greater depths in the soil profile, i.e., C which is necessary for the denitrification process (Fennessy and Cronk 1997). Opposite results, i.e., more NO_3-N removed below grassed zones, were obtained by Groffman *et al*. (1991), Lowrance *et al*. (1995) and Schnabel *et al*. (1996). In the case of Lowrance *et al*. (1995) the young age of the trees at the time of the study may have led to the low denitrification rates in the soil below the forested areas.

According to our results alder seems to be more efficient than aspen with regard to N retention during summer, less efficient during spring and early autumn and the two tree species have equal retention efficiency in late autumn (Fig. 2). Thus we postulate that on an annual basis, the difference between the two species is negligible with regard to retention efficiency of N. The two types of trees are thus equally suitable in a forest-covered BZ. In a study of Mander *et al*. (1996), the atmospheric N_2 fixation was significantly lower in an alder stand in an intensively loaded test site as compared with that by trees in a less loaded site. Mander *et al*. (1996) conclude that riparian alder forests are effective buffers on stream banks and lake shores.

In an agricultural field, most of the export of total P will be particulate P. Particles and particulate P will mainly be transported to BZs with surface runoff and the processes affecting the retention will mainly be sedimentation and filtration. In Norway, for instance, up to 89% of the total P in the inlet water to a BZ was particulate (Syversen 2002b). In this study the columns with trees had better retention of SS, P_{tot} (sum of dissolved and particulate P) and PO_4-P than the columns with grass. The soil structure was not examined in this study, but all the added water infiltrated the soil in all columns, and thus variation in the sedimentation and infiltration capacity could not be the reason for the observed differences. For SS and particulate P, the difference could be due to a better filtering capacity in columns with trees as compared with that in columns with grass. The reason for this phenomenon was not examined further. In this study P was added as PO_4-P (in order to obtain a high input P concentration) and thus most of the P added was dissolved. Sorption to the soil and uptake in the vegetation will then be the important retention mechanisms. The higher retention in columns with trees as compared with that in columns with grass could during summer and early autumn be explained as a higher uptake rate in the trees.

A previous study in Norway (Syversen 2005) reported higher retention efficiency of SS in a forest BZ as compared with that in a grass-covered BZ (field study with surface runoff). This was explained by a good filtering efficiency of the mosses covering the soil surface in the forest. For P_{tot} (occurring mostly as dissolved P) there was no significant difference between BZs with trees and grass (Syversen 2005). In other field studies it was shown that release of especially dissolved P from forested BZs may occur. The reasons for this phenomenon are thought to be leaching from the soil surface and decaying grass residue during spring (Osborne and Kovacic 1993, Uusi-Kämppä 2005). It has been postulated that the soil in a BZ may eventually become saturated with P, and that this may lead to the release of P. As the soil used in the columns in this experiment was collected from a field, and not from a BZ, it was probably not saturated with P. This, however, could have been the case with the soils in the studies mentioned above. Available sorption sites for P in the soil could thus be the reason that retention rather than leakage of PO_4-P was observed in this work. The P sorption capacity of different soils also varies a lot, depending on e.g., the amount of aluminium- and iron-oxides. Thus in order to fully explain the sorption of P in this work versus leakage of P in the studies of Osborne and Kovacic (1993) and Uusi-Kämppä (2005), a comparison of the soil characteristics would have to be done.

The effect of adding high concentrations of nutrients and particles versus low concentrations were examined in this study. In most cases the relative retention efficiency (%) was equal for the two concentrations or higher for the high concentration. A high particle concentration in the runoff water may enhance the aggregation of finer particles into larger ones, which are then more easily filtered in the BZ. The denitrification rate is known to increase with NO_3-N concentrations in soil up to a certain level and is then thought to be independent of the NO_3-N concentration (Granli and Bøckmann 1994). Haycock and Pinay (1993) found that riparian BZs were effective regarding NO_3-N retention irrespective of loading rates if the loading was routed via subsurface pathways. Higher concentration of nutrients in soil could also lead to higher uptake rates in plants.

In this study it was seen that the retention of the nutrients P and N was generally better during spring, summer and early autumn as compared with that in late autumn (Table 1). This could indicate that in our study, uptake by the vegetation may have played a vital role, and that denitrification could be of minor importance as the soil was mostly aerobic due to free drainage through the soil columns. For SS and C_{org}, where filtration in the soil was suggested to be the main retention mechanism, less difference between the seasons was observed.

In this work where only vertical flow has been considered, trees were found to be better than grass in retaining pollutants. In an agricultural field, however, the environmental conditions will differ from the studied conditions. In a field there may be steep slopes leading to concentrated flow through the BZ rather than shallow and uniform flow. Further, parts of the soil may be frozen during winter leading to a reduced infiltration capacity. With such conditions, less water will infiltrate the soil and sedimentation processes will probably be more important for the retention capacity of the BZ. However, during less extreme surface runoff episodes, parts of the water will normally infiltrate the soil in the BZ, and in such cases the results in this work suggest that trees may be beneficial for the retention capacity of the zone, by preventing nutrients from reaching shallow groundwater.

Conclusions

The results from this study suggest that trees will have a beneficial effect on the retention efficiency in BZs where the water enters as subsurface flow or a large part of the surface flow infiltrates the soil. In our study uptake by vegetation seemed to play a major role and seemed to be partly responsible for the better performance of BZ with trees than BZs with grass only. Further, despite its N-fixating capacity alder seems to be just as suitable in a forest covered BZ as aspen. In this study the retention efficiency (%) of P was in general lower than was the case for SS and C_{org}. In the field, this pattern will probably change, as a larger part of the P will be particulate. The retention of the nutrients P and

N was generally better during spring, summer and early autumn as compared with that in late autumn, again pointing to uptake in vegetation as an important retention mechanism.

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