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Surface Water Quality

Nutrient losses over time via surface runoff and subsurface drainage from an agricultural field in northern Sweden

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Abstract
Nitrogen (N) and phosphorus (P) losses, via both surface runoff and subsurface drainage water, were monitored in an agricultural field in northern Sweden for 32 yr. The objective was to determine losses of N and P in a long-term perspective in relation to meteorological factors and impacts of agricultural land use, with a focus on relative contributions of surface runoff and subsurface drainage water to N and P losses. In order to collect surface runoff water, an embankment was installed on three sides of the field, and the fourth side had an open ditch that drove runoff water to a measuring station. Subsurface water draining from the field was collected in a fishbone-shaped drainage system that terminated at the measuring station. In 50% of years (16/32), mean annual concentration of total N (TN) was significantly higher in subsurface drainage water than in surface runoff water. An opposing trend was seen for total P (TP), with mean annual concentration being significantly higher in surface runoff water than in subsurface drainage water in all but 3 of the 32 yr monitored. Years with a barley crop had higher TN concentration in subsurface drainage water but no difference in surface runoff compared with years with ley. In contrast, years with barley had lower TN concentration in surface runoff than years with ley, with no difference in TP in subsurface drainage water.

1 | INTRODUCTION

Phosphorus (P) and nitrogen (N) can be transported from agricultural land to surrounding watersheds via both surface runoff and subsurface drainage, increasing the risk of eutrophication of surface water. In northern Sweden, a large proportion of annual surface runoff occurs during snowmelt in spring, and this seasonal flow pattern significantly affects the path taken by water and nutrients draining from agricultural fields. Runoff during snowmelt increases surface runoff relative to subsurface drainage due to partially frozen soil impeding infiltration and movement to subsurface drains (Griffith et al., 2020). However, snowmelt is generally less erosive than runoff caused by rainfall (Ulén, 2003). According to Griffith et al. (2020), up to 87% of cumulative total P (TP) can be lost through surface runoff in such circumstances, with subsurface drainage being a minor pathway for P losses at their hillslope study site with major surface runoff during snowmelt. A Finnish study found similar

Abbreviations: TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus.

concentrations of TP in surface runoff and subsurface drainage water from two clayey soils (Uusitalo et al., 2001). Tan and Zhang (2011) found that only 3% of total flow and 3–5% of TP losses from a clay soil occurred via surface runoff, with the rest occurring via subsurface drainage, although this was probably due to extensive preferential flow through the soil at their specific study site.

In the case of N, surface runoff generally accounts for a minor part of losses from agricultural fields, making up ∼20% of cumulative export relative to subsurface drainage losses in the study by Griffith et al. (2020). In a Norwegian study, the relative contribution of N losses via surface runoff were similar for six cropping systems studied, and there were significant differences in N losses via subsurface drainage between these cropping systems (Korsaeth & Eltun, 2000). In another study of two agricultural fields in Norway, Bechmann (2014) found that the majority of N losses occurred through subsurface drainage (95 and 87%, respectively) relative to surface runoff.

Long-term monitoring of water quality in the agricultural landscape is of great importance for understanding and mapping losses and nutrient cycling in agricultural systems. This paper presents results from long-term monitoring at 1 of 13 individual agricultural sites in Sweden established between 1973 and 1988. The results are from Field 14AC in northern Sweden, the only site with monitoring of both subsurface drainage and surface runoff water; the other sites only have subsurface drainage monitoring systems. These agricultural fields provide a unique time series of monitoring of N and P losses and their correlation with agricultural management, soil properties, and weather conditions. The objective of the present study was to assess losses of N and P in subsurface drainage and surface runoff water from an agricultural field in northern Sweden during 32 yr and to determine how the losses vary (a) in the long-term perspective, (b) with season within years, and (c) with cropping system in the field. Concentrations of chemical parameters, such as selected ions, in subsurface drainage and surface runoff water were also assessed.

Core Ideas

- The site was characterized by long, cold winters and a ley–barley cropping system.
- Surface runoff had a distinct peak during snowmelt in April (49% of yearly surface runoff).
- Total N content was ∼38% higher in subsurface drainage water than in surface runoff water.
- Total P content was ∼85% higher in surface runoff water than in subsurface drainage water.
- Crops grown at the site affected yearly losses of N and P in contrasting ways.

2 | MATERIALS AND METHODS

The monitored field (national code 14AC) occupies an area of 8 ha and is situated at the Röbäcksdalen Field Research Station in northern Sweden (63˚48′29.1″ N, 20˚14′31.9″ E). The experimental site was established in the 1950s as a drainage experiment and has been maintained in its present form since 1988. Silty loam soil texture (61% silt, 34% sand, and 5% clay in topsoil) is evenly distributed across the field, except for a small area with slightly higher clay content. Soil pH was 6.1, and extractable P-AL was 10.3 mg 100 g^{-1}, which is in the range of good agronomic status. Detailed soil characteristics are presented in Supplemental Table S1. Mean annual temperature in the region is 3.9 ˚C, and mean annual precipitation is 635 mm (Umeå/Röbäcksdalen, climatological standard normal 1991–2020; Swedish Meteorological and Hydrological Institute, https://www.smhi.se).

