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Water and Nutrient Transport on a Heavy Clay Soil in a Fluvial Plain in The Netherlands

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In flat areas, transport of dissolved nutrients by water through the soil matrix to groundwater and drains is assumed to be the dominant pathway for nutrient losses to ground- and surface waters. However, long-term data on the losses of nutrients to surface water and the contribution of various pathways is limited. We studied nutrient losses and pathways on a heavy clay soil in a fluvial plain in The Netherlands during a 5-yr period. Average annual nitrogen (N) and phosphorus (P) losses to surface water were 15.1 and 3.0 kg ha^{-1} yr^{-1}, respectively. Losses were dominated by particulate N (50%) and P (70%) forms. Rapid discharge through trenches was the dominant pathway (60–90%) for water and nutrient transport. The contribution of pipe drains to the total discharge of water and nutrients was strongly related to the length of the dry period in the preceding summer. This relationship can be explained by the very low conductivity of the soil matrix and the formation of shrinkage cracks during summer. Losses of dissolved reactive P through pipe drains appear to be dominated by preferential flow based on the low dissolved reactive P concentration in the soil matrix at this depth. Rainfall occurring after manure application played an important role with respect to the annual losses of N and P in spring when heavy rainfall occurred within 2 wk after manure application.

Transport of nitrogen (N) and phosphorus (P) from agricultural land to surface waters contributes to enrichment of surface waters and eutrophication (Correll, 1998). A large part (68%) of the land area in The Netherlands is used for agriculture. For decades, N and P surpluses per hectare on agricultural land in The Netherlands were among the highest in Europe (Csathó and Radimszky, 2009), especially in areas with high livestock densities (Reijneveld et al., 2010). Agriculture is responsible for more than 50% of all nutrient loads to surface waters in The Netherlands (Emissieregistratie, 2010). Dairy farming is the largest producer of animal manure in The Netherlands, producing approximately 70% of the total annual manure production (CBS, 2010). However, information on nutrient budgets and losses of nutrients from dairy farms to surface waters in The Netherlands is limited, especially for clay soils. To overcome this lack of knowledge, a study was set up at a dairy farm on a fluvial clay soil drained by trenches and pipe drains.

In areas with a flat topography such as in The Netherlands, nutrient losses from agricultural land to surface waters are often assumed to be dominated by (subsurface) leaching, whereas surface runoff is considered to be negligible (Culley et al., 1983; Heathwaite and Dils, 2000; Algoazany et al., 2007). In The Netherlands, most of the research on nutrient losses has been performed in areas with noncalcareous sandy soils where nutrient surpluses are high due to the presence of intensive livestock farming systems (Breeuwsma et al., 1995). In these areas, relatively large N and P losses to groundwater and surface water occur due to the low denitrification rates and limited binding capacity of the soil for P (Schoumans and Groenendijk, 2000). Because for sandy soils leaching through the soil matrix is the dominant process, the research focus has been on losses of dissolved N and P forms, whereas losses of particulate forms have received much less attention. However, studies on clay soils in other countries have demonstrated that particulate losses of P can play a dominant role in the transport of P from agricultural land to surface waters, not only in

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Abbreviations: COLE, coefficient of linear extensibility; DIN, dissolved inorganic nitrogen; DRP, dissolved reactive phosphorus; DUP, dissolved unreactive phosphorus; IC, ion chromatography; IL, incidental loss; PN, particulate nitrogen; PP, particulate phosphorus; SOM, soil organic matter; TDN, total dissolved nitrogen; TDP, total dissolved phosphorus; TN, total nitrogen; TP, total phosphorus.

surface runoff but in pipe drainage as well (Culley et al., 1983; Turtola and Jaakkola, 1995; Beauchemin et al., 1998; Ulén and Persson, 1999; Turtola and Kemppainen, 1998; Djodjic et al., 2000). In contrast to P, particulate N losses from agricultural land have received little attention in international literature. Furthermore, preferential transport of water and nutrients through cracks and macropores is known to play an important role in heavy clay soils (Bouma and Wösten, 1979; Turtola and Paajanen, 1995; Addiscott et al., 2000; Geohring et al., 2001). This pathway may lead to losses of N and in particular P from soils with only limited contents of N and P in the soil matrix that would otherwise contribute little to nutrient losses. Although the above-mentioned pathways and processes have been identified before, few studies have considered the losses of N and P and their speciation in combination with a comprehensive description and quantification of their transport routes in areas with a flat topography over a prolonged period. Knowledge about the contribution of different pathways to nutrient losses and about the forms in which N and P are lost is essential to the development strategies to minimize nutrient losses to surface water. Nitrate-N and particulate N and P forms can best be trapped using wetlands, but dissolved P forms could be trapped using reactive materials that are placed, for example, around or at the ends of pipe drains or at the ends of trenches (Chardon et al., 2012).

The aim of this study was to quantify the N and P losses by the different pathways (overland flow, matrix flow, and macropore flow) to surface water from a heavy clay soil under grassland of a dairy farm in an area with a flat topography. This analysis is done by studying the timing and speciation of the discharge of N and P from trenches and pipe drains.

Materials and Methods
Experimental Field

The study was performed on a grassland field on a dairy farm near Waardenburg, which is located in a fluvial plain in the central part of The Netherlands (51°51″N, 5°14″E). The soil was a heavy clay and classified as a Eutric Fluvisol (FAO, 1988). The field was about 175 m long and 90 m wide and was drained by two trenches and 12 pipe drains (Fig. 1). The short side of the field adjoined a ditch that received all water discharged from the field. The ditch was also fed by other similar fields that were not monitored, and the total size of the catchment was about 40,000 m². The trenches and pipe drains were installed perpendicular to the ditch. The trenches had a width and depth of 0.5 m and had an intermediate distance of about 45 m. The land between the trenches was slightly (∼0.4 m) elevated compared with the trenches to facilitate rapid water drainage. The pipe drains had an intermediate distance of about 7 m and were installed at about 0.8 m below the soil surface. The groundwater level varied between 0 and 0.5 m below the soil surface in the winter period and dropped in summer to more than 1 m depth.

Agricultural Management and Nutrient Balances

The grassland field was dominated by English ryegrass (*Lolium perenne*) and was cut for silage and grazed between cuts in each year, which is common practice on dairy farms in The Netherlands. The number of grass harvests varied from six
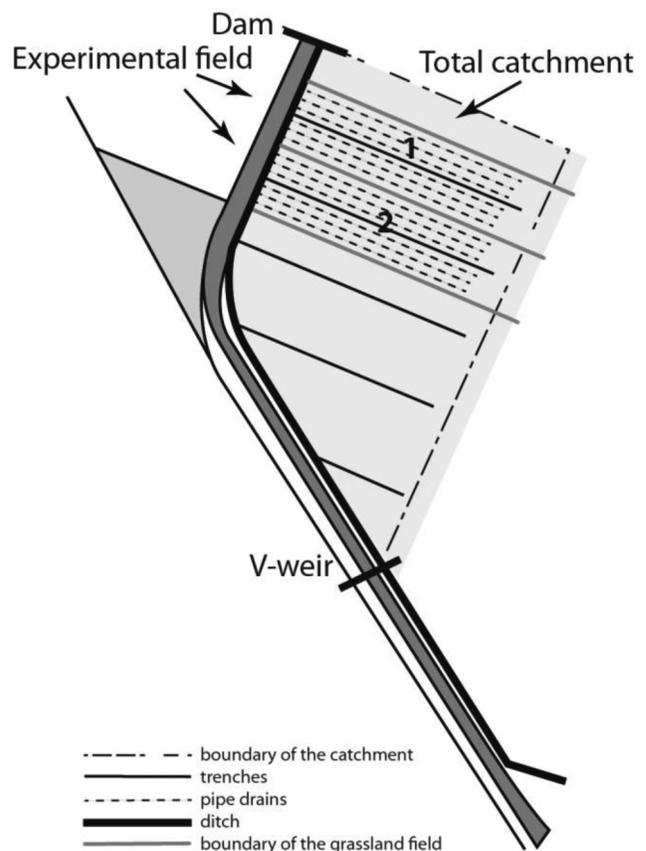

Fig. 1. Map of the catchment, experimental grassland field, and layout of drainage system with trenches, pipe drains, and ditches.

to nine per year. The agronomical N and P balances of the field for the years 2002–2004 and the years 2006 and 2007 were calculated by taking the difference between the input and output terms of the nutrient balances. These agronomical balances, referred to as "soil surface balances," do not include environmental nutrient losses like denitrification, leaching, or storage in the soil solid phase. Agronomical N and P balances are commonly used as environmental indicators (Csathó and Radimszky, 2009). Input terms of N and P were the application of inorganic fertilizer and cattle slurry, cattle feces deposited by grazing cows, and atmospheric deposition. Cattle slurry was applied two to three times a year in spring and summer using a trailing foot. Inorganic N fertilizer (calcium ammonium nitrate) was applied monthly in the period from March to June, and P fertilizer (triple super phosphate) was applied once a year in early spring. Output terms were grass cut for silage and grass consumed by grazing. The field was visually checked for N fixing legumes, which were generally absent, so biological N fixation was ignored in the N balance. The sizes of the input and output terms of the agronomical N and P balances (Table 1) were taken from van der Salm et al. (2007) and Koopmans et al. (2009). Within the experimental period, the N balance decreased from 200 kg N ha^{-1} in 2002 to 55 kg N ha^{-1} in 2007. Inorganic fertilizer and cattle slurry were the major N inputs, and silage was the major output. The P balance tended to decrease from 40 kg ha^{-1} in 2002 to −11 kg ha^{-1} in 2007. Similarly to N, cattle slurry and inorganic fertilizer were the major P inputs and silage was the major output. The N balance in 2002 was close to the average N balances on Dutch dairy

farms (Langeveld et al., 2007). The average P balance over the period 2002 to 2007 was close to the average P balance for Dutch dairy farms on clay soils (14 kg ha^{-1}) in The Netherlands (De Klijne et al., 2007).

