BOREAL ENVIRONMENT RESEARCH 10: 191–201 ISSN 1239-6095
Helsinki 30 June 2005 

# Does the use of riparian buffer zones in forest drainage sites to reduce the transport of solids simultaneously increase the export of solutes?

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Nieminen, M., Ahti, E., Nousiainen, H., Joensuu, S. & Vuollekoski, M. 2005: Does the use of riparian buffer zones in forest drainage sites to reduce the transport of solids simultaneously increase the export of solutes? *Boreal Env. Res.* 10: 191–201.

Riparian buffer zone areas (BZAs) effectively reduce sediment transport and are considered as the most important water protection method in forest drainage sites in Finland. However, it has been questioned whether BZAs are a significant source of nutrients and other dissolved constituents to water-courses. At seven locations in south-central Finland a buffer zone was created below a drainage site and the effects on the concentrations of dissolved organic carbon (DOC), dissolved P, Fe and Al in through-flow were studied for 4–7 years. The effect of the two smallest BZAs (< 0.1% of watershed area) on through-flow quality was negligible. The three medium-sized BZAs (0.15%–0.23% of watershed area) either had no effect on through-flow quality or slightly increased solute concentrations (3%–30%). At the two largest BZAs (> 1% of watershed area) the concentrations of Fe either increased or decreased and the concentrations of DOC, Al and P were either unaffected or decreased (15%–27%). It was concluded that, although increased leaching may occur from some individual sites, BZAs are unlikely to act as a general source of P, Al, Fe, or DOC to water courses.

## Introduction

In all about 13 million hectares of peatlands and paludified mineral soil sites have been drained for forestry in the Nordic (Finland, Sweden, Norway) and Baltic (Estonia, Latvia, Lithuania) countries and Russia. Forestry drainage has been particularly intensive in Finland (> 5 million hectares), where the portion of drained peatland forests from the total forestry area is almost 20%. Although drainage has greatly increased the area of productive forestry sites, it is on the other hand considered the most harmful forestry measure from the viewpoint of water quality protection. It has been shown that especially the concentrations of suspended peat and mineral soil particles in discharge waters from peatlands increase after drainage. High loads of suspended solids (SS) are usually associated with the actual ditching work (Heikurainen *et al*. 1978, Joensuu *et al*. 1999), but even afterwards, high concentrations may occur due to erosion of bare soil surfaces in the ditches (Heikurainen *et al*. 1978, Hynninen and Sepponen 1983).

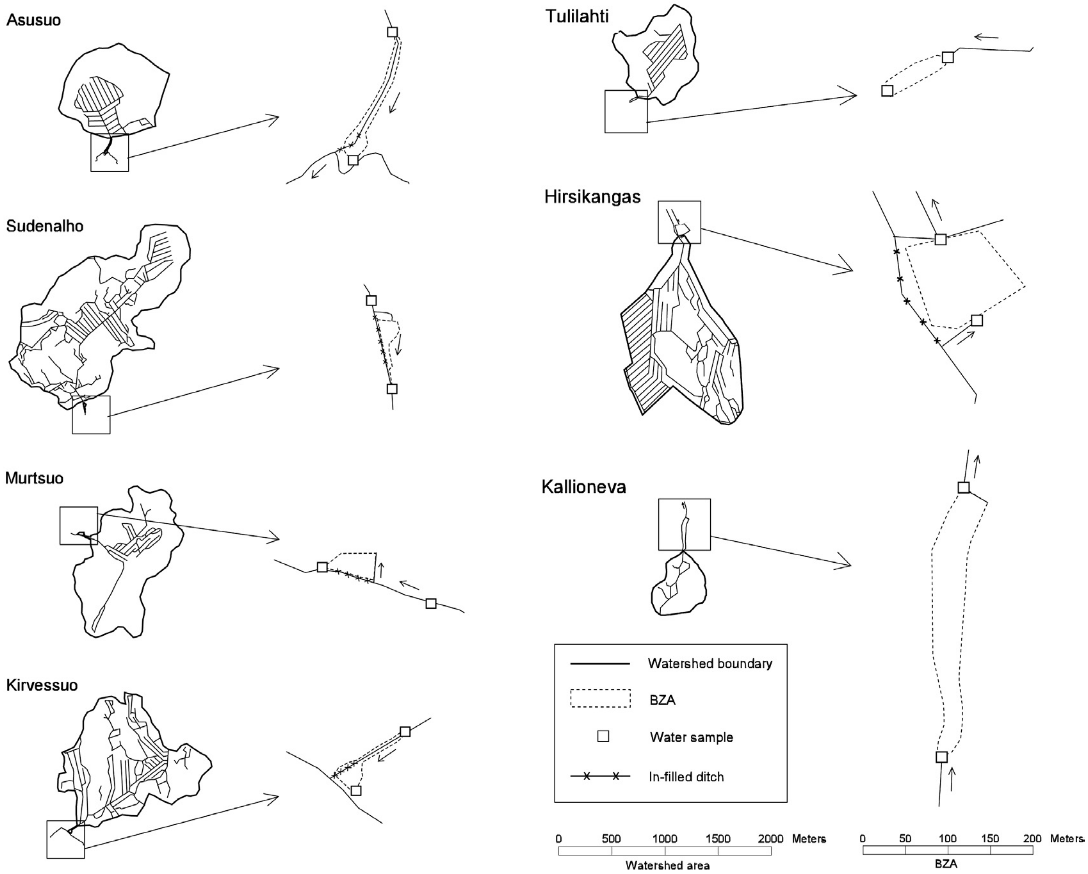


**Fig. 1**. The watershed areas and buffer zones at Asusuo, Sudenalho, Murtsuo, Kirvessuo, Tulilahti, Hirsikangas and Kallioneva.