Crops grown at the site over the years are typical for a dairy farm in the region, with mainly perennial ley (mix of timothy [*Phleum pratense* L.] and red clover [*Trifolium pratense* L.]) and barley (*Hordeum vulgare* L.). Smaller sub-areas (<1 ha) within the field are used for short-term and long-term field trials, which in some years have included other crops, such as Irish potato (*Solanum tuberosum* L.) and reed canarygrass (*Phalaris arundinacea* L.). The field is managed by research farm staff according to ordinary farming practices, and information about agricultural practices (e.g., crops and fertilization) is reported annually (Table 1). Cow manure (usually 30 t ha^{-1}) and fertilizer were usually applied in May or June. Spring barley and the undersown ley mixture were sown in late May or early June. Moldboard ploughing was performed in September or October. Spring barley was harvested in September, and ley was harvested two or three times during June–September. The smaller sub-areas within the field sometimes had other management practices or timing.

The subsurface drainage system (mainly clay pipes, ∼1 m depth) in the field is laid out in a fishbone pattern with ∼25 m spacing, with the main pipe (diameter, 125 mm) entering an underground measuring station at the side of the field (Figure 1). Surface runoff water is collected by a ditch situated along one side of the field with an incline toward an underground measuring station. To keep surface runoff water within the field, a soil embankment surrounds the sides (Figure 1). The terrain in the field is gently undulating, with a slope of ∼0.5–1% toward the ditch and the measuring station.

2.1 | Experimental station, water sampling, and analysis

Subsurface drainage water and surface runoff water from the field are conducted at the measuring station, where the water

TABLE 1 Crops grown in Field 14AC during the study period (1988–2020) and amounts of N and P applied annually in manure and fertilizer

Year	Crop acreage			Manure		Fertilizer	
	2–8	1–2	<	N	P	N	P
	ha			kg ha^{-1}			
1988	barley	ley[a]	potato			38	11
1989	barley	ley	oilseed rape			19	18
1990	barley/ley		oats			63	25
1991	ley	barley		81	11	43	9
1992	ley	barley	oats	81	11	46	17
1993	ley	barley		48	7	48	16
1994	barley	ley	potato			33	9
1995	barley	oats/winter wheat	ley	48	7	46	14
1996	barley		ley/oats/peas	48	7	46	11
1997	barley		ley			43	6
1998	ley	barley	potato	8	1	20	6
1999	barley		ley/oats/peas	48	7	41	1
2000	barley		ley			60	8
2001	barley/ley					42	11
2002	ley	barley	oats	48	7	53	20
2003	ley/barley			48	7	71	12
2004	barley/ley		field bean	48	7	49	10
2005	barley		ley	48	7	31	11
2006	barley	ley		81	11	46	7
2007	barley	ley				39	7
2008	barley	reed canarygrass				52	14
2009	barley		ley			59	0
2010	ley	reed canarygrass				54	6
2011	ley	reed canarygrass	barley			62	5
2012	ley	reed canarygrass	barley			44	1
2013	ley	ryegrass	barley			44	2
2014	ley	ryegrass/barley		97	14	48	5
2015	barley		ley	97	14	41	0
2016	ley	barley		113	16	11	0
2017	ley	barley/oats		8	1	61	1
2018	ley	barley		8	1	130	0
2019	ley		barley	97	14	75	2

[a]Mix of timothy and red clover.

flow is slowed down in two separate concrete dams in which the water level is recorded over a Thomson V-notch. The water level is recorded continuously with a water stage recorder, and the chart is digitalized on an hourly basis, based on which water flow is calculated. Since 2010, the water level has been recorded by a CR1000 data logger (Campbell Scientific Ltd.). Manual water sampling (grab sampling) is performed at the V-notches every second week during drainage periods. Since 2010, flow-proportional water subsamples (~20 ml per occasion) have been taken using peristaltic pumps after 0.1 mm of runoff and collected in glass bottles. The glass bottles are emptied every second week during drainage periods for analysis of the water.

Since 2010, total phosphorus (TP), phosphate-phosphorus (PO_4–P), TN, nitrate-nitrogen plus nitrite-nitrogen (NO_3^-–N + NO_2–N), total organic carbon (TOC), and suspended material have been analyzed in flow-proportional water samples; ammonium nitrogen (NH_3^+–N), pH, alkalinity, and electrical conductivity are analyzed in grab samples. Before 2010, all analyses were performed on grab samples. The methods used for analysis during the study period (1988–2020) are presented in Supplemental Table S2.

