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Long-term monitoring of buffer zone efficiency under different cultivation techniques in boreal conditions

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ABSTRACT

Vegetative buffer zones (BZs) between fields and watercourses are one way to minimize phosphorus (P) losses from fields to surface runoff and thus decrease eutrophication and blue-green algal blooms in lakes and coastal waters. A 6-plot experimental field was established in clay soil (Vertic Cambisol) in SW Finland in 1991 to study long-term changes in functioning of BZs and their retention capacity for total solids (TS), total P (TP), dissolved reactive P (DRP) and particulate P (PP) in different seasons. The steep slope in lower sections of four plots (18 m wide × 70 m long) was planted with 10-m-wide mowed grass buffer zones (GBZ) or unmowed vegetated buffer zones (VBZ) growing natural herbage and shrubs. Surface runoff water samples from the GBZ and VBZ plots were compared to samples from plots cultivated without a buffer (NBZ). The source field area in all plots and the steep slope (12–18%) on the NBZ were ploughed in autumn, and sown with barley (*Hordeum vulgare*) or oats (*Avena sativa*) in spring (conventional tillage, 1991–2001), sown with grass and grazed (72–234 cow grazing days ha^{-1} yr^{-1}; 2003–2005) and direct drilled without tillage (2006–2008). Surface soil samples (0–2 cm) were taken from the BZs in autumn and spring to evaluate the level of plant-available P (P_{Ac}) extracted with 0.5 M NH_4–acetate–0.5 M acetic acid at pH 4.65. The BZs were most effective at decreasing TS, TP and PP with conventional tillage, less so with direct drilling and least effective with grazing. In a conventionally tilled field, the TS and TP removal efficiencies were over 50% and 27–36%, respectively, for the BZs as compared to the NBZ. In the VBZ plots, the DRP load was, however, 60% greater than in the NBZ or GBZ plots. In direct drilling, the surface runoff losses were smaller than in conventionally tilled NBZ plots. The lowest losses of TS, TP and PP were found during grazing for all plots, but with grazing the DRP load, 0.3–0.4 kg ha^{-1} yr^{-1}, was higher than during grain growing in all treatments. The GBZ and VBZ were effective in retaining P in summer and autumn, whereas in spring their retention capacity was decreased. The reason for high DRP losses in spring was the high P_{Ac} in surface soil and frozen broken plant tissues in the VBZ and the grazed source field. Mowing and removing of swathe from the GBZ decreased the DRP losses.

1. Introduction

Several cultivation methods have been adopted to decrease field erosion and P losses to water. Erosion potential can be decreased by leaving stubble and straw on the soil surface (Alakukku et al., 2004; Turtola et al., 2007), using a catch crop in winter (Bechmann et al., 2005), and direct drilling (Puustinen et al., 2005; Ulén and Kalisky, 2005). However, P losses in surface runoff can sometimes increase due to frozen catch crop residues (Bechmann et al., 2005) or, from directly drilled soil surfaces, due to an increased level of soluble P in the surface soil (Muukkonen et al., 2009). Phosphorus losses to water are minimized by decreasing soil erosion, using less P fertilizer and lowering soil P status (Sharpley et al., 2001; Uusitalo et al., 2007a).

Establishment of buffer zones (BZs) between field areas and watercourses is an additional way to control transport of diffuse pollutants (Dillaha et al., 1989; Ahola, 1990). The BZs are under permanent plant cover and they are not tilled, fertilized, manured or sprayed with herbicides. In Finland, 3-m-wide buffer strips have been compulsory along watercourses and 15-m-wide BZs have become more common since 1995, when the country introduced measures to implement the Agri-Environmental Programme (EEC,

Abbreviations: BZ, buffer zone; DRP, dissolved reactive phosphorus; GBZ, grass buffer zone; NBZ, no-buffer zone; P_{Ac}, soil P extracted with 0.5 M acetic acid–0.5 M ammonium acetate at pH 4.65; P_w, soil P extracted with water (1:60); PP, particulate phosphorus; TP, total phosphorus; TS, total solids; VBZ, vegetated buffer zone.

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1992). The current total area of BZs and buffer strips along watercourses and main ditches is over 10,000 ha. The plants on 15-m-wide BZs must be harvested annually and therefore they are sometimes grazed by a few cows, heifers, horses or sheep. Buffer zones mitigate in particular losses of eroded soil particles, particulate P (PP), total P (TP) and other soil-bound pollutants in surface runoff water (e.g. Dillaha et al., 1989; Uusi-Kämppä et al., 2000; Syversen, 2002) whereas the retention of soluble pollutants such as dissolved reactive P (DRP) may be poor (Dillaha et al., 1989; Uusi-Kämppä, 2005). In some studies, however, the trapping of DRP by BZs has been found to be considerable (e.g. Vought et al., 1991; Cole et al., 1997). This also depends on site factors as related to low velocity through the BZ.

There are only a few studies on the DRP retention of buffer zones in boreal climate areas, where freezing and thawing may influence BZ function (e.g. Syversen, 2002, 2005; Väänänen et al., 2006). In most studies, the retention of eroded soil particles and different fractions of P and N as well as other pollutants from surface runoff by BZs has been investigated. There are some studies dealing with the nutrient uptake of different plants in BZs (e.g. Mander et al., 1997; Søvik and Syversen, 2008), but there is a lack of studies on the effectiveness of each trapping mechanism. Nitrogen dynamics of BZs has been studied (e.g. Hefting et al., 2005) but there is little information on, for example, changes in soluble P concentrations in soils of BZs. Agricultural soil tests are generally used to identify areas of excessive P exports, and soil P has been found to predict the concentration of DRP in runoff—the greater the soil P concentration, the higher the DRP concentration and vice versa (Sharpley et al., 1986; Uusitalo and Jansson, 2002; McDowell et al., 2007).

In most studies, the removal capacity of BZs has been studied during a few runoff events, for example after manure application to an adjacent source field and using artificial rainfall to produce surface runoff. We studied the effectiveness of GBZs and VBZs at decreasing losses in surface runoff under natural conditions with rainfall and snow melting for over 17 yr on the same experimental field. Thus, the long-term changes in soil P status and removal capacity of BZs, including effects due to the cold season, could be followed.

Grazing of dairy cattle is most common in western and central Finland, where up to 10% of the field area can be grazed; the total grazing area of the country is ca 100,000 ha (4.5% of the total arable land). There is often less erosion on grasslands than on conventionally tilled cereal fields (e.g., Puustinen et al., 2005; Turtola et al., 2007), whereas TP and DRP losses in surface runoff can be greater from grasslands due to top dress fertilization (Turtola and Jaakkola, 1995). On the other hand, intensive grazing at high stocking density increases erosion and P losses (Bilotta et al., 2008).

Autumn ploughing and harrowing of the soil in spring before sowing the crops have been normal methods in Finland for decades. During recent years, however, direct drilling (minimal or no cultivation before seed is drilled into soil), has become a more popular method (160,000 ha is 7% of land under cultivation and fallow in Finland; Information Centre of the Ministry of Agriculture and Forestry, 2009). Due to stubble cover in winter, the risk of soil erosion is reduced on direct drilled fields. Therefore, the usefulness of BZs for the control of erosion in connection with direct drilling has been debated along with the question of whether TP losses could be smaller from direct drilled fields than from conventionally tilled ones. When direct drilling results in enrichment of P in the surface soil, DRP losses may increase in surface runoff (Puustinen et al., 2005; Muukkonen et al., 2009).

The objective of this study was to evaluate and compare in boreal climate the quantity and quality of surface runoff from a source field with a 10-m-wide BZ to the quantity and quality of runoff from a source field without a BZ. The buffer treatments were: (1) an annually mowed (swathe removed) grass buffer zone (GBZ), (2) an unharvested vegetated buffer zone with natural vegetation (VBZ) and (3) no buffer zone (NBZ) established in the lower end of the plots in 1991. The long-term removal efficiency for TS, TP, PP and DRP in surface runoff for GBZ and VBZ was studied on the experimental field with conventional tillage (1992–2001), grazing by cows (May 2003–April 2006) and direct drilling (May 2006–December 2008). Additionally, the impact of plant-available P (P_{Ac}) in the surface soil layer (0–2 cm) of the BZs on DRP loads was investigated.