High SS loads have numerous adverse effects on aquatic ecosystems (Fairchild *et al*. 1987, Newcombe and MacDonald 1991). For example, high SS concentrations reduce the numbers and diversity of aquatic invertebrates and different fish species, especially salmon. High SS loads also reduce primary production by decreasing light penetration and disrupting plant cells and respiratory surfaces. Furthermore, sediments play an important role in the sorption, storage, transport, and release of various contaminants.

To decrease the transport of SS to water courses in practical peatland forestry in Finland, riparian buffer zone areas (BZAs) are presently being created downstream from drainage areas. Buffer wetlands are usually created by simply conducting discharge waters from drained peatlands to pristine mires or, occasionally, also to paludified mineral soils. However, because most peatlands in Finland have been drained, a common practice is to create buffer zones by restoring and rewetting sections of drained peatlands by filling in or blocking the main drainage ditches (Silvan 2004). The sizes of BZAs used in practical forestry may vary considerably but rarely exceed one hectare. If only productive forestry land is available for the construction of the buffer, narrow (generally < 10-m wide) riparian buffer strips may be used (Liljaniemi *et al*. 2003). As a deviation from those strips, we here define BZAs as areas where the size of the protective, intact area between drainage area and water-course is at least several hundreds of square meters.

BZAs have proven to be an effective means in decreasing the transport of SS. Sufficiently large and correctly designed BZAs may capture 70%–100% of the sediment in the through-flow water (Sallantaus *et al*. 1998, Vasander *et al*. 2003, Nieminen *et al*. 2005). However, although BZAs effectively decrease SS transport, they may on the other hand increase the export of soluble phosphorus (P) (Gehrels and Mulamoottil 1989, Vasander *et al*. 2003). A BZA created by rewetting and restoring a former peatland drainage area reduced SS concentration from about 100 mg $l^{-1}$ to 1 mg $l^{-1}$, but increased P concentrations in downstream waters from a level of < 25 $\mu$g $l^{-1}$ to a peak concentration of as high as 300 $\mu$g $l^{-1}$ (Sallantaus *et al*. 1998). However, another BZA in that study had no effect on P concentrations in discharge waters and it is still unclear whether the BZA-induced P leaching is a common problem. It is also unclear if BZAs act as a sink or source for other soluble nutrients, heavy metals and soluble organic substances. In this study, we monitored water inflow and outflow at seven BZAs in peatland dominated watersheds in south-central Finland, and studied if BZAs had significant effects on the concentrations of dissolved organic carbon (DOC), P, iron (Fe) and aluminium (Al) in through-flow water.

## Material and methods

The study was carried out at seven watershed areas in south-central Finland. At each watershed there was an old peatland drainage area and a buffer zone area (BZA) was designed below it (Fig. 1 and Table 1). The Asusuo, Sudenalho, Murtsuo, Kirvessuo and Hirsikangas BZAs were constructed by filling in the main outlet ditch from the upstream drainage area and conducting the water to an adjacent undisturbed and flat mire area (at Hirsikangas, Murtsuo and Sudenalho via a distribution ditch). No active BZA construction operations were needed at 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. According to a careful leveling of the BZAs and the watershed areas upstream, the sizes of BZAs varied from 0.09 to 1.03 hectares, accounting for 0.05%–4.88% of the area of the watershed.

**Table 1**. Background information about the studied buffer zone areas.

| | Asusuo | Sudenalho | Murtsuo | Kirvessuo | Tulilahti | Hirsikangas | Kallioneva |
|---|---|---|---|---|---|---|---|
| Location | 60°26´N 23°38´E | 60°44´N 22°14´E | 61°01´N 28°19´E | 61°14´N 25°16´E | 63°01´N 26°59´E | 64°04´N 26°40´E | 62°16´N 23°48´E |
| Area (ha) | 0.20 | 0.09 | 0.16 | 0.12 | 0.09 | 1.01 | 1.03 |
| Area, percentage of watershed area | 0.23 | 0.05 | 0.15 | 0.09 | 0.18 | 1.12 | 4.88 |
| Site description | Pristine mire | Pristine mire | Drained peatland forest | Drained peatland forest | Paludified mineral soil | Pristine mire | Pristine mire |
| Site type[a)] | Tall-sedge spruce swamp | Herb-rich tall-sedge fen | *Vaccinium myrtillus* type | Herb-rich type | *Vaccinium vitis-idaea* type | Low-sedge bog | Tall-sedge fen |
| Stand description | *Betula pubescens* dominated | Open mire | *Betula pubescens* dominated | *Picea abies* dominated | *Pinus sylvestris* dominated | Open mire | Open mire |
| Stand volume ($m^3$ $ha^{-1}$) | 80 | 0 | 80 | 100 | 30 | 0 | 0 |
| Peat depth | > 1 m | > 1 m | > 1 m | > 1 m | < 0.1 m | > 1 m | > 1 m |

[a)] Site types for pristine mires and drained peatlands according to Heikurainen and Pakarinen (1982), for mineral soils according to Cajander (1926).