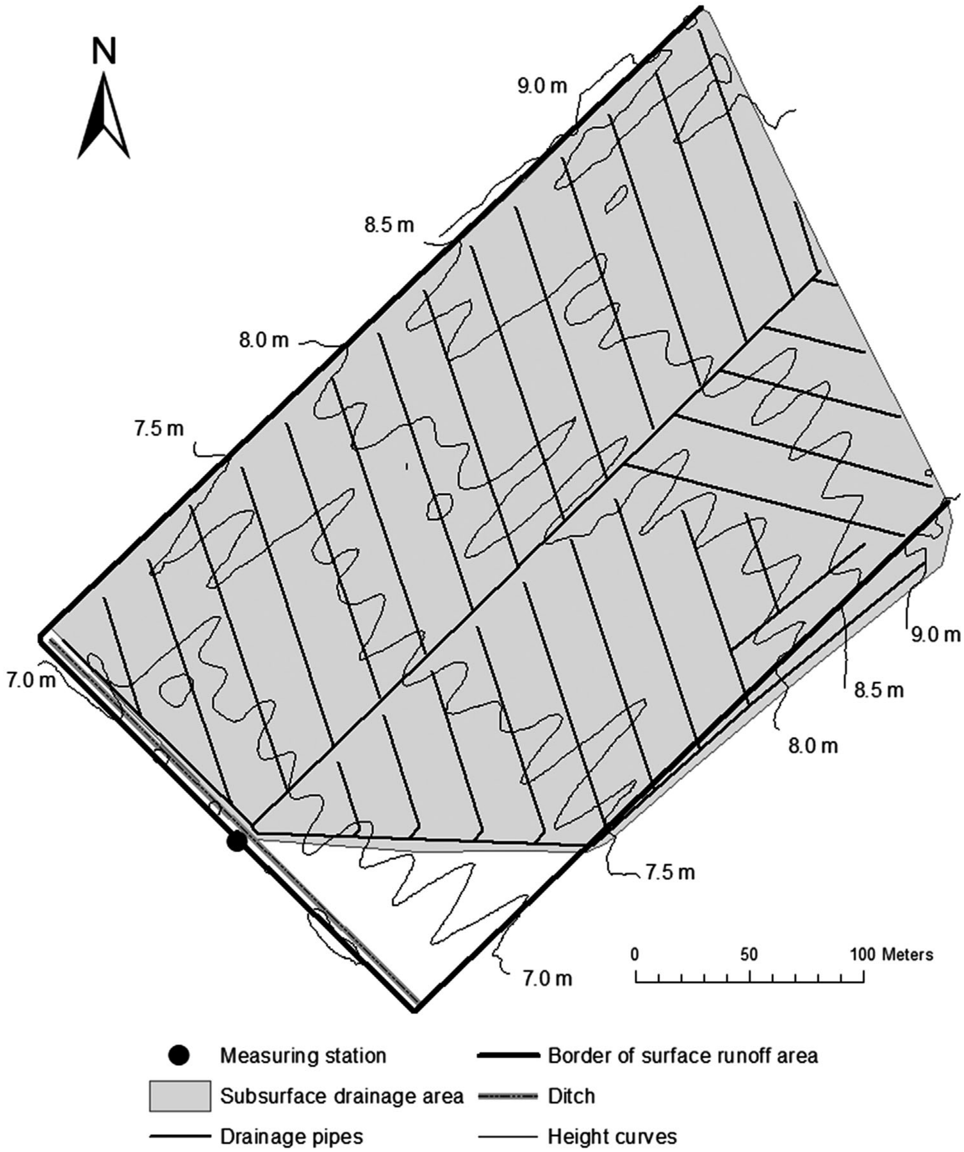

FIGURE 1 Schematic diagram of Field 14AC, showing subsurface drainage system and runoff collection system

2.2 | Calculations and statistics

Daily runoff and leaching loads of nutrients were calculated from the measured data by multiplying the concentration in each sample by the daily amount of drainage during the 2-wk period prior to the sampling date. Monthly and annual values were obtained by accumulation of daily values during a month or during the agrohydrological year, which corresponds to the period 1 July–30 June. Mean monthly and annual mean concentrations of nutrients were obtained by dividing the accumulated monthly/annual load by the monthly/annual amount of drainage from the field.

Amounts of manure and mineral fertilizer applied were calculated from the quantity spread on a known section within the field and re-calculated for the total area (8 ha) to get an approximate value for the field. The content of N and P in cow manure was assumed to be 4.3 kg N t^{-1} and 0.6 kg P t^{-1} (Andersson et al., 2020).

The runoff data did not meet normality requirements, and therefore a nonparametric test was used. Differences between annual concentrations and transported amounts (load) in subsurface drainage and surface runoff were tested for significance using a Wilcoxon test ($p < .05$). A Kruskal–Wallis test was used to test for differences between concentrations and transported amounts of N and P and crop grown on the field (barley, barley/ley, ley; $p < .05$, $n = 4$–14). Relationships between concentrations and load of N and P and estimated amounts of N and P applied to the field were tested with a regression model ($p < .05$, $n = 32$). Relationships between concentrations and load of suspended material, TOC, pH, and N and P fractions were tested with a linear regression model

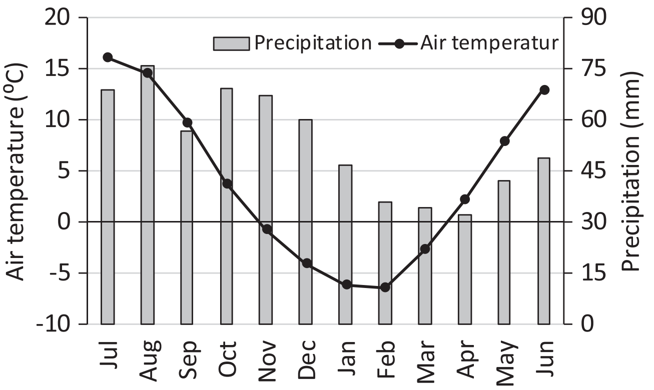

FIGURE 2 Mean monthly air temperature (circles, ˚C) and mean monthly precipitation (bars, mm) at the study site (Umeå/Röbäcksdalen, climatological standard normal 1991–2020, Swedish Meteorological and Hydrological Institute)

($p < .05$, $n = 10$–32). All statistical analyses were performed in JMP Pro 15.

3 | RESULTS AND DISCUSSION

3.1 | Weather conditions and hydrology

The weather at the field site was characterized by temperatures below 0 ˚C during November–March and consequently a long period of frozen ground (Figure 2). The summers had monthly average temperatures above 10 ˚C and were short (June–August) and relatively cool. During November–April, some of the precipitation fell as snow, in some years in substantial amounts that remained on the ground for several months. Mean monthly runoff during the measuring period, as surface runoff and subsurface drainage, varied during the year, and the trend differed for these two flow paths (Figure 3a). Surface runoff displayed a distinct peak during snowmelt in April (49% of mean annual surface runoff).

