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RIPARIAN BUFFER STRIPS AS A MULTIFUNCTIONAL TOOL IN AGRICULTURAL LANDSCAPES

Effectiveness of Unfertilized Buffer Strips for Reducing Nitrogen Loads from Agricultural Lowland to Surface Waters

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Unfertilized buffer strips (BS) are widely accepted to reduce nitrogen (N) loads from agricultural land to surface water. However, the relative reduction of N load or concentration (BS effectiveness, BSE), varies with management and local conditions, especially hydrogeology. We present novel experimental evidence on BSE for 5-m-wide grass BS on intensively drained and managed plain agricultural lowland with varying hydrogeology. We selected characteristic sites for five major hydrogeological classes of the Netherlands and installed paired 5-m-wide unfertilized grass (BS) and reference (REF) treatments along the ditch. The REF was managed like the adjacent field, and BS was only harvested. Treatments were equipped with reservoirs in the ditch to collect and measure discharge and flow proportional N concentration for 3 or 4 yr. In addition, N concentration in upper groundwater was measured. We found a statistically significant BSE of 10% on the peat site. At the other sites, BSE for N was low and statistically insignificant. Low BSE was explained by denitrification between adjacent field and ditch, as well as by the site-specific hydrologic factors including low proportion of shallow groundwater flow, downward seepage, low residence time in the BS, and surface runoff away from the ditch. We emphasize that a REF treatment is needed to evaluate BSE in agriculture and recommend reservoirs if drainage patterns are unknown. Introduction of a 5-m-wide BS is ineffective for mitigating N loads from lowland agriculture to surface waters. We expect more from BS specifically designed to abate surface runoff.

Surface water quality is a major concern in areas with intensive agriculture due to runoff and leaching of nutrients. Nitrogen (N) and phosphorus (P) loads have negative ecological impacts and hinder water use. Improving surface water quality is particularly challenging in rural areas because agriculture is a nonpoint source. Nutrient legislation in the Netherlands since 1986 focused on source measures and substantially reduced nutrient surpluses, but surface water quality still does not comply with current water quality limits (EU, 1991) or with ecological goals of the Water Framework Directive (EU, 2000; Hoogervorst, 2009). Therefore additional mitigation measures are considered: extra source measures, measures that reduce nutrient transport from agricultural fields to surface water, and measures that reduce further transport or impact of nutrients in the surface water system itself.

Unfertilized buffer strips (BS) are a widely recognized mitigation option, both for N and P (Barling and Moore, 1994; Dorioz et al., 2006; Dosskey, 2002; Mayer et al., 2005, 2007; Muscutt et al., 1993; Parkyn, 2004; Polyakov et al., 2005; Wenger, 1999). Slope, landscape, and hydrogeology are key factors governing buffer strip effectiveness (BSE) (Burt et al., 2002; Dorioz et al., 2006; Hill, 1996; Hoffmann et al., 2006, 2009; Mayer et al., 2005, 2007; Puckett 2004; Ranalli and Macalady, 2010; Rassam et al., 2008; Sabater et al., 2003; Vidon and Hill, 2004; White and Arnold, 2009).

For N, most records on BSE refer to nitrate retention. According to Hill (1996) and Ranalli and Macalady (2010), upper aquifers between 1 and 4 m thick are best for nitrate retention in riparian flood plains. They transfer shallow, horizontal groundwater flow, with sufficient residence time in the active layer of the riparian soil for nitrate removal through uptake by vegetation and denitrification. If riparian top soils are less permeable, influent precipitation surplus is deflected through lower aquifers or across the surface, both reducing BSE (Hill, 1996; Ranalli and Macalady, 2010). Balestrini et al. (2011) and Borin and Bigon (2002) reported high BSE for traditional BS with trees and grass in the Italian Po Valley. However, there is

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Abbreviations: BS, unfertilized (grass) buffer strip(s) or treatment; BSE, buffer strip effectiveness; bss, below soil surface; FIA, flow injection analyzer; L, location; P, period; PS, precipitation surplus; R, replicate; REF, reference strip or treatment; SFA, segmented flow analyzer; T, treatment.

no experimental evidence yet on the effectiveness of newly introduced grass BS in plain deltas with deeply permeable soil and abundant ditches, like the Netherlands. As deltas are often densely populated, both land and surface water are intensively used and it is relevant to also know BSE for these circumstances.

The first goal of this research was to provide experimental evidence on BSE for N in plain agricultural lowland with a suitable and novel experimental method (Heinen et al., 2011). We then investigated site-specific influences on BSE for N.

Materials and Methods

Hydrogeology and Field Site Description

The relative contribution of shallow and deep groundwater to discharge is expected to determine BSE for N (Hill, 1996) and depends on the following factors in the Netherlands (Van Bakel et al., 2007):

1. ditch density: the more ditches, the shallower the discharge flow
2. depth and conductivity of the upper aquifer: the deeper and more permeable, the deeper the discharge flow
3. resistance of the aquitard below the upper aquifer: the more resistant, the shallower the discharge flow

Ditch density was taken from the Water Information System (Rijkswaterstaat, 1995) and the topographical map of the Netherlands (Bregt and van Raamsdonk, 1998; Heuvelmans, 1998). Information from the National Groundwater Model (Pastoors, 1992) and the geological map (Zagwijn and van Staalduinen, 1975) was used for depth and conductivity of the soil profiles. The final hydrogeological classification is a compromise between more differentiation and lower number (i.e., larger area) of classes (Fig. 1). Area percentage refers to the whole of the Netherlands.

a. *Shallow sand*: sandy aquifer with slope on impermeable subsoil <1 m below soil surface (bss), area 2.4%. All precipitation surplus discharges through the shallow aquifer.
b. *Deep sand*: deep (>>4 m bss) sandy aquifer, area 33.5%. Shallow discharge flow paths starting near the ditch, deeper flow paths starting further away from the ditch. Situations with downward seepage and/or regional flow are not depicted in Fig. 1 but also pertain to this class.
c. Sandy aquifer with less-permeable top soil, area 1.4%. Ditch bottom in the aquifer. Predominant deeper flow paths.
d. *Holland peat*: less-permeable deep aquifer in peat soil, area 12.8%. Predominant shallow flow paths.
e. *Interrupted sand*: deep sandy aquifer, interrupted by less-permeable loam layer below the ditch bottom (1–4 m bss), area 16.1%. Both shallow and deep flow: ratio depends on conductivity of aquifer and loam layer.
f. *Holland clay*: less-permeable deep aquifer in clay soil, area 33.7%. Tile drain discharge predominates because the majority of clay soils is tile drained.