The Sudenalho, Hirsikangas and Kallioneva BZAs were pristine, treeless mires. Except for the areas next to the in-filled ditch, the Asusuo BZA was also classified as an undrained, pristine mire according to the site type classification of peat soils used in Finland (Heikurainen and Pakarinen 1982). It was covered by a dense, < 10-m-tall birch stand (*Betula pubescens* Ehrh.). Due to drainage the ground vegetation at the Murtsuo and Kirvessuo BZAs had transformed from the pristine state and they were classified as drained peatland forests. The Murtsuo BZA was dominated by a dense birch (*B. pubescens*) stand, but in connection with building a new electricity line about half of the area was clear-cut in 1999. The Kirvessuo BZA was characterized by a mixed spruce (*Picea abies* Karst.), pine (*Pinus sylvestris* L.) and birch (*B. pubescens*) stand and a relatively large open area in the middle. The Tulilahti BZA was a paludified mineral soil forest of the *Vaccinium vitis-idaea* type (Cajander 1926) and it had been cut in a seed tree position a few years before the start of the study. Except for the areas near the surrounding mineral soils, the depth of the peat layer was > 1 m at all 6 peatland dominated BZAs.

The only BZA on a mineral soil site (Tulilahti) was characterized at its lowest parts by a number of big rocks and the waters from the upstream drainage area mostly traveled as channel flow between these rocks and bulk soil (silty till). Most of the water flow at the other BZAs occurred as overland flow (or sheet flow) across the relatively flat buffer areas. Generally, the contribution of channel flow to total surface flow at the BZAs constructed on peat soils appeared to depend largely on the size of BZA, i.e. channel flow was considerable at small BZAs, but almost totally absent at Hirsikangas and Kallioneva. Similarly, the importance of subsurface flow may be expected to be strongly related to BZA size and considerable subsurface flow unlikely occurs at the very small BZAs, such as Sudenalho and Kirvessuo.

At each BZA, sampling of inflow and outflow waters was started as soon as the BZA construction operations were finished. This was in spring 1995 at Murtsuo and Asusuo, 1996 at Kirvessuo, Tulilahti and Sudenalho and 1998 at Kallioneva and Hirsikangas. The sampling (twice a week in spring, weekly during other seasons) continued until the end of 2000 (Sudenalho and Tulilahti) or 2001 (all other BZAs). 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) or at a natural flow channel.

In the laboratory, the samples were filtered through 1.0 $\mu$m fibre-glass filters and the filtrates analysed for dissolved P, Al and Fe by ICP/AES; ARL 3580, and for DOC, with Shimadzu carbon analyser. The total number of samples collected from the Asusuo BZA was 129 for both inflow and outflow water. The numbers of samples for the other areas were: Murtsuo 213, Kirvessuo 128, Sudenalho 71, Tulilahti 119, Hirsikangas 81, and Kallioneva 78.

Owing to the small size of the BZAs relative to the areas of the watersheds, no differences in runoff between inflow and outflow water sampling positions were assumed. Thus, the change in through-flow concentration (mg $l^{-1}$), rather than in solute load (kg $ha^{-1}$), was used as the parameter for determining the impact of BZAs on the transport of solutes. This was also because, in the absence of defined outflow water channels at Asusuo and Kirvessuo, it was not possible to measure runoff.

Paired-sample *t*-test was used to test if the differences in DOC, P, Fe and Al concentrations between inflow and outflow samples were statistically significant. All samples collected at each BZA were used in the calculations.

## Results

The two smallest BZAs (Sudenalho and Kirvessuo, 0.05% and 0.09% of the area of watershed, respectively) had very little effect on through-flow quality (Figs. 2–5). A slight increase in P and Fe concentrations in through-flow occurred at Kirvessuo, but no significant differences between inflow and outflows waters were found at Sudenalho (Table 2).

The three medium-sized BZAs (Asusuo, Murtsuo and Tulilahti, 0.15%–0.23% of the area of watershed) generally increased the transport