The runoff via both pathways was low during the warmest months (June–August), when crop growth was intense and most precipitation water was taken up by the plants. Little flow of water occurred during the winter months (January–February), when the soil was usually frozen and precipitation fell as snow and stayed on the ground. During the rain-rich months of September–November and May, when there was no growing crop and the soil was not frozen, a larger proportion of total runoff occurred as subsurface drainage.

In the measuring period of 1988–2020, mean annual precipitation was 633 mm, of which 47% ended up as runoff (Figure 4). Subsurface drainage constituted 36% of total runoff and as an annual average was 107 mm, whereas surface runoff as an annual average was 189 mm. Runoff amount varied greatly between years, as did precipitation amount (range, 351–988 mm).

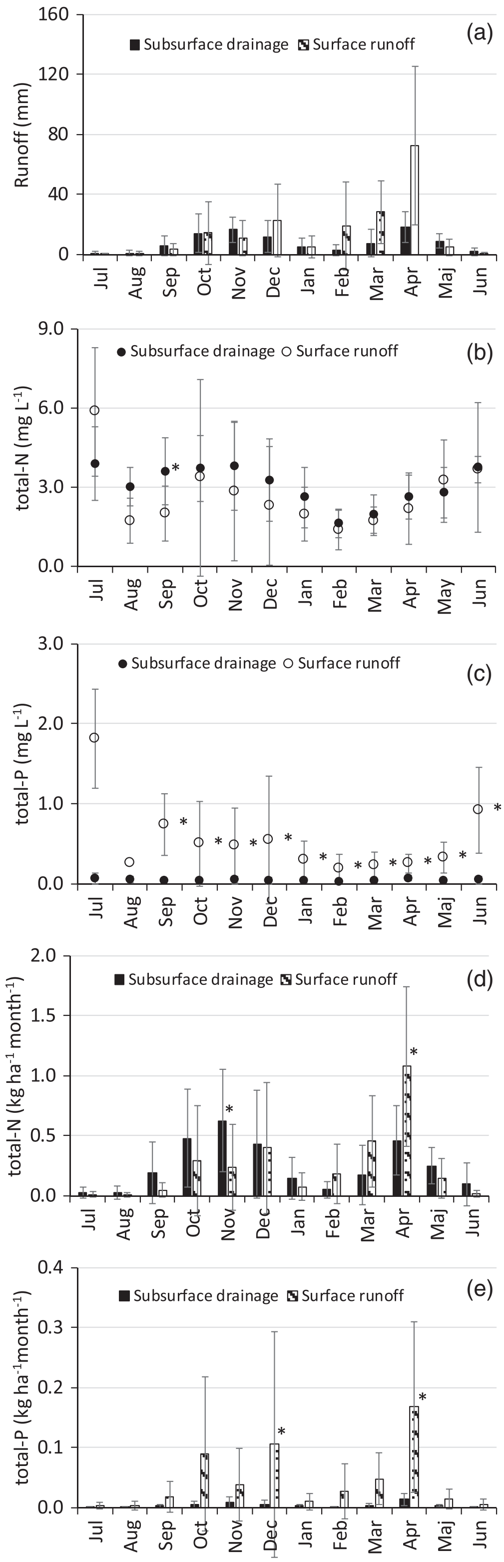

FIGURE 3 (a) Mean monthly average runoff (mm); concentration (mg L^{-1}) of (b) N and (c) P; and load (kg ha^{-1} mo^{-1}) of (d) N and (e) P in subsurface drainage water (black bars and circles) and surface runoff water (striped bars and open circles) from Field 14AC in the period 2010–2020 (flow-proportional sampling). Mean and SD. *Significant difference between subsurface and surface runoff values for that month (Wilcoxon test; $p < .05$, $n = 10$)

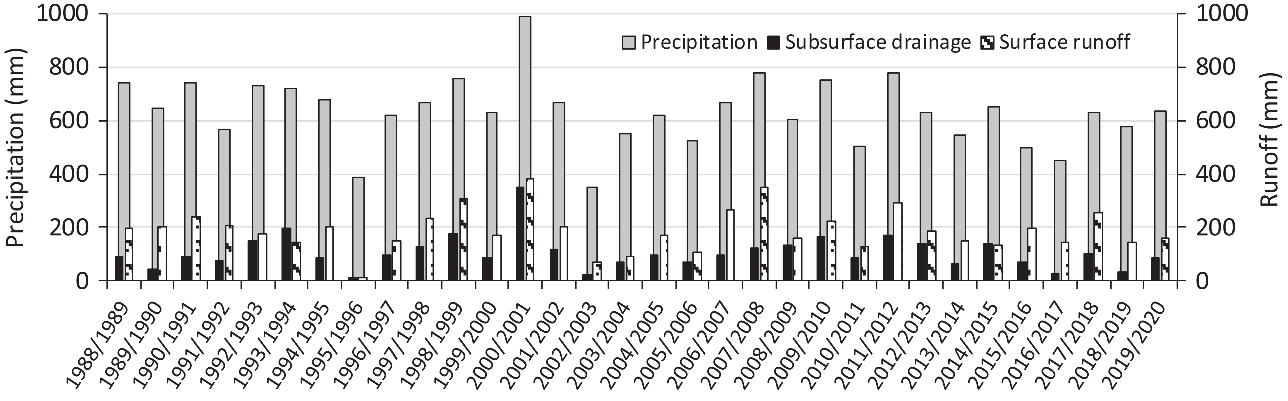

FIGURE 4 Mean annual precipitation (mm) at the study site (grey bars) and mean annual runoff (mm) from Field 14AC as surface runoff (striped bars) and subsurface drainage (black bars)

