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Effectiveness of buffer strips without added fertilizer to reduce phosphorus loads from flat fields to surface waters

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Abstract

Buffer strips with no added fertilizers are a mitigation measure to reduce P loads from agricultural land to surface water. However, the experimental evidence on their effectiveness (BSE) has been from sloping locations with shallow flow and surface runoff. The aim of this experimental study was to quantify BSE for P on flat agricultural lowland, predominantly with deep flow. We selected sites characteristic of five major hydrogeological classes in the Netherlands and in each experimental field installed paired 5-m-wide unfertilized grass (BS) and reference treatments (REF) that abutted the ditch. The REF treatments were managed similar to the adjacent grass or maize field, but BS treatments were only harvested. Each treatment had a reservoir in the ditch to collect and measure discharge and flow-proportional P concentration for 3 or 4 yr. We also measured net P withdrawal, the P status of the soil and P concentration in upper groundwater. We found a significant BSE for P of 61% on the site with the shallowest flow and steepest slope (2%). At the other sites, BSE was low and statistically insignificant. We conclude that harvested unfertilized buffer strips reduce P loads from flat fields only in specific areas with high surface runoff and/or shallow flow, especially in combination with a high original soil P status.

Keywords: Buffer strip, buffer strip effectiveness, hydrogeology, phosphorus, surface water quality

Introduction

Surface water quality is often a major concern in areas with intensive agriculture owing to runoff of nutrients. Excess nitrogen (N) and phosphorus (P) loads hinder water use and have negative ecological impacts. Mitigation measures are currently being considered both in the Netherlands (Hoogervorst, 2009) and in other EU countries (Schoumans *et al*., 2011) not to exceed water quality standards (EU, 1991) and to achieve the ecological goals of the Water Framework Directive (EU, 2000).

Unfertilized buffer strips are a widely recognized mitigation option to reduce N and P transport from fields to surface water (Heinen *et al*., 2011; Dorioz *et al*., 2006 for P; Mayer *et al*., 2005, 2007 for N). However, their relative N and P reduction in load, or buffer strip effectiveness (BSE), varies greatly, ranging from below zero to almost 100% (e.g. White & Arnold, 2009). BSE depends on the nutrient input load, width, vegetation, maintenance (nutrient removal with sediment or biomass), time since installation and site conditions. The key site factors governing BSE are slope and hydrogeology (Noij *et al*., 2011), but there is no available experimental evidence from well-drained, virtually flat fields with deep permeable soils that occur over most of the Netherlands. Newly installed unfertilized buffer strips on flat fields may behave very differently from existing ones on sloping land next to natural streams. Nutrient loads in surface runoff and groundwater flowing from sloping land to the upper layers of riparian buffer strips are subject to infiltration (N, P), sedimentation of solids (P, N), denitrification (NO_3-N), plant uptake (N, P), adsorption to the soil matrix (PO_4-P, NH_4-N) and storage of organic matter (N, P), but the flow paths from a deep permeable flat field towards a ditch might be below the active topsoil of the recently installed buffer strip.

We provided experimental evidence for a low BSE for N on five characteristic Dutch agricultural lowland sites (Noij *et al*. (2011). The BSE for P will probably be different because the transport processes and behaviour of P in the soil differ from those of N (e.g. Gächter *et al*., 2004). The prime

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goal of this study was therefore to obtain experimental evidence on BSE for P for the same five sites. The key transport route determining BSE for P under sloping conditions is clearly surface runoff with associated solid transport (see e.g., Dorioz *et al.*, 2006; Hoffmann *et al.*, 2009). On a permeable level site, less surface runoff occurs and groundwater flow is likely to be more important. Shallow flow and high groundwater level tend to increase original P loads because topsoil has a higher P status than the underlying soil (Schoumans *et al.*, 2009). As P loss via groundwater increases exponentially with higher P status of the soil (Schoumans & Groenendijk, 2000), wet soils with high P status are most critical (Schoumans, 2004). An unfertilized but harvested buffer strip is expected to withdraw P from the soil and thus to lower the P status of the soil as shown in P mining experiments in which P was removed intentionally from the soil with biomass (Van der Salm *et al.*, 2009). As a result, net P withdrawal from the unfertilized buffer strip is expected to reduce the P load from the strip and thus to increase BSE. Also, a higher original P status is expected to improve BSE for P because a Langmuir type P sorption curve predicts a greater effect of P mining at higher sorbed P levels (Koopmans *et al.*, 2004). The second aim of our research was to test the hypothesis that BSE for P is correlated positively with the volume of surface runoff and shallow flow, the original P status of the soil and the accumulated P withdrawal from the buffer strip.

Material and methods

Experimental set-up

We selected five experimental sites that are characteristic of five of the six major hydrogeological classes of the Netherlands (Figure 1, Table 1a, Noij *et al.*, 2011). The fields on which the experiments were sited are typical for the Netherlands: flat, rectangular and on at least one side bordered by a ditch. Before the Spring of 2006, paired treatments were installed at all sites. These, referred to as replicate A, consisted of an unfertilized grass buffer strip (BS) and a reference strip (REF), cropped and managed like the contiguous field (Figure 2). In *Beltrum* and *Zegveld*, two additional replicates B and C were installed in 2007. Experiments ran until Spring 2009 in *Loon op Zand* and *Lelystad* (three growing and leaching seasons), and until Spring 2010 at the other sites (four growing and leaching seasons). A winter crop was grown on the maize sites (*Beltrum* and *Lelystad*). All grass strips were harvested and sampled for aboveground P uptake throughout the season (REF ca. 6 cuts and BS ca. 4 cuts); the maize REF was harvested and sampled only once per year.

The BS and REF were both 5 m wide and 15 m long. At the ditch end of each treatment, a 5-m-long wooden reservoir was installed, with its long side centred on the treatment strip and extending into the middle of the ditch to collect surface