Classes b, e, and a provide a hydrogeological sequence with increasing proportion of shallow flow. Classes d and f belong to the so-called Holland profile. We selected five experimental sites that are characteristic for each of the major hydrogeologic classes (except c). We refer to these sites here by the names of the villages to which they belong (Table 1) and refer to the entire classes with the italicized names above (Fig. 1). The sandy sites are drained

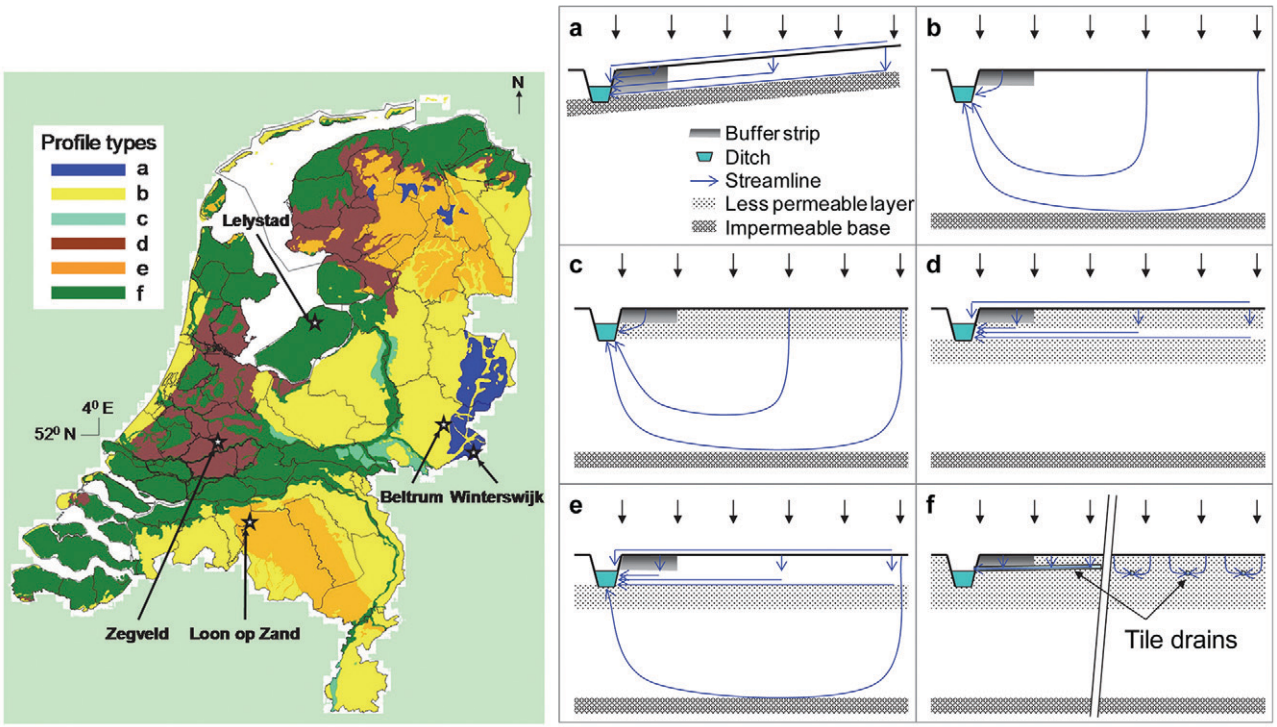

Fig. 1. Geographical distribution (left) and profile (right) of hydrogeologic classes in the Netherlands (Van Bakel et al., 2007). Selected experimental locations (left) and expected flow paths (right). (a) *Shallow sand*: sandy aquifer with slope on impermeable subsoil <1 m below soil surface (bss), area 2.4%. (b) *Deep sand*: deep sandy aquifer, area 33.5%. (c) Sandy aquifer with less-permeable top soil, area 1.4%. (d) *Holland peat*: less-permeable deep aquifer in peat soil, area 12.8%. (e) *Interrupted sand*: deep sandy aquifer, interrupted by less-permeable loam layer, area 16.1%. (f) *Holland clay*: less-permeable deep aquifer in tile drained clay soil, area 33.7%.

by ditches (Beltrum, Loon op Zand) or a small modified natural stream (Winterswijk). Zegveld and Lelystad are situated below sea level in a polder with controlled water level. Tile drain spacing at Lelystad was 8 m. Zegveld is a moorland site with grazed grassland, drained by abundant parallel ditches (60 m apart). This area suffers from soil subsidence due to peat mineralization (Schothorst, 1977), which has led to concave fields with elevated ditch borders. Therefore, these fields partly drain surface runoff through the middle and parallel to the ditch. For the soil information of the experimental sites, refer to Table 2.

Experimental Setup

Between October 2005 and February 2006, paired treatments were installed at all locations: an unfertilized grass BS and a reference strip (REF) cropped and managed like the adjacent field (Replicate A, Fig. 2). At only Beltrum and Zegveld, two extra paired treatments (Replicates B and C) were installed before the start of the second leaching season. At the grassland sites, the existing sward remained; at maize (*Zea mays* L.) sites, grass was sown in the BS to establish a normal sward. All grass strips (BS and grassland REF) were harvested and sampled for N withdrawal throughout the season, maize REF once a year. Like the rest of the field, the REF was cropped and managed according to farmers' practice, including slurry and fertilizer application, except for an obligatory uncultivated strip of 0.25 m (for grassland) or 0.5 m (for maize) from the edge of the ditch bank. Both treatments were installed along the ditch, 5 m wide and 15 m long. Opposite the center of each treatment, a 5-m-long wooden reservoir, reaching to the middle of the ditch, collected all surface and subsurface discharge from the field. At Lelystad, the treatments were 25 m and the reservoirs 16 m long, so as to collect outflow from two subsurface drains. In Winterswijk, both reservoirs were enlarged in 2007 from 5 to 12.5 m long to increase the discharge area (Table 1). Treatments were longer than reservoirs to prevent interaction between treatments (Fig. 2). Reservoir walls consisted of 0.045 m thick tongue and groove planks driven down to approximately 1.5 m below the bottom of the ditch. Once a year, reservoirs were pumped empty for visual inspection of leakage through the walls. Except for Zegveld, we mounted additional walls of composite wood board with bentonite between the two walls to prevent any leakage.

The water level in the reservoir was maintained at ditch water level by pumping out excess water (tolerance 0.01 m). In Zegveld and occasionally Loon op Zand, water had to be pumped in during summer to compensate for infiltration from ditch to soil.

We added a deuterium tracer at the outer edge of all treatments (Fig. 2) before the first leaching season (2006; Replicates B and C 2007), and measured its breakthrough in the reservoirs throughout the experiment as an indicator for hydrological lag time.

Sampling and Measurement Protocol

Discharge (Q, m^3) from the reservoir was measured at the pump outlet with a flow meter and logged by a programmable data taker that activated an automatic sampler at fixed discharge amounts to take water samples from the reservoir. If water had to be pumped in, samples were taken from the ditch for analysis. Sampling bottles were filled in five steps, each step corresponding to approximately 1 mm of precipitation surplus (PS). Water samples were immediately stored in an on-site refrigerator (<4°C) and transported to the laboratory once a week for analysis (including partly filled bottles); if no water was present in a sampling bottle, a sample from the reservoir was taken manually (if water was present).

Suction cups (polyester acrylate, porosity ~65%, pore diameter ~0.45 μm, inert to N) were installed in the soil inside both treatments and in the adjacent field (Fig. 2). Cups were placed at five depths covering the range between mean highest and mean lowest groundwater levels as presented in Table 1. The sampling

Table 1. Experimental field conditions. See Fig. 1 for hydrogeology.

Site, hydrogeology	Slope	Soil (FAO, 2002)	Land use	Water divide†	MHG; MLG‡	Ditch bottom§	DWL in summer and winter§	Coordinates, elevation
				m	cm bss	cm bss	cm bss	m above sea level
Beltrum, deep sand	≤1%	Sandy soil of periglacial aeolic origin (gleyic podzol)	Fodder maize; grass winter crop	60¶, 130#	40; 140	130	112 126	52°04′56″N, 06°32′11″E, 17
Zegveld, Holland peat	0	Peat soil(terric histosol)	Grassland	30¶,#	25; 80	140	90 90	52°8′22″N 4°50′11″E, −3
Winterswijk, shallow sand	2%	Sandy soil on boulder clay <1 m bss (Eutric Gleysol)	Grassland	80††	30; >200	138	125 131	51°54′57″N, 6°43′22″E, 45
Loon op Zand, interrupted sand	0	Sandy soil (Haplic Podzol)	Grassland	15¶, 75#	70; >180	154	132 111	51°37′28″N, 5°5′36″E, 9
Lelystad, Holland clay	0	Silty clay loam (Calcaric Fluvisol)	Maize	150¶,#	70;120	137	128 132	52°32′25″N, 5°33′021″E, −4

† The rainwater surplus at both sides of the water divide (wd) flows away in opposite directions. In sloping areas, wd is fixed by the highest contour line in the field, but in a plain it is the dynamic position of maximum elevation of the groundwater plane. It may be determined as the average maximum groundwater elevation in a transect perpendicular to the ditches, which is often located halfway between two ditches. The theoretical discharge area is calculated as wd × reservoir length (Fig. 2).