Years with similar mean annual precipitation did not necessarily have similar runoff because runoff depended strongly on the timing of precipitation and whether it fell as rain or snow. When precipitation fell as snow on frozen ground, a larger proportion ended up as surface runoff than as subsurface drainage. There was a lag time from when the snow melted on the soil surface until the soil thawed and within-soil flow began. The higher annual runoff via surface runoff than subsurface drainage (Figure 4) was mainly due to high flow during snowmelt, when the soil was frozen and no water passed through the drainage system (Figures 2 and 3a). Thus, most snowmelt water left the field by the aboveground pathway. A similar flow pattern was seen by Griffith et al. (2020) and Uusitalo et al. (2018), where the latter found that 55–60% of annual surface runoff occurred during ∼1 mo of snowmelt, which is a little higher than in this study (mean, 49%) (Figure 3a).

In a Finnish field experiment, 60% of total flow from untilled plots occurred via surface runoff, whereas for plots ploughed in autumn the surface runoff share was only 20% (Turtola et al., 2007). Compared with the Finnish study site, Field 14AC was characterized by untilled soil rather than autumn-ploughed soil during the measurement period. However, the period with frozen ground was probably longer for Field 14AC than at the Finnish site, and it therefore had a larger proportion of surface runoff.

3.2 | N and P losses in surface runoff and subsurface drainage

In general, the concentrations of N and P followed a similar trend (Figure 3b,c), with the highest concentrations in June and July and low values during the coldest months (January–March), when biological activity in the soil is normally low. Despite high concentrations of N and P in runoff water, the total losses (load transported from the field) were small due to the low runoff during the summer months (Figure 3d,e). However, the variation within months was very high, especially for losses but also for nutrient concentrations, which resulted in large annual variations (Figure 3). The concentration and load of P with subsurface drainage water was low in all months relative to that in surface runoff, whereas the concentration and load of N showed less difference between the two transport paths.

The mean annual concentration of TN was significantly higher ($p < .05$) in subsurface drainage water than in surface runoff water in 50% of the 32 yr analyzed (Figure 5). For mean annual concentration of TP, 3 of the 32 yr showed no difference between the flows, and in all other years surface runoff water had higher concentrations ($p < .05$) than subsurface drainage water (Figure 5). Consequently, there was a contrasting trend in the concentrations of TN and TP. As an annual mean for the 32 yr of measurements, TN concentration was 3.7 and 2.3 mg L^{-1} for subsurface drainage and surface runoff, respectively; mean annual TP concentration was 0.04 and 0.27 mg L^{-1}, respectively.

Total export (i.e., surface and subsurface) showed a similar pattern to the concentrations of N and P, but the differences in runoff pathways were generally not statistically significant (Figure 6). Nitrogen losses were greater via subsurface drainage than surface runoff, whereas P displayed the opposite trend, with greater losses via surface runoff. Mean annual load of TN(subsurface and surface runoff) for the period 1988–2020 was 7.7 kg ha^{-1} yr^{-1}; 56% of these losses occurred via subsurface drainage (Figure 6). In a previous study, Manninen et al. (2018) found that at least 51%, and up to 93%, of the load of dissolved organic N was exported by subsurface drainage, with the remaining smaller proportion occurring via surface runoff. In a Norwegian field experiment, losses of TN through both subsurface and surface runoff ranged between 18 and 35 kg ha^{-1} yr^{-1}, depending on the type of cropping system (Korsaeth & Eltun, 2000) (i.e., the losses were much greater than in this study). Mean annual