Table 1
The mean values (±S.D.) for organic carbon, $pH_{(water)}$, plant-available P, Ca, K and Mg in the soils (0–20 cm) of the experimental field and the upper and lower sections of the buffer zones (BZ) in autumn 1991. $N = 2$.

	Field	Upper section of the BZs	Lower section of the BZs
Org. C (%)	3.0 (±0.3)	2.4 (±0.2)	2.3 (±0.2)
$pH_{(water)}$	6.1 (±0.1)	6.2 (±0.2)	6.3 (±0.1)
P_{Ac} (mg L^{-1})	8.0 (±0.9)	7.4 (±1.5)	5.8 (±1.2)
Ca (mg L^{-1})	2360 (±140)	2500 (±300)	2560 (±200)
K (mg L^{-1})	230 (±10)	230 (±10)	230 (±10)
Mg (mg L^{-1})	520 (±30)	680 (±130)	750 (±120)

2. Materials and methods

2.1. The experimental field

The 10-m-wide BZs were established on a 6-plot field on clay soil (Vertic Cambisol; FAO, 2006) at Jokioinen (60°48′N and 23°28′E), SW Finland in June 1991 (Uusi-Kämppä and Yläranta, 1992). The plant-available concentrations of Ca, K, Mg and P in the plough layer (Table 1) were at a "satisfactory" or "good" level. To prevent surface runoff water from flowing from one plot to another, the plots were isolated to a depth of 60 cm by a plastic sheet and on the surface by a soil bank. The experimental field was surrounded by an open ditch to conduct surface runoff flow away from the outside field area (Fig. 1).

A seed mixture containing timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*) was sown with a companion crop of spring barley (*Hordeum vulgare*) in two GBZs (10 m × 18 m)

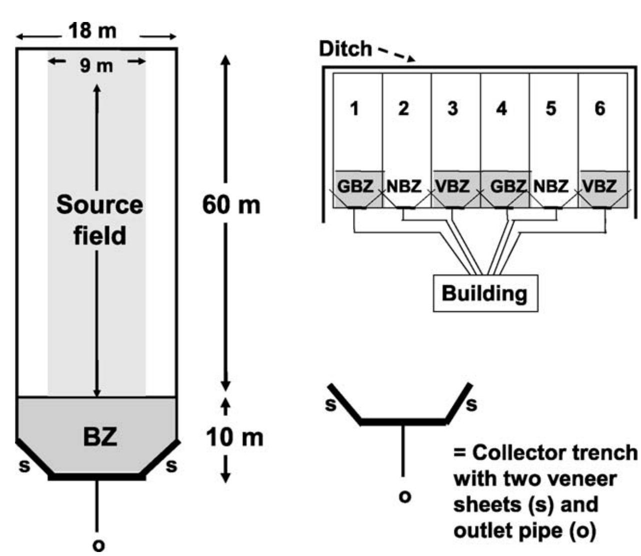

Fig. 1. Schematic diagram of the Lintupaju field since autumn 2001. GBZ, 10-m-wide grass buffer zone; NBZ, no buffer zone; VBZ, 10-m-wide vegetated buffer zone growing natural herbs and shrubs.

Table 2
Experimental years, crops, amounts of mineral fertilizer (mf) and slurry (s), and the annual TN, soluble-N, P, and K applications.

Years	Crops	Amounts of fertilizer (kg ha^{-1}) slurry (t ha^{-1})	TN, soluble-N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	K (kg ha^{-1} yr^{-1})
1991–2001	Barley/oats	mf (450)	90	18	32
2002	Barley + grass	mf (350)	90	7	11
2003	Grass	mf (580)	151	0	6
		dung[b]	12	2	
2004	Grass	mf (310)	81	6	9
		mf (400)[a]	104	0	4
		dung[b]	39	6	
2005	Grass	mf (500)[a]	130	0	5
		dung[b]	28	4	
2006	Barley	mf (350)[a]	91	0	4
	Winter wheat	s (20)	40, 24	6	na
2007	Winter wheat	mf (350)	91	0	4
2008	Spring wheat	s (60)	93, 50	19	95
		mf (200)	54	0	2

na: not analysed.
[a] The slope of the NBZ was not fertilized; the slope of the NBZ was not sown in spring 2006.
[b] Estimated amounts of dung P and N of suckler cows (Ministry of the Environment, 2009).

in May 1991. Common bent (*Agrostis tenuis*) was sown in June 1991 and small plants of birch (*Betula*), goat willow (*Salix caprea*), mountain currant (*Ribes alpinum*), European cranberry bush (*Viburnum opulus*), alder (*Alnus*), maple (*Acer platanoides*) and mountain ash (*Sorbus aucuparia*) were planted in two VBZs in October 1991. The results for the treatment plots with the 10-m-wide GBZs and VBZs were compared with those from control plots without a buffer zone (Fig. 1). Timothy, meadow fescue, white clover (*Trifolium repens*), dandelion (*Taraxacum* sp. Weber) and meadow vetchling (*Lathyrus palustris*) plants were mowed and their residue was annually removed from the GBZs. Hardwood trees and shrubs, as well as herbs and wild flowers (common bent, timothy, field sow-thistle (*Sonchus arvensis*), scentless mayweed (*Tripleurospermum inodorum* Sch. Bip) and yarrow (*Achillea millefolium*)) in the VBZs were not mowed.

The source field area was fairly levelled, with a slope of a few percent, whereas the BZs were on a steep slope (12–18%; Uusi-Kämppä, 2005) which is typical in SW Finland. The field was sub-drained, but the layout did not allow sampling of the sub-drainage water. The ploughing, harrowing, application of slurry and sowing were done by backing up the machinery to the lower end of the source area from where the work was started and this was repeated until the plots were completed. The GBZs were chosen to the study, because they are common due to easy establishment by sowing on farms. Grass is mowed to prevent spreading of weeds on BZs. The VBZs were more like natural riparian areas which cannot be harvested with mowing machines due to shrubs and trees. The BZ width of 10 m was chosen according to studies of (Dillaha et al., 1989; Ahola, 1990). The 18 m wide and 70 m long experimental plots could be cultivated by agricultural equipments of farmers, and Puustinen et al. (2005) had used the plot size of 18 m wide and 50 m long.

The source field and slope in the NBZ were ploughed in September–October, 1992–1995 and 1998–2001, and stubble-cultivated to a depth of 0–15 cm in October 1996 and 1997. Barley or oats (*Avena sativa*) were sown in the spring, 1992–2001, following fertilization rate of 18 kg P ha^{-1} and 90 kg N ha^{-1} annually, which were typical applications of fertilizers on most Finnish farms at that time (Table 2). According to Agri-Environmental Programme, the required P fertilization on the source field was either 18 kg P ha^{-1} due to satisfactory P_{Ac} status or 15 kg P ha^{-1} for cereals according to the basic level (Yli-Halla et al., 2001). In spring 2002, timothy and meadow fescue were sown with a companion crop of barley. The source area on each plot and the slope of the NBZ were rotationally grazed by heifers and dry cows (72, 234 and 128 cow grazing days ha^{-1} in summers 2003, 2004 and 2005, respectively). The pasture was grazed by cattle two or three times a year for 12–22 days in each time. The grass on the source field was sprayed with glyphosate in August 2005, and barley was direct drilled into the grass stubble the following spring. In the NBZ plots, the grass on the slope area was sprayed with glyphosate on 14, July 2006. After harvesting the barley in August 2006, 20 t ha^{-1} cattle slurry was surface applied to the source field area and to the slope of the NBZ, after that winter wheat was directly drilled. In following spring, the wheat was fertilized with ammonium nitrate fertilizer and then it was harvested in August. In the beginning of May 2008, 60 t ha^{-1} of cattle slurry was applied to the source field and the NBZ slope (Table 2). Since direct drilling of wheat was delayed for 3 days after the slurry application, part of NH_4-N was most probably volatilized into air. Part of the N was given in mineral fertilizer due to high P:N rate in slurry. Amounts of slurry and N fertilizers conformed with regulations of the nitrate directive. The wheat was harvested in October 2008.