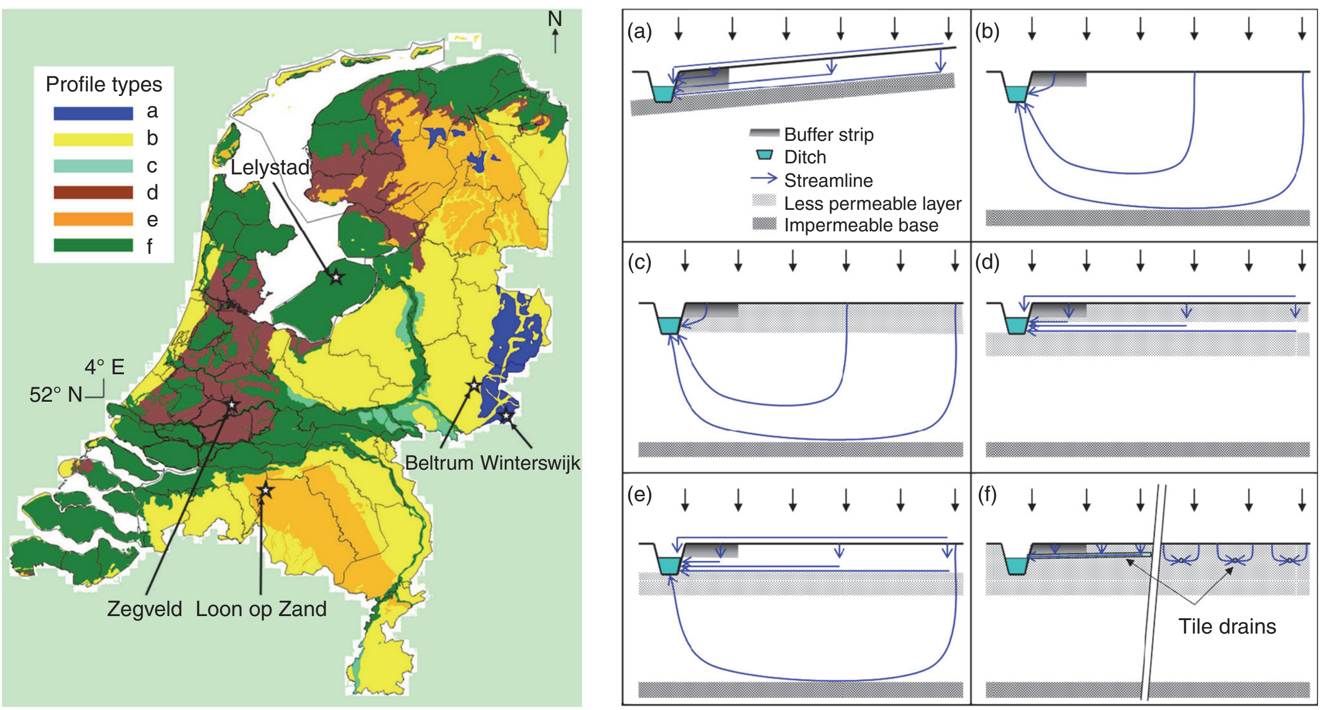

Figure 1 Main hydrogeologic classes of the Netherlands (Van Bakel *et al.*, 2007): geographical distribution with selected experimental locations (left) and hydrogeologic profile including expected flow paths (right): (a) Shallow sand, (b) Deep sand, (c) Sandy aquifer, less permeable top soil (no site chosen), (d) Holland peat, (e) Interrupted sand and (f) Holland clay. See also Table 1a.

Table 1 Experimental field conditions

(a) Hydrogeology

Hydrogeological class	Description	Area % NL	Area % Agriculture	Selected site location
a) *Shallow sand*[a]	Gently sloping sandy aquifer on impermeable subsoil at < 1 m depth. All precipitation surplus discharges through the shallow aquifer	2.4	2.5	*Winterswijk*
b) *Deep sand*[a]	Deep sandy aquifer, at > 4 m depth. Shallow discharge flow paths starting near the ditch, deeper flow paths starting further away	33.5	29.1	*Beltrum*
c) Sandy aquifer, less permeable topsoil	Ditch bottom in the aquifer. Most flow paths deep	1.4	1.6	Not selected for low area
d) *Holland peat*[b]	Deep aquifer in less permeable peat soil. Predominantly shallow flow paths	12.8	12.9	*Zegveld*
e) *Interrupted sand*[a]	Deep sandy aquifer, interrupted by less permeable loam layer below the ditch bottom, at depths 1–4 m. The shallow/deep flow ratio depends on the aquifer/loam layer conductivity ratio	16.1	15.7	*Loon op Zand*
f) *Holland clay*[b]	Deep aquifer in less permeable clay soil. Tile drain discharge predominates because most clay soils are tile drained	33.7	38.2	*Lelystad*

[a]Classes b, e and a provide a hydrogeological sequence with increasing proportion of shallow flow. [b]Classes d and f belong to the Holland profile.

(b) Other field characteristics (for soil data see Table 1c)

Site	Slope	Soil (FAO, 2002)	Land use	Water divide[a] (m)	MHG, MLG[e] (cm bs)	Ditch bottom[f] (cm bs)	Ditch water level[f] in summer and winter (cm bs)	N, E Coordinates and elevation (m above sea level)
Beltrum	≤1%	Sandy soil of periglacial aeolic origin (Gleyic podzol)	Fodder maize Grass winter crop	60[b], 130[c]	40, 140	130	112, 126	5°04′56′, 06°32′11′ 17
Zegveld	0	Peat soil (Terric histosol)	Grassland	30[b,c]	25, 80	140	90, 90	52°8′22′, 4°50′11′ −3
Winterswijk	2%	Sandy soil on boulder clay < 1 m bs (Eutric Gleysol)	Grassland	80[d]	30, > 200	138	125, 131	51°54′57′, 6°43′22′ 45
Loon op Zand	0	Sandy soil (Haplic Podzol)	Grassland	15[b], 75[c]	70, > 180	154	132, 111	51°37′28′, 5° 5′36′ 9
Lelystad	0	Silty clay loam (Calcaric Fluvisol)	Fodder maize Grass winter crop	150[b,c]	70, 120	137	128, 132	52°32′25′, 5°33′021′ −4

[a]At the water divide (wd), the precipitation surplus flows away in opposite directions. In sloping areas, wd is fixed by the highest contour line in the field, but in a flat area it is the dynamic position of maximum elevation of the groundwater plane. It may be determined as the average maximum elevation from groundwater elevation measurements in a transect perpendicular to the ditches, which is often located midway between two ditches. [b]Top of measured groundwater level. [c]Midway between two ditches. [d]Top of the slope. [e]Mean highest and lowest groundwater levels in cm below ground. [f]As both levels are expressed in relation to ground level, the ditch water level measured from the bottom is calculated as db–dwl.