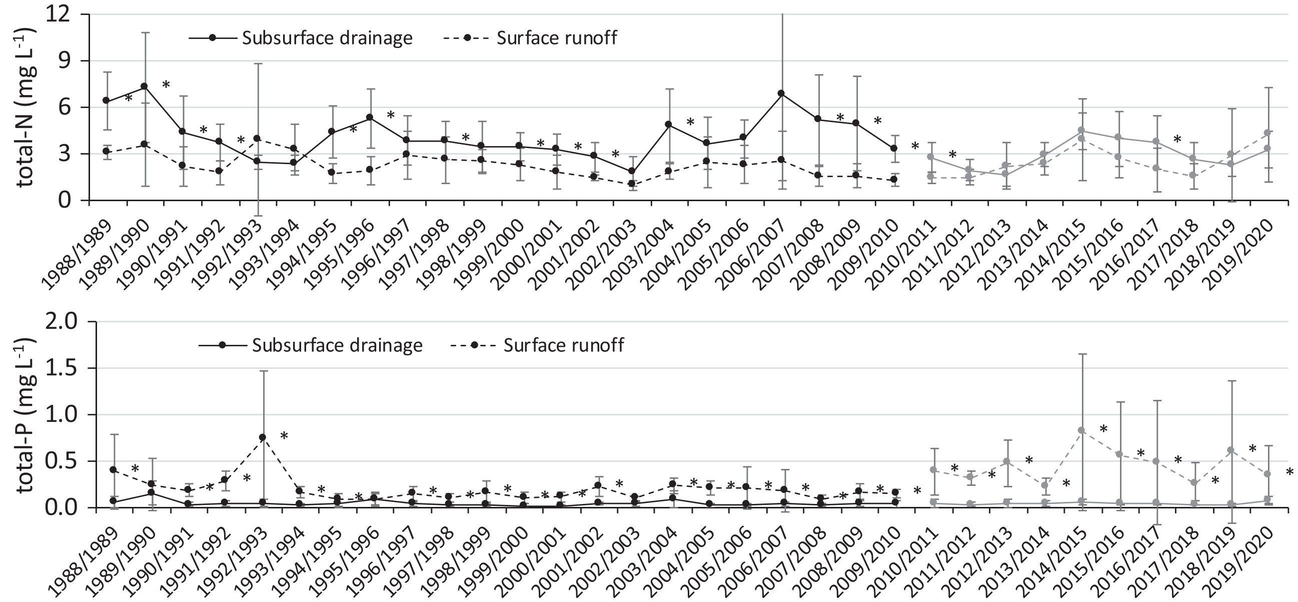

FIGURE 5 Mean annual concentration (mg L^{-1}) of total N (upper panel) and total P (lower panel) in subsurface drainage water (filled line) and surface runoff water (dashed line) from Field 14AC. Mean of monthly values; error bars show SD. Black series are by manual sampling and grey series by flow-proportional sampling. *Significant difference between subsurface and surface runoff values for that year (Wilcoxon test; $p < .05$, $n = 12$)

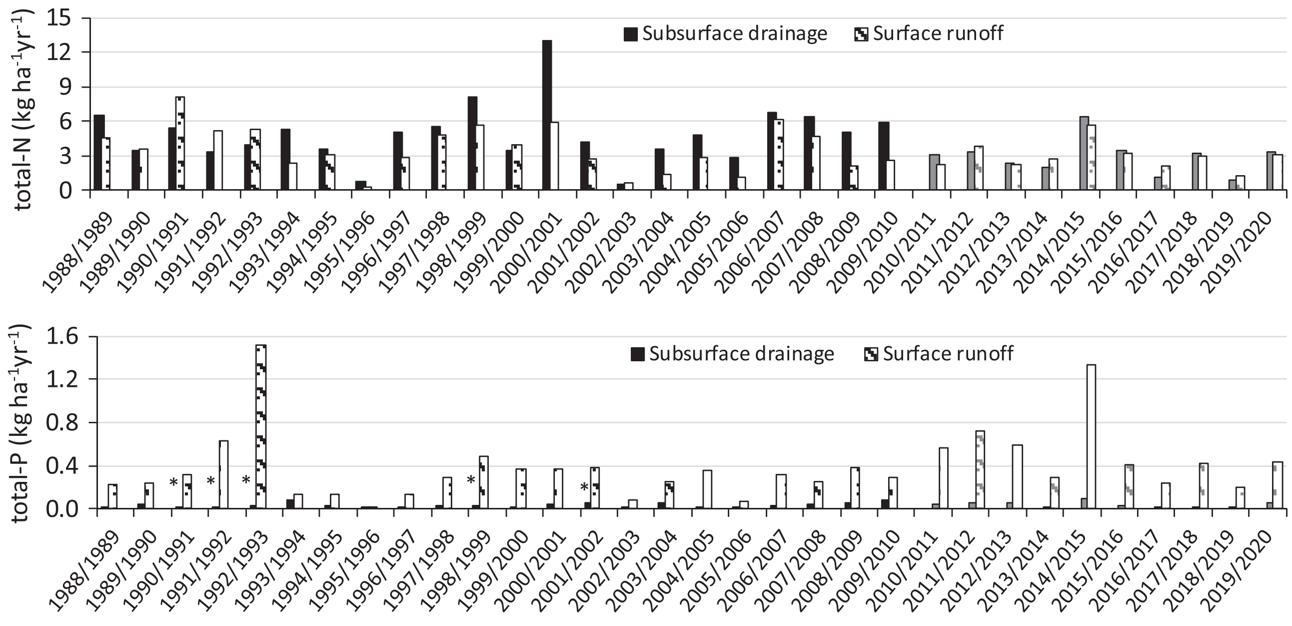

FIGURE 6 Mean annual load (kg ha^{-1} yr^{-1}) of total N (upper panel) and total P (lower panel) in subsurface drainage water (filled line) and surface runoff water (dashed line) from Field 14AC. Black series are by manual sampling; grey series by flow-proportional sampling. Bars show sum of monthly load during the respective agrohydrological year (July–June). *Significant difference between subsurface and surface runoff values for that year (Wilcoxon test; $p < .05$, $n = 12$)

load of TP from Field 14AC in the period 1988—2020 was 0.43 kg ha^{-1} yr^{-1}, and of these losses, only 9% occurred via subsurface drainage (Figure 6). Losses of 4.3 kg N ha^{-1} yr^{-1} and 0.14 kg P ha^{-1} yr^{-1} have been reported previously for a small stream catchment in an agricultural landscape near Field 14AC (Stjernman Forsberg, 2016). These lower values compared with our study site were most likely due to dilution of groundwater, precipitation, and runoff from non-arable land in the stream.

Load of TN and TP showed a positive relationship to load of TOC and suspended material in both subsurface drainage and surface runoff water (Supplemental Table S3). This indicates that most N and P were lost from the field with organic material. Furthermore, load of suspended material and TOC was positively related in subsurface drainage water but not in surface runoff (Supplemental Table S3), suggesting that suspended material in surface runoff water contained soil particles in varying amounts different years.

Compared with other individual long-term monitoring sites in agricultural fields in Sweden, Field 14AC had lower concentrations and losses of TN in subsurface drainage water and among the lowest concentrations and losses of TP (Norberg et al., 2020). Long-term edge-of-field water quality monitoring data such as our study of Field 14AC is unique in Sweden and provides measured data on nutrient leaching via both subsurface drainage water and surface runoff. The cold climate and short summers in northern Sweden lead to a relatively short period of microbial activity and mineralization of N, which was one of the reasons for the low leaching losses measured at the site. Another reason for the lower export is that the field is often cropped year-round, at least partly, with ley for forage, which can take up any mineralized soil N. In an American study, it was found that on average 48% of TP lost from experimental fields occurred via subsurface drainage (Smith et al., 2015), although in that study there was no long cold period followed by snowmelt. Another American study at a site with periods of snowmelt found that a major part of cumulative TP was lost via surface runoff during snowmelt events (Griffith et al., 2020).