2.2. Water samples

Surface and near-surface runoff (referred to hereafter as surface runoff) to a depth of 0.3 m was collected in a 9-m-wide modified collector trench (Fig. 2) designed by Puustinen (1994) at the lower end of each plot. Surface runoff losses were measured/calculated for an area of 9 m × 70 m when the source field was autumn ploughed and sown in spring (conventional tillage) between 1991 and 2002. Since autumn 2001, surface runoff water from the edges of the plots has been led by installed veneer sheets to collector trenches and the runoff losses have been calculated for an area of

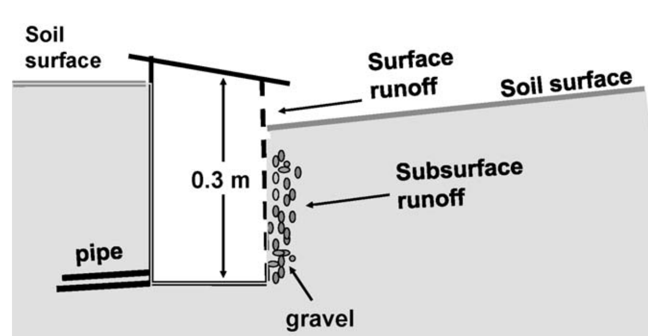

Fig. 2. A cross-sectional diagram of the collector trench.

18 m × 70 m (Fig. 1). Grass covered the whole source area during the grazing years, while the 1.5-m-wide grassy borders between plots were out of production during direct drilling years. During peak flows, the water volume might have been greater than measured from the directly drilled field due to small holes which appeared in the veneer sheets.

The volume of surface runoff water was measured with tipping buckets of 5 L, tripping a microswitch attached to a data collecting device that counted the tips. Flow-weighted water samples were collected with funnels conducting 0.1% of total discharge into plastic canisters. Annually, 15–30 water samples (representing runoff from 1 to 40 mm) were collected for laboratory analyses. Sampling was done daily during peak runoff periods in spring and weekly or biweekly in other time. In 1991–1994, the samples were stored without filtration in polyethylene bottles in the dark (4 °C) for some days or weeks before determining the nutrient concentrations. Since spring 1995, the DRP was analysed in the sampling day. Due to high runoff volume in spring, sampling was done daily and DRP analyses were done in 24 h after sampling. In other times, water was collected into canisters for several days before sampling. Study years were divided into three experimental periods: spring (from 1st January to the date of sowing or fertilization in May), summer (from sowing/fertilization to ploughing or the end of the grazing period in September or October) and autumn (from ploughing or the end of the grazing period to 31st December).

In order to estimate erosion, total solids (TS) were determined as evaporated residue after drying at 105 °C. The DRP was determined by the molybdate blue method (Murphy and Riley, 1962) after filtration (pore size 0.45 μm before 1995, and 0.2 μm since 1995). Total P was analysed following the molybdate blue method after peroxodisulfate digestion. Dissolved reactive P and TP were determined using a FIAstar autoanalyzer according to Finnish standards SFS 3025 (1986a) and SFS 3026 (1986b), respectively. The PP concentration was calculated as the difference between TP and DRP. Water samples of autumn 1991, spring 1992, autumn 1994, and those from autumn 2001 to spring 2003 were excluded from the statistical analysis due to incomplete sampling or high erosion caused by the building of the veneer sheets. In spring 2003, unusual nutrient losses from stubble field (after an extremely dry year) were not included in statistical analyses but the DRP losses are described in the text. The results from stubble field (autumn 2002–spring 2003) could not be included in conventional tillage due to untillage but they could not either be included in pasture phase due to unsubstantial grass cover.

2.3. Soil, plant and slurry samples

Three soil samples were taken from each BZ in spring and autumn. Separate sampling lines were situated approximately 1.0, 5.0 and 8.5 m from the collectors in the lower, middle and upper sections of the BZs, respectively. Soil was initially sampled to depths of 0–10 and 10–20 cm with a drill (20 subsamples from each depth). In 1995–1999 and 2003–2005, surface soil was sampled from 0–2, 2–5, and 5–10 cm layers (four cores for each depth level were pooled). Surface samples were dug up using a shovel, and soil layers were separated with a mortar trowel.

Plant-available phosphorus (P_{Ac}), calcium (Ca), magnesium (Mg) and potassium (K) were extracted from air-dried and homogenized soil samples using 0.5 M NH_4–acetate–0.5 M acetic acid at pH 4.65 (Vuorinen and Mäkitie, 1955) following Finnish agronomic soil testing method. In November 2008, soil samples from 17-yr-old BZs were taken for analyses of water extractable P (P_w) method by Hartikainen (1982; soil to solution rate 1:60, extraction time 21 h), which was determined by the molybdate blue method in extracts filtered through 0.2 μm polycarbonate filters. The Olsen method (Olsen P, $NaHCO_3$, pH 8.5) was also used to analyse soil P status in 1998 and 1999 (Olsen et al., 1954). Organic carbon (C) was determined using a LECO C-N-autoanalyser. In addition, the depth of frost was measured from the colour change in methylene blue tubes buried in the soil in the GBZ, VBZ and NBZ and source field in winter months from November 1997 to April 2000 and from November 2002 to February 2004.

Above-ground biomass was sampled before harvesting the grass on the GBZ in summer. In autumn, biomass was sampled on the GBZ and VBZ. Five subsamples (0.2 m × 0.2 m) were collected from each BZ so that the grass was cut leaving a stubble of 1 cm. Plant samples were dried at first at 60 °C overnight and then for dry matter determination at 105 °C. Slurry samples were taken during spreading and analysed for pH and concentrations of total N (Kjeldahl), NH_4-N, K and P as described by Mattila and Joki-Tokola (2003).

2.4. Statistical analyses

Statistical analyses were based on the experimental design used, which was a randomized complete block design. Three adjacent plots were included in one block. Measurements were repeated at several time-points during the study. The following statistical model 'Repeated measurements ANOVA for randomized complete block design' takes into account the experimental design and the correlation between repeated measurements:

$$y_{ijk} = \mu + \text{block}_i + \text{tre}_j + \text{block} \times \text{tre}_{ij} + \text{time}_k + \text{time} \times \text{block}_{ik} + \text{time} \times \text{tre}_{jk} + \varepsilon_{ijk}$$

where block_i, $\text{block} \times \text{tre}_{ij}$, $\text{time} \times \text{block}_{ik}$ and ε_{ijk} are the random effects of the ith block (i = 1, 2), block-by-treatment interaction, block-by-measurement time interaction and residual effect, respectively. All the random effects were assumed to be mutually independent. Tre_j, time_k and $\text{time} \times \text{tre}_{jk}$ represent fixed effects of treatment (j = NBZ, GBZ, VBZ), measurement time (k = 1, ...) and their interaction, respectively. The statistical model was fitted using the REML-estimation method and SAS/MIXED software (version 9.1).

Distributions of all concentration data were skewed. Logarithm transformations were used to normalize the data distributions before statistical analyses. All the estimates were transformed back to the original scale. However, standard errors are not possible to transform back.

The proportions of P_{AC} in the 0–2 and 2–5 cm layers were statistically analysed so that the response variable was the logarithm of the difference between the two depths. This means that results can be interpret as the proportion of P_{AC} 0–2 cm to P_{AC} 2–5 cm. P_{AC} was measured from three different sections of the field and data from different sections were analysed separately.

When the data on P_{Ac} in the surface soil (0–2, 2–5 and 5–10 cm) was analysed statistically, the data included two repeated factors: time and depth. This kind of model was not possible to fix and therefore all the measurement times were analysed separately. This means that the depth was used as a repeated factor in the analyses using the model reported earlier.