Soil Characteristics

Soil samples were taken from the field in the autumn of 2003 from four different horizons (A_{pg}, C_g, C_{gr}, and C_r) to a depth of 1.5 m at five positions chosen randomly along four transects perpendicular to the ditch (Koopmans et al., 2005). Sampling of cattle manure and urine patches was avoided. Soil samples taken from the same horizon and transect were bulked; with four horizons and four transects, this resulted in 16 samples. Soil samples were dried at 40°C. Aggregates were broken up to pass a 2-mm sieve and were used to determine pH, soil organic matter (SOM), and different soil P pools. For the analysis of the shrinking potential of the soil, $CaCO_3$, soil texture, and total soil N content, a composite sample of the four soil samples from each horizon was used. The soil shrinkage potential can be expressed as the coefficient of linear extensibility (COLE) and was measured by drying soil clods (Bronswijk and Evers-Vermeer, 1990). For The Netherlands, a soil moisture range varying from saturation to oven dry (105°C) is normally used because this range gives good information about the swelling and shrinkage potential to be expected under Dutch conditions (Tiktak et al., 2012b). The pH, SOM, $CaCO_3$, and soil texture were determined using standard analytical procedures (Houba et al., 1997). The pH was measured in a settling 1:5 (w/v) suspension of soil in water. Soil organic matter was determined by loss-on-ignition in a muffle furnace at 550°C, and a correction was made for the amount of water bound to clay minerals. Calcium carbonate was determined by measuring the volume of CO_2 produced after the addition of HCl. Soil texture was determined via pipette and sieve after removal of $CaCO_3$ and organic matter. Soil solution was simulated by the extraction of soil with 0.01 mol L^{-1} $CaCl_2$ at a soil to solution ratio of 1:10 (w/v) (Houba et al., 2000). The $CaCl_2$ extracts were shaken on a reciprocating shaker at 165 strikes per minute. After centrifugation (1800 × g), ortho-P was measured colorimetrically as dissolved reactive P (DRP) using the molybdenum-blue method of Murphy and Riley (1962). Inorganic soil P was determined after extraction of soil with 0.5 mol L^{-1} H_2SO_4 and total P after combustion of organic matter in a muffle furnace (550°C), followed by extraction with 0.5 mol L^{-1} H_2SO_4 (Kuo, 1996). In these extracts, P was measured as DRP. Organic P was calculated as the difference between total P and inorganic P. Total N was determined after soil digestion with a mixture of H_2O_2 and H_2SO_4 under the influence of Se as a catalyst; salicylic acid ($C_7H_6O_3$) was added to prevent loss of nitrate (Novozamsky et al., 1983).

Measurement Program of Water Discharge and Nutrient Losses

In the periods 2002 to 2005 and 2006 to 2008, water discharge and nutrient losses from the pipe drains and trenches to the ditch were monitored continuously. The 12 pipe drains in the field were grouped into two sets of six adjacent drains. Water discharge from the two trenches and from the two sets of pipe drains was led to small collectors, each with a V-notch opening. Water discharge was recorded continuously by measuring the water level in the collectors. Water samples were taken by an autosampler (ISCO 3220 flow meter and a refrigerated ISCO 3700 sampler; Teledyne Isco Inc., Lincoln, NE) at discharge intervals of 0.12 mm. Upstream of the field, the ditch was blocked by a dam (Fig. 1). A weir with a V-notch opening and an autosampler was placed in the ditch downstream of the field. The water level near the weir was recorded continuously to measure the water discharge. Water samples were taken at discharge intervals of 0.25 mm. Water samples were stored in the dark and refrigerated at 5°C. Water samples were collected weekly and passed through a 0.45-μm filter (Aqua 30; Whatman, Piscataway, NJ) on arrival in the laboratory. The filtered and unfiltered samples were stored in the dark at 5°C and analyzed within 1 wk after collection. We divided the experimental period of our study into hydrological years, with each year lasting from 1 October to 30 September. Within the periods 2002 to 2005 and 2006 to 2008, there were five hydrological years (i.e., 2002/2003, 2003/2004, 2004/2005, 2006/2007, and 2007/2008). Winter was defined as the period from 1 October to 31 March in the subsequent year; summer was defined as the period from 1 April to 30 September.

Chemical Analyses of Water Samples

In the filtered water samples taken in the period 2002 to 2005, concentrations of NH_4 and (NO_2+NO_3)-N were measured, which were added and are referred to in this study as dissolved inorganic nitrogen (DIN). Ammonium was measured colorimetrically using continuous flow injection, and (NO_2+NO_3)-N was measured by ion chromatography (IC) using a Dionex DX-120 IC (Dionex, Sunnyvale, CA) system in combination with an UV detector for

Table 1. Agronomical nitrogen and phosphorus balances of the grassland field.

	N					P				
	2002	2003	2004	2006	2007	2002	2003	2004	2006	2007
	——————————————————————————— kg ha^{-1} ———————————————————————————									
Fertilizer	132	139	189	178	201	25	23	23	5	8
Cattle slurry	390	321	206	252	195	69	55	31	40	35
Cattle droppings	14	44	21	3	0	0	1	1	0	0
Deposition	34	34	34	53	53	1	1	1	1	1
Total input	570	538	450	486	449	95	80	56	46	44
Silage	324	285	388	350	344	50	40	57	44	48
Grazing	46	96	32	6	50	5	10	5	2	6
Total output	370	381	420	356	394	55	50	62	46	55
Balance	200	157	30	130	55	40	30	−6	0	−11

NO_2 and a conductivity detector for NO_3. Ortho-P was determined in these samples by IC using a conductivity detector. Because ortho-P in the filtered water samples taken in the period 2006 to 2008 was measured as DRP using the molybdenum-blue method (Murphy and Riley, 1962), the ortho-P measured by IC was referred to as DRP for simplicity. In a study by Ros et al. (2010), ortho-P concentrations measured by IC and as DRP in 1:10 (w/v) soil water extracts obtained from clay, sand, and peat soils were in good agreement. In the unfiltered water samples, Kjeldahl-N was determined (Jones and Case, 1990). After acid digestion of the samples with $K_2S_2O_8$, which converts organic N to NH_4, Kjeldahl-N was measured colorimetrically as NH_4. Because N present in the water samples as NO_2 and NO_3 is not recovered by the Kjeldahl procedure, (NO_2+NO_3)-N was added to Kjeldahl-N to calculate total N (TN). Total P (TP) in the unfiltered water samples was measured colorimetrically as DRP after acid digestion of the sample with $K_2S_2O_8$ (Ebina et al., 1983). In the filtered water samples taken in the period 2006 to 2008, DIN and TDN were measured using a segmented flow analyzer (SFA) (Skalar SK[12]). Dissolved organic N (DON) was calculated as the difference between TDN and DIN. Total dissolved phosphorus (TDP) was determined with an inductively coupled plasma–atomic emission spectrometer (Vista Pro; Varian). Dissolved unreactive P (DUP) was calculated as the difference between TDP and DRP. In the unfiltered water samples, TN and TP were measured by SFA after acid digestion of the sample (Ebina et al., 1983). Particulate N (PN) and particulate P (PP) were calculated as the difference between TN and TDN and TP and TDP, respectively. To calculate the nutrient losses from the field to the ditch through pipe drains and trenches, water discharge measured over each time interval was multiplied with the concentrations of the different N and P forms measured in the same period.

Meteorology

Precipitation was based on data from nearby meteorological stations in Geldermalsen and Herwijnen, which are located 7 km northeast and 9 km west of the field, respectively. Until November 2007, precipitation at the field was taken as the average of the values at each meteorological station. Thereafter, precipitation was recorded at the field with a tipping bucket rain gauge. Evapotranspiration was obtained from the meteorological station at Herwijnen and was based on the Makkink equation (Makkink, 1957), which calculates the reference evapotranspiration for grassland based on global radiation and temperature. Precipitation surplus at the field was calculated as the difference between precipitation and evapotranspiration. The 30-yr average precipitation and evapotranspiration amounted to 785 and 543 mm yr^{-1}, respectively, which leads to an average precipitation surplus of 242 mm yr^{-1} (Royal Dutch Meteorological Institute, 2010). The 30-yr average temperature was 9.8°C, with a minimum monthly average of 2.8°C in January and a maximum of 17.4°C in July.

Results and Discussion
Soil Properties

The chemical and physical characteristics of the soil samples taken from the grassland field are presented in Tables 2 and 3, respectively. The soil is a heavy clay soil, with a clay content varying between 46.7 and 58.5% and a silt content varying between 39.5 and 48.5%. Clay soils represent 42% of the agricultural land in The Netherlands, of which 13% are heavy clay soils (van der Salm et al., 2006). The soil has a COLE between 0.16 and 0.33, indicating a very high potential for shrinkage (Soil Survey Staff, 1975). The pH and $CaCO_3$ content increased with depth, whereas the opposite was true for SOM. Total soil P was 747 mg P kg^{-1} in the A_{pg} horizon and was larger than in the lower soil horizons. Organic soil P in the A_{pg} horizon amounted to 451 mg P kg^{-1} and showed a clear decrease with depth. In the upper horizon, 60% of total soil P was organic, but this decreased to 16 to 17% in the C_{gr} and C_r horizons. The elevated organic soil P level in the upper soil horizon is probably due to the contribution of organic P from grass residues. In the A_{pg} horizon, $CaCl_2$–extractable DRP was

Table 2. Selected chemical characteristics of the samples taken from the different soil horizons of the grassland field.

Soil horizon	Soil layer	pH (H_2O)	SOM†	$CaCO_3$	Total N	P-$CaCl_2$	Organic P‡	Total P
	m		———— g kg^{-1} ————			———— mg kg^{-1} ————		
A_{pg}	0–0.4	6.7 ± 0.2	54 ± 9	4	3.4	0.21 ± 0.12	451 ± 98	747 ± 143
C_g	0.4–1.0	7.6 ± 0.2	23 ± 7	7	1.6	0.06 ± 0.02	160 ± 73	494 ± 80
C_{gr}	1.0–1.3	7.7 ± 0.2	20 ± 5	19	ND§	0.10 ± 0.03	88 ± 62	580 ± 47
C_r	1.3–1.5	7.7 ± 0.2	25 ± 7	72	ND	0.09 ± 0.04	83 ± 24	523 ± 48

† SOM, soil organic matter.

‡ Calculated as difference between total P and inorganic P.

§ ND, not determined.

Table 3. Selected physical characteristics of the samples taken from the different soil horizons of the grassland field.

Soil horizon	Soil layer	Clay (<2 μm)	Silt (2–50 μm)	Sand (>50 μm)	COLE†
	m	————	% ————		–
A_{pg}	0–0.4	56.8	40.6	2.6	0.21
C_g	0.4–1.0	58.5	39.5	1.9	0.16
C_{gr}	1.0–1.3	53.1	42.5	4.3	0.17
C_r	1.3–1.5	46.7	48.5	4.8	0.33

† COLE, coefficient of linear extensibility.

0.21 mg P kg⁻¹; CaCl₂–extractable DRP decreased in the lower horizons. The solubility of P in this soil was very low, with CaCl₂–extractable P contributing less than 0.1% to total soil P.