Table 1 (*continued*)

(c) Soil characteristics of the experimental sites. For P status, see Table 3

Site	Replicate	Depth (cm)	OM % mass	< 2 μm[1]	< 16 μm	< 50 μm	> 50 μm	ρ_d g/cm^3	pH-H_2O
Beltrum	A	0–30	5.7	1.9	4.0	7.3	92.7	1174	5.7
		30–100	3.4	2.2	3.1	6.5	93.5	1701	5.6
	B	0–30	5.0	4.2	5.0	8.0	92.0	n.d.	6.0
		30–100	1.2	2.5	2.7	4.2	95.8	n.d.	5.9
	C	0–30	5.5	3.3	5.7	9.1	90.9	n.d.	6.1
		30–100	1.6	4.2	4.9	7.0	93.0	n.d.	5.8
Zegveld	A	0–30	52.0	70.8	83.2	83.3	16.7	562	5.0
		30–100	74.2	47.7	64.4	76.3	23.7	188	4.8
	B	0–30	51.1	66.9	74.5	78.5	21.5	562	5.0
		30–100	75.8	64.0	73.5	72.5	27.5	188	5.0
	C	0–30	48.8	63.8	76.8	75.5	24.5	562	5.3
		30–100	72.0	71.3	82.1	83.8	16.2	188	5.0
Winterswijk	A	0–30	6.6	6.7	13.4	18.4	81.6	1428	6.1
		30–60	3.9	33.1	43.5	48.4	51.6	1408	5.6
Loon op Zand	A	0–30	3.3	0.6	2.8	7.1	92.9	1549	5.9
		30–100	1.5	0.0	1.5	8.0	92.0	1568	5.5
Lelystad	A	0–30	2.6	14.2	24.6	35.8	64.2	1586	7.2
		30–100	1.7	4.6	8.8	19.9	80.1	1386	8.2

[1]Soil texture in 100 g/g on mineral basis.

and subsurface discharge from the field (Figure 2). At *Lelystad,* the treatments were 25 m long and the reservoirs 16 m long to ensure that outflow from two subsurface drains was collected. Both the *Winterswijk* reservoirs were extended in length from 5 to 12.5 m in 2007 to increase the discharge area. Treatments were longer than reservoirs to prevent interaction between treatments. Reservoir walls consisted of 4.5-cm-thick tongue and groove planks driven down to 1.5 m below the bottom of the ditch. We mounted additional walls of composite wood board with bentonite between the two walls to prevent any leakage. The reservoirs were emptied once a year and visually inspected for leakage through the walls. The reservoir water level was maintained at ditch water level by pumping out excess water (tolerance 1 cm). In *Zegveld* and occasionally *Loon op Zand*, water had to be pumped in during the summer to compensate for infiltration into the soil.

Measurements, sampling and analyses

Precipitation surplus (*PS* mm) was calculated from on-site precipitation measurements minus evapotranspiration estimated from data from nearby weather stations, applying a crop factor of 1 during the leaching season and the theoretical discharge area of the water divide (Table 1b) times the length of the reservoirs (Figure 2). Discharge (Q, m^3) from the reservoir was measured at the pump outlet with a flow meter and logged by a programmable data collector that activated an automatic sampler at fixed discharge volumes to take water samples from the reservoir. If water had to be pumped in, ditch water was sampled for analysis. Sampling bottles were filled in five steps, each step corresponding to ca. 1 mm of precipitation surplus. Water samples were immediately stored in an on-site refrigerator (< 4 °C) and transported to the laboratory once a week for analysis (even if the bottles were only partly filled); if no water was present in a sampling bottle, a sample from the reservoir was taken manually (if water was present). Reservoir water samples were mixed thoroughly and then split into three subsamples. The first unfiltered subsample was analysed for total P (P_t) with a segmented flow analyser (SFA) after persulphate-borate destruction (NEMI I-4650-03 and I-2650-03; http://www.nemi.gov). The second subsample was analysed in the same way, but after filtering over 0.45 μm (Whatman RC55 regenerated cellulose membrane), to measure total soluble P (P_{ts}). The third subsample was filtered likewise and analysed for PO_4-P with SFA in 0.01 M $CaCl_2$. Upper groundwater was sampled with suction cups (Figure 2) and analysed for PO_4-P (SFA).

Aboveground plant material was sampled at harvest. Maize was harvested once per year; grass from the REF was harvested in ca. 6 cuts and grass from BS in ca. 4 cuts. Samples were weighed before and after drying (70 °C), and dry subsamples were ground for destruction with H_2SO_4/H_2O_2/Se to determine total P content. We calculated P surplus as recorded fertilizer rate minus net withdrawal by the harvested crop. The absolute treatment effect on P surplus is P surplus REF minus P surplus BS.

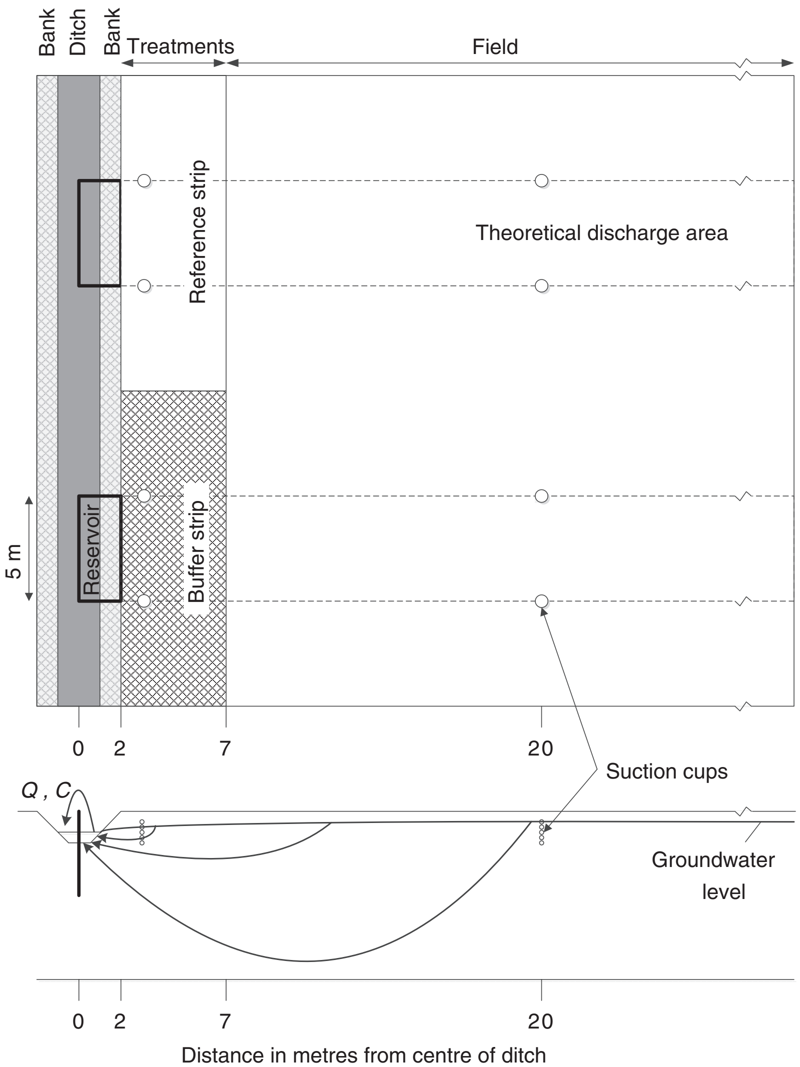

Figure 2 Layout of one replicate of the experimental site at Beltrum (see also Heinen *et al.*, 2011). In Beltrum and Zegveld, three replicates were installed, only one at the other sites.