3. Results and discussion

3.1. Surface runoff

Surface runoff was highest in spring (50–100 mm), being lower in autumn (20–40 mm) and negligible in summer (<10 mm; Fig. 3). In boreal areas, high runoff volumes are typical in spring due to melting snow and rainfalls (Øygarden, 2000; Syversen, 2002). In summer, low surface runoff was due to decline of rainfall

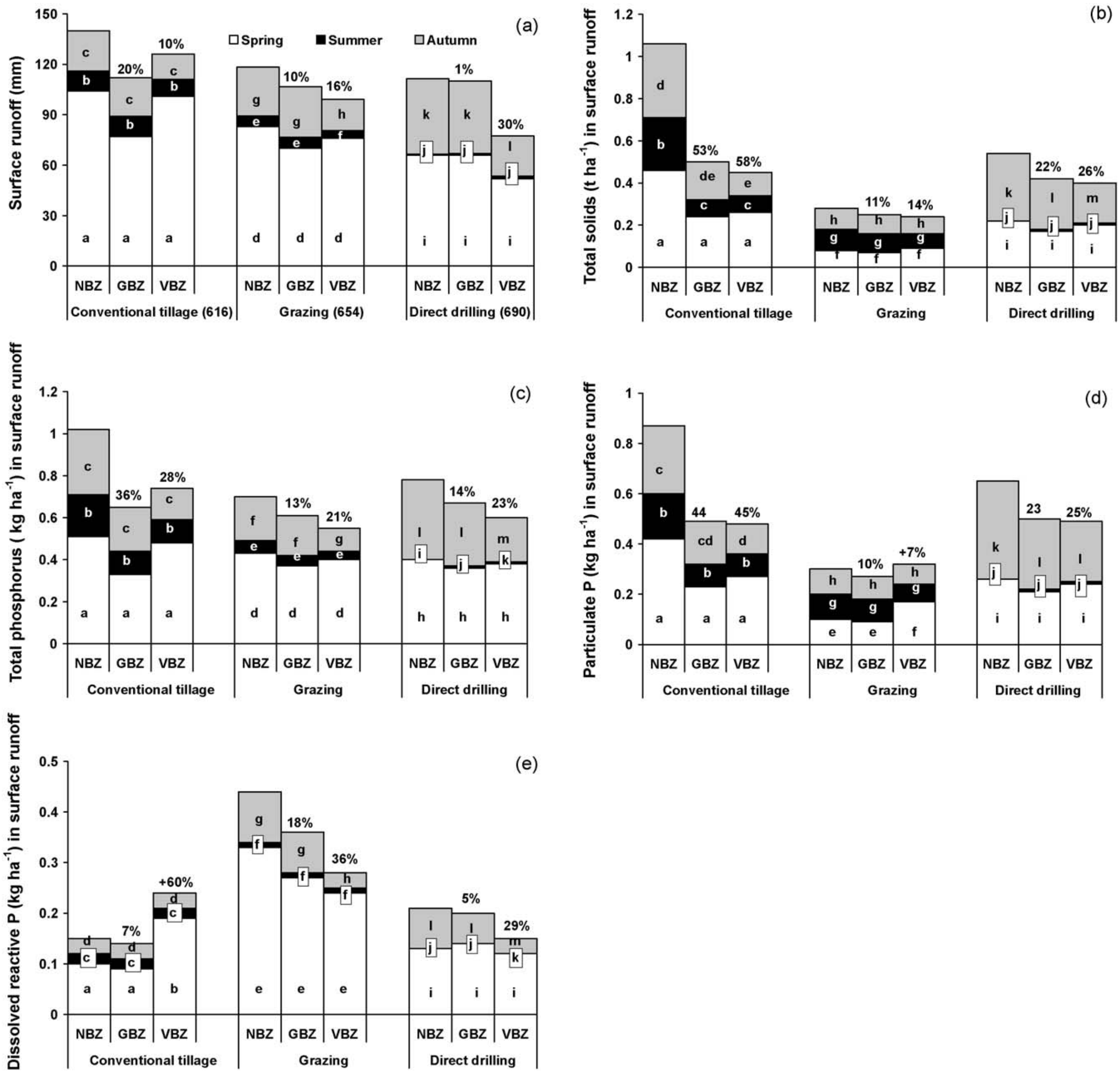

Fig. 3. Estimates of seasonal surface runoff, and losses of total solids, total phosphorus, particulate P and dissolved reactive P in surface runoff during conventional tillage, grazing and direct drilling. Different letters in bar graphs indicate significant difference at $p < 0.05$. NB: The different scales of the phosphorus figures. Average annual precipitation (mm) is in parenthesis after the cultivation methods in *X*-axis. Decrease of losses (percent) is presented above the bar graphs of GBZ and VBZ. See Fig. 1 for abbreviations.

and increase of evapotranspiration demands. These conditions result in the cracking of the clay soil and a high infiltration rate through macropores during heavy showers; whilst after re-swelling of the soil in the autumn, the infiltration rate was reduced and resulted in high lateral overland flow (Pietola et al., 2006).

Annual surface runoff volumes varied from 70 to 230 mm, being highest between 1998 and 2000 and lowest in 1993, 1995 and 2003. There was also a variation in surface runoff volume and nutrient losses between two plots of the same treatment due to natural differences or sampling errors among the plots. The highest runoff volumes were measured from the central plots (nos. 2–4), whereas lower volumes were found for the lateral plot numbers 1, 5 and 6 (Uusi-Kämppä and Kilpinen, 2000). That contributed to a lack of significant differences in losses of TS, TP and PP between the NBZ and GBZ or NBZ and VBZ in conventionally tilled fields, although the arithmetic means showed the highest losses in surface runoff from the NBZ plots. Part of the surface runoff water missed the collector trenches. Therefore, veneer sheets were installed in 2000 to collect the water from the whole plot area.

In the grazed NBZ, soil structure was destroyed and infiltration was low (Pietola et al., 2006). Low infiltration increased surface runoff volume in the NBZ (Fig. 3). During the grazing and direct drilling phases, the annual surface runoff volume was significantly less in the VBZ than in the NBZ and GBZ due to low autumn runoff (Fig. 3).

3.2. Erosion

The grass cover on the GBZ and VBZ decreased TS losses by mitigation erosion on steep slopes. In addition to preventing losses from the buffer area itself, the BZs can retain settled soil particles.

Table 3
Estimates of total solids (TS), total P (TP), particulate P (PP) and dissolved reactive P (DRP) concentrations in 70 m long plots without a buffer zone (NBZ), with a 10 m wide grass buffer zone (GBZ) or a vegetated buffer zone (VBZ) when the source field was under conventional tillage, grazing or direct drilling.

	NBZ	GBZ	VBZ
TS ($g L^{-1}$)			
Conventional tillage	1.06 a	0.59 b	0.53 b
Grazing	0.30	0.28	0.31
Direct drilling	0.44 a	0.45 a	0.57 b
TP ($mg L^{-1}$)			
Conventional tillage	0.97	0.71	0.78
Grazing	0.72	0.64	0.73
Direct drilling	0.69	0.66	0.90
PP ($mg L^{-1}$)			
Conventional tillage	0.83	0.57	0.56
Grazing	0.33	0.31	0.38
Direct drilling	0.51	0.50	0.69
DRP ($mg L^{-1}$)			
Conventional tillage	0.12 a	0.13 a	0.19 b
Grazing	0.32	0.28	0.33
Direct drilling	0.17	0.15	0.20

Means with different letters in the same row are significantly different at the 0.05 probability level.

In the conventionally tilled field (1992–2001), the TS removal efficiency was over 50% for the GBZ and VBZ (Fig. 3) as compared to the NBZ. The estimated annual TS concentration was also the highest (1.1 $g L^{-1}$) in the surface runoff entering from the NBZ, being twice that of the corresponding estimates for the VBZ and GBZ ($p < 0.05$) (Table 3). In Virginia, USA, 9-m-wide BZs reduced sediment yields by 83% and most of the sediment was trapped on the first meters of the BZs (Dillaha et al., 1989). In Norway, the sediment retention varied from 80% to 90% on BZs (Syversen, 2005). In our field the sediment removal efficiency was smaller than in other studies due to small clay particles in surface runoff. Big particles are easily settled from surface runoff than small ones (e.g., Kronvang et al., 2005; Syversen and Borch, 2005).