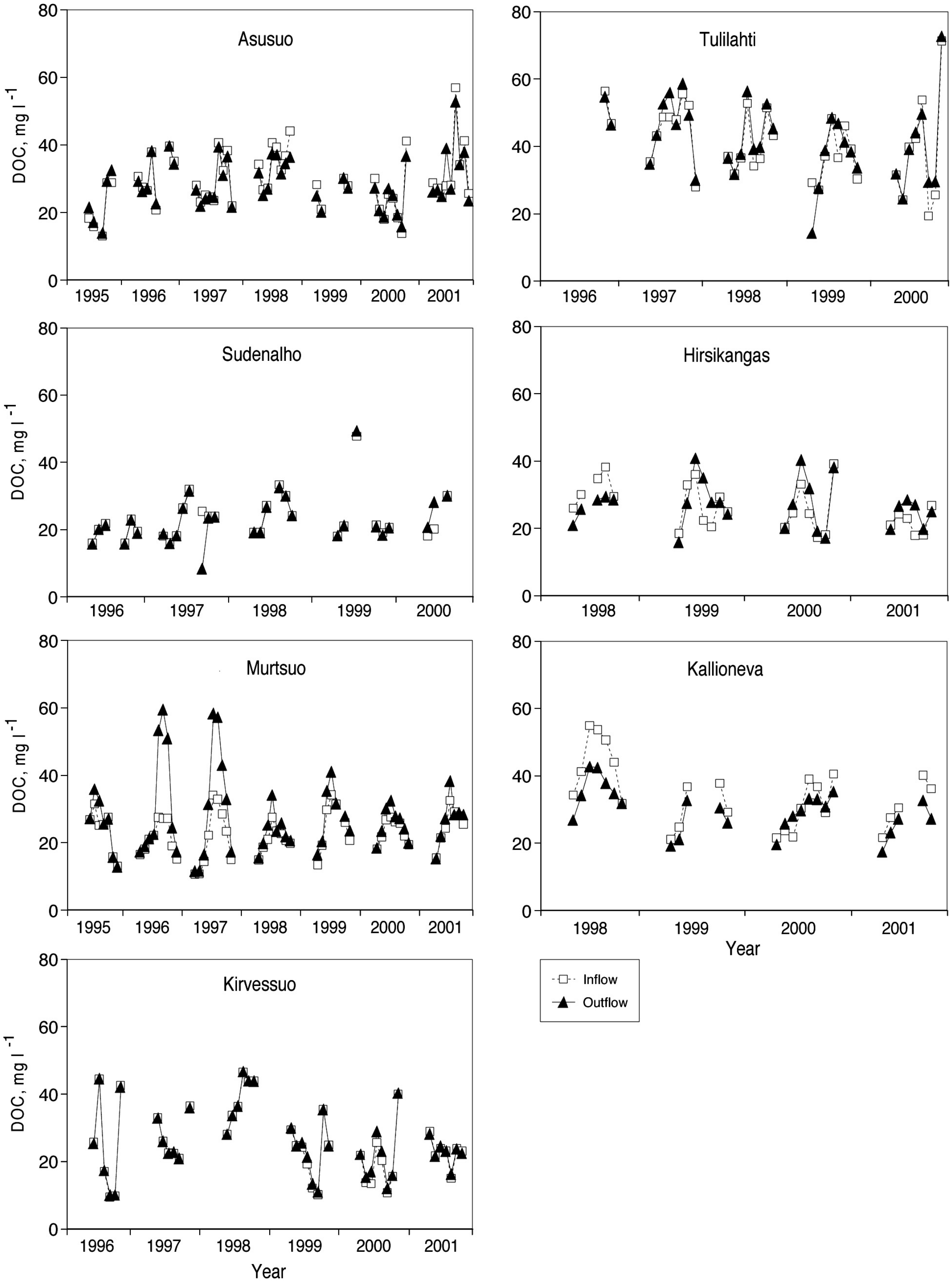


**Fig. 2**. Mean monthly DOC concentrations in water inflow and outflow at each BZA.

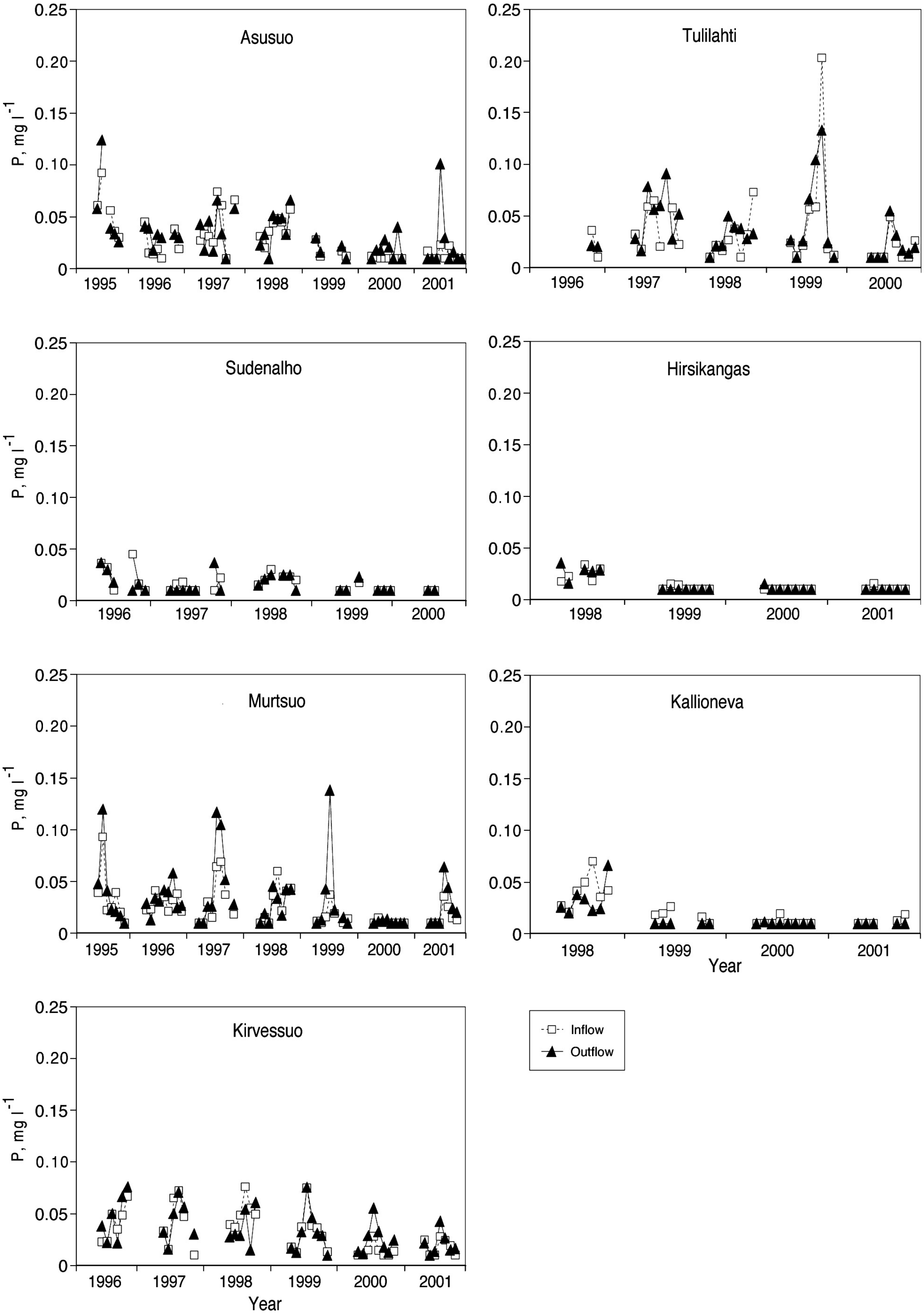


**Fig. 3**. Mean monthly P concentrations in water inflow and outflow at each BZA.

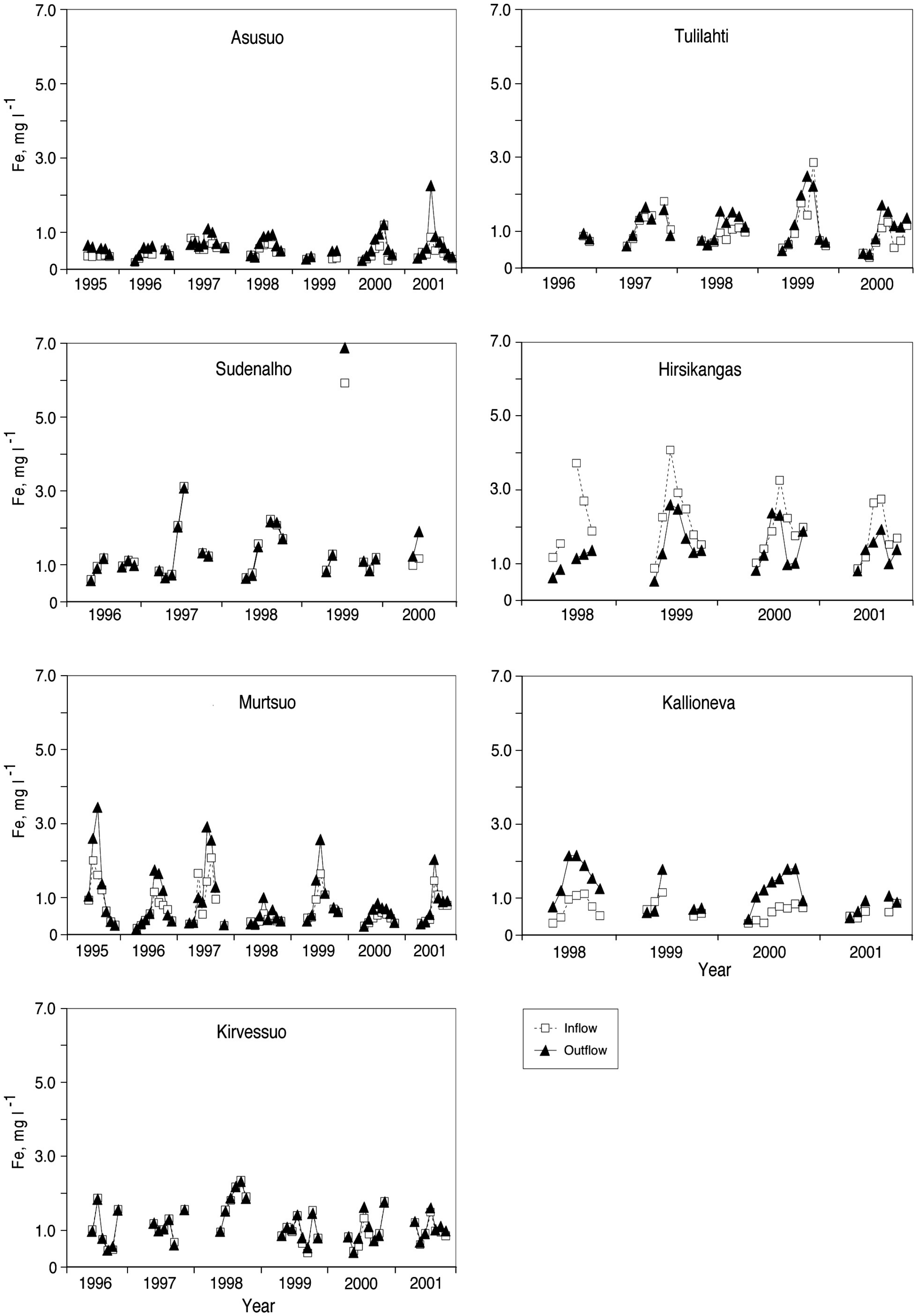