Water Balance

Discharge of water from the grassland field to the ditch was mainly confined to the winter period, when precipitation exceeds the evapotranspiration of grass. Water discharge in summer was rare and limited to short periods with excessive rainfall. The average precipitation surplus of the five winter periods (October–March) amounted to 311 mm. The average water discharge from the ditch, which received all discharge from the field, was almost equal to this precipitation surplus (Fig. 2). Hence, upward seepage or leaching of water to a deeper aquifer was negligible. Indeed, an impermeable heavy clay layer with a thickness of 8 m is present in the subsoil of the field, which prevents vertical passage of water. The small difference between the discharge of the ditch and the precipitation surplus also indicates that the effect of changes in soil moisture content on the water balance were almost negligible. The average water discharge of the pipe drains and trenches to the ditch was 10% lower than the average discharge of the ditch (Fig. 2). This difference may be due to overland flow that did not reach the trenches or to seepage through the bank of the ditch. These water transport routes were not measured and were not included in the water balance. Moreover, the field covers only 40% of the total size of the catchment. The remaining part of the catchment draining to the ditch is comparable to the experimental field, but small differences in water discharge from this unmeasured part of the catchment may contribute to the 10% difference between discharge through the ditch and discharge through the pipe drains and trenches.

Water Transport Routes

The annual water discharge of the trenches varied between 145 and 256 mm (Fig. 3). Trenches were the main route for the transport of water, and they discharged on average 69% of the precipitation surplus. The water discharge through the pipe drains varied between 25 and 95 mm and accounted on average for 21% of the precipitation surplus. The relative importance of water discharge through the pipe drains was low compared with literature data for artificially drained sites in flat areas in other countries. Several studies in the United Kingdom, New Zealand, Canada, and the United States showed contributions of pipe drains to total water discharge between 70 and 92% (Algoazany et al., 2007; Culley et al., 1983; Logan et al., 1994; McDowell et al., 2005; McGechan, 2002). Most of the soils in these studies had a lighter texture (silty clay–clay loam) than the soil from the field studied here, which allows for more water transport toward the pipe drains. However, field experiments in Finland on soils with a texture comparable to the soil of the field showed a contribution of pipe drainage amounting to about 30 to 56% of the total water discharge (Koivusalo et al., 1999; Turtola and Paajanen, 1995; Turtola and Jaakkola, 1995), which is higher than the values recorded at our field. In our study, the lower contribution of pipe drainage to total water discharge is probably due to the presence of trenches. The land between the trenches had a slight curvature toward the trenches, which facilitated rapid transport of water to the
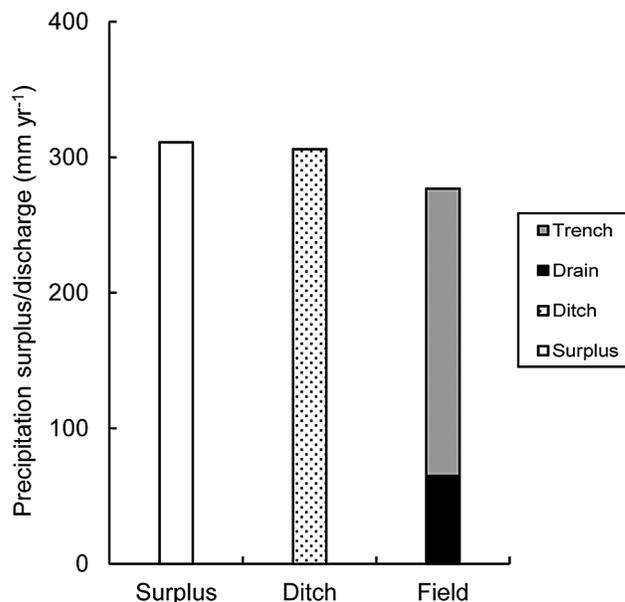

Fig. 2. Average precipitation surplus, discharge of the ditch, and discharge from the grassland field to the ditch through pipe drains and trenches of the different hydrological years in the periods 2002–2005 and 2006–2008.
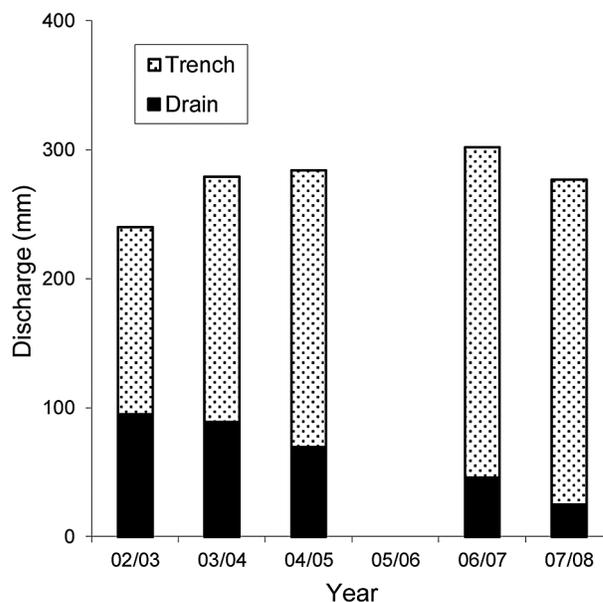

Fig. 3. Discharge of water through trenches and pipe drains to the ditch in each hydrological year of the periods 2002–2005 and 2006–2008. In the year 2005/2006, no measurements were done.

trenches. Accordingly, ponding was avoided, and infiltration of water into the soil and subsequent transport via the pipe drains to the ditch was limited. Similar artificial drainage networks, such as grassed waterways, surface or field drains, and furrows (e.g., Addiscott et al., 2000; Barlow et al., 2003; Fiener and Auerswald, 2009), are common on somewhat heavier textured soils worldwide.

Temporal Dynamics in Water Transport Routes

The annual contribution of pipe drainage to the total water discharge varied between 8 and 38% (Fig. 3). The variation in pipe

drainage seems to be related to differences in the precipitation surplus in summer, which lasts from April until October, preceding the winter, during which most of the water discharge occurs. The summer of 2002 was relatively dry, with a mild but continuous monthly precipitation deficit ranging from −10 to −28 mm. After this dry summer, water discharge in autumn was equally divided between the pipe drains and trenches and gradually decreased during the winter (Fig. 4A). In contrast, the summer of 2007 was wet, with a precipitation surplus of 101 mm. The monthly precipitation surplus in this summer ranged from 46 to 90 mm, except for April and August, which had precipitation deficits of −86 and −28 mm, respectively. After the wet summer of 2007, the contribution of pipe drainage to the total water discharge was low in autumn and almost ceased in December (Fig. 4B). The precipitation surplus may have influenced the
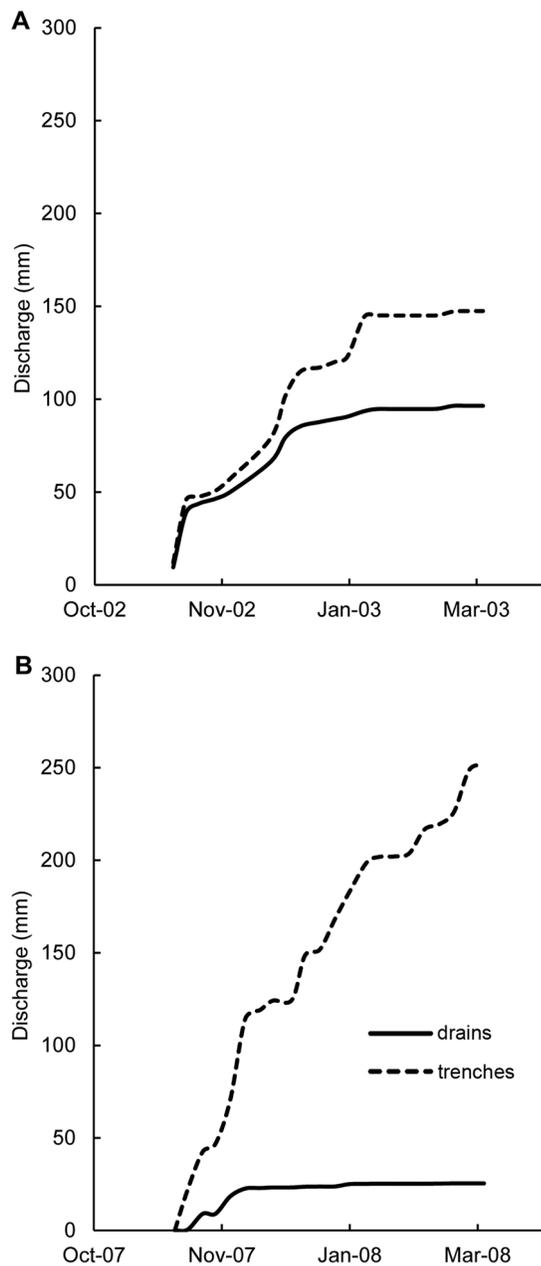

Fig. 4. Discharge of water through trenches (broken line) and pipe drains (solid line) in the winter after a dry summer in 2002 (A) and after a wet summer in 2007 (B).

swelling and shrinking of the heavy clay soil. During prolonged dry periods, shrinkage cracks are formed in clay soils (Bouma and Wösten, 1979; Bronswijk et al., 1995; Arnold et al., 2005), which allows for vertical water transport from the soil surface toward the pipe drains by macropore flow. The soil at this site has a very high COLE (Table 3) and is thus susceptible to the formation of shrinkage cracks. Large shrinkage cracks were regularly observed at the soil surface and in undisturbed soil samples up to a depth of 1 m during dryer periods. Continuous macropores were observed up to a depth of 1 m in a soil formed in similar clay deposits, with a somewhat lighter texture (28–37% clay) and a COLE of 0.10, located 40 km east of the grassland field (Tiktak et al., 2012a). Also in the dry summer of 2002, large clay cracks were present at the grassland field, which may explain the higher contribution of pipe drainage to the total water discharge in the winter of 2002/2003. In the course of the winter, the clay rewets and swells and shrinkage cracks disappear (Bouma and Wösten, 1979; Bronswijk et al., 1995; Arnold et al., 2005), which reduces the water discharge through pipe drains because the soil matrix of the field has a very low saturated hydraulic conductivity of about 1.3 mm d^{-1} (van der Salm et al., 2006). The summer of 2007 was wet, and shrinkage cracks were not visible at the soil surface, which may explain the lower water discharge through the pipe drains in 2007/2008 compared with 2002/2003.