The mean annual losses of TS in surface runoff were smallest (0.2–0.3 $t ha^{-1}$) from the grazed source field. This agrees with findings of Haan et al. (2003) who observed in Iowa, USA, that BZs and rotational grazing of cattle can greatly control sediment losses from pastures. However, sediment loss from directly drilled field plots (0.5 $t ha^{-1} yr^{-1}$) was as high as that from the conventionally tilled field with BZs (Fig. 3). The efficiency of GBZs and VBZs in retaining TS was lower than observed earlier for conventional tillage, but the losses on the grazed and directly drilled NBZ plots were also lower than that they had been previously in conventional tillage. The source field in all plots and the slope of the NBZ were grazed but the cattle was excluded from the GBZ and VBZ.

Surface runoff volume was 19 mm but the losses of TS (1.3 $t ha^{-1}$) and TP (0.6 $kg ha^{-1}$) were high in the NBZs after heavy rainfalls (200 mm) between May 14 and June 15, 1995. The BZs decreased TS and TP losses by 80% and 40–50%, respectively. High TS loads (1.5 $t ha^{-1} yr^{-1}$) were also measured from the NBZ after autumn stubble cultivation in 1996 and 1997. During these erosion periods, the TS concentrations were as high as 7–22 $g L^{-1}$ (Fig. 5). High TS losses were found in the surface runoff from the NBZ (2.7 $t ha^{-1} yr^{-1}$) after heavy autumn rainfalls and the absence of sub-zero conditions in the clay soil in autumn 2000 (Uusi-Kämppä, 2005). During above mentioned events, the removal capacity of TS was almost 70% for the BZs, whereas their average annual removal capacities were between 30% and 60% in conventionally tilled field. Occasional heavy rainfall events can severely erode bare soils or soils with poor plant cover, resulting in large sediment loads. However, these loads are effectively trapped by BZs established at the field edge.

3.3. Losses of TP and PP in surface runoff

In conventional tillage, the PP removal efficiency was 45% for GBZs and VBZs as compared to the PP losses from the NBZs (Fig. 3). Instead, the removal efficiency for TP load was 36% and 27% for the GBZs and VBZs, respectively, which were lower than in other Nordic studies (51–97%; Uusi-Kämppä et al., 2000). In this field study, the small TP removal in the VBZs was partly due to the 90% increase in DRP losses ($p = 0.05$) in the VBZs in spring. Significantly, the TP concentrations were highest in the surface runoff from the NBZ in autumn and summer (1.4 and 1.8 $mg L^{-1}$, respectively), but the differences were small among treatments in spring (Fig. 4). The average removal efficiency for TP concentrations were 26–31% and 34–49% in autumn and summer, respectively. The PP concentration (0.83 $mg L^{-1}$) was also one-third lower in the VBZ and GBZ than in the control but the difference was not statistically significant (Table 3). Settlement of soil particles, which also bind part of the P, is an important removal method of PP. According to Norwegian results, a narrow BZ of 5 m wide can significantly decrease TP losses since the trapping of TP is highest within the first few meters of the BZ (Uusi-Kämppä et al., 2000). In our study, particle sediment deposition was smaller than in Norwegian studies due to small soil particles in Finnish clay soils. Soil particles with PP may also infiltrate into large soil pores and tracks (Uusitalo et al., 2001) in dry seasons.

In grazing and direct drilling, the estimated TP losses (0.6–0.8 $kg ha^{-1} yr^{-1}$) in the NBZ were as high as those in the GBZ and VBZ during conventional tillage. The PP load (0.3 $kg ha^{-1} yr^{-1}$) from pasture was 34% and 46% of that from conventionally tilled and directly drilled fields, respectively (Fig. 3). With grazing, the TP load was smallest in the VBZ due to lower surface runoff in autumn, whereas the PP load was highest in the VBZ due to a high PP concentration in spring surface runoff.

In conventional tillage and pasture phase, the concentrations of TS, PP and TP in surface runoff water were highest in autumn and in summer (Fig. 4) while the greatest losses of TS, PP and TP were measured in spring due to the high water volume (Fig. 3). The purification efficiency of the BZs was lower in spring than in summer or autumn, partly due to low infiltration into the swollen and frozen soil.

According to the results from three successive years of direct drilling, the BZs decreased the losses of TP and PP by 14–23% and 25%, respectively (Fig. 3). There were no significant differences in spring and summer surface runoff among treatments, whereas the lowest losses were observed in the VBZ in autumn due to low surface runoff.

3.4. Losses of DRP

3.4.1. Convention tillage

Although the removal efficiencies of TS, TP and PP were good for GBZ and VBZ on conventionally tilled fields, the removal efficiency of DRP was poor. In fact, the DRP load increased by 60% in the VBZ (Fig. 3). The highest DRP concentration was in the VBZ (0.19 $mg L^{-1}$), whereas the DRP concentration in the GBZ (0.13 $mg L^{-1}$) did not usually differ from the NBZ (Table 3). Especially during spring runoff, the DRP concentrations in the VBZ were 50% and 40% higher ($p < 0.001$) than in the NBZ and GBZ, respectively (Fig. 4). In spring, the DRP load increased by 90% on the VBZ (Fig. 3). The BZs did not work well in cool spring season, when surface runoff and P losses were the highest. In some other studies (e.g., Vought et al., 1991; Cole et al., 1997), DRP has been found to be retained well in BZs during the growing season. On the other hand, Dillaha et al. (1989) showed that DRP losses became elevated in BZs over the course of years due to the release of previously stored or trapped P within BZs.

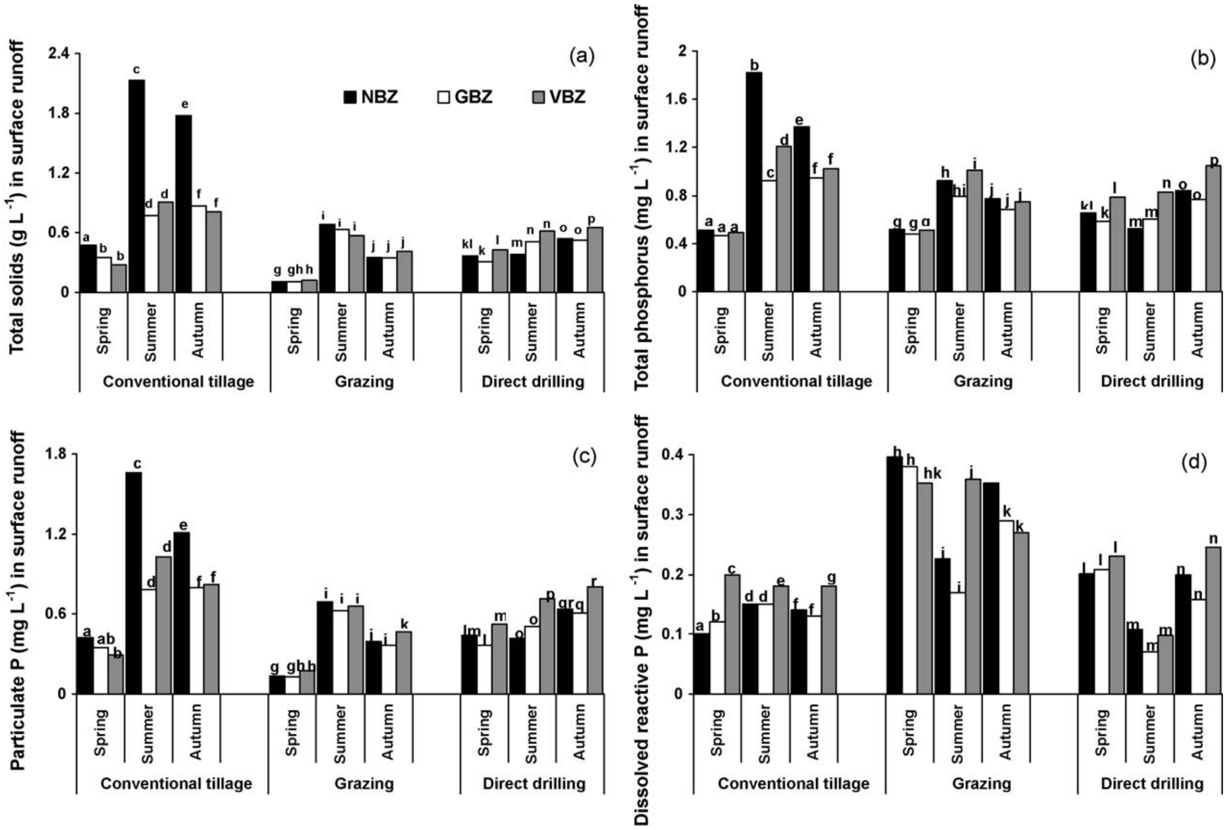

Fig. 4. Estimates of seasonal concentrations of total solids, total phosphorus, particulate P and dissolved reactive P in surface runoff during conventional tillage, grazing and direct drilling. Different letters in bar graphs indicate significant difference at $p < 0.05$. NB: the different scales of the phosphorus figures. See Fig. 1 for abbreviations.