Cade-Menun et al. (2013) concluded that N and P in snowmelt runoff are mainly present in dissolved form rather than particulate form and that the particulates present seem to be organic matter rather than soil. This supports our findings where, as an annual mean for 2010–2020, only 34% (14–62%) of TP in surface runoff was present as particulate P, and 89% (71–100%) of TP in subsurface drainage water was present as particulate P (data not shown). During the same period (2010–2020), surface runoff contained 51% (32–76%) dissolved phosphate (PO_4–P), whereas subsurface drainage contained only 14% (4–25%) as annual mean. Due to the low soil pH (5.1; Supplemental Table S1) in the deeper parts of the soil profile (60–90 cm), fixation of dissolved P by aluminum and iron minerals was promoted (Penn & Camberato, 2019), leaving mainly P bound to particles in the subsurface drainage water. Furthermore, particulate P showed a positive relationship to TOC in both subsurface drainage and surface runoff, indicating that particulate P was mainly from organic matter (Supplemental Table S3). However, dissolved phosphate had no clear relationship to TOC or suspended material in runoff, which was expected because PO_4–P does not attach to particles (Supplemental Table S3). Uusitalo et al. (2018) found 35–40% particulate P in TP in surface runoff and 70–80% particulate P in TP in subsurface drainage from a clayey soil. In surface runoff at sites dominated by melted snow, P can be attached to soil particles and to organic matter that has been milled and fragmented during winter. Moreover, freeze–thaw events can damage plant cells and alter the P form in leachate from particulate to dissolved form (Liu et al., 2014). Furthermore, soil can act as an efficient filter for leachable P (Riddle & Bergström, 2013), which may be one of the reasons why TP was lower in subsurface drainage water than in surface runoff (Figure 6).

In 22 of the 32 yr (1988–2010), three fractions of N were analyzed: TN, NO_3–N, and NH_4–N (Table 2). During this period, 85% of TN in subsurface drainage water was in the form of NO_3–N and 2% as NH_4–N. The proportions were quite different in surface runoff, where 29% of TN was in the form of NO_3–N and 18% as NH_4–N. Similar proportions have been reported for water leaving unfertilized plots in a Finnish field experiment (Turtola & Kemppainen, 1998). Typically, NO_3–N is the dominant N fraction in subsurface drainage water from agricultural fields (Norberg et al., 2020; Stenberg et al., 2012) because NH_4–N is easily bound to soil particles or nitrified by microorganisms, whereas NO_3–N is more mobile in the soil solution. In surface runoff, NH_4–N and NO_3–N left Field 14AC in very similar proportions, and the majority of TN was bound as organic forms of N. This was due to poorly degraded organic material leaving the field, mainly in snowmelt, and NH_4 had not yet been mineralized to NO_3. Manual sampling, which was the standard method at the study site before 2010, reflects the nutrient status in water at the time of sampling, whereas flow-proportional sampling captures water quality more continuously. With manual sampling only every second week, short-term events, like elevated flows following heavy rains or rapid snowmelt, can either be missed or nutrient concentrations can be overestimated for the actual period, whereas flow-proportional sampling can encompass even brief changes in water quality. The P concentration in water appears to be particularly sensitive to the sampling method, with generally higher concentrations with flow-proportional sampling due to P losses often occurring through erosion following short-term peak flow. For instance, Ulén et al. (2015) found higher estimated leaching losses of particulate P with flow-proportional sampling than with manual sampling for a monitoring field similar to Field 14AC. However, mean annual TP concentration in drainage water from Field 14AC was the same (0.04 mg L^{-1}) for both manual sampling (1988–2009) and flow-proportional sampling (2010–2018). This lack of difference could be related to the low soil clay content in the field soil because P is often lost with clay particles. On the other hand, mean annual TP concentration in surface runoff water from the field was 0.33 mg L^{-1} for the manual sampling period and 0.53 mg L^{-1} for the flow-proportional sampling period. A reason for this difference can be that snowmelt often occurs in short periods due to short-term fluctuations in temperature or precipitation, which could easily be missed with manual sampling.

TABLE 2 Concentrations and load of selected nutrients and parameters in subsurface drainage and surface runoff water from Field 14AC