The relative contribution of pipe drainage to the total water discharge in a hydrological year tends to decrease linearly (R^2 = 0.45) with the size of the precipitation surplus in the preceding summer (Fig. 5A). However, a large scatter exists between the various hydrological years. For example, the relative contribution of pipe drains to the total water discharge was much higher in 2002/2003 than in 2006/2007, whereas the summers preceding the winters in these hydrological years had a similar precipitation surplus. The summer of 2002 had a moderate but continuous precipitation deficit. On the other hand, July 2006 was fairly dry and was followed by an extremely wet August, which led to rewetting of the soil and disappearance of part of the clay shrinkage cracks. Moreover, the wet conditions in late summer led to poaching of the topsoil by grazing cattle and closing of the entries to cracks near the soil surface as well as soil compaction. In addition to the precipitation deficit, the length and the timing of the dry period may affect the formation of cracks and thus the relative contribution of pipe drainage to the total water discharge. Indeed, the relative contribution of pipe drainage was strongly correlated (R^2 = 0.97) to the number of consecutive months with a monthly precipitation deficit during summer (Fig. 5B). A multiple linear regression equation including the number of dry months and the monthly precipitation surplus did not lead to further improvement (data not shown).

Flux-Weighted Nutrient Concentrations and Total Nutrient Losses

The flux-weighted TP and TN concentrations in pipe drain and trench waters clearly exceeded the Dutch thresholds for TP (0.15 mg L^{-1}) and TN (2.2 mg L^{-1}) in surface waters (Table 4). Moreover, TP and TN concentrations in the ditch water were above these thresholds. Total P losses from the field to the ditch varied between 1.0 and 7.2 kg ha^{-1} yr^{-1}, with an average

of 3.0 kg ha^{-1} yr^{-1} (Fig. 6). This average is somewhat larger than the average TP loss from an artificially drained grassland plot on a heavy clay soil with a low soil P fertility status in Finland, as reported by Turtola and Jaakkola (1995). In their study, the average TP loss through pipe drains and surface runoff amounted to 1.6 kg ha^{-1} yr^{-1} at annual P inputs (42 and 84 kg ha^{-1} yr^{-1}), which were within the range of P inputs at our grassland field (Table 1). For N, total losses were between 8.6 and 19.0 kg ha^{-1} yr^{-1}, with an average of 15.1 kg ha^{-1} yr^{-1} (Fig. 6). This average is at the low end of the range in average TN losses from a fine sand under grass in Finland, which varied between 10 and 54 kg ha^{-1} yr^{-1} (Turtola and Kemppainen, 1998) and is lower than the TN losses on dairy farms on sand (73 kg N ha^{-1} yr^{-1}) and peat soils (38 ha^{-1} yr^{-1}) in The Netherlands (van Beek et al., 2009).

Incidental Losses

Differences in total nutrient losses between the five hydrological years were large, especially for P (Fig. 6). Annual TP loss varied by a factor of 7.1, whereas annual TN loss varied by a factor of 2.2. The variation in annual TP loss could not be explained by variation in the annual P balance (Fig. 6). The P balance tended to decrease with time during the period 2002 to 2008 (Table 1). In 2004 and 2006 to 2007, the P balance was zero or had negative values, meaning that more P was removed from the soil than was applied. Despite the negative P balance in some years, significant changes in the pool of total P were not expected during the experimental period (van der Salm et al., 2009) because the size of the total soil P pool is relatively large compared with the maximum value of the negative P balance. For example, total soil P in the upper 0.2 m of the grassland field amounted to 1742 kg ha^{-1}, whereas the maximum value of the negative P balance was only −11 kg ha^{-1}. In contrast, the negative P balance may have affected the pool of soluble P because the amount of CaCl$_2$–extractable DRP in the upper 0.2 m was only 0.49 kg ha^{-1}. However, DRP hardly contributed to the TP losses from the field.

Incidental losses (ILs) seemed to play an important role in controlling at least a part of the TP losses from the grassland field. According to Withers et al. (2003), fresh applications of P may cause ILs of dissolved and particulate forms of P to surface waters by surface runoff or subsurface leaching when precipitation interacts directly with animal manure or inorganic P fertilizer spread onto the soil surface. When ILs occur, they may contribute 50 to 98% of the TP loss within a hydrological year (Withers et al., 2003). In March 2005, P was applied in the form of inorganic fertilizer (25 March) and cattle slurry (1 March) to the field at rates of 18 and 20 kg ha^{-1}, respectively. Precipitation in the last week of March led to 8 mm of water discharge via pipe drains and trenches to the ditch. Consequently, the average weekly DRP and TP concentrations increased to 3.3 and 7.1 mg L^{-1}, respectively, in pipe drain water and 30 and 35 mg L^{-1}, respectively, in trench water (Fig. 7). During this IL, 56% of the TP loss in 2004/2005 took place, which explains, in part, the large TP loss in this hydrological year. Also in March 2004, P was applied in the form of cattle slurry at a rate of 12 kg ha^{-1}, which was followed 2 wk later by precipitation and 19 mm of water discharge through the trenches and 2 mm of water
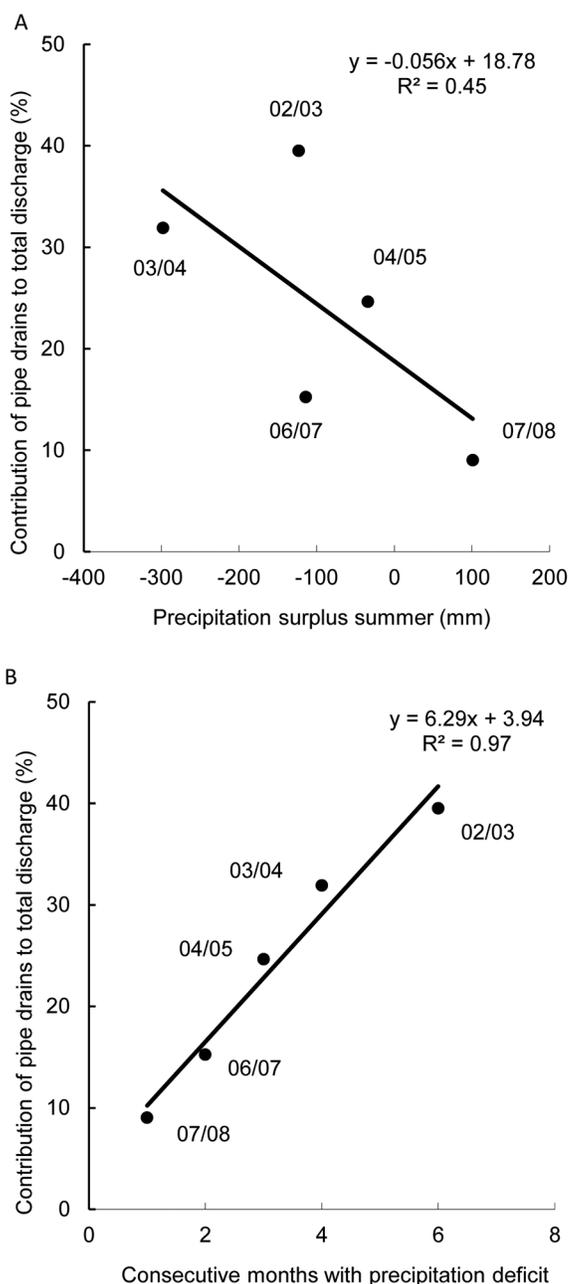
Fig. 5. Relative contribution of pipe drains to the total discharge from the grassland field as a function of the precipitation surplus in the preceding summer (A) and as a function of the number of consecutive dry months in the preceding summer (B).

discharge through the drain pipes. This IL accounted for 43% of the TP loss in 2003/2004. The ILs in March 2004 and in March 2005 also explain the high contribution of DRP to the TP losses through the trenches. In 2003/2004 and in 2004/2005, DRP contributed 67 and 65% to the TP losses through trenches, respectively, which is much higher than in the other hydrological years (Fig. 8). The above-mentioned ILs also influenced the contribution of DRP to the TP losses through pipe drains, which was 39% in 2003/2004 and 22% in 2004/2005 (Fig. 8), whereas in other hydrological years the contribution of DRP was on average 15%. Postponing the application of manure and fertilizers in spring to episodes with favorable weather forecasts could be used as a strategy

Table 4. Average flux-weighted concentrations of dissolved inorganic and total nitrogen and dissolved reactive and total phosphorus in pipe drain, trench, and ditch waters in the periods 2002–2005 and 2006–2008.

| | Flux-weighted average nutrient concentrations† | | | |
	DIN	TN	DRP	TP
	———————————— mg L⁻¹ ————————————			
Pipe drains	1.02	4.37	0.16	0.73
Trenches	1.47	6.46	0.64	1.32
Ditch	0.78	4.05	0.44	1.00

† DIN, dissolved inorganic nitrogen; DRP, dissolved reactive phosphorus; TN, total nitrogen; TP, total phosphorus.
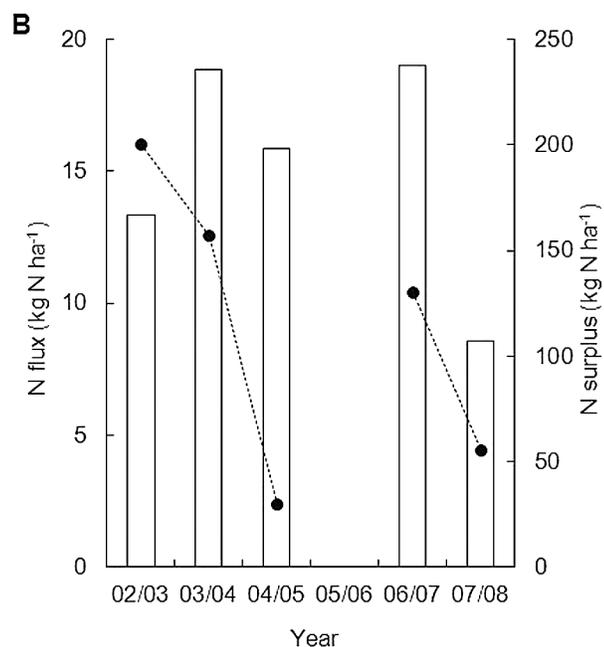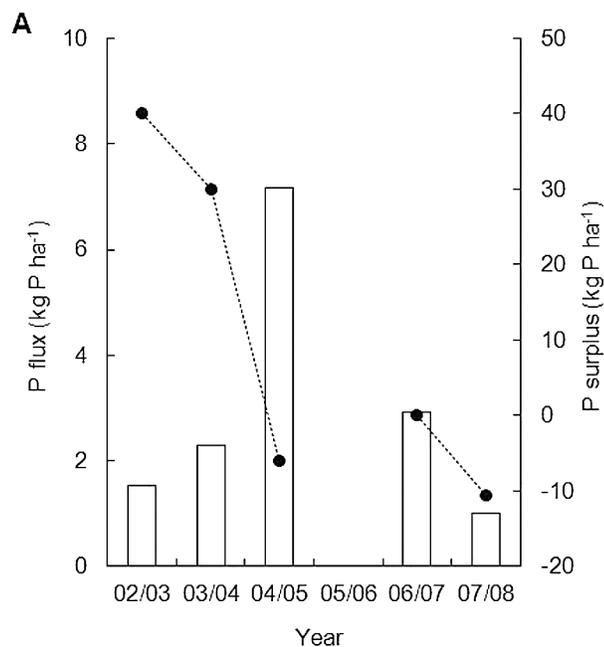