Surface runoff water containing DRP infiltrates into soil pores, in which case part of the P is adsorbed to soil surface and walls of macropores. Sorption/desorption of P is an equilibrium reaction governed by the amount of Al and Fe oxides in soil, their P saturation and soil pH (Murrmann and Peech, 1969; Hartikainen, 1981, 1982). Sorption is initially fast but continues slowly for several days. The slow phase is attributable to the diffusion of P into the porous oxide materials, which renders P less desorpable. Väänänen et al. (2006) found the sorption by soil to be the most important sink in forestry BZs for P (being 92% of the retained ^{32}P) under early spring high flow conditions. Although the adsorption of DRP is an important retention mechanism of P, some DRP may be desorbed from soil.

One purification mechanism in BZs is nutrient uptake by plants. In our field, the annual P uptake by above-ground biomass was up to 2.4–10.2 kg P ha^{-1} (Räty et al., 2009). If the plants are not harvested, part of the uptaken P is released from the frozen plants tissues, as probably happened in the VBZ during conventional tillage. Earlier e.g., Timmons et al. (1970), Sharpley (1981), Ulén (1984) and Bechmann et al. (2005) have found P to be released into surface runoff water directly through the decomposition of plant residues. In our field, after the first frost in autumn 2005, substantial decreases in P content of above-ground plant material were detected, being 0.5, 2.5 and 6.1 kg ha^{-1} in the grazed NBZ, GBZ and VBZ, respectively (Räty et al., 2009). According to Stutter et al. (2009), BZs can lead to an increased release of P to waters. They found that establishment of BZs enhanced soil P cycling, increasing soil P solubility and the potential to leach P into entering waters. In the GBZ, the P_{Ac} in surface soil and DRP losses in surface runoff were much smaller in the VBZ plots, since the GBZ was mowed regularly and the grass swathe was removed. In 1998, the above-ground biomass was not mowed in the GBZ, and later in autumn and the following spring there were elevated DRP concentrations (0.2–0.6 mg L^{-1}) in surface runoff (Fig. 5).

For practical agriculture, however, the introduction of BZs have a smaller effect on the net DRP losses in surface runoff when the whole catchment area has a larger cultivated field area than in our experiment, since the ratio of BZs and source fields would be less than in our study (1:6). This view was also confirmed by Fiener and Auerswald (2009), who studied the effects of grassy water ways on DRP loads from German agricultural watersheds.

High DRP losses, 0.5, 0.6 and 0.9 kg ha^{-1} in the NBZ, GBZ and VBZ, respectively, were also measured in surface runoff in spring 2003 (between phases of conventional tillage and grazing) even though the surface runoff was about half of the general spring runoff (40, 60 and 80 mm in the NBZ, GBZ and VBZ, respectively). Summer 2002 had been particularly warm and long up to late September, until snow suddenly covered green leaves of plants and trees on October 4th. In fact, there was no surface runoff in summer and autumn 2002. The concentration of DRP in surface runoff was extremely high, up to 2.8 mg L^{-1} (Fig. 5) in spring 2003. One other reason for high DRP losses and concentrations might be that the maximum depth of the frost penetration varied from 60 to100 cm in the field on April 22nd, decreasing infiltration capacity in the BZs and the source field. At the same time, however, the soil had partly thawed, thus the 0–8 and 0–28 cm layers were leached by surface runoff water in the BZs and the poorly grassed source field areas, respectively.

3.4.2. Pasture

During the grazing phase (summer 2003–spring 2006), the mean DRP losses (0.3–0.4 kg ha^{-1} yr^{-1}) as well as mean DRP concentrations (0.28–0.33 mg L^{-1}) were high in all treatments. In contrast to conventional tillage, the removal efficiency of DRP loss

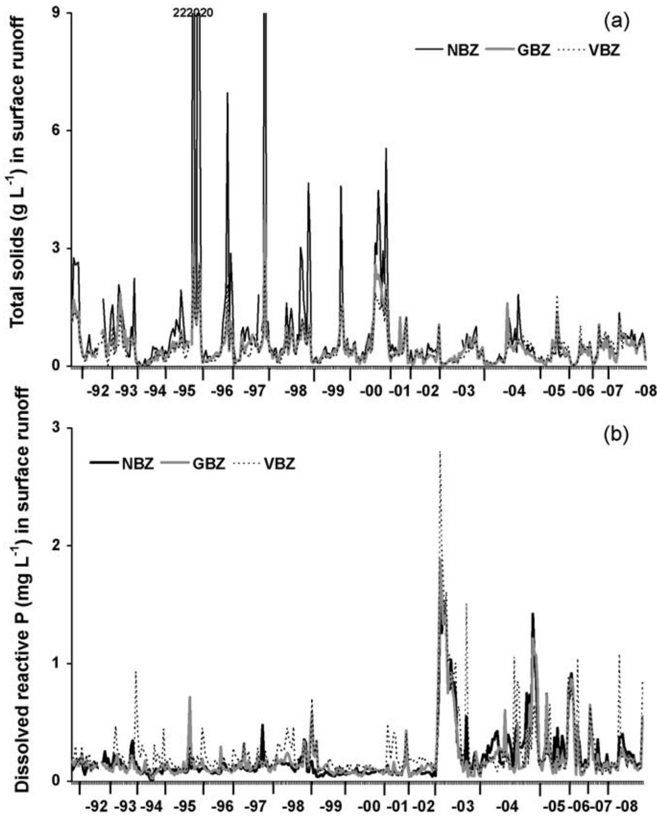

Fig. 5. Concentrations of total solids and dissolved reactive P in surface runoff water sampled from conventionally tilled (1991–2001), grazed (2002–May 2006) and direct drilled fields (June 2006–2008). See Fig. 1 for abbreviations. The concentration of total solids was off scale three times in the NBZ plots.

was 36% for the VBZ ($p = 0.05$) as compared to the NBZ plots, due to low surface runoff on the VBZ (Fig. 3). The infiltration was higher in the GBZ and VBZ than in grazed NBZ, where the soil was more compacted after the trampling of cows (Pietola et al., 2006).

There were no significant differences in DRP removal efficiencies in spring or summer, but in autumn, the DRP removal efficiency was 67% and 22% for the VBZ and GBZ, respectively, as compared to the NBZ (Fig. 3). In the VBZ plots, the DRP concentration was high (0.36 mg L^{-1}) in summer, being 36% and 53% higher than in the grazed NBZ ($p < 0.001$) and GBZ ($p < 0.01$), respectively (Fig. 4). Although the DRP removal efficiency was 36% for the VBZ, there were no differences in annual DRP concentrations among treatments during grazing (Table 3).