Soil P status per treatment was determined at the start and end of the experiment. We pooled 10–20 samples from each 10-cm soil layer up to a depth of 100 cm. On the maize fields, we sampled the 0- to 30-cm layer and 10-cm soil layers to a depth of 100 cm. At the start of the experiment, we filled the auger holes with bentonite to prevent hydrological short cuts. Soil samples were dried (40 °C), sieved (2 mm) and extracted with acid ammonium oxalate to determine aluminium (Al_{ox}), iron (Fe_{ox}) and phosphorus (P_{ox}, all in mol/kg) with ICP-AES (Novozamsky *et al.*, 1986). The degree of phosphorus saturation (PSD) was computed according to Van der Zee *et al.* (1990):

$$\mathrm{PSD} = \frac{\mathrm{P_{ox}}}{0.5(\mathrm{Al_{ox}} + \mathrm{Fe_{ox}})} 100\%.$$

Labile soil P was determined on SFA according to soil analysis for current fertilizer recommendations on grassland (P-AL, mg P_2O_5/100 g dry soil in ammonium lactate extract, Egner *et al.*, 1960) and arable soil (Pw, mg P_2O_5/L dry soil in 60/1 v/v water/soil extract, Sissingh, 1971).

Data analysis

Flow-averaged leaching concentration, $\overline{C}$ (g/m^3), was computed according to Heinen *et al.* (2011):

$$\overline{C} = \frac{\sum QC}{\sum Q} \tag{1}$$

where Q represents discharge (m^3) and the product Q times C represents the P load (g). Sums were calculated for periods of equal discharge to reduce the influence of spatial variation in discharge on the treatments (Heinen *et al.*, 2011). $\overline{C}$ was computed for each individual leaching season. The lowest discharge at the end of the leaching period was used for each leaching season and each pair of treatments. We also computed an average $\overline{C}$ for all leaching seasons based on the summed loads and discharges of all leaching seasons (Heinen *et al.*, 2011).

BSE was computed in two ways. BSE_I was based on flow-weighted means (Heinen *et al.*, 2011):

$$\mathrm{BSE_I} = 1 - \frac{\overline{C}_{\mathrm{BS}}}{\overline{C}_{\mathrm{REF}}}. \qquad (2)$$

$\mathrm{BSE_{II}}$ was based on average concentrations C_{avg} of separate discharge and reservoir concentration measurements:

$$\mathrm{BSE_{II}} = 1 - \frac{C_{\mathrm{BS,avg}}}{C_{\mathrm{REF,avg}}}. \qquad (3)$$

We did a restricted (or residual) maximum likelihood analysis (VSNI, 2010; directive REML in GenStat). As the fixed model in REML, we used constant + Location (L) + Treatment (T) + Season (S) + L T + L S + T S + L T S. The random model was L R (Replicate) + L R T + L R S + L R T S. Locations were *Beltrum*, *Zegveld*, *Winterswijk*, *Loon op Zand*, and *Lelystad;* treatments were BS and REF; replicates were A, B and C; and the leaching seasons (S) were 2006/2007, 2007/2008, 2008/2009 and 2009/2010. We tested the null hypothesis that there was no difference between REF and BS. The *F* probability (*P*-values) obtained for the fixed model terms was used to assess significance ($P < 0.05$). We did an integrated statistical analysis for all locations and replicates and also partial analyses for the two sites with three replicates (*Beltrum* and *Zegveld*). In the partial analyses, all terms with L were removed from the model. Although we used log-transformed data of P_t reservoir concentration in REML for better correspondence with normal distribution of residuals, back-transformed data were used in equation 3 and are presented below.

To judge the relevance of the treatment effect, we also calculated the absolute difference REF–BS ($\Delta\overline{C}$) and the corresponding difference in load $\Delta\,\overline{C} * Q_{\mathrm{avg}}$, where Q_{avg} is the average Q for all treatments per location.

Results and discussion

Site hydrology

A more extensive description of the site hydrology is given by Noij *et al.* (2011). At the *deep sand* site, *Beltrum*, the ground is gently undulating (country slope < 1%, Table 1b). This site is drained by a ditch that is normally dry during the summer (Table 1b). Average recovery of precipitation surplus *PS* in the reservoirs was low (ca. 60%), which was confirmed by a steady-state streamline analysis (Heinen *et al.*, 2011). Only flow paths starting within 30 m from the ditch and with a maximum depth of 7 m below ground reached the reservoir. Flow paths starting between 30 m and the water divide at 60 m (Table 1b) bypassed treatment strips and reservoirs at greater depths and thus contributed to regional flow. Only flow paths starting within 15 m from the ditch passed through the first metre of upper groundwater below the treatment, and they contributed only about 50% to discharge (ca. 25% of *PS*). We did not observe surface runoff at this location.

Table 2 Effect of buffer strip on net P withdrawal by the crop

Site	Crop	Net P withdrawal kg/ha/yr		
		BS	REF	BS-REF
Beltrum	Maize[a]	11	−16	27
Zegveld	Grass[a]	30	19	11
Winterswijk	Grass[a]	39	21	18
Loon op Zand	Grass[b]	24	7	17
Lelystad	Maize[b]	6	−14	20

[a]Average for experimental period 4 yr. [b]Average for experimental period of 3 yr.

At the *interrupted sand* site, *Loon op Zand*, there was very little discharge to the ditch (only 14% of *PS*). *PS* was not even completely recovered from the first 15 m. Surface runoff was physically impossible because the edge of the strip was higher. Water between 15 and 75 m from the ditch contributed to regional groundwater flow in the aquifer below the loam layer (Hoogland *et al.*, 2010).

At *Winterswijk*, the *shallow sand* site with a gentle slope (2%), discharge to the modified natural stream was very fast and residence time in the treatments was only 0.03 yr (we applied the methodology of Gelhar & Wilson, 1974). Discharge was much greater from the BS than from the REF because the field slope resulted in a larger discharge area. Although we expected there to be surface runoff in *Winterswijk* because of hydrogeology and slope, we recorded only a few small reservoir concentration peaks just after precipitation events and these were negligible in comparison with total loads. Data collected from surface runoff collection gutters at this site since 2008 confirm these observations (Appels, 2013).