Fig. 6. Total P (A) and total N losses (B) losses from the grassland field in each hydrological year of the periods 2002–2005 and 2006–2008 (bars) and the P and N surpluses of the field (circles). In the year 2005/2006, no measurements were done.
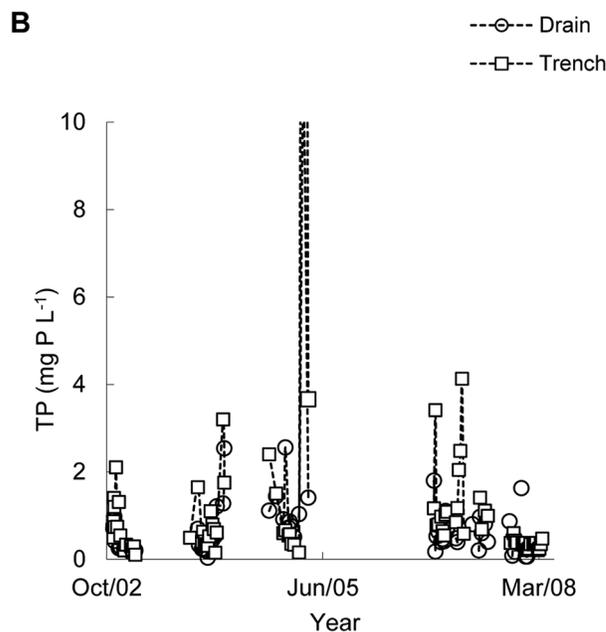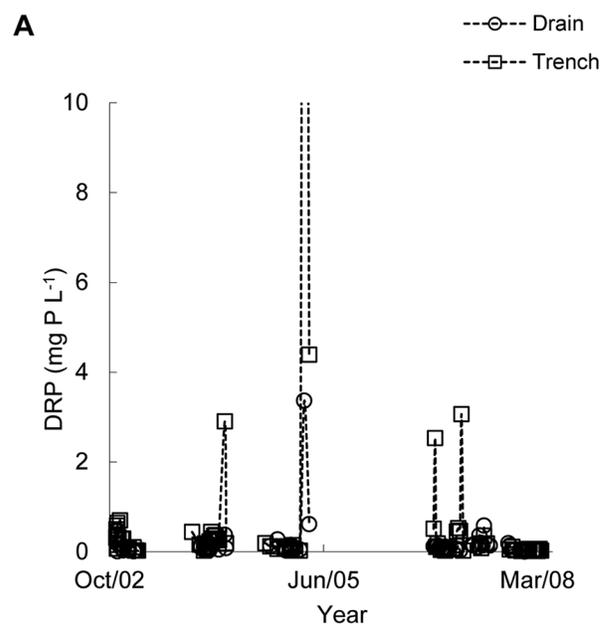
Fig. 7. Dissolved reactive P (DRP) (A) and total P (TP) (B) concentrations in pipe drain and trench waters during the monitoring periods 2002–2005 and 2006–2008. In March 2005, concentrations of DRP and TP in the trench water increased to 30 and 35 mg L⁻¹, respectively.
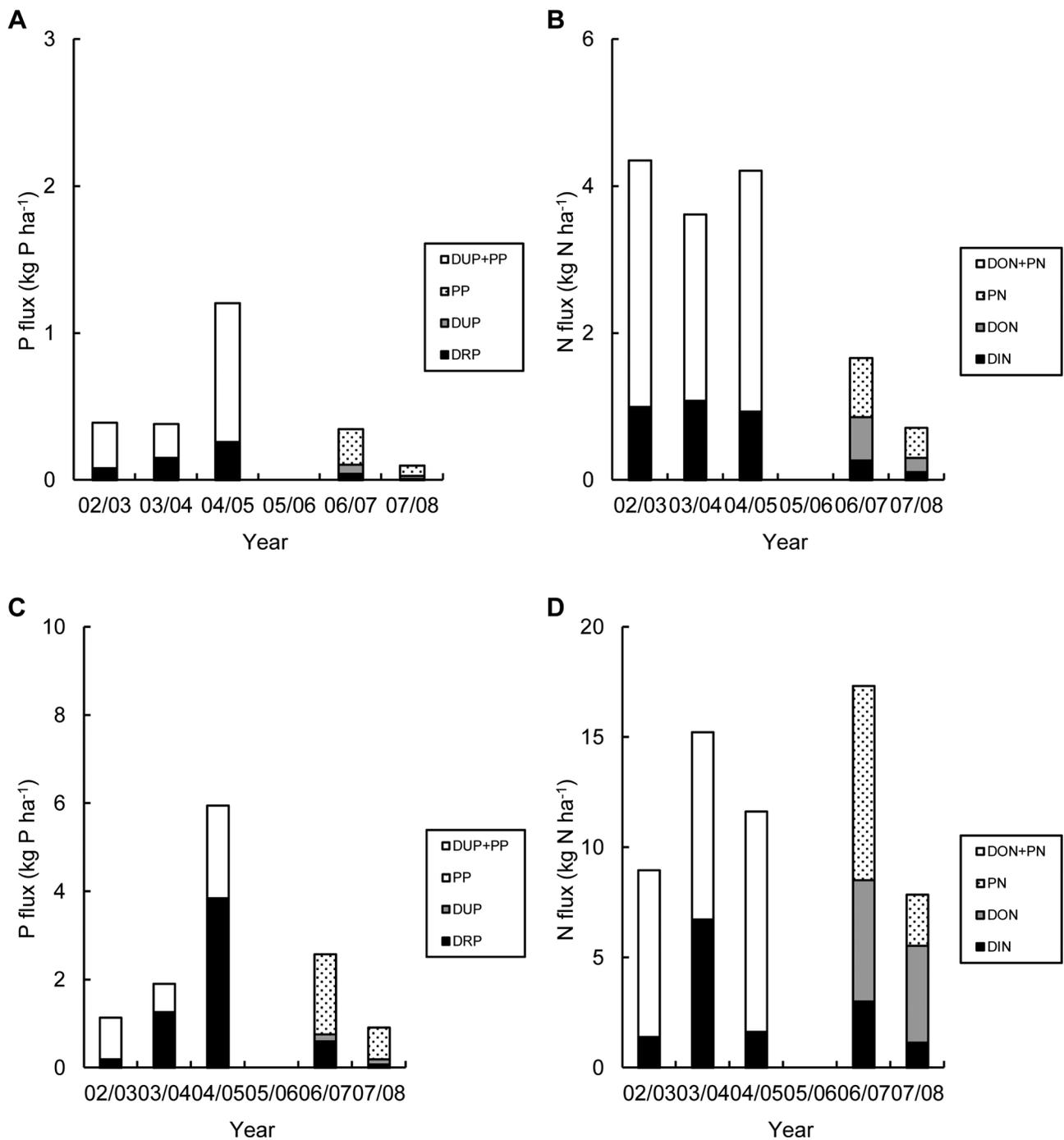
Fig. 8. Losses of different P and N forms via pipe drains (A and B) and via trenches (C and D) in each hydrological year of the periods 2002–2005 and 2006–2008. DIN, dissolve inorganic N; DON, dissolved organic N; DRP, dissolved reactive P; DUP, dissolved unreactive P; PN, particulate N; PP, particulate P.

to mitigate major ILs such as in March 2003/2004 and in March 2004/2005.

Nutrient Transport Routes

Total P losses from the field to the ditch through the pipe drains varied between 0.10 and 1.2 kg ha^{-1} yr^{-1}, with an average of 0.48 kg ha^{-1} yr^{-1} (Fig. 8A). For the trenches, TP losses were between 0.91 and 6.0 kg ha^{-1} yr^{-1}, with an average of 2.5 kg ha^{-1} yr^{-1} (Fig. 8C). Transport of P through pipe drains accounted for, on average, 16% of the annual TP loss, while the remaining 84% was transported through trenches. These results are in good

agreement with those of Turtola and Jaakkola (1995). In their study, P transport through pipe drains contributed, on average, 22% to the annual TP loss from a heavy clay soil under grass, even though the slope of their field (1–4%) was considerably greater than the slope of our field (<1%). Total N losses through pipe drains varied between 0.71 and 4.4 kg ha^{-1} yr^{-1}, with an average of 2.9 kg ha^{-1} yr^{-1} (Fig. 8B). For the trenches, TN losses were between 7.9 and 17.3 kg ha^{-1} yr^{-1}, with an average of 12.2 kg ha^{-1} yr^{-1} (Fig. 8D). Similar to P, trenches were the main route for the transport of N, with, on average, 81% of the annual TN loss, while the pipe drains contributed, on

average, 19%. Hence, most of the water (Fig. 3) and nutrients were transported from the field to the ditch through trenches despite the flat topography of the field. The average contribution of the pipe drains to the total water discharge was somewhat higher (21%) than their contribution to the total losses of P (16%) and N (19%).

Differences in annual total nutrient losses from the grassland field through pipe drains were large, especially for P, varying by a factor of 12.0, whereas annual TN loss varied by a factor of 6.1 (Fig. 8A and 8B). These differences could largely be explained by annual differences in the transport routes for water. Similar to the transport of water (Fig. 5B), the contribution of pipe drainage to the losses of P and N in a hydrological year was related to the number of consecutive months with a monthly precipitation deficit during the preceding summer (Fig. 9A, 9B). However, the relationships established for DRP (Fig. 9A), DIN, and TN (Fig. 9B) showed more scatter, and their correlation coefficients were lower (R^2 = 0.61, 0.55, and 0.77 for DRP, DIN, and TN, respectively) than for the transport of water (R^2 = 0.96) (Fig. 5B) and TP (R^2 = 0.96) (Fig. 9A) through pipe drains. One of the explanations for the observed scatter may be the occurrence of ILs in some years, leading to a stronger increase in nutrient loads in trenches compared with the ditches and thus a reduction of the relative contribution of pipe drains.