On the pasture, the DRP in surface runoff originated from the dried, frozen and thawed grass residue, in concurrence with the findings of Timmons et al. (1970) and Ulén (1984), from the high concentration of plant-available P in surface soil (Sharpley et al., 1986) and dung patches (Chardon et al., 2007; Soinne et al., 2008). The amount of dung P was 2–6 kg ha^{-1} yr^{-1}, if one dry cow excretes as much P as a suckler cow (10 kg yr^{-1}; Ministry of the Environment, 2009). In our study, the DRP losses were high from the grazed NBZ due to a higher surface runoff water volume on the compacted soil surface. The DRP concentrations were usually slightly higher on the NBZ than on the VBZ and GBZ (Fig. 4). If a pasture is kept more for exercising than grazing of the cattle, a wider ungrazed BZ is needed. According to Ekholm (1998), P reduction measures should be targeted at algal-available P rather than at TP for effective mitigation of eutrophication and DRP is the most clear algae-available concentration.

After treating the grass on the source field with glyphosate in August 2005, high DRP losses (0.6 kg ha^{-1}) were measured once again the following spring. Elevated DRP losses in runoff from the plants treated with glyphosate was also found in the studies of Ulén and Kalisky (2005) and Uusitalo et al. (2007b).

3.4.3. Directly drilling

The DRP loads were 0.06 kg ha^{-1} yr^{-1} higher in the directly drilled field than in conventionally tilled NBZ plots (Fig. 3). This was due to P fertilization into surface soil from there DRP can be leached into surface runoff. There were no significant differences in the DRP losses among treatments in spring, and the losses were negligible in summer. In autumn, however, the DRP load was lower in the VBZ than in the GBZ ($p = 0.01$) and NBZ ($p < 0.001$). The smaller DRP load on the VBZ was due to the smaller surface runoff (higher infiltration). The concentrations of TS, TP, PP and DRP were, however, higher in the VBZ than in the GBZ or NBZ (Table 3, Fig. 4).

On the directly drilled field, the losses of TS, PP, TP and DRP were 26%, 25%, 23% and 29%, respectively, smaller in the VBZ than in the NBZ, whereas their concentrations showed an opposite trend (Figs. 3 and 4). The lower load in the VBZ was thus due to lower runoff. The planted trees might also have increased evapotranspiration and P uptake in the VBZ. More research is needed to examine the effectiveness of BZs in fields under long-term direct drilling. The real losses were higher from the direct drilling than what we calculated due to small holes in the veneer sheets and the grassed borders of 1.0–1.5 m around the plots, and the unsown area at the lower ends of the plots, which were impossible to sow with big machinery.

The retention of P improved in the VBZ over the years, possibly due to improved infiltration (Pietola et al., 2006), enhanced rates of soil P cycling (Stutter et al., 2009) and the increased P uptake by trees and shrubs. Mander et al. (1997) reported plant uptake of P to be higher in young tree stands than in old Estonian forests, which would support the idea that the higher P uptake of growing trees and shrubs is important in the VBZ. Although the DRP load decreased by 36% in the VBZ, the load was still high. If the source field is under grass, the DRP loss is high from the source field and the increasing effect of the BZs on DRP losses is less important, especially in spring.

Thus the management of the source field above (crops, cultivation technique, soil P status), management of the BZs (mowing, grazing), the season (freezing and thawing events) and weather conditions, such as heavy rainfalls and drought, have a great effect on the efficiency of the BZs in boreal areas. Besides drought creates cracks into clay soils it also kills plants of which nutrients may be released into runoff water just like after freezing and thawing events (Timmons et al., 1970). The total surface runoff flow, sediment and nutrient concentrations in surface runoff, and retention capacity of BZs varied significantly according time (Tables 4 and 5).

3.5. Plant-available P in soil of the buffer zones

Plant-available P in soil was measured to estimate P adsorption into soil and DRP losses. At the beginning of the study (June 1992), there were no differences in the amounts of P_{Ac} in the 0–10 cm layer in the GBZ, VBZ and NBZ due to annual ploughing and harrowing. Nor were there any significant differences in P_{Ac} values (0–10 cm) between the upper (near the source field) or middle sections of the BZs over the experimental period from June 1992 to September 1994 (8 samplings). In contrast, in the lower section of the BZs, a P_{Ac} value of 4.8 mg L^{-1} (average estimate) was measured in the GBZ, which was significantly lower than the values obtained for the NBZ (7.5 mg L^{-1}, $p = 0.03$) and the VBZ (7.2 mg L^{-1}, $p = 0.03$). Weaver et al. (1988) found that the differences in rapidly released *P* concentrations in sandy soil under different treatments would have been difficult to detect over a short period

Table 4
ANOVA results for surface runoff, and amounts of total solids (TS), total P (TP), particulate P (PP), dissolved reactive P (DRP) presented in Fig. 3. Table includes test statistics, degrees of freedom (df) and statistical significance for effect of treatment (NBZ, GBZ, and VBZ), measurement time and their interaction.

Variable	Effect	*F*-value	df	*p*-Value
Surface runoff	Treatment	0.35	2, 2	0.74
	Time	112.46	37, 37	<0.001
	Treatment × time	1.91	74, 73	<0.01
TS load	Treatment	1.78	2, 2	0.36
	Time	62.11	37, 37	<0.001
	Treatment × time	2.37	74, 73	<0.001
TP load	Treatment	0.54	2, 2	0.65
	Time	83.96	37, 37	<0.001
	Treatment × time	2.26	74, 73	<0.001
PP load	Treatment	0.78	2, 2	0.56
	Time	62.08	37, 37	<0.001
	Treatment × time	1.98	74, 73	<0.01
DRP load	Treatment	0.14	2, 2	0.87
	Time	123.75	37, 37	<0.001
	Treatment × time	3.33	74, 73	<0.001

Table 5
ANOVA results for concentrations of total solids (TS), total P (TP), particulate P (PP), dissolved reactive P (DRP) presented in Fig. 4 and in Table 3. Table includes test statistics, degrees of freedom (df) and statistical significance for effect of treatment (NBZ, GBZ, and VBZ), measurement time and their interaction.

Variable	Effect	*F*-value	df	*p*-Value
TS concentration	Treatment	15.68	2, 2	0.06
	Time	73.34	38, 38	<0.001
	Treatment × time	5.47	76, 75	<0.001
TP concentration	Treatment	3.23	2, 2	0.24
	Time	47.49	38, 38	<0.001
	Treatment × time	3.21	76, 75	<0.001
PP concentration	Treatment	3.98	2, 2	0.20
	Time	75.93	38, 38	<0.001
	Treatment × time	3.06	76, 75	<0.001
DRP concentration	Treatment	7.71	2, 2	0.11
	Time	65.17	38, 38	<0.001
	Treatment × time	3.17	76, 75	<0.001

if the soil had been sampled from the 0 to 10 cm layer in comparison to their method of sampling the 0–2 cm layer. A large volume of sampled soil (0–10 cm) would have diluted many of the changes in the 0–2 cm layer of soil where fertilizers were broadcast. Therefore we also started in May 1995 to sample the BZ soil from the depths of 0–2, 2–5 and 5–10 cm instead of the depth of 0–10 cm.

3.6. Changes at the surface (0–2 cm)

Sampling surface soil from 0 to 2 cm revealed differences in P_{Ac} values among the NBZ, GBZ and VBZ (Fig. 6). At the end of the study, the P_{Ac} concentration in the VZB was twice that in the NBZ and GBZ. Also the Olsen P was highest (60 mg L^{-1}) in the VBZ (0–2 cm), while lower amounts (45 and 33 mg L^{-1}) were found in the NBZ and GBZ, respectively, in 1998 (Uusi-Kämppä, 2005). These high soil P_{Ac} in the VBZ can partly explain the high DRP losses from the VBZ during conventional tillage. Sharpley et al. (1986) had found the DRP concentration to increase if the soil P concentration had enhanced. A low salt concentration in surface runoff water as well as low temperature may induce P desorption from surface soil in spring (Yli-Halla and Hartikainen, 1996) and thus increase DRP losses to surface runoff in BZs in spring.