Both *Lelystad*, *Holland clay,* and *Zegveld*, *Holland peat,* are situated below sea level in a polder with controlled water level. At *Lelystad,* the tile drains are 8 m apart; here, *PS* was recovered completely in the reservoirs without surface runoff. *Zegveld* is a moorland site with grazed grassland, drained by parallel ditches 60 m (instead of the usual 30 m) apart. Soil subsidence because of peat mineralization (Schothorst, 1977) has resulted in the concave fields that slope away from the ditches. Some of the surface runoff drains through the centre of the field and parallel to the ditch, especially during the second half of the winter. At replicate C, *PS* was not completely recovered in the reservoirs. Water infiltrating within 18 m from the ditch flows through the upper 1 m of groundwater, but water from the water divide at 30 m can reach 4 m below ground before entering the ditch (Noij *et al.*, 2011).

Net P withdrawal

Net P withdrawal in the BS ranged from 6 to 39 kg/ha/yr, and at all sites was higher than in the REF (−21 to

Table 3 Effect of buffer strip on P status of the soil

		PSD[a], %						Pw, mgP_2O_5/L						P-AL, mg $P_2O_5/100$ g					
		REF			BS			REF			BS			REF			BS		
Site	Depth	Start	End	Start–end	Start	End	Start–end	Start	End	Start–end	Start	End	Start–end	Start	End	Start–end	Start	End	Start–end
Beltrum	0–30	49.2	49.2	−0.01	49.9	44.4	5.41	26.3	25.0	1.29	28.4	20.7	7.74	51.6	50.6	1.07	54.1	47.0	7.10
	30–50	11.1	11.1	−0.02	12.9	12.4	0.49	2.1	2.0	0.15	3.0	3.3	−0.34	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zegveld	0–10	17.2	17.0	0.17	16.6	17.3	−0.75	21.9	29.7	−7.78	19.7	22.3	−2.65	23.9	26.2	−2.27	23.9	24.7	−0.79
	10–30	9.0	11.4	−2.44	8.3	12.0	−3.67	5.9	10.2	−4.27	5.3	9.3	−4.05	9.8	14.3	−4.52	9.3	15.5	−6.14
	30–50	2.9	5.9	−3.06	2.7	5.2	−2.49	2.3	3.7	−1.33	2.0	3.8	−1.79	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Winterswijk	0–10	33.0	26.6	6.46	30.8	28.8	2.00	41.3	32.0	9.33	36.8	26.0	10.77	47.4	36.7	10.77	44.5	36.7	7.79
	10–30	35.0	24.6	10.42	40.1	32.6	7.48	29.8	23.0	6.80	35.9	24.5	11.37	48.1	36.5	11.58	51.1	45.6	5.55
	30–50	14.1	14.5	−0.42	21.4	18.8	2.59	11.2	7.5	3.69	18.5	9.0	9.50	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Loon op Zand	0–10	74.1	62.6	11.53	65.5	59.5	6.00	65.7	35.0	30.69	46.9	39.0	7.89	46.3	33.9	12.38	37.8	30.5	7.37
	10–30	61.1	57.4	3.77	49.5	55.8	−6.27	38.7	28.0	10.69	27.0	30.5	−3.47	37.6	35.5	2.09	37.5	33.8	3.67
	30–50	32.7	37.8	−5.00	26.9	32.0	−5.10	9.1	12.0	−2.89	6.0	7.5	−1.50	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Lelystad	0–30	17.1	17.1	0.00	18.4	17.7	0.71	38.4	32.0	6.41	40.5	27.0	13.48	35.7	37.1	−1.43	42.2	36.2	6.04
	30–50	7.5	7.4	0.07	9.4	10.5	−1.13	9.0	5.0	4.02	14.7	11.5	3.22	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

[a]Phosphorus Saturation Degree = 100 $P_{ox}/0.5$ (Fe_{ox} + A_{ox}) %, molar ratio based on acid oxalate extract.

Table 4 Effect of buffer strip on upper groundwater PO_4-P concentration (C_{gw}). Detection limit 0.02 g/m^3

	C_{gw}, 50 percentile			C_{gw}, 90 percentile		
Site	REF	BS	REF–BS	REF	BS	REF–BS
Beltrum	0.001	0.001	0.000	0.005	0.011	−0.006
Zegveld	0.002	0.002	0.000	0.019	0.009	0.009
Winterswijk	0.045	0.006	0.039	0.069	0.055	0.014
Loon op Zand	0.004	0.002	0.002	0.030	0.008	0.022
Lelystad	0.019	−0.001	0.020	0.042	0.018	0.023

16 kg/ha yr; Table 2). The difference in net P withdrawal between BS and REF ranged from 11 to 27 kg/ha/yr. In many other studies (e.g. Stutter *et al.*, 2009), P was not withdrawn from the BS because biomass was not harvested; this might account for the low BSE reported. Intentional P removal from the soil with biomass is often referred to as P mining (Koopmans *et al.*, 2004; Van der Salm *et al.*, 2009). Van der Salm *et al.* (2009) found a higher net P withdrawal (28–40 kg/ha/yr P) in P-mined grass plots in the Netherlands, than we did; this is because the plots had been fertilized with other nutrients to maximize net P withdrawal.

P status of the soil

There was a noticeable decline in P status in the topsoil of the BS at all mineral soil sites between the start and end of the experiment (Table 3). It was most pronounced for Pw and P-AL. The decline in P status found in REF can be attributed to spatial and temporal variations in the analyses. At depths below 30 cm, the BS effect was small and inconsistent, except at *Winterswijk*. These results are in accordance with those of the P mining study of Van der Salm *et al.* (2009), which started in 2002 and in which soil sampling was more frequent and intensive. They too have reported that the difference in P status decreased with depth and that the most pronounced differences were for available P fractions. Obviously, the differences they found increased over time as net P withdrawal accumulated. The effect of an unfertilized buffer strip may also therefore be expected to increase with time.

There was no noticeable effect of BS on the P status of the peat soil (Table 3). Van der Salm *et al.* (2009) also found that the peat soil at *Zegveld* reacted more slowly to P mining than mineral soils. They attribute this to the much greater buffer capacity of the peat soil, that is, the ratio between adsorbed and dissolved P at equilibrium, as a high buffer capacity would result in a longer time lag before P mining becomes effective (Koopmans *et al.*, 2004).