‡ MHG, mean highest groundwater; MLG, mean lowest groundwater level in cm below soil surface (bss).

§ DWL, ditch water level. As both levels are expressed in relation to soil surface level, the ditch water level measured from the bottom is calculated as ditch bottom – ditch water level.

¶ Top of measured groundwater level.

Half the distance between two ditches.

†† Top of the slope.

frequency was six to seven times per leaching season and two to three times during the summer season. In Replicate A of Beltrum, sampling ran from December 2006 to the end of the experiment (total 32). For Beltrum B and C, sampling started November 2007 (total 22) and for all other locations in 2008 (total Zegveld 13, Loon op Zand 18, Winterswijk 6, and Lelystad 10). The first cup just below the groundwater level was used to sample upper groundwater, except in Winterswijk, where groundwater levels were too dynamic. Here we used the cups of 80 and 100 cm bss. Upper groundwater measurements are referred to herein with the position perpendicular ("treatment" and adjacent "field") and parallel to the ditch ("REF" and "BS"; Fig. 2). This means that the position "field, BS" is located outside the BS treatment.

Analytical Procedures

Reservoir water samples were split into three subsamples after thorough mixing. The first unfiltered subsample was analyzed for total nitrogen (N_t) with a segmented flow analyzer (SFA) after persulfate-borate destruction (NEMI I-4650-03 and I-2650-03; www.nemi.gov). The second subsample was analyzed in the same way, but after filtering over 0.45 μm (Whatman RC55 regenerated cellulosis membrane) to measure total soluble N (N_{ts}). The third subsample was filtered likewise and analyzed for NO_3–N (+NO_2–N), NH_4–N, (all in 0.01 M $CaCl_2$ with SFA), and Cl (flow injection analyzer, FIA).

The groundwater samples were analyzed for N_{ts}, NO_3–N and NH_4–N (SFA), and Cl (FIA). Groundwater concentrations will be denoted as C_{gw}.

Data Analysis

We calculated the time and discharge needed to reach 50% of final tracer recovery and used this as an indicator for hydrological time lag (details in Heinen et al., 2011). Measured discharge Q (m^3) in reservoirs was divided by discharge area (Table 1) to obtain Q in millimeters. Discharge area was calculated with a water divide (Table 1) based on the position of the maximum measured groundwater level, except in Winterswijk, where it was based on the top of the slope (Table 1). Discharge Q (mm) was further divided by precipitation surplus (PS) to calculate the ratio Q/PS. Precipitation was measured on site, and estimated evapotranspiration was taken from nearest weather station. If Q/PS < 1, part of PS is lost from the observed system, whereas Q/PS > 1 indicates input from other sources than PS.

We calculated N surplus as N fertilizer rate minus N withdrawal by the crop. The absolute treatment effect on N surplus is N surplus REF minus N surplus BS.

We used decreasing NO_3–N/Cl concentration ratio between field and treatment (both C_{gw}), and between treatment (C_{gw}) and reservoir ($\overline{C}$) as an indirect indicator for denitrification, according to Altman and Parizek (1995) and Mengis et al. (1999). The precondition is that other causes for changing ratio, such as mixing with other groundwater or plant uptake, can be excluded.

The flow-averaged leaching concentration, $\overline{C}$ (g m^{-3}), was computed according to (e.g., Chaubey et al., 1994; 1995; Heinen et al., 2011):

$$\overline{C} = \frac{\sum QC}{\sum Q} \qquad [1]$$

where Q times C represents the load. Sums were calculated for periods of equal discharge, instead of more common periods of equal time, to reduce the influence of spatial variation in discharge on the treatments (Heinen et al., 2011). For each leaching season and each pair of treatments, the lowest discharge at the end of the leaching period was used. We also computed an average $\overline{C}$ for all leaching seasons (c.f. Heinen et al., 2011).

Buffer strip effectiveness based on reservoirs was computed in two different ways. The first calculation, BSE_1, was based on flow-weighted means according to Heinen et al. (2011):

Table 2. Soil characteristics of the experimental sites.

Site, hydrogeology	Replicate	cm bss†	OM† % mass	<2 μm‡	<16 μm	<50 μm	>50 μm	ρ_d† g cm^{-3}	pH-H_2O
Beltrum, deep sand	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, Holland peat	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, shallow sand	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, interrupted sand	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, Holland clay	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

† bss, below soil surface; OM, organic matter; ρ_d dry bulk density .

‡ Soil texture in 100 g g^{-1} on mineral basis.

§ n.d., not determined.

$$\mathrm{BSE_I} = 1 - \frac{\overline{C}_{\mathrm{BS}}}{\overline{C}_{\mathrm{REF}}} \quad [2]$$

The second calculation, $\mathrm{BSE_{II}}$, was based on average concentrations C_{avg} of separate discharge and reservoir concentration measurements, resulting from the statistical analysis described below:

$$\mathrm{BSE_{II}} = 1 - \frac{C_{\mathrm{BS,avg}}}{C_{\mathrm{REF,avg}}} \quad [3]$$

We conducted 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) + period (P) + L×T + L×P + T×P + L×T×P. The random model was L×R (replicate) + L×R×T + L×R×P + L×R×T×P. Locations were Beltrum, Zegveld, Winterswijk, Loon op Zand, and Lelystad; treatments were BS and REF; replicates were A, B and C; and the periods were the leaching seasons 2006–2007, 2007–2008, 2008–2009, and 2009–2010. We tested the null hypothesis that there is no difference between REF and BS. The *F* probability (*P* values) obtained for the fixed model terms were used to assess significance ($P < 0.05$). Both an integrated statistical analysis for all locations and replicates and partial analyses were performed for the two sites with three replicates (Deep and Peat). In the partial analyses all terms with L were removed from the model.