**Fig. 4**. Mean monthly Fe concentrations in water inflow and outflow at each BZA.

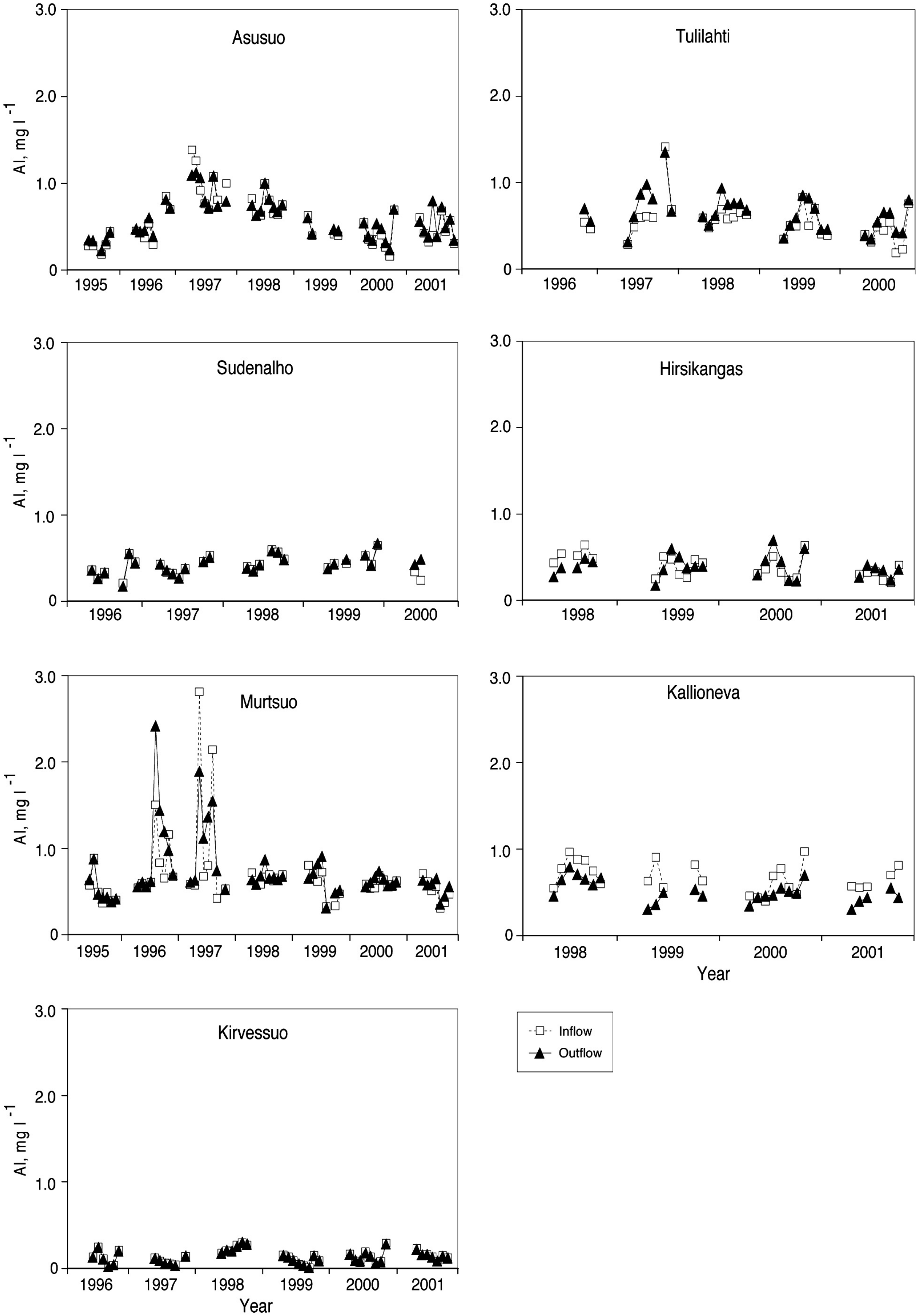


**Fig. 5**. Mean monthly Al concentrations in water inflow and outflow at each BZA.

of DOC, P, Fe and Al. The increase in DOC concentrations was high only at Murtsuo, but the concentrations of Fe increased significantly at all three areas (Table 2). The increase in DOC from Murtsuo was particularly high in 1996–1997 (Fig. 2) and the increase in P concentrations in 1997 and 1999 (Fig. 3). The concentrations of Al in through-flow from these three medium-sized BZAs increased by 5%–19.6%, the concentrations of Fe by 16.8%–29.5% and the concentrations of P by 6.5%–19.2% (Table 2).