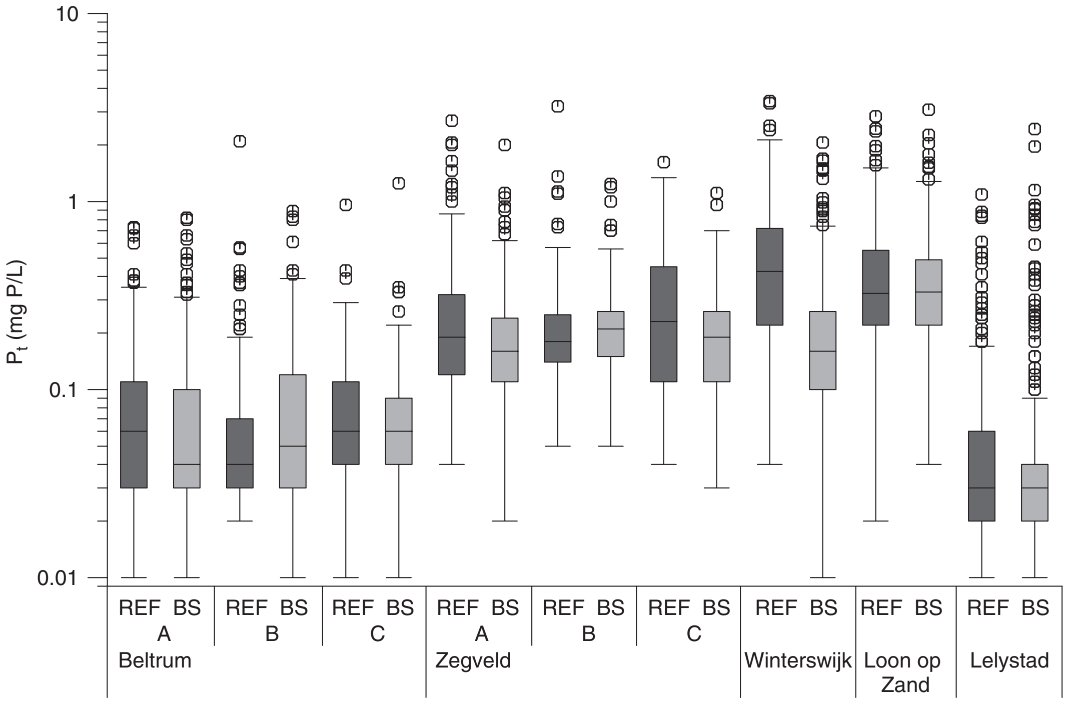

Figure 3 Total P concentration (P_t) in reservoirs of all locations, treatments and replicates during the entire experiment summarized in Box-Whisker plots: minimum value, 1st, 2nd (median) and 3rd quartile, maximum value. Outliers (symbols) > 3 times box range.

Table 5 Flow-weighted average P concentration in reservoirs (g/m^3) and buffer strip effectiveness (%). Standard deviations (±) for reservoirs are based on replicates (*Beltrum* and *Zegveld*)

Species	REF, BS, BSE_I	*Beltrum*	*Zegveld*	*Winterswijk*	*Loon op Zand*	*Lelystad*
Pt	REF	0.078 ± 0.012	0.251 ± 0.138	0.536	0.527	0.034
	BS	0.066 ± 0.017	0.219 ± 0.132	0.208	0.504	0.028
	BSE_I	15.45 ± 4.64	12.73 ± 7.01	61.17	16.54	4.36
Pts	REF	0.019 ± 0.006	0.146 ± 0.071	0.114	0.234	0.024
	BS	0.019 ± 0.005	0.134 ± 0.083	0.052	0.196	0.019
	BSE_I	3.64 ± 1.50	8.44 ± 4.11	54.58	20.76	16.50
PO4-P	REF	0.006 ± 0.008	0.093 ± 0.044	0.056	0.156	0.011
	BS	0.001 ± 0.000	0.082 ± 0.052	0.021	0.112	0.008
	BSE_I	87.57 ± 124.40	11.50 ± 5.47	62.67	31.25	28.37

Upper groundwater concentration

We did not detect a clear treatment effect on upper groundwater PO_4-P concentrations (C_{gw}), mainly because C_{gw} was very low. Only 24 of 222 samples (and only three of 111 paired REF and BS samples) were above the detection limit (0.02 g/m^3 PO_4-P). Fraters *et al.* (2008) also found such low values below 148 sandy soil farms in the Netherlands (median C_{gw} < 0.06 g/m^3 PO_4-P, which was their detection limit). Nevertheless, there are indications of a treatment effect in the peak C_{gw} values at *Winterswijk*, *Loon op Zand* and *Lelystad* (Table 4, 90 percentiles) and in the median C_{gw} at *Winterswijk* (50 percentiles).

P concentration in reservoirs

All P_t concentration measurements in reservoirs are summarized in Box-Whisker plots (Figure 3). Median P_t concentrations range from 0.03 g/m^3 in *Lelystad* to 0.42 g/m^3 for REF in *Winterswijk*. Reservoir concentrations were very variable temporally (Figure 3) with outliers as great as 3 g/m^3 P_t. We observed no clear periodicity. Median values for *Beltrum* and *Lelystad* compare well with those for ditch water from 11 farms on sandy soil elsewhere in the Netherlands (< 0.06 g/m^3 P_t; Fraters *et al.*, 2008). However, P_t (total) and P_{ts} (soluble) reservoir concentration are higher at our other sites on