Regular mowing and swathe removal from GBZs decreased P_{Ac} in the surface soil as well DRP concentrations and losses in surface runoff. Thus the annual mowing and removal of grass swathe in

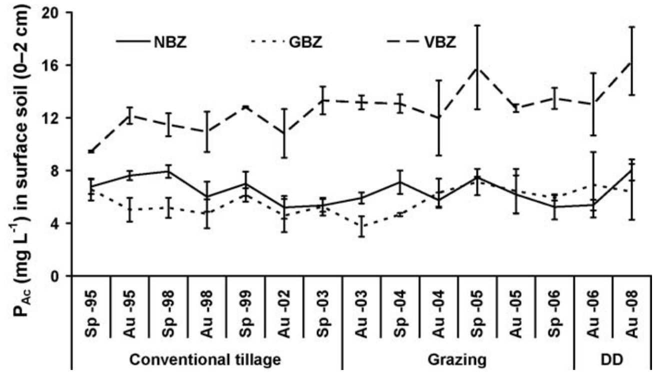

Fig. 6. Mean concentration of plant-available P (P_{Ac}) in the surface soil (0–2 cm) on the slope area of the plots. The bars show maximum and minimum values. The source area above and the slope of the NBZ were conventionally tilled, grazed, and direct drilled (DD). The samples were taken from upper, middle and lower sections of BZs from spring 1995 to spring 1999 and in autumn 2008, from upper and lower parts from autumn 2002 to autumn 2005, and from middle parts in 2006. See Fig. 1 for abbreviations. Sp, spring; Su, summer; Au, autumn.

15-m-wide BZs is demanded in Finland. If mowing is difficult in shrubby BZs, grazing of these areas might be allowed for removal of biomass and thus P from the BZ. The herd must, however, be small enough and stay only briefly in the BZs to minimize trampling.

There were also differences in P_{Ac} estimates (0–2 cm) in different sections of the BZs. In the lower section of the 10-m-wide BZs, the highest P_{Ac} estimate, 11.6 mg L^{-1} (near "satisfactory" for agronomic soils: Yli-Halla et al., 2001), was detected in the VBZ ($p < 0.01$), the estimates being 7.3 and 4.7 mg L^{-1} (between "rather poor" and "fair") for the NBZ and GBZ, respectively. Also, in the middle section of the BZs, the P_{Ac} was highest ($p = 0.04$) in the VBZ, the average estimates were 11.3 (satisfactory), 5.2 and 5.5 mg L^{-1} (fair) for the VBZ, NBZ and GBZ, respectively.

In the upper section (near the source field), the situation was different compared to other sections since the interactions of the treatment and sampling time were significant ($p < 0.01$). In the GBZ, the P_{Ac} values were highest in May 1995, with very high values found in October 2004, April 2005 and October 2005. Probably, mowing decreased the P_{Ac} when the source field was conventionally tilled. In the VBZ, the P_{Ac} was slightly higher ($p = 0.05$) between 2002 and 2005 (grazing) than the P_{Ac} between 1995 and 1999 (conventional tillage). Probably grazing of the source field increased P_{Ac} values in the upper section of the GBZ and VBZ. In the NBZ, this effect was not found due to P fertilization (18 kg ha^{-1} yr^{-1}) of the slope of the NBZ in conventional tillage (1995–2001) compared to only one P fertilization of 6 kg P ha^{-1} in spring 2004 over three grazing years.

3.7. Comparison of P_{Ac} values at different soil depths (0–2 cm vs. 2–5 cm)

Differences in P_{Ac} between two surface soil layers (0–2 cm vs. 2–5 cm) were small in 1995 and increased thereafter. In the upper and middle sections of BZs, the proportion of estimated P_{Ac} in the upper depth to the estimated P_{Ac} in the lower depth was great in GBZ and VBZ (Fig. 7). There were no differences between the two surface layers in the fertilized NBZ due to soil tillage. In lower sections of BZs, there were no significant differences among treatments, although the highest differences between estimates of two layers seemed again to be in the VBZ. The soil P_{Ac} values were the same in the two deeper layers (2–5 and 5–10 cm).

In autumn 2008, the levels of P_w were also highest in surface soil (0–2 cm), the level decreased rapidly in the deeper layers of 2–5

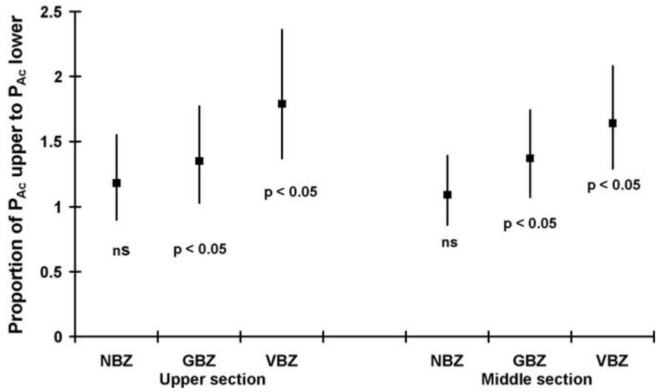

Fig. 7. The proportion of estimated plant-available (P_{Ac}) in the upper depth layer (0–2 cm, P_{Ac} upper) to estimated P_{Ac} in the lower depth layer (2–5 cm, P_{Ac} lower) with a confidence interval of 95% in the NBZ, GBZ and VBZ during study phases. See Fig. 1 for abbreviations.

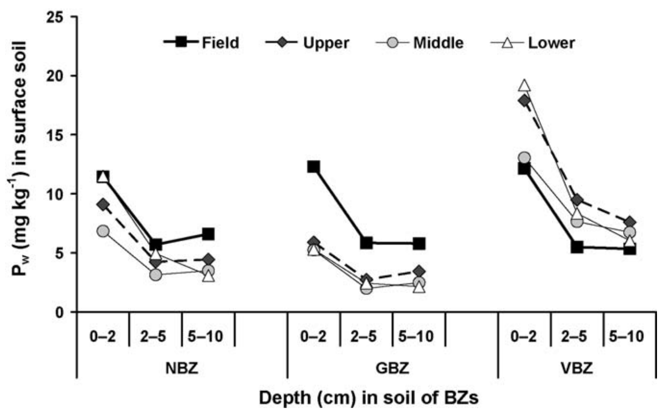

Fig. 8. Mean of water extractable P (P_w) in the surface soil (0–2, 2–5 and 5–10 cm) in the source field and upper, middle and lower sections of the NBZ, GBZ and VBZ on 13 November, 2008. See Fig. 1 for abbreviations.

and 5–10 cm (Fig. 8). In the VBZ plots, the P_w in the buffer area was higher than in the source field, whereas in the GBZ and NBZ plots, the P_w was highest in the source field. The high P_w in the VBZ and in the source field were the sources of DRP into surface runoff. Greenhouse experiments have also shown a rapid reduction in soluble P and rapidly available soil P on grass with zero P application and mowing of the grass several times per year (van der Salm et al., 2009). Mowed BZs can also work as mining soil P, thus decreasing P leaching. Phosphorus removal via mowing of GBZ plants was greatest when the harvest time was during flowering or seed-bearing stages (Uusi-Kämppä and Kilpinen, 2000).

According to Stutter et al. (2009), BZs can lead to an increased release of P to waters. They found that establishment of BZs enhanced soil P cycling, increased soil P solubility and the potential to leach P into entering waters. In the GBZ, the P_{Ac} in surface soil and DRP losses in surface runoff were much smaller than in the VBZ plots, which may be due to the fact that the GBZ was mowed and the swath was removed.

4. Conclusions

Losses of TS and PP from the grazed field were low compared to losses from the conventionally tilled field, whereas the DRP losses were higher than those in the cereal fields. The P status (P_{Ac}, P_w and Olsen P) in the surface soil (0–2 cm) was elevated after a few years in unmowed VBZs, where the P from plant residues enriched the soil surface, enhancing the DRP losses in surface runoff in spring. If P transport is to be minimized from surface runoff in boreal areas, it is important to harvest and collect the swathe from the BZs, particularly to mitigate DRP losses. In the VBZs with shrubs, the retention of DRP increased during the years, due to smaller runoff water volumes because of better infiltration, but the DRP concentrations were not lower than in the GBZ or NBZ. New methods are needed to increase DRP retention during spring runoff, even if the DRP originates from source fields like the pasture in this study.

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