Finally, BSE was also calculated based on average upper groundwater concentrations nearest to the ditch, according to

$$\mathrm{BSE_{III}} = 1 - \frac{C_{\mathrm{gw,BS,avg}}}{C_{\mathrm{gw,REF,avg}}} \quad [4]$$

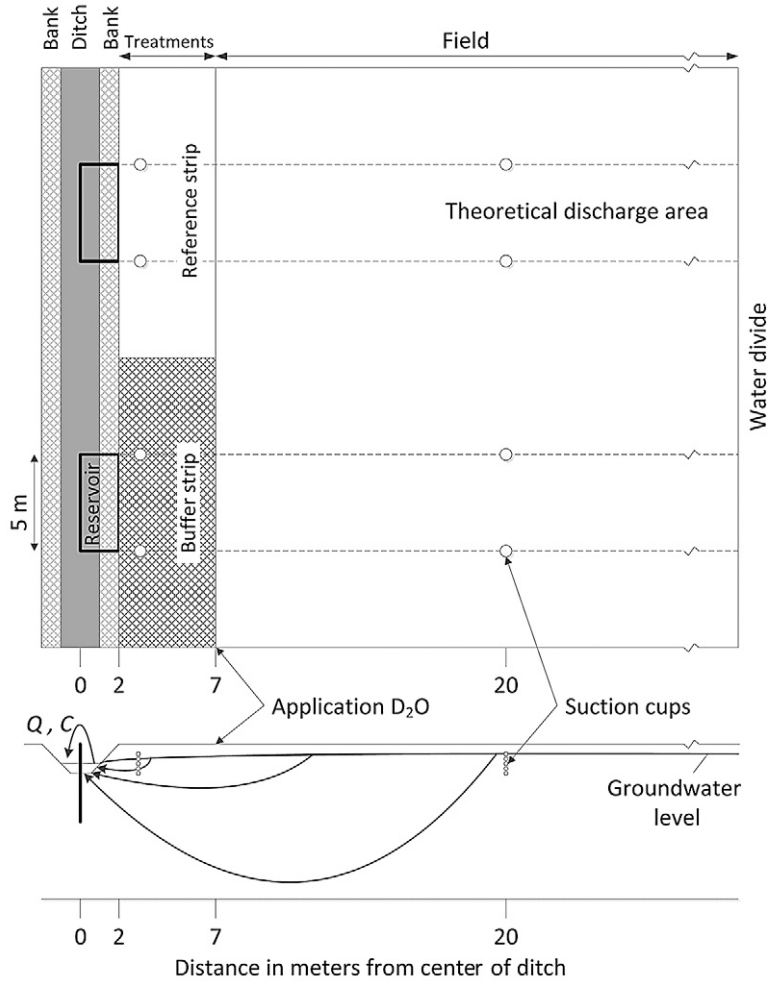

Fig. 2. Aerial layout of one replicate of the experiment (above) and corresponding transect (below). More details in Heinen et al. (2011).

Results

This section is subdivided by the experimental sites that are characteristic for a hydrogeological class. Per site, we describe results for tracer recovery and hydrology (Table 3), N surplus (Table 4), N in upper groundwater (Table 5), N in reservoirs (Fig. 3), and BSE (Fig. 4, Tables 6 and 7). Table 8 summarizes site-specific effects on BSE for the discussion.

Beltrum, Deep Sand

At Beltrum, 50% of final tracer recovery was reached within 136 to 778 d. Final tracer recovery ranged from 36 to 98% (Table 3). The average recovery of PS in the reservoirs was low (*Q*/PS = 0.61). According to steady-state stream line analysis with FLONET (Molson and Frind, 2010; see Heinen et al., 2011, their Fig. 3), flow paths starting within 30 m from the ditch and with a maximum depth of 7 m bss reached the reservoir. Hence, only about half of the expected area discharged to reservoirs. Flow paths, starting between 30 m and the water divide at 60 m (Table 1), by-passed treatments strips and reservoirs at greater depths, thus contributing to regional flow. Only flow paths starting within 15 m from the ditch passed through the first meter of upper groundwater below the treatments and contributed only ~25% of PS to *Q*. Consequently, water from the area 15 to 30 m away from the ditch reached a depth of 2 to 7 m bss and also contributed ~25% of PS to *Q*. We did not observe surface runoff at this location.

The unfertilized BS caused lower N surplus, compared with the fertilized REF treatment (Table 4), which was reflected in lower upper groundwater N concentration (C_{gw}) below BS, but not in lower BS reservoir concentration ($\overline{C}$, Table 5). Observed C_{gw} (NO_3–N) and $\overline{C}$ (N_t) corresponded well with median C_{gw} below 148 sandy soil farms (11.5 g m^{-3} NO_3–N, 14.2 g m^3 N_t) and median $\overline{C}$ (ditches: 14.0 g m^3 N_t) at 11 sandy soil farms in the Netherlands (Fraters et al., 2008).

At greater depth below both treatments (>2 m bss), we found equal higher nitrate and Cl concentration (~30 g m^{-3} N; >30 g m^{-3} Cl). Reservoir Cl concentration was in between the concentration of deep and upper groundwater. We observed decreasing NO_3–N/Cl ratio between both treatments and reservoirs. As mixing and plant uptake during the leaching period could be excluded, we attributed this decrease to denitrification. Denitrification was less at the BS (Table 5; NO_3–N/Cl 1.29 → 0.72, compared with 1.53 → 0.55).

All concentration measurements in reservoirs were summarized in Box-Whisker plots (Fig. 3). At all mineral soil sites, but

most clearly at Beltrum, N_t in reservoirs mainly consisted of N_{ts}, and N_{ts} mainly of NO_3–N. At Beltrum, we observed the highest maximum (35 g m^{-3} N_t) and the highest median N_t concentration (15 g m^{-3} N_t).

Based on NO_3–N in upper groundwater, BSE_{III} was 66% (Table 5). Based on both N_t and NO_3–N in reservoirs, however, BSE_I was on average −17.2% (Fig. 4a, Table 6), corresponding to an absolute difference in reservoir N_t concentration between REF and BS of −2.5 g m^{-3} N (Fig. 4b). BSE_I was quite variable between replicates and leaching seasons (−101.8 to 22.8%, Fig. 4a) and therefore not significant (Table 7; BSE_{II} = −14.8%; P = 0.583). High variability of negative BSE can be expected for mathematical reasons (Heinen et al., 2011). Given its statistical insignificance and negative value, $BSE_{I,II}$ for N is best interpreted as nil at Beltrum.

Loon op Zand, Interrupted Sand

At Loon op Zand, both tracer recovery and discharge were very low and similar for both treatments (Table 3). Note that Q/PS was not calculated with the expected water divide (75 m, Table 1) but with the observed water divide (15 m, Table 1). With the expected water divide, Q/PS would be only 0.14. Even from the first 15 m, PS was not completely recovered (Q/PS = 0.66). Nevertheless, 50% of final tracer recovery was reached within 2 yr. Surface runoff was physically impossible due to an elevated border. Low discharge motivated a separate study (Hoogland et al., 2010). They installed a detailed grid of groundwater wells (1 per 12.5 m^2) to observe the groundwater plane in time, showing high spatial and temporal variability in groundwater elevation due to the erratic relief of the cryoturbated loam layer (top 1.5–2.5 m bss, thickness 0.5–1.5 m). Water between 15 and

Table 3. Final tracer recovery (TR), number of days ($t_{0.5}$) and accumulated amount of water discharge ($Q_{0.5}$) since tracer application at half of final TR. Sum of discharge during leaching seasons for which buffer strip effectiveness was calculated (Q), corresponding precipitation surplus (PS), and number of flow-weighted reservoir samples (n). Q in mm and PS are calculated from a water divide based on the top of measured groundwater level (top of the slope for Winterswijk); see Table 1.