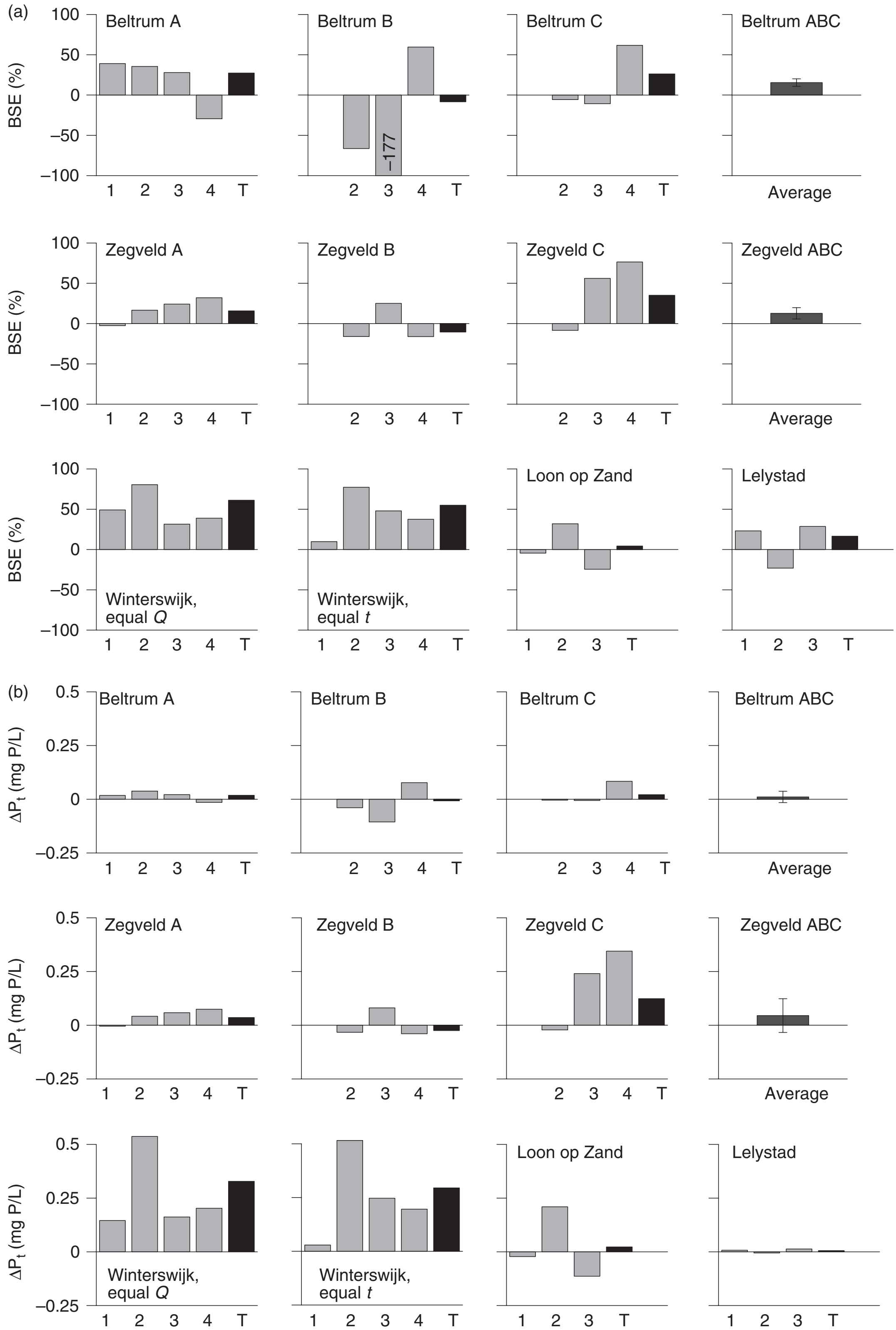

Figure 4 (a) Buffer strip effectiveness (BSE_I; equation 2) for flow-weighted average total P concentration (P_t) and (b) absolute difference in P_t between REF and BS (ΔP_t), for different seasons (1, 2, 3, 4 and total), locations and replicates, for periods of equal discharge *(Q)* and in Winterswijk also for equal time (*t*) periods.

Table 6 Buffer strip effectiveness (BSE_{II}) based on averages (C_{avg}) of separate reservoir P_t concentration measurements from statistical analysis (equation 3), corresponding average differences between both treatments (REF–BS) and *P*-values for the terms location (L), treatment (T), leaching season (S) and mutual interactions

	REF–BS	BSE_{II}	*P*-values						
	g/m^3	%	L	T	S	L T	L S	T S	L T S
All locations	0.0227	17.7	< 0.001	0.010	0.013	0.031	0.293	0.997	0.289
Winterswijk	0.2312	56.9							
Loon op Zand	0.0013	0.3							
Lelystad	−0.0012	−4.3							
Only *Zegveld*	0.0386	16.9		0.207	0.487			0.138	
Only *Beltrum*	0.0059	11.8		0.319	0.063			0.745	

sandy soils (*Loon op Zand* and *Winterswijk*) and for the peat site *Zegveld* (Table 5).

The major fraction of P_t was particulate P_t–P_{ts} (> 0.45 μm) at the sandy soil sites, and soluble P_{ts} (< 0.45 μm) at both other sites (Table 5). We did not study the nature of particulate P. Although surface runoff played a minor role in our experiments, particulate P could still play a role in subsurface transport, as has been reported for structured sandy loam and clay soils (Schelde *et al*., 2006; Ulen and Persson, 1999; Uusitalo *et al*., 2001; Van der Salm *et al*., 2011). However, our particulate P may also include P_{ts} converted into living biomass during its residence in the reservoirs. Average residence time at *Beltrum* and *Winterswijk* was ca. 2 days, but was longer at the beginning and the end of the leaching season, which is when higher temperature and light intensity promote biomass growth. Note that only the PO_4-P fraction of reservoirs could be compared with C_{gw} (suction cups). Hence, we could not distinguish aquatic biomass from particulate P originating from soil or groundwater.

Buffer strip effectiveness

At *Beltrum,* we found a negligible absolute treatment effect of 0.012 g/m^3 (Figure 4b, Table 5), corresponding to a difference in P load of 0.01 kg/ha/yr. Average BSE_I was 15% (Figure 4a, Table 5). The effect of BS varied greatly between seasons (Figure 4), and therefore, BSE_{II} was statistically insignificant (Table 6: $P = 0.319$).

The low $\overline{C}$ and BSE found for P at *Beltrum* were expected, because no surface runoff towards ditch or reservoirs was observed, and groundwater level (Table 1b) remained below the topsoil layer where PSD was higher than deeper in the soil profile (Table 3). The observed treatment effect on P status (Table 3) was therefore not reflected in lower values for C_{gw} PO_4-P (Table 4) and $\overline{C}$ P_{ts} (Table 5). All P fractions remained far below the environmental limit (0.10 g/m^3) with P_{ts} even below the detection limit of 0.02 g/m^3.

At *Loon op Zand,* both BSE_I and REF–BS were low and variable for P_t (Figure 4, Table 5). The calculated difference in corresponding P load was only 0.04 kg/ha/yr. Although BSE_{II} was significant in the integrated REML analysis (Table 6, $P = 0.010$), the overall treatment effect (REF-BS 0.0227 g/m^3) was entirely caused by *Winterswijk* (REF-BS 0.2312 g/m^3). Note that the interaction with location was also significant (L T, $P = 0.031$). The effect of BS at *Loon op Zand* was most pronounced for the dissolved fractions P_{ts} and PO_4-P (Table 5), probably because of the very high PSD (Table 3; Koopmans *et al*., 2004). REF–BS for $\overline{C}$ PO_4-P was highest for this site (0.044 g/m^3, Table 5). At this site only, the P_t concentration in the ditch outside the reservoirs (not shown) was twice the value inside reservoirs throughout the experimental period. This indicates that P loads were large, even before the experiment, and that the ditch bottom therefore had a high P status. It is possible that potential differences between BS and REF were minimized by P release from the reservoir bottom.