The strong relationships between the transport of water and nutrients and the length of the period with a precipitation deficit indicate that transport of water and nutrients through macropores (shrinkage cracks) may have a strong influence on the nutrient losses through pipe drains. Ortho-P is strongly bound by the soil matrix, and DRP concentrations in pipe drain water would be low if macropores were absent. An estimate of the DRP concentration in the soil solution can be obtained by performing an extraction of the soil with 0.01 mol L^{-1} $CaCl_2$ (Houba et al., 2000; McDowell and Sharpley, 2001). The average $CaCl_2$–extractable DRP amounts to 0.06 mg kg^{-1} at the depth of the pipe drains, corresponding to a DRP concentration of 0.006 mg L^{-1}. If the DRP losses through pipe drains were fully attributed to matrix flow using a DRP concentration of 0.006 mg L^{-1}, the total DRP loss over the whole experimental period would be 0.02 kg ha^{-1}, accounting for only 5% of the measured DRP loss. However, the DRP concentration measured in a 1:10 (w/v) 0.01 mol L^{-1} $CaCl_2$ extract probably underestimates the concentration in the soil solution due to the wide (1:10) soil to solution ratio (Koopmans et al., 2004). A comparison of the DRP concentrations in soil solutions, as measured with rhizon soil solution samplers with the results of the $CaCl_2$ extraction method using 10 different soils, showed that the average DRP concentration in the soil solution was 1.5 times higher than that in the $CaCl_2$ extracts (van Rotterdam-Los, 2010). Accordingly, the result of the $CaCl_2$ extraction method may be interpreted as a lower limit for the DRP concentration in the soil matrix. The average DRP concentration in pipe drain water in late winter before the first fertilization in spring (0.06 mg L^{-1}) may be used as an alternative upper limit for the DRP concentration measured in the $CaCl_2$ extract. In late winter, the DRP concentrations in pipe drain water may be close to the concentrations in the soil solution within the soil matrix because very few macropores are expected to be present
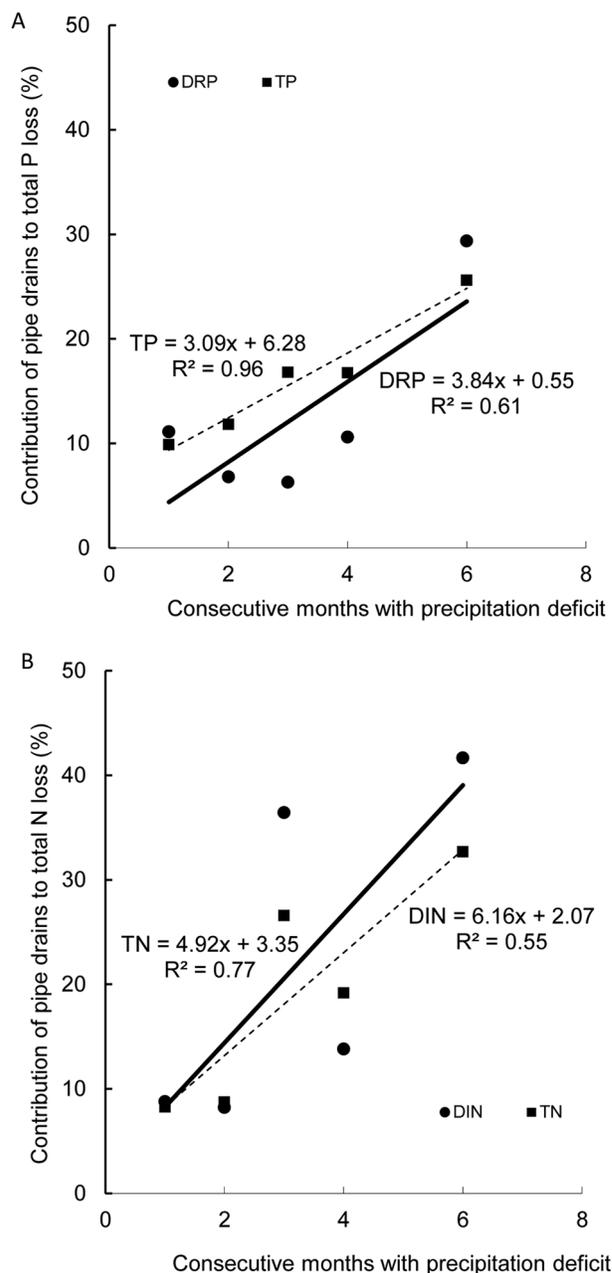

Fig. 9. Relative contribution of pipe drains to the total P (TP) and dissolved reactive P (DRP) loss (A) and total N (TN) and dissolve inorganic N (DIN) discharge loss (B) from the grassland field as a function of the number of consecutive dry months in the preceding summer.

due to the swelling of the clay soil. Moreover, sources for N and P are absent due to the lack of fertilization. The observed average DRP concentration in pipe drain water in late winter was also close to the average regional groundwater concentration in this area (0.04 mg L^{-1}) (Rozemeijer et al., 2005). The transport of DRP through the pipe drains resulting from matrix flow would be 0.21 kg ha^{-1} over the whole experimental period when based on the DRP concentration in late winter, which accounts for 35% of the measured DRP loss through the pipe drains. These two calculations indicate that 65 to 95% of the DRP losses through pipe drains may be the result of DRP transport through macropores toward the pipe drains, depending on the method chosen to estimate the DRP concentrations

in the soil matrix. Based on the concentrations in late winter, the contribution of the macropores for the more mobile solutes, such as DUP+PP, DON+PN, and DIN, was calculated to be 17, 39, and 55%, respectively.

Nutrient Forms in Pipe Drain and Trench Waters

In the period 2006 to 2008, loss of P through pipe drains was dominated by PP, which varied from 69 to 71% of TP (Fig. 8A). The contributions of DUP and DRP to the total losses were much lower, amounting to 18 to 19% and 10 to 13%, respectively (Fig. 8A). The P losses via the trenches was dominated by PP as well and ranged from 71 to 78%, whereas contributions of DUP and DRP amounted to 6 to 13% and 9 to 23%, respectively (Fig. 8C). In the same period, PN contributed 48 to 57% to the N losses from the pipe drains and 30 to 51% to the TN losses from the trenches (Fig. 8B, 8D). Contributions of DON and DIN to the TN losses from the pipe drains were 27 to 35% and 15 to 16%, respectively, whereas these N forms varied around 15 to 16% and 15 to 17% of the TN losses from the trenches (Fig. 8B, 8D). Hence, transport of particulate nutrient forms from the grassland field through pipe drains and trenches to the ditch was especially important for P and to a lesser extent for N. Because TDP and TDN concentrations in pipe drain and trench waters were not measured in the period 2002 to 2005, it was not possible to distinguish between DUP and PP forms and between DON and PN forms in this period. Contributions of DUP+PP to TP losses from the pipe drains and trenches in the period 2002 to 2005 varied between 61 and 85% and 33 and 83%, respectively (Fig. 8A, 8C). For DON+PN, the contributions were between 70 and 78% and 56 and 86% of the TN losses from the pipe drains and trenches, respectively (Fig. 8B, 8D). Because PP and PN were the quantitatively most important forms of P and N in the pipe drain and trench waters in the period 2006 to 2008, the particulate forms of these nutrients may have contributed largely to the annual TP and TN losses in the first period as well. The importance of PP forms in the transport of P from agricultural land to surface waters has been recognized in various studies, not only for surface runoff (Sharpley and Syers, 1983; Turtola and Jaakkola, 1995; Turtola and Kemppainen, 1998) but also for pipe drainage. For example, >50% of TP losses through pipe drains from clay and silt loam soils has been demonstrated to occur in the particulate form (Turtola and Jaakkola, 1995; Beauchemin et al., 1998; Ulén and Persson, 1999; Turtola and Kemppainen, 1998; Djodjic et al., 2000; McDowell and Koopmans, 2006). The role of PN in the transport of N from agricultural soils to surface waters has, however, received much less attention than the role of PP. In surface runoff, the contribution of PN to annual TN losses from a clay loam soil under conventional tillage and conservation tillage amounted to 12 and 26%, respectively (Tiessen et al., 2010), which is lower than the contribution of PN to the TN losses from the trenches in our study.

Detailed knowledge of the specific forms constituting PP and PN in pipe drain water remains limited (Toor et al., 2004). Concentrations of PP and PN in pipe drain and trench waters in 2006/2007 and in 2007/2008 clearly peaked when cattle slurry was applied in spring (Fig. 10). Cattle slurry may have been the primary source of these particulate nutrient forms.

Beside ortho-P, orthophosphate monoester compounds, such as inositol hexa*kis*phosphate, are important constituents of P in dairy manure (Toor et al., 2005a). Leaching of P from grassland soils treated with farm dairy effluent was found to occur mainly in the form of particulate unreactive P forms, which may, in part, consist of clay–inositol hexa*kis*phosphate complexes (Toor et al., 2003, 2005b). In the autumn and winter of 2006/2007 and 2007/2008, PP and PN concentrations in the pipe drain and trench waters were clearly lower than in spring (Fig. 10). In these periods, other processes than the application of cattle slurry may have been responsible for the PP and PN losses. Total soil P content in the soil solid phase was high throughout the soil profile of the field (Table 2). Clay-sized soil fractions are generally enriched in P, due to the high specific surface area in comparison with the silt- and sand-sized fractions, and exhibit an increased risk for erosion (Pierzynski et al., 1990). For example, Uusitalo et al. (2001) found clear
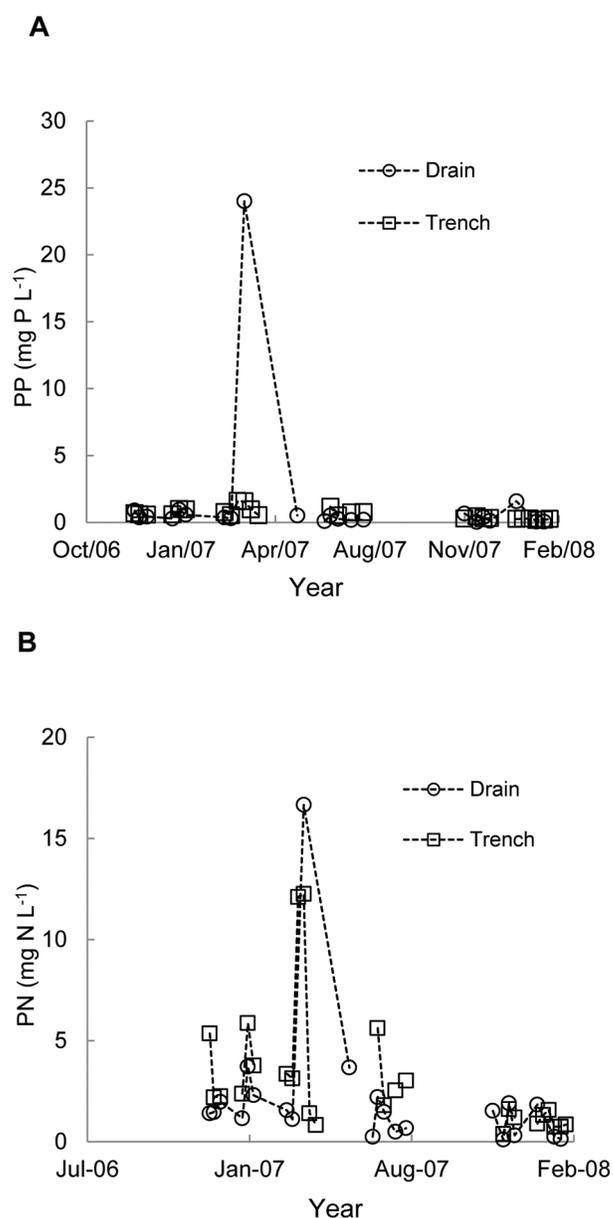
A