Site, hydrogeology	Replicate	Period	Treatment†	TR	$t_{0.5}$	$Q_{0.5}$	Q	Q	PS	Q/PS		n
											Avg.‡	
				%	d	m^3	m^3	mm	mm			
Beltrum, deep sand	A	2006–2010	REF	40.0	146	45	132	439	866	0.51	0.61	153
			BS	36.3	411	51	133	443	866	0.51		152
	A	2007–2010	REF				82	272	538	0.51	0.61	97
			BS				88	294	538	0.55		93
	B	2007–2010	REF	66.9	136	28	90	299	542	0.55		109
			BS	36.9	790	63	95	317	542	0.58		84
	C	2007–2010	REF	97.8	496	65	119	395	502	0.79		92
			BS	63.3	778	71	107	357	502	0.71		96
Zegveld, Holland peat	A	2006–2010	REF	32.1	147	67	164	1097	1106	0.99	0.89	340
			BS	32.2	260	87	180	1200	1106	1.09		333
	A	2007–2010	REF				80	636	744	0.72	0.83	197
			BS				110	732	744	0.98		182
	B	2007–2010	REF	2.1	771	102	110	734	752	0.98		199
			BS	6.8	586	83	115	765	752	1.02		206
	C	2007–2010	REF	1.1	677	58	60	403	758	0.53		149
			BS	5.3	771	85	86	574	758	0.76		183
Winterswijk, shallow sand	A	2006–2007	REF	28.7	140	78	88	220	471	0.47	0.55	66
			BS	78.4	84	43	120	300	471	0.64		86
	Enlarged reservoirs	2007–2010	REF	45.1			410	410	860	0.48	0.72	147
			BS	89.0			820	820	860	0.95		268
Loon op Zand, interrupted sand	A	2006–2009	REF	1.3	663	39	38	512	752	0.68	0.66	156
			BS	1.6	467	26	36	486	752	0.65		156
Lelystad, Holland clay	A	2006–2009	REF	21.1	692	1617	1958	816	779	1.05	1.11	217
			BS	20.8	114	820	2191	913	779	1.17		308

† BS, buffer strip; REF, reference.

‡ Average Q/PS per location (either six or two reservoirs).

Table 4. Average nitrogen balance (kg ha^{-1} yr^{-1} N) of buffer (BS) and reference (REF) treatments.

Site, hydrogeology	Crop	BS	REF		
		Surplus†	Fertilizer rate	Crop withdrawal	Surplus
Beltrum, deep sand	Maize	–65	174	139	36
Zegveld, Holland peat	Grass	–280	288	368	–80
Winterswijk, shallow sand	Grass	–217	425	374	51
Loon op Zand, interrupted sand	Grass	–134	316	325	–4
Lelystad, Holland clay	Maize	–29	171	168	3

† Surplus = 0 fertilizer rate – crop withdrawal.

75 m contributed to regional groundwater flow in the aquifer below the loam layer. Even water in the treatments partly moved away from the ditch. Geostatistical simulation revealed high variability of discharge area (or Q) along the ditch. On 10 Apr. 2008, for example, median discharge area for the 5-m reservoir was 17 m^2, and 95% was <50 m^2. Results taken from the Netherlands Hydrological Modeling Instrument (Delsman et al., 2008) showed that similar discharges may be expected in 36% of interrupted sand.

Lower N surplus in the BS (Table 4) was reflected in lower C_{gw} but not in lower $\overline{C}$ (Table 5, Fig. 3). The difference in C_{gw} between "field, REF" and REF (15 g m^{-3} N) was larger than the difference between REF and BS (5 g m^{-3} N). Denitrification occurred between field and treatments, as well as between REF and reservoir (NO_3–N/Cl, Table 5, no mixing or plant uptake).

Based on NO_3–N in upper groundwater, BSE_{III} was 90% (Table 5). Based on reservoirs, however, BSE_I for N_t varied between leaching seasons from −15.1 to 18.1%, with an average of 10.4%, corresponding to a reduction of 0.75 g m^{-3} N_t (Fig. 4b). In the overall statistical analysis, there is no significant treatment effect for N_t (Table 7; BSE_{II} = −6.8%; P = 0.644), nor any interaction with treatment (L×T, T×S), but a significant effect of location, season, and their interaction (L×S). The seasonal effect dominated the smaller treatment effect in the integrated analysis. Given the low and variable BSE_I and the insignificance of BSE_{II} in the integrated analysis, $BSE_{I,II}$ based on reservoirs is best interpreted as nil for Loon op Zand as well.

Winterswijk, Shallow Sand

At Winterswijk, the fastest, highest, and most variable tracer recovery was observed (Table 3). In addition, discharge was very fast and different between BS and REF from the beginning (Table 3). The hydrologic system was highly dynamic; based on the travel time distribution of water in a thin aquifer

Table 5. Average upper groundwater concentration (C_{gw}) in treatments (buffer strip [BS] and reference [REF]) and adjacent field opposite REF and BS (Fig. 2), and flow-weighted average concentration in both reservoirs ($\overline{C}$). Standard deviations (±) for reservoirs in Beltrum and Zegveld are based on replicates, for upper groundwater on separate samplings.

Site, hydrogeology	Period	Species	$\overline{C}$ reservoir		C_{gw} treatments		C_{gw} field	
			Ref	BS	Ref	BS	Ref	BS
Beltrum, deep sand	06/10	NO_3–N	14.02 ± 4.72	16.43 ± 2.75	25.84 ± 12.69	8.69 ± 10.36	29.16 ± 15.27	26.50 ± 13.80
		Cl	25.70 ± 6.44	22.75 ± 3.63	16.86 ± 7.21	6.75 ± 4.71	18.27 ± 11.45	17.50 ± 11.46
		NO_3–N:Cl	0.55 ± 0.23	0.72 ± 0.17	1.53 ± 1.00	1.29 ± 1.78	1.60 ± 1.30	1.51 ± 1.27
Zegveld, Holland peat	08/10	N_{ts}†	7.99 ± 5.07	7.44 ± 4.81	11.78 ± 13.76	13.21 ± 9.75	11.33 ± 6.38	8.78 ± 7.61
		NO_3–N	1.12 ± 1.12	0.63 ± 0.72	7.66 ± 13.23	8.64 ± 9.70	5.77 ± 5.79	3.39 ± 7.03
		Cl	34.66 ± 21.54	34.21 ± 21.04	17.71 ± 4.02	16.77 ± 6.02	22.67 ± 7.81	19.96 ± 7.06
		NO_3–N:Cl	0.03 ± 0.04	0.02 ± 0.02	0.43 ± 0.75	0.52 ± 0.61	0.25 ± 0.27	0.17 ± 0.36
Winterswijk, shallow sand	08/10	NO_3–N	3.33	7.12	4.52 ± 2.66	2.18 ± 3.61	17.14 ± 13.35	14.14 ± 5.48
		Cl	20.81	19.59	18.04 ± 3.23	15.54 ± 5.38	23.92 ± 11.06	15.54 ± 5.34
		NO_3–N:Cl	0.16	0.36	0.25 ± 0.15	0.14 ± 0.24	0.72 ± 0.65	0.91 ± 0.47
Loon op Zand, interrupted sand	08/09	NO_3–N	3.99	2.97	5.11 ± 4.78	0.40 ± 0.35	19.97 ± 8.94	4.05 ± 1.15
		Cl	22.06	19.86	14.97 ± 8.73	6.04 ± 1.12	17.12 ± 9.00	17.54 ± 8.55
		NO_3–N:Cl	0.18	0.15	0.34 ± 0.38	0.07 ± 0.06	1.17 ± 0.81	0.23 ± 0.13
Lelystad, Holland clay	08/09	NO_3–N	2.41	2.06	0.91 ± 1.10	0.23 ± 0.57	5.83 ± 5.04	2.30 ± 2.66
		Cl	102.49	94.31	13.18 ± 3.60	17.24 ± 14.79	14.30 ± 3.22	16.27 ± 15.23
		NO_3–N:Cl	0.02	0.02	0.07 ± 0.09	0.01 ± 0.04	0.41 ± 0.36	0.14 ± 0.21

† Only in Zegveld, NO_3–N is not the dominant N species.