The two largest BZAs (Kallioneva and Hirsikangas, 4.88% and 1.22% of the area of watershed, respectively) had different effects on through-flow quality. While the Kallioneva BZA significantly decreased the transport of DOC, Al and P, there were no significant differences between the inflow and outflow concentrations at Hirsikangas (Table 2). The effects of the Kallioneva and Hirsikangas BZAs on through-flow Fe concentrations differed also greatly. A very high increase in Fe occurred at Kallioneva, but a significant reduction was observed at Hirsikangas.

**Table 2**. The average DOC, P, Fe and Al concentrations (± S.D. ) in inflow and outflow water samples and their reductions by the studied BZAs. Significant ($p < 0.05$) difference between inflow and outflow concentrations is indicated by an asterisk.

| | | Asusuo | Sudenalho | Murtsuo | Kirvessuo | Tullilahti | Hirsikangas | Kallioneva |
|---|---|---|---|---|---|---|---|---|
| DOC | In (mg l$^{-1}$) | 28.5 ± 8.5 | 21.7 ± 6.0 | 22.8 ± 5.8 | 24.6 ± 11.8 | 40.4 ± 13.6 | 25.3 ± 6.9 | 35.6 ± 10.5 |
| | Out (mg l$^{-1}$) | 27.9 ± 7.7 | 21.6 ± 6.3 | 28.7 ± 12.8 | 25.3 ± 11.4 | 41.7 ± 12.6 | 25.4 ± 6.7 | 30.2 ± 7.1 |
| | Red. (mg l$^{-1}$) | 0.6* | 0.1 | −5.9* | −0.7* | −1.3* | −0.2 | 5.4* |
| | Red., percentage of In | 2.0 | 0.8 | −25.9 | −2.8 | −3.2 | −0.7 | 15.2 |
| P | In (mg l$^{-1}$) | 28 ± 22 | 21 ± 16 | 26 ± 24 | 31 ± 24 | 35 ± 44 | 14 ± 11 | 22 ± 20 |
| | Out (mg l$^{-1}$) | 31 ± 25 | 20 ± 14 | 31 ± 31 | 34 ± 23 | 37 ± 35 | 14 ± 12 | 16 ± 16 |
| | Red. (mg l$^{-1}$) | −3* | 1 | −5* | −3* | −2* | 0 | 6* |
| | Red., percentage of In | −10.7 | 4.8 | −19.2 | −9.7 | −6.5 | 0.0 | 27.3 |
| Fe | In (mg l$^{-1}$) | 0.45 ± 0.24 | 1.21 ± 0.81 | 0.68 ± 0.59 | 1.05 ± 0.52 | 0.98 ± 0.56 | 1.90 ± 0.92 | 0.69 ± 0.28 |
| | Out (mg l$^{-1}$) | 0.59 ± 0.29 | 1.21 ± 0.81 | 0.88 ± 0.78 | 1.09 ± 0.51 | 1.14 ± 0.61 | 1.26 ± 0.64 | 1.19 ± 0.50 |
| | Red. (mg l$^{-1}$) | −0.14* | 0.00 | −0.19* | −0.04* | −0.20* | 0.65* | −0.50* |
| | Red., percentage of In | −29.5 | 0 | −28.3 | −4.1 | −16.8 | 34.0 | −72.2 |
| Al | In (mg l$^{-1}$) | 0.57 ± 0.30 | 0.40 ± 0.13 | 0.74 ± 0.74 | 0.12 ± 0.008 | 0.55 ± 0.24 | 0.38 ± 0.13 | 0.70 ± 0.21 |
| | Out (mg l$^{-1}$) | 0.59 ± 0.27 | 0.40 ± 0.13 | 0.83 ± 0.71 | 0.12 ± 0.008 | 0.65 ± 0.26 | 0.36 ± 0.12 | 0.52 ± 0.14 |
| | Red. (mg l$^{-1}$) | −0.02* | 0.00 | −0.08* | 0.00 | −0.10* | 0.02 | 0.18* |
| | Red., percentage of In | −5.0 | 0.0 | −10.9 | 0 | −19.6 | 4.9 | 26.1 |

## Discussion

Although highly increased export rates previously have been found from wetland buffers used in forest drainage areas (e.g. Sallantaus *et al*. 1998, Vasander *et al*. 2003), relatively small changes in through-flow P concentrations were observed in the present study. Differences in nutrient outflow in different studies may be related to differences in hydrological conditions and soil chemistry. It has been hypothesized that P outflow increases especially if a drained peatland site is restored and rewetted and used as a BZA, because the P bound by Fe oxides and hydroxides during the drained state is easily released in waterlogged conditions (e.g. Mahapatra and Patrick 1969, Jensen *et al*. 1999). Two of the BZAs in the present study were constructed on drainage sites (Murtsuo and Kirvessuo) and through-flow P concentrations did increase significantly. Although the increases in P concentrations in the present study were relatively small, the results support the conclusions by Sallantaus (2004) that water quality impacts need to be carefully considered when restoring and rewetting drained peatlands back to wetland ecosystems. This is especially true if the restoration sites comprise high proportion of the local watershed area.