B

Fig. 10. Concentrations of particulate P (PP) and particulate N (PN) in pipe drain and trench waters in 2006–2008.

indications for the transport of P-enriched suspended clay particles by surface runoff and pipe drainage from a clay soil in Finland. Hence, erosion of P-enriched clay particles may have contributed to TP losses from the field.

Most of the N within the soil solid phase is of organic nature (Stevenson, 1982). King et al. (2009) found a strong correlation between total C and total N in sediments in runoff from a furrow-irrigated field. Thus, losses of PN are likely to occur in the form of transportable organic matter (Royer et al., 2007) or of complexes of clay with organic matter (Schulten et al., 1996).

Practical Implications and Conclusions

In this study, water and nutrient losses from a grassland field were studied during a 5-yr period. Our results showed that trenches are the dominant pathway for water and nutrients despite the level terrain. Annual nutrient losses were dominated by particulate forms. Rainfall occurring after manure application caused incidental N and P losses through the trenches and the pipe drains. The annual contribution of the pipe drains to the total water and nutrient discharge of the field was related to the number of months with a precipitation deficit in the preceding summer. This relationship can be explained by the very low conductivity of the soil matrix and the formation of shrinkage cracks during summer. The results of this study showed that the magnitude of nutrient losses and the transport routes varied strongly from year to year. Accordingly, data including at least a normal, a wet, and a dry year are necessary to gain insight into nutrient losses and transport routes and to develop successful strategies to minimize losses from agricultural land to surface waters. In this case, postponing the application of manure and fertilizers in spring to episodes with favorable weather forecasts could be used to decrease nutrient losses to surface water.

References

Addiscott, T.M., D. Brockie, J.A. Catt, D.G. Christian, G.L. Harris, K.R. Howse, N.A. Mirza, and T.J. Pepper. 2000. Phosphate losses through field drains in a heavy cultivated soil. J. Environ. Qual. 29:522–532. doi:10.2134/jeq2000.00472425002900020021x

Algoazany, A.S., P.K. Kalita, G.F. Czapar, and J.K. Mitchell. 2007. Phosphorus transport through subsurface drainage and surface runoff from a flat watershed in east central Illinois, USA. J. Environ. Qual. 36:681–693. doi:10.2134/jeq2006.0161

Arnold, J.G., K.N. Potter, K.W. King, and P.M. Allen. 2005. Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. Hydrol. Processes 19:589–603. doi:10.1002/hyp.5609

Barlow, K., D. Nash, H. Turral, and R. Crayson. 2003. Phosphorus uptake and release in surface drains. Agric. Water Manage. 63:109–123. doi:10.1016/S0378-3774(03)00177-X

Beauchemin, S., R.R. Simard, and D. Cluis. 1998. Forms and concentration of phosphorus in drainage water of twenty-seven tile-drained soils. J. Environ. Qual. 27:721–728. doi:10.2134/jeq1998.00472425002700030033x

Bouma, J., and J.H.M. Wösten. 1979. Flow patterns during extended saturated flow in two, undisturbed swelling clay soils with different macrostructures. Soil Sci. Soc. Am. J. 43:16–22. doi:10.2136/sssaj1979.03615995004300010003x

Breeuwsma, A., J.G.A. Reijerink, and O.F. Schoumans. 1995. Impact of manure on accumulation and leaching of phosphate in areas of intensive livestock farming. p. 239–249. In K. Steele (ed.) Animal waste and the land-water interface. CRC Press, Boca Raton, FL.

Bronswijk, J.J.B., and J.J. Evers-Vermeer. 1990. Shrinkage of Dutch clay soil aggregates. Neth. J. Agric. Sci. 38:175–194.

Bronswijk, J.J.B., W. Hamminga, and K. Oostindie. 1995. Field-scale solute transport in a heavy clay soil. Water Resour. Res. 31:517–526. doi:10.1029/94WR02534

CBS. 2010. StatLine. Dierlijke mest en mineralen; productie naar diercategorie. CBS, Den Haag/Heerlen. Available at http://statline.cbs.nl/StatWeb/publication/?VW=T&DM=SLNL&PA=37767&D1=a&D2=0&D3=a&HD=080623-1603&HDR=G1,T&STB=G2 (verified 2 Dec. 2011).

Chardon, W.J., J.E. Groenenberg, E.J.M. Temminghoff, and G.F. Koopmans. 2012. Use of reactive materials to bind phosphorus. J. Environ. Qual. (in press). doi:10.2134/jeq2011.0055.

Correll, D.L. 1998. The role of phosphorus in the eutrophication of receiving waters: A review. J. Environ. Qual. 27:261–266. doi:10.2134/jeq1998.00472425002700020004x

Csathó, P., and L. Radimszky. 2009. Two worlds within EU27: Sharp contrasts in organic and mineral nitrogen-phosphorus use, nitrogen-phosphorus balances, and soil phosphorus status: Widening and deepening gap between western and central Europe. Commun. Soil Sci. Plant Anal. 40:999–1019. doi:10.1080/00103620802693151

Culley, J.L.B., E.F. Bolton, and V. Bernyk. 1983. Suspended solids and phosphorus loads from a clay soil: I. Plot studies. J. Environ. Qual. 12:493–498. doi:10.2134/jeq1983.00472425001200040011x

De Klijne, A., A.E.J. Hooijboer, D.W. Bakker, O.F. Schoumans, and A. van den Ham. 2007. Environmental quality and nutrient surplus. Background report on the environmental quality of the Evaluation of the Fertilizers Act 2007. (In Dutch with English abstract.) Report 680130001/2007. National Institute of Public Health and Environment (RIVM), Bilthoven, the Netherlands.

Djodjic, F., B. Ulén, and L. Bergström. 2000. Temporal and spatial variations of phosphorus losses and drainage in a structured clay soil. Water Res. 34:1687–1695. doi:10.1016/S0043-1354(99)00312-7

Ebina, J., T. Tsutsui, and T. Shirai. 1983. Simultaneous determination of total nitrogen and total phosphorus in water using peroxodisulfate oxidation. Water Res. 17:1721–1726. doi:10.1016/0043-1354(83)90192-6

Emissieregistratie. 2010. Jaarcijfers 2008. RIVM, Bilthoven; PBL, Bilthoven; CBS, Den Haag; RWS-Waterdienst, Lelystad; Alterra, Wageningen; Agentschap.nl, Utrecht, Deltares, Utrecht en TNO, Utrecht. Available at http://www.emissieregistratie.nl (verified 2 Dec. 2011).

FAO. 1988. FAO-Unesco soil map of the world. Revised legend. Prepared by the Food and Agriculture Organization of the United Nations. FAO, Rome.

Fiener, P., and K. Auerswald. 2009. Effects of hydrodynamically rough grassed waterways on dissolved reactive phosphorus loads coming from agricultural watersheds. J. Environ. Qual. 38:548–559. doi:10.2134/jeq2007.0525

Geohring, L.D., O.V. McHugh, M.T. Walter, T.S. Steenhuis, M.S. Akhtar, and M.F. Walter. 2001. Phosphorus transport into subsurface drains by macropores after manure applications: Implications for best manure management practices. Soil Sci. 166:896–909. doi:10.1097/00010694-200112000-00004

Heathwaite, A.L., and R.M. Dils. 2000. Characterising phosphorus loss in surface and subsurface hydrological pathways. Sci. Total Environ. 251–252:523–538. doi:10.1016/S0048-9697(00)00393-4

Houba, V.J.G., J.J.G. van der Lee, and I. Novozamsky. 1997. Soil and plant analysis. Part 1: Soil analysis procedures. Wageningen Univ., Wageningen, the Netherlands.

Houba, V.J.G., E.J.M. Temminghoff, G.A. Gaikhorst, and W. van Vark. 2000. Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. Commun. Soil Sci. Plant Anal. 31:1299–1396. doi:10.1080/00103620009370514

Jones, J.B., Jr., and W.W. Case. 1990. Sampling, handling, and analyzing plant tissue samples. p. 389–427. In R.L. Westerman (ed.) Soil testing and plant analysis. 3rd ed. SSSA, Madison, WI.

King, A.P., K.J. Evatt, J. Six, R.M. Poch, D.E. Rolston, and J.W. Hopmans. 2009. Annual carbon and nitrogen loadings for a furrow-irrigated field. Agric. Water Manage. 96:925–930. doi:10.1016/j.agwat.2009.01.001

Koivusalo, H., M. Paasonen-Kivekas, T. Karvonen, and P. Vakkilainen. 1999. Water and nitrogen balance on a cultivated field: A characteristic hill-

slope approach. p. 157–162. *In* L. Heathwaite (ed.) Impact of land-use change on nutrient loads from diffuse sources. Proc. IUGG 99 Symposium HS3, Birmingham, July 1999. IAHS Publ. no. 257. IAHS Press, Wallingford, UK.

Koopmans, G.F., W.J. Chardon, I. Lubbers, J. Oenema, A. van den Toorn, and C. van der Salm. 2009. Diffuse loading of surface water with nutrients from grassland on a heavy clay soil: Monitoring of nutrient emission and speciation on a dairy farm near Waardenburg. (In Dutch.) Rep. 1738. Alterra, Wageningen, the Netherlands.