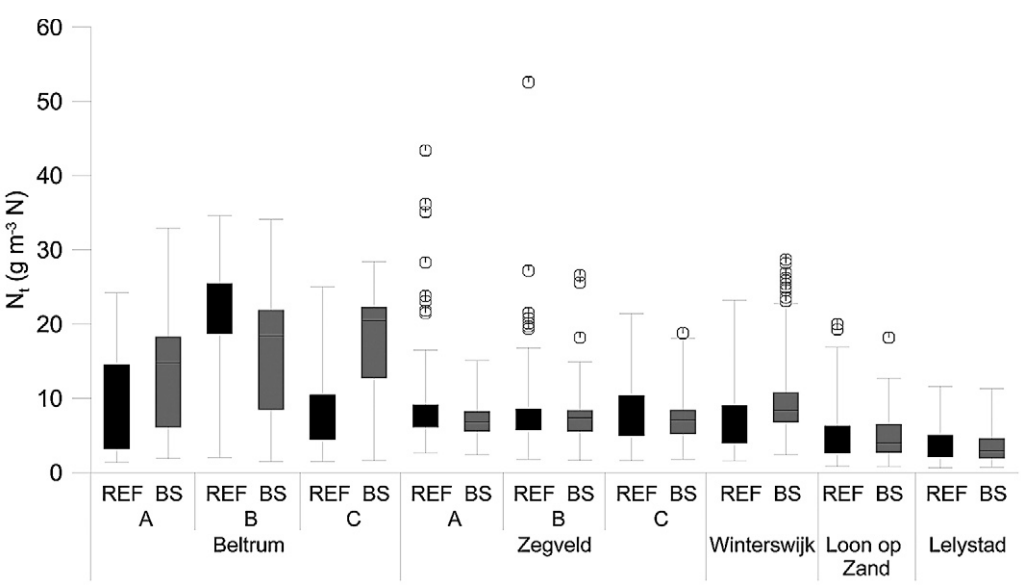

Fig. 3. Total N concentration (N_t) in reservoirs of all locations, treatments, and replicates during the entire experiment, summarized in Box-Whisker plots: minimum value, first, second (median), and third quartile, maximum value. Outliers (symbols) >3 times box range. BS, buffer strip; REF, reference strip.

(Gelhar and Wilson, 1974), residence time in the treatments was only 0.03 yr.

We suspected hydrologic spatial variability was caused by the erratic gullies, some decimeters wide and deep, in the top of the impermeable boulder clay layer that we detected with ground-penetrating radar. We enlarged the treatments and reservoirs (from 5 to 12.5 m) in 2007 to reduce this effect, but the opposite occurred. Between 2007 and 2010, discharge at BS was twice as much compared with REF during leaching seasons. The apparent discharge area of the BS proved to be much larger compared with REF. The top of the slope was about 80 m from the stream, but the contour lines deviated away from the stream opposite the BS, which likely caused extra discharge to the reservoir of the BS.

At Winterswijk, difference in C_{gw} between field and treatments (12 g m^{-3} N) was much larger than between REF and BS (2 g m^{-3} N, Table 5). Therefore, we did not calculate BSE_{III}. Denitrification occurred during transport from field to treatments (Table 5, NO_3–N/Cl). At this site, N concentration of the BS reservoir was much higher than REF (Table 5, Fig. 3). Measured total accumulated N_t load (data not shown) was about 9 kg N_t (7 kg NO_3–N) for BS, compared with 3 kg N_t (1.6 kg NO_3–N) for REF.

In Winterswijk, the equal discharge period for calculating BSE_I (Eq. [1–2]) lasted until the beginning of the third season only, due to the very different discharge (Q) between BS and REF. Therefore, we also present BSE_I for equal time periods (Fig. 4), to cover the entire experimental period. Average BSE_I for N_t varied from −29.4 to −118.9%, with an average of −48.3% for equal discharge and −52.9% for equal time, corresponding to −3.3 g m^{-3} N. In contrast to the other sandy sites, the negative treatment effect was substantial and consistent for all years and dominated the seasonal effect (Fig. 4).

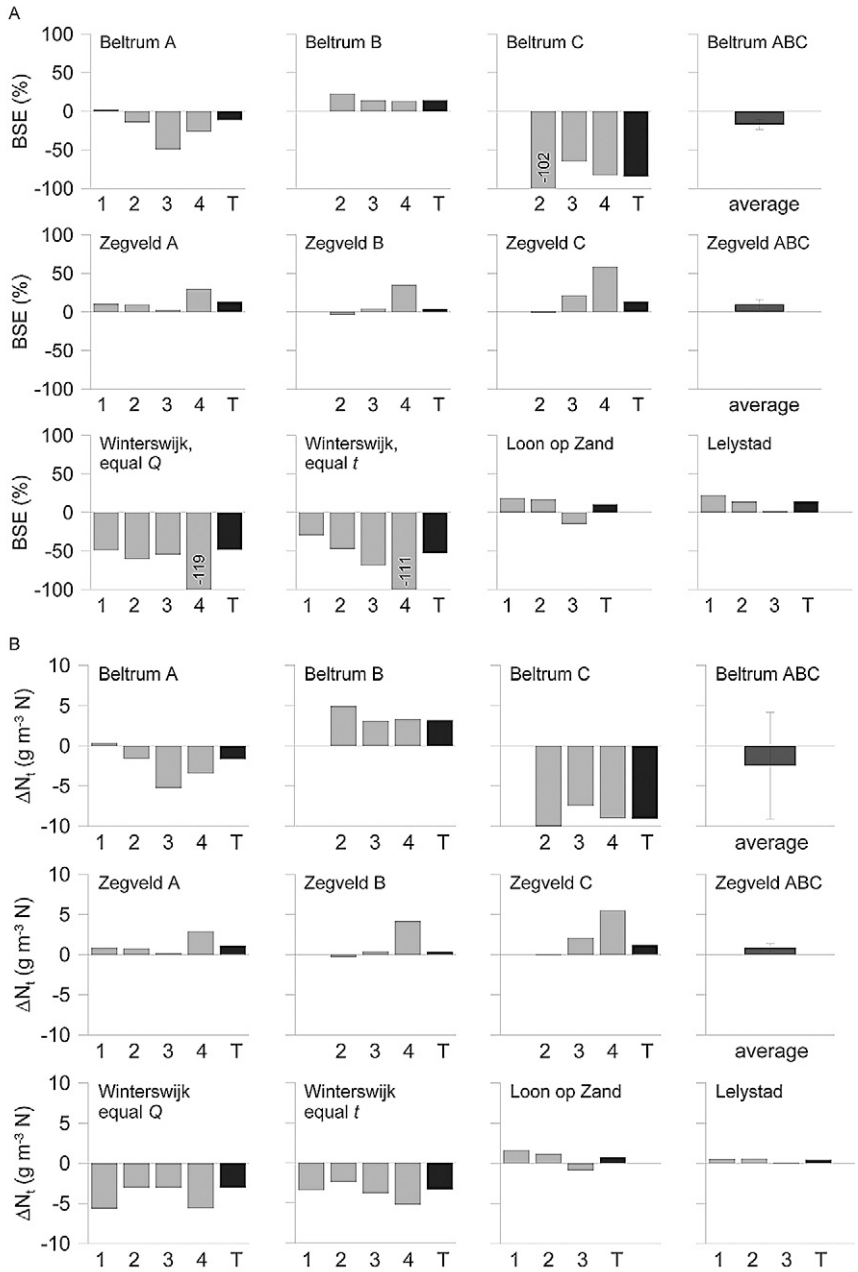

Fig. 4. (a) Buffer strip effectiveness (BSE_I; Eq. [2]) for flow-weighted average total N concentration (N_t), and (b) absolute difference in N_t between reference strip (REF) and buffer strip (BS) (ΔN_t), both for different leaching seasons (1, 2, 3, 4, and total [T]), locations, and replicates, for periods of equal discharge (Q) and in Winterswijk also for equal time (t) periods.