Differences in nutrient leaching from different study areas may also be related to different harvesting strategies. Forestry areas intended to be transformed to BZAs are sometimes harvested with the aim of removing merchantable parts of the tree stems. Another reason to harvest BZAs may be to restore drained and forested peatlands back to natural mire ecosystems (Vasander *et al.* 2003). Especially the concentrations of P and DOC may be expected to increase after timber harvesting of peatland dominated BZAs (Lundin 1999, Nieminen 2003, 2004). In the present study no harvesting operations were performed, except at the Murtsuo BZA where the highest increases in through-flow P and DOC concentrations of the seven study sites were observed (Table 2). However, the increase in P and DOC concentrations from Murtsuo was not high only after harvesting operations but high increases also occurred before them in 1995–1998 (Figs. 2 and 3). This suggests that increase in P and DOC was due to water logging caused by BZA construction operations rather than because of harvesting operations. Nevertheless, it should be noted that the risk of nutrient leaching from BZAs following harvesting is higher than from other forest sites, particularly because water-logged conditions often prevail and the adsorption of the nutrients released from felling residues by the soil is therefore poor. Thus, should BZAs be harvested, whole-tree harvesting may be an environmentally better alternative than stem-only harvesting.

Converting previously fertilized areas into wetland buffer zones may also increase nutrient leaching as has often been observed where sections of agricultural soils have been transformed to wetland buffer zones (e.g. Ann *et al.* 2000). The BZAs in the present study were constructed on unfertilized areas, but the Vanneskorpi BZA in the study by Vasander *et al.* (2003) had been previously fertilized. This may explain the dramatic increase in downstream P concentrations, although simultaneous harvesting and rewetting operations may also have had a strong influence on P leaching from Vanneskorpi.

When interpreting the results of the present study, it should also be noted that the inflow P concentrations were relatively low at all seven BZAs. The concentrations at the Hirsikangas BZA (14 $\mu$g $l^{-1}$), in particular, were low compared with earlier studies from catchments with high peatland proportion (e.g. Kortelainen and Saukkonen 1998). If the inflow concentrations are high, as when using wetlands for wastewater treatment, some retention of P usually occurs (Nichols 1983, Dubuc *et al.* 1986, Kent 1987). The concentrations of the other constituents (Fe, Al, DOC) were not low compared with earlier studies (Kortelainen and Saukkonen 1998, Liljaniemi *et al.* 2003).

The impacts of BZAs in the present study concerning all the studied water quality parameters varied significantly between the study sites and it is thus difficult to generalize about the effects of BZAs on discharge quality. It can be concluded, however, that small BZAs (Sudenalho and Kirvessuo, < 0.1% of the area of watershed) have very little effect on through-flow quality. It should also be noted that reduced concentrations of DOC, dissolved P, Al and Fe only occurred either at Hirsikangas or Kallioneva, i.e. the two largest BZAs (> 1% of the area of watershed). It thus appears that, to achieve any reduction in the concentrations of these elements, such large BZAs are needed. Liljaniemi *et al.* (2003) also suggest that more extensive buffer areas than just a few meter-wide strips are needed in order to control the export of pollutants from drained peatlands. However, it should be noted that the more significant effect of large BZAs on local water quality may not be only because of their more effective nutrient retention, but also because large BZAs discharge proportionally more water than small BZAs.

A possible explanation for the differences in the behavior of Fe is also that significant release occurs from the BZAs constructed on minerotrophic peatlands (Asusuo, Murtsuo, Sudenalho, Kirvessuo and Kallioneva), but ombrotrophic peatlands (Hirsikangas) adsorb Fe from through-flow water. However, whether site characteristics are decisive, more information is needed on the behavior of Fe at different types of BZAs.

Although increased solute leaching occurred from some BZAs in the present study, there were also sites where through-flow solute concentrations decreased. It can therefore be concluded that, although increased leaching may occur from some individual sites, BZAs are unlikely to act as a general source of soluble pollutants into water courses. As BZAs are efficient in retaining SS, their use in water quality protection in connection with forestry drainage is important. However, constructing BZAs on previously fertilized areas or on former drainage sites may enhance P leaching to water courses. Timber harvesting in connection with BZA construction operations may also increase nutrient leaching. However, although some solute leaching would occur during BZA construction operations and a few years after, BZAs may turn into nutrient-accumulating systems in the long-term (Liljaniemi *et al*. 2003). Thus, the final evaluation of the capacity of BZAs to remove soluble nutrients from discharge waters needs to be based on relatively long-term studies. In order to be able to predict which type of BZAs would act as nutrient-accumulating systems, future research is also needed.

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*Received 24 November 2004, accepted 25 April 2005*