Koopmans, G.F., W.J. Chardon, P. de Willigen, and W.H. van Riemsdijk. 2004. Phosphorus desorption dynamics in soil and the link to a dynamic concept of bioavailability. J. Environ. Qual. 33:1393–1402. doi:10.2134/jeq2004.1393

Koopmans, G.F., W.J. Chardon, and C. van der Salm. 2005. Disturbance of water-extractable phosphorus determination by colloidal particles in a heavy clay soil from the Netherlands. J. Environ. Qual. 34:1446–1450. doi:10.2134/jeq2005.0028

Kuo, S. 1996. Phosphorus. p. 869–919. *In* D.L. Sparks (ed.) Methods of soil analysis. Part 3. SSSA Book Ser. 5. SSSA, Madison, WI.

Langeveld, J.W.A., A. Verhagen, J.J. Neeteson, H. Van Keulen, J.G. Conijn, R.L.M. Schils, and J. Oenema. 2007. Evaluating farm performance using agri-environmental indicators: Recent experiences for nitrogen management in the Netherlands. J. Environ. Manage. 82:363–376. doi:10.1016/j.jenvman.2005.11.021

Logan, T.J., D.J. Eckert, and D.G. Beak. 1994. Tillage, crop and climatic effects on runoff and tile drainage losses of nitrate and four herbicides. Soil Tillage Res. 30:75–103. doi:10.1016/0167-1987(94)90151-1

Makkink, G.F. 1957. Testing the Penman formula by means of lysimeters. J. Inst. Water Eng. 11:277–288.

McDowell, R.W., and G.F. Koopmans. 2006. Bioavailability of dissolved organic phosphorus in pasture and cultivated soils treated with different rates of nitrogen fertiliser. Soil Biol. Biochem. 38:61–70. doi:10.1016/j.soilbio.2005.03.026

McDowell, R.W., R.M. Monaghan, L.C. Smith, G.F. Koopmans, and I. Stewart. 2005. Enhanced losses of phosphorus in mole-tile drainage water following short-term applications of dairy effluent to pasture. p. 55–76. *In* A.R. Burk (ed.) Water pollution: New research. Nova Sci. Publ., Hauppauge, NY.

McDowell, R.W., and A.N. Sharpley. 2001. Approximating phosphorus release from soils to surface runoff and subsurface drainage. J. Environ. Qual. 30:508–520. doi:10.2134/jeq2001.302508x

McGechan, M.B. 2002. Effects of timing of slurry spreading on leaching of soluble and particulate inorganic phosphorus explored using the MACRO model. Biosystems Eng. 83:237–252. doi:10.1006/bioe.2002.0115

Murphy, J., and J.P. Riley. 1962. A modified single solution method for the determination of phosphate in natural waters. Anal. Chim. Acta 27:31–36. doi:10.1016/S0003-2670(00)88444-5

Novozamsky, I., V.J.G. Houba, R. van Eck, and W. van Vark. 1983. A novel digestion technique for multi-element plant analysis. Commun. Soil Sci. Plant Anal. 14:239–249. doi:10.1080/00103628309367359

Pierzynski, G.M., T.J. Logan, S.J. Traina, and J.M. Bigham. 1990. Phosphorus chemistry and mineralogy in excessively fertilized soils: Quantitative analysis of phosphorus-rich particles. Soil Sci. Soc. Am. J. 54:1576–1583. doi:10.2136/sssaj1990.03615995005400060011x

Reijneveld, J.A., P.A.I. Ehlert, A.J. Termorshuizen, and O. Oenema. 2010. Changes in the soil phosphorus status of agricultural land in the Netherlands during the 20th century. Soil Use Manage. 26:399–411. doi:10.1111/j.1475-2743.2010.00290.x

Ros, G.H., C. Tschudy, W.J. Chardon, E.J.M. Temminghoff, C. van der Salm, and G.F. Koopmans. 2010. Speciation of dissolved organic nutrients in grassland soils. Soil Sci. 175:15–26. doi:10.1097/SS.0b013e3181c8ef3c

Royal Dutch Meteorological Institute. 2010. Data available at http://www.knmi.nl (verified 2 Dec. 2011).

Royer, I., D.A. Angers, M.H. Chantigny, R.R. Simard, and D. Cluis. 2007. Dissolved organic carbon in runoff and tile-drain water under corn and forage fertilized with hog manure. J. Environ. Qual. 36:855–863. doi:10.2134/jeq2006.0355

Rozemeijer, J., J. Griffioen, and H. Passier. 2005. The concentration of phosphorus in regional seepage water in the Netherlands. (In Dutch.) Rep. 005.105B0710. TNO, Utrecht, the Netherlands.

Schoumans, O.F., and P. Groenendijk. 2000. Modeling soil phosphorus levels and phosphorus leaching from agricultural land in the Netherlands. J. Environ. Qual. 29:111–116. doi:10.2134/jeq2000.00472425002900010014x

Schulten, H.R., P. Leinweber, and B.K.G. Theng. 1996. Characterization of organic matter in an interlayer clay-organic complex from soil by pyrolysis methylation-mass spectrometry. Geoderma 69:105–118. doi:10.1016/0016-7061(95)00054-2

Sharpley, A.N., and J.K. Syers. 1983. Transport of phosphorus in surface runoff as influenced by liquid and solid fertilizer phosphate addition. Water Air Soil Pollut. 19:321–326.

Soil Survey Staff. 1975. Soil taxonomy: A basic system for soil classification for making and interpreting soil surveys. USDA Agric. Handbook 436. U.S. Govt. Print Off., Washington, DC.

Stevenson, F.J. 1982. Origin and distribution of nitrogen in soil. p. 1–42. *In* F.J. Stevenson et al. (ed.) Nitrogen in agricultural soils. ASA, CSSA, SSSA, Madison, WI.

Tiessen, K.H.D., J.A. Elliott, J. Yarotski, D.A. Lobb, D.N. Flaten, and N.E. Glozier. 2010. Conventional and conservation tillage: Influence on seasonal runoff, sediment, and nutrient losses in the Canadian prairies. J. Environ. Qual. 39:964–980. doi:10.2134/jeq2009.0219

Tiktak, A., R.F.A. Hendriks, and J.J.T.I. Boesten. 2012a. Simulation of movement of pesticides towards drains with a preferential flow version of PEARL. Pest Manag. Sci. (in press) doi:10.1002/ps.2262.

Tiktak, A., R.F.A. Hendriks, J.J.T.I. Boesten, and A.M.A. van der Linden. 2012b. A spatially distributed model of pesticide movement in Dutch macroporous soils. Vadose Zone J. (in press).

Toor, G.S., B.J. Cade-Menun, and J.T. Sims. 2005a. Establishing a linkage between phosphorus forms in dairy diets, feces, and manures. J. Environ. Qual. 34:1380–1391. doi:10.2134/jeq2004.0232

Toor, G.S., L.M. Condron, B.J. Cade-Menun, H.J. Di, and K.C. Cameron. 2005b. Preferential phosphorus leaching from an irrigated grassland soil. Eur. J. Soil Sci. 56:155–168. doi:10.1111/j.1365-2389.2004.00656.x

Toor, G.S., L.M. Condron, H.J. Di, and K.C. Cameron. 2004. Seasonal fluctuations in phosphorus loss by leaching from a grassland soil. Soil Sci. Soc. Am. J. 68:1429–1436. doi:10.2136/sssaj2004.1429

Toor, G.S., L.M. Condron, H.J. Di, K.C. Cameron, and B.J. Cade-Menun. 2003. Characterization of organic phosphorus in leachate from a grassland soil. Soil Biol. Biochem. 35:1317–1323. doi:10.1016/S0038-0717(03)00202-5

Turtola, E., and A. Jaakkola. 1995. Loss of phosphorus by surface runoff and leaching from a heavy clay soil under barley and grass ley in Finland. Acta Agric. Scand. B Soil Plant Sci. 45:159–165.

Turtola, E., and E. Kemppainen. 1998. Nitrogen and phosphorus losses in surface runoff and drainage water after application of slurry and mineral fertilizer to perennial grass ley. Agric. Food Sci. Finl. 7:569–581.

Turtola, E., and A. Paajanen. 1995. Influence of improved subsurface drainage on phosphorus losses and nitrogen leaching from a heavy clay soil. Agric. Water Manage. 28:295–310. doi:10.1016/0378-3774(95)01180-3

Ulén, B., and K. Persson. 1999. Field-scale phosphorus losses from a drained clay soil in Sweden. Hydrol. Processes 13:2801–2812. doi:10.1002/(SICI)1099-1085(19991215)13:17<2801::AID-HYP900>3.0.CO;2-G

Uusitalo, R., E. Turtola, T. Kauppila, and T. Lilja. 2001. Particulate phosphorus and sediment in surface runoff and drainflow from clayey soils. J. Environ. Qual. 30:589–595. doi:10.2134/jeq2001.302589x

van Beek, C.L., C. van der Salm, A.C.C. Plette, and H. van de Weerd. 2009. Nutrient loss pathways from grazed grasslands and the effects of decreasing inputs: Experimental results for three soil types. Nutr. Cycling Agroecosyst. 83:99–110. doi:10.1007/s10705-008-9205-z

van der Salm, C., W.J. Chardon, G.F. Koopmans, J.C. van Middelkoop, and P.A.I. Ehlert. 2009. Phytoextraction of phosphorus-enriched grassland soils. J. Environ. Qual. 38:751–761. doi:10.2134/jeq2008.0068

van der Salm, C., J. Dolfing, M. Heinen, and G.L. Velthof. 2007. Estimation of N losses via denitrification from a heavy clay soil under grass. Agric. Ecosyst. Environ. 119:311–319. doi:10.1016/j.agee.2006.07.018

van der Salm, C., J. Dolfing, J.W. van Groenigen, M. Heinen, G. Koopmans, J. Oenema, M. Pleijter, and A. van den Toorn. 2006. Diffuse loading of surface water with nutrients from grassland on a heavy clay soil. Monitoring of nutrient emission on a dairy farm in Waardenburg. (In Dutch.) Rep. 1266. Alterra, Wageningen, The Netherlands.

van Rotterdam-Los, D. 2010. The potential of soils to supply phosphorus and potassium. Processes and predictions. PhD thesis, Wageningen Univ., Wageningen, the Netherlands.

Withers, P.J.A., B. Ulén, C. Stamm, and M. Bechmann. 2003. Incidental phosphorus losses: Are they significant and can they be predicted? J. Plant Nutr. Soil Sci. 166:459–468. doi:10.1002/jpln.200321165