Lelystad, Holland Clay with Tile Drains

Both discharge and final tracer recovery were similar for both treatments in Lelystad (Table 3). Although N-surplus was clearly lower for BS (Table 4), the difference in C_{gw} between REF and BS was smaller than the difference between field and treatments or reservoirs, and smallest of all sites (Table 5). Therefore, we did not calculate $BSE_{III.}$ Average C_{gw} and N_t in reservoirs (Fig. 3) were also lowest at Lelystad. Due to the marine origin of the soil, Cl concentration was higher in both reservoirs compared with other locations.

Average BSE_I for N_t was 13.9%, corresponding to only 0.44 g m^{-3} (Fig. 4). Given the insignificant treatment effect for N_t in the overall statistical analysis, the very small BS effect at Lelystad is best interpreted as nil.

Zegveld, Holland Peat

Tracer recovery at Zegveld was faster and higher at Replicate A compared with Replicates B and C (Table 3). Nevertheless, 50% of final recovery was also reached at Replicates B and C within 771days. Discharge was less variable than tracer recovery, both within and between treatment pairs. The average Q/PS ratio indicated almost complete recovery of PS in the reservoirs. According to the steady-state stream lines (FLONET; Molson and Frind, 2010), water starting 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 bss before entering the ditch.

Also at Zegveld, N-surplus was lower due to BS treatment (Table 4), but this was not reflected in lower C_{gw} or $\overline{C}$ at the BS, either for NO_3–N or for N_{ts} (including NO_3–N, NH_4–N, and soluble organic N; Table 5). We also presented N_{ts} at Zegveld because organic matter dominates N dynamics at this peat site. Also at this site, differences in C_{gw} between field, treatments, and reservoirs were more pronounced than between BS and REF. Hence, we did not calculate BSE_{III}. Nitrate and NO_3–N/Cl ratio increased between field and treatments, and decreased between treatments and reservoirs, which points to net nitrate production in the field and denitrification in the upper groundwater between treatments and reservoirs. By consequence, the lowest nitrate concentration was found in both reservoirs at Zegveld (Table 5, Fig. 3). Results for $\overline{C}$ N_t (Fig. 3), N_{ts}, and NO_3–N (Table 5) correspond well with values reported before for the Western peat district (4–8 g m^3 N_t, 0–3.5 g m^3 NO_3–N; Van Beek, 2007).

Average BSE_I for N_t was 9.8%, corresponding to only 0.87 g m^{-3} N (Fig. 4). BSE_I was negative only in the first season of Replicates B and C. Zegveld was the only location with a significant treatment effect on N_t (Table 7, BSE_{II} = 15.1%, P = 0.005). For nitrate, BSE_{II} was not significant in the statistical analysis (Table 7). Reservoir N_t mainly consisted of soluble organic N and to a lesser extent NH_4–N.

Discussion

We found very low BSE for N at all five sites characteristic for lowland agriculture, much lower than BSE values reported for other circumstances (e.g., Barling and Moore, 1994; Dosskey, 2002; Mayer et al., 2005, 2007; Muscutt et al., 1993; Parkyn, 2004; Polyakov et al., 2005; Wenger, 1999). The BS effect was only statistically significant in Zegveld (Holland peat). At this site, BSE_I was also low (10%, Table 6), especially compared with the relatively large proportional area of BS (17%) on these narrow fields. At all sites, low BSE can be explained (i) by N removal through denitrification in the soil of treatments and adjacent field and (ii) by hydrologic factors (Table 8).

Denitrification

Although the unfertilized BS reduced N surplus at all sites (Table 4), this was only reflected in lower C_{gw} below BS in Beltrum (deep sand) and Loon op Zand (interrupted sand) (Table 5). Corresponding BSE_{III} was 66 and 90%, respectively. We did not calculate BSE_{III} for Zegveld, Winterswijk, and Lelystad because low C_{gw} at BS could not be attributed to treatment: C_{gw} was also low at REF. At all sites except Beltrum, the difference in C_{gw} between REF and BS was smaller than between adjacent field and treatments (Table 5). Judged by decreasing NO_3–N/Cl ratio (Table 5), this was caused by denitrification in the soil between field and treatments (Table 8), except in Zegveld (Holland peat). At the peat site, net production of nitrate occurred, causing even higher C_{gw} at the BS (Table 5, N_{ts}). Mineralization of abundant organic matter and subsequent denitrification have annihilated potential differences between REF and BS. Denitrification also played a role during transport between treatments and reservoirs (Table 8). At all mineral soil sites, denitrification between REF and reservoir exceeded denitrification between BS and reservoir (Table 5) and therefore leveled out potential differences between both treatments.

Table 6. Buffer strip effectiveness (BSE, %) for five locations, based on flow averaged reservoir concentration (BSE_I; Eq. [2]) and based on statistical analysis of individual reservoir concentration measurements (BSE_{II}; Eq. [3]).

Species	BSE	Beltrum Deep sand	Zegveld Holland peat	Winterswijk Shallow sand	Loon op Zand Interrupted sand	Lelystad Holland clay
N_t	I	–17.2 ± 6.4†	9.8 ± 6.3†	–48.3	10.4	13.9
	II	–14.8	15.1	–61.6	5.9	5.1
N_{ts}	I	–16.6 ± 6.2†	6.9 ± 4.4†	–62.5	9.9	13.2
	II	n.d.	n.d.	n.d.	n.d.	n.d.
NO_3–N	I	–17.2 ± 6.4†	44.1 ± 43.8†	–113.6	25.6	14.5
	II	–14.8	42.3	–147.1	23.9	8.0
Cl	I	11.5 ± 3.4†	1.3 ± 0.8†	5.9	10.0	8.0
	II	9.1	1.6	4.3	7.4	10.8

† Average and standard deviation refer to three replicates.

Table 7. Buffer strip effectiveness, based on statistical analysis of individual reservoir concentration measurements (BSE_{II}; Eq. [3]), and corresponding average difference in reservoir concentration (C_{avg}) between both treatments (REF – BS). *P* values for the terms location (L), treatment (T), leaching season (S), and mutual interactions.

Analysis for	Species	REF–BS	BSE_{II}	*P* values						
		C_{avg} g m^{-3}	%	L	T	S	L×T	L×S	T×S	L×T×S
All locations	N_t	–0.68	–6.8	0.061	0.644	0.008	0.848	0.022	0.592	0.392
	NO_3–N	–0.94	–15.3	0.025	0.525	0.001	0.846	0.005	0.479	0.772
	Cl	2.58	6.8	<0.001	0.046	<0.001	0.118	<0.001	0.235	0.005
Only Zegveld, Holland peat	N_t	1.36	15.1		0.005	0.841			0.044	
	NO_3–N	0.44	42.3		0.257	0.169			0.179	
	Cl	0.59	1.6		0.790	0.001			0.342	
Only Beltrum, deep sand	N_t	–2.34	–14.8		0.583	0.023			0.649	
	NO_3–N	–2.13	–14.8		0.578	0.001			0.573	
	Cl	2.34	9.1		0.262	0.007			0.649	