At *Winterswijk, shallow sand,* we found an average BSE_I of 61% and REF-BS of 0.328 g/m^3 P_t (Figure 4, Table 5), corresponding with an estimated difference in P load of 0.72 kg/ha/yr. Although particulate P was most responsible for this difference, P_{ts} and PO_4-P also showed a clear treatment effect (Table 5). The significant treatment effect on P_t in the integrated statistical analysis (Table 6) was almost entirely caused by the effect in *Winterswijk* (BSE_{II} = 56.9%, REF-BS = 0.2312 g/m^3 P_t), and at that site, the treatment effect was consistent for all years (Figure 4).

At Winterswijk, there was also a clear difference in net P withdrawal (Table 2) and Pw declined more in the BS than in the REF (Table 3). Furthermore, we found a lower median C_{gw} PO_4-P (Table 4) and $\overline{C}$ for the BS than for the REF (Table 5). It was expected that *Winterswijk* would have the highest BSE because this site had the shallowest flow and the soil had a high P status (Table 3). The large amount of particulate P in reservoirs could not be explained by surface runoff (see preceding section *P concentration in reservoirs*).

A negative BSE for N is reported for *Winterswijk, shallow sand* (Noij *et al*., 2011), but we found a clear positive effect for P. The negative BSE for N was attributed to higher discharge and N input load from the field to BS, which could not be compensated for by N removal in the BS, because of the very low residence time (0.03 yr; estimated denitrified fraction 0.054). Yet this residence time exceeds the time needed for soil P and P in soil solution to reach equilibrium (1 day; Koopmans *et al*., 2004), that is, for BS to take effect.

At *Lelystad,* we found an average BSE_I of 4% for P_t, and REF–BS < 0.01 g/m^3 (Figure 4; Tables 5 and 6). The estimated difference in P loads was only 0.02 kg/ha/yr. Although Pw, P-AL, C_{gw} and $\overline{C}$ were consistently lower in BS than in REF (Tables 3, 4 and 5), a low BSE could be expected in *Lelystad* because both PSD (Table 3) and groundwater level were low (Table 1b). The groundwater level was low as a result of the tile drains and the low ditch water level (Table 1b). Tile drainage prevented shallow flow and surface runoff.

At *Zegveld*, *Holland peat*, the $\overline{C}$ P_t and P_{ts} were high. Particulate P was also high (Table 5), probably because of surface runoff. Concentrations were about 50% lower than the concentrations in ditch water reported by Van Beek (2007) for another site in *Holland peat*. Van Beek *et al*. (2004) attribute 33–83% of P load from the same site to the eutrophic subsoil and report very high C_{gw} at depths below 50 cm (0–10 g/m^3 P). However, we found a very low PSD of 2–8% between 50 and 200 cm depth at *Zegveld*, and C_{gw} PO_4-P was negligible (Table 4).

Despite substantial $\overline{C}$ the BS effect was small (Figure 4, Table 5) and not significant (Table 6). Average BSE_I was 13%. and REF–BS was only 0.032 g/m^3 for $\overline{C}$ P_t (Figure 4, Table 5), and less for P_{ts} and PO_4-P. The corresponding difference in P_t load was obviously also small (0.06 kg/ha/yr).

Synthesis and conclusion

High BSE for P (61%) was found on the site with very shallow flow and gentle slope in accord with our hypothesis. The BSE was low and statistically insignificant at all other sites, even those with high P status (*Loon op Zand*, *Beltrum*), because there was no shallow flow. We conclude that the occurrence of shallow flow or surface runoff is a precondition for BS to be effective in mitigating P pollution, even in flat sites with permeable soil. On such sites, buffer strips are not effective if fields are tile drained (as in *Lelystad*) or if there is deep infiltration (as in *Beltrum* and *Loon op Zand*). Although there was shallow flow and surface runoff at *Zegveld* (the *Holland peat* site), here the low BSE for P can be attributed to the negligible effect on the P status of the BS peat soil (see below). The shallower the flow, the better the BSE for P, but the same is not true for the BSE for N. We have reported that there is a point beyond which shallow flow becomes too shallow and the BSE for N decreases because residence time is too short as in *Winterswijk, shallow sand* (Noij *et al*., 2011). Our finding confirms the ideal aquifer depth range (1–4 m below ground) for BSE for NO_3-N as suggested by Hill (1996).

As there was only one mineral soil site with substantial shallow flow, we could not directly test our hypothesis that BSE for P is related positively to the original P status and to accumulated net P withdrawal from the BS. However, at *Loon op Zand*, *interrupted sand,* the greatest difference in reservoir PO_4-P concentration between REF and BS corresponds with the highest P status (Table 5). This indicates that BSE is likely to be high in situations with high P status and a greater volume of shallow flow than in *Loon op Zand*. A greater volume of shallow flow can be expected on 64% of the area of *interrupted sand* in the Netherlands (Hoogland *et al*., 2010; Table 1a).

The effect of accumulated net P withdrawal on P status of the mineral soils was still small after 3 or 4 yr and for the peat soil was negligible. However, the P mining experiments of Van der Salm *et al*. (2009), which started in 2002 and ended in June 2012, show that the soil P status in the BS will continue to decline over time and will extend more deeply. Therefore, our hypothesis that BSE increases with ongoing net P withdrawal still stands. It would explain why no P load reduction was found in other buffer strip studies in which no net P withdrawal was achieved (e.g. Stutter *et al*., 2009). Net P withdrawal is key to effective buffer strips for P unless particulate P runoff is predominant. However, it will be more difficult to achieve net P withdrawal by means of a traditional riparian buffer strip with trees and shrubs than by means of the grassy field borders as in our study. This drawback outweighs probably the potential advantage of a deeper rooting buffer vegetation to achieve P removal. Another factor in addition to vegetation and management that will determine accumulated P withdrawal and thus BSE for P is the time since BS installation. When the buffer capacity of the soil is high, the time lag before P mining takes effect is longer (Van der Salm *et al*., 2009; Koopmans *et al*., 2004); the same must apply to the BSE for P.

Finally, shallow flow and/or surface runoff is a precondition for effective unfertilized buffer strips for P, even on flat well-drained land. Our results suggest strongly that BSE for P is related positively to the original soil P status, the accumulated net P withdrawal from the buffer strip from frequent harvesting and removal of biomass, and time. The time needed for the buffer strip to take effect further depends on the soil's buffer capacity: the ratio between adsorbed and dissolved P at equilibrium. It therefore follows that buffer strips will reduce effectively P loads from flat fields only if the strips are harvested, and there is high surface runoff and/or shallow flow, especially in combination with high original P status.

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