Hydrologic Factors

In Beltrum (deep sand), about half of PS discharged via deeper groundwater (>7 m bss) and by-passed treatments and ditch (Table 8). Reservoirs were filled with a mixture of affected shallow (1–2 m bss) and unaffected deeper groundwater (2–7 m bss), with relatively high nitrate and Cl concentration. Therefore $\overline{C}$ for Cl was in between deep (>30 g m^{-3} Cl) and upper groundwater concentration below treatments and field (Table 5). At Loon op Zand (interrupted sand), only a minor part of the *PS* of the field was recovered in the reservoirs, due to downward seepage. At Winterswijk (shallow sand), low residence time in the treatments (0.03 yr) hampered nitrate removal, especially during winter. Even if we apply a year-round average first-order denitrification rate for upper groundwater in the Netherlands (1.84 yr^{-1}; Heinen et al., 2011), nitrate removal in a 5-m strip remains below 5.4% {100%×[1 − exp(−1.84×0.03)]}. Hence, N load from treatments to reservoirs practically equaled incoming loads from the adjacent field, and negative BSE was caused by higher incoming N load in the BS. Higher N load ($Q\overline{C}$) at the BS could be largely explained by higher discharge (Table 3). By consequence, residence time and denitrification between field and reservoirs were lower at BS, causing also higher $\overline{C}$ NO_3–N and NO_3–N/Cl for BS (Table 5). At Winterswijk, a potential treatment effect below the narrow strips (5 m) could easily be outdone by spatial variability in the much larger discharge area of the adjacent field (5–80 m, Fig. 2). Such spatial variability may relate to both N dynamics (N surplus → C_{gw} → $\overline{C}$) and discharge (Q).

At Lelystad (Holland clay), we did not expect any BSE because drain pipes by-pass the treatment (Muscutt et al., 1993). Treatments (5 m) represented only ~3% of the water divide distance (150 m, Table 1). Even if BS reduced N leaching to upper groundwater by 100%, BSE could not exceed 3%. Lower $\overline{C}$ at BS can be explained by dilution because the BS reservoir received ~10% more discharge (Table 3; see also $\overline{C}$ Cl in Table 5).

High spatial variability of tracer recovery and Q/PS between treatment pairs in Zegveld is attributed to the observed erratic surface runoff pattern. During winter, groundwater reached soil surface and pools appeared (Appels et al., 2011), part of which flowed from the more elevated border of the ditch to the lower center of the field. This surface runoff was not recovered in the reservoirs (Table 3; Q/PS < 1) and must have reduced BSE.

Evaluation of the Method

The experimental period (three or four leaching seasons) was sufficient to overcome hydrological time lag at all sites because 50% of final recovery was reached within about two leaching seasons (Table 3). We succeeded in recovering the major part of PS in the reservoirs. Spatial differences in tracer recovery and discharge (Q/PS) between and within treatment pairs were likely caused by variation of soil and hydrological properties, including surface runoff at Zegveld (Holland peat). Rozemeijer et al. (2010) and Van der Velde et al. (2010) also found substantial variability in discharge along the ditch with the same type of reservoirs. Discharge variability along the ditch is also well known from drain pipes. Hoogland et al. (2010) confirmed spatial variability of discharge by geostatistical modeling of measured groundwater levels along the ditch. As we used flow-weighted concentration for periods of equal discharge for BSE assessment, we excluded an effect of discharge, except for Winterswijk.

At most sites low C_{gw} and $\overline{C}$ at BS were not caused by treatment. We were able to detect this because of the REF treatment in the experimental set-up. Dosskey (2002) and Heinen et al. (2011) already stressed the importance of including a REF treatment to avoid incorrect attribution of processes to the BS that may also occur without, such as denitrification or mixing with deeper groundwater. Most authors checked or corrected for mixing, but not for denitrification in a situation without BS. Whether earlier assessments of BSE without REF were incorrect depends on the research question. If introduction of BS on agricultural fields was evaluated, as in our study, the added value of BS compared with REF should have been established. However, if the effectiveness of a lower natural riparian zone next to upland agricultural area was evaluated, as in Balestrini (2008), Dhondt et al. (2002, 2006), Hefting (2003), and Hoffmann et al. (2006), a REF is less relevant. Such research aims at quantifying the functioning of an already-existing ecotone (Haag and Kaupenjohann, 2001). The Italian Po Valley provides an intermediary case with traditional

Table 8. Explanatory factors for low buffer strip effectiveness (BSE) for nitrogen in lowland agriculture.

Factor	Experimental sites and hydrogeologic class				
	Beltrum, deep sand	Loon op Zand, interrupted sand	Winterswijk, shallow sand	Zegveld, Holland peat	Lelystad, Holland clay
Low contribution of affected shallow flow and surface runoff to discharge, i.e., high contribution of unaffected deep groundwater	X				
Downward seepage, not reaching the ditch	X	X			
Drain pipes by passing treatments					X
Low discharge		X			
Low residence time in treatments			X		
Unequal discharge (area) of treatments			X		X
Surface runoff away from ditch				X	
Denitrification between field and ditch	X†	X‡	X‡	X†,§	X¶

† Predominantly between treatments and ditch (0–5 m).

‡ Predominantly between field and treatments (>5 m from ditch).

§ Contributes less to the explanation of low BSE because total nitrogen is not dominated by nitrate.

¶ Contributes very little to the explanation of low BSE because of drain pipes.

(i.e., existing) BS with trees and grass along agricultural fields (5–8 m wide). Reported high BSE for NO_3–N was assessed without REF and attributed to the hydrologic effect of the trees and denitrification (Balestrini et al., 2011; Borin and Bigon, 2002). We expect lower BSE values in case a REF would have been used because denitrification would also occur without BS.

Reservoirs proved valuable for our situation with unknown contribution from different flow paths. They revealed high spatial variability along ditches. Therefore, reservoir measurements before BS installation would further improve the experimental set-up (Heinen et al., 2011).

Upscaling

The effectiveness of BS for N proved to be controlled by site-specific factors (Table 8). Hence, BS would have to be tailor-made, but our results predict little perspective for effective BS application in lowland plains. At sites with pipe drains that cover 40% of agriculture in the Netherlands (Massop et al., 2000), BS are not effective, as suggested previously by Muscutt et al. (1993). For the relatively uniform Holland peat area (12.8%), BSE proved to be low. As for the sandy soils, our results correspond to nitrate removal on flood plains differentiated by aquitard depth range (Hill, 1996: optimum 1–4 m bss). At deep sand (33.5%), the aquifer clearly runs too deep (>>4 m bss) and at shallow sand (2.4%) too shallow (<1 m bss) for effective BS. Best perspectives are likely offered by interrupted sand (16.1%), if sufficient lateral groundwater flow occurs, which is not the case in 36% of this class due to downward seepage, as at our site Loon op Zand. At the remaining 64%, BSE will depend on groundwater level and organic matter dynamics that control denitrification.

We expect higher BSE if surface runoff occurs (Mayer et al., 2005, 2007). Fast transport routes reduce leveling of differences between BS and REF. Although surface runoff played a minor role in our study, it certainly occurs on plain fields (Appels et al., 2011). However, BS would need to be specifically designed for effective abatement of surface runoff. Narrow BS with grass (<<5 m) could already prevent surface runoff of soil particles and spills of agrochemicals that easily occur if the agricultural land is utilized up to the very edge of the ditch. They further contribute to stabilization of the ditch bank and to biodiversity and could therefore be considered good agricultural practice.

In conclusion, introduction of a 5-m-wide grass BS to reduce N loads from lowland agriculture to surface water is not effective. Low BSE is caused by site-specific factors governing hydrology and denitrification in the soil between field and ditch. Experimental evaluation of BSE in agriculture should include a reference treatment. Reservoirs are recommended in case of unknown discharge flow paths.

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