Parameter	Subsurface drainage		Surface runoff		Year of sampling[a]
	mg L^{-1}	kg ha^{-1} yr^{-1}	mg L^{-1}	kg ha^{-1} yr^{-1}	
Total N	3.7a (1.4)	4.3a (2.5)	2.3b (0.8)	3.4a (1.8)	1988–2020
NO_3–N	3.7a (1.3)	3.7a (2.1)	0.5b (0.3)	1.0b (0.6)	1988–2020
NH_4–N	0.07b (0.03)	0.08b (0.05)	0.32a (0.15)	0.60a (0.38)	1988–2010
Total P	0.04b (0.03)	0.04b (0.02)	0.27a (0.19)	0.39a (0.32)	1988–2020
Particulate P	0.04a (0.02)	0.04b (0.03)	0.12a (0.17)	0.19a (0.22)	2010–2020
PO_4–P	0.01b (0.01)	0.01b (0.01)	0.09a (0.09)	0.15a (0.14)	1994–2020
Suspended material	20 (5)a	23b (16)	27 (34) a	52a (59)	1988–2020
Total organic C	5 (1)b	5b (3)	10 (3)a	18a (10)	1998–2020
K^+	11 (2)a	13a (8)	7 (2)b	14a (9)	1988–2010
Na^+	28 (5)a	33a (19)	4 (2)b	9b (9)	1988–2010
Mg^{2+}	16 (2)a	19a (11)	2 (1)b	4b (3)	1988–2010
Ca^{2+}	55 (7)a	62a (36)	12 (5)b	25b (17)	1988–2010
Cl^-	30 (7)a	34a (19)	8 (3)b	16b (12)	1988–2010
SO_4–S	76 (15)a	88a (53)	7 (4)b	16b (14)	1988–2010
pH	5.3 (0.4)b		6.3 (0.2)a		1988–2020
Conductivity, mS m^{-1}	50 (9)a		22 (7)b		1988–2020
Alkalinity, meq L^{-1}	0.3 (0.2)a		0.4 (0.2)a		1988–2020
Runoff, mm	107b (64)		189a (77)		1988–2020

Note. Mean (SD) values for years of sampling. Different letters denote significant differences between subsurface drainage and surface runoff (Wilcoxon test, $p < .05$, n = years of measurement).

[a]Manual sampling, 1988–2010; flow-proportional sampling, 2010–2020.

3.3 | Impact of agricultural practices on N and P leaching losses

Kruskal–Wallis tests revealed higher annual concentration of TN in subsurface drainage water when the field was dominated by barley than when dominated by ley, and a similar trend was seen for leaching load of TN, whereas there was no difference in surface runoff ($p < .05$) (Supplemental Table S4). Korsaeth and Eltun (2000) also observed no difference between cropping systems for N losses in surface runoff but observed significantly lower N losses in subsurface drainage from cropping systems with perennial ley than from arable systems with only annual crops. Leaching losses of N in drainage water from ley–dominated cropping systems are generally low due to year-round soil cover by vegetation and a long growing period with plant uptake of nutrients.

Phosphorus exhibited an opposing trend to N, with lower annual concentrations of TP in surface runoff water and lower TP load during years dominated by barley than years dominated by ley (Supplemental Table S4). No such differences were seen for subsurface drainage ($p < .05$) (Supplemental Table S4). Other studies have also demonstrated that the presence of ley instead of a barley crop can decrease losses of particulate P in surface runoff (Turtola & Kemppainen, 1998) due to the grass cover preventing soil erosion. In the present study, the concentration and load of dissolved P (PO_4–P) in surface runoff water were higher during years dominated by ley than in years when the field was mainly under a barley crop, but no such difference was seen for subsurface drainage ($p < .05$, $n = 26$; data not shown). This is probably due to freeze–thaw events fragmenting plant material left on the ground and releasing large amounts of dissolved P to surface snowmelt runoff.

No relationship was detected between yearly application of N or P in manure/fertilizer and mean annual concentration or load of N or P ($p > .05$) (Table 1; Figures 5 and 6). This is probably because the yearly supply of fertilizer and manure was low (in total, 82 kg N ha^{-1} and 13 kg P ha^{-1}) (Table 1) and often applied in May or June (i.e., to the growing crop). The low yearly supply was because fertilizer and manure seldom were applied on the entire field. The timing of manure application can affect the losses of nutrients. For example, Delin and Stenberg (2020) found that spring application of cattle slurry resulted in lower subsurface leaching losses of NO_3–N than autumn application. However, in a similar cropping system with undersown ley in spring barley, Turtola and Yli-Halla (1999) observed higher PO_4–P concentrations in surface runoff from experimental plots treated with mineral fertilizer and manure compared with unfertilized control plots. In that study, the PO_4–P concentration in surface runoff from unfertilized plots was lower (0.033 mg L^{-1}) than in the present study (0.09 mg L^{-1}), but the concentration in surface runoff from plots with high application rates of manure and mineral fertilizer was much higher (0.62 mg L^{-1}). Turtola and Yli-Halla (1999) concluded that the elevated P concentration in surface runoff water was caused by build-up of P in the upper few centimeters of the soil following application of manure and mineral fertilizer.

3.4 | Water chemistry and ions in subsurface drainage and surface runoff

There were higher concentrations of ions (K^+, Na^+, Mg^{2+}, Ca^{2+}, Cl^-, and SO_4–S) in subsurface drainage than in surface runoff water, and a similar trend was seen for ion load except in the case of K^+, where there were no differences between the flows (Table 2). Uhlen (1989) observed lower concentrations of ions in runoff water but found that the concentration ratio between subsurface drainage and surface runoff was similar for all ions except for K^+. A Finnish study on a sandy soil with grazed grass and grass–clover swards reported similar losses of K^+, Ca^{2+}, and Mg^{2+} through subsurface and surface runoff as in the present study (Järvenranta et al., 2014). The leaching losses observed for Field 14AC were at the lower end of the range of K^+, Ca^{2+}, and Mg^{2+} values recorded in a lysimeter study with mineral soils (Yläranta et al., 1996). However, in an American study on a silt loam with fertilized pastures grazed during summer, leaching losses of soluble ions (Na^+, Mg^{2+}, Ca^{2+}, Cl^-) were found to occur mainly through subsurface flow, with <2% via surface runoff (Owens et al., 2003), probably due to low surface runoff. Concentration and load of TOC were lower in subsurface drainage water than in surface runoff water due to on-ground transport of plant material, mainly during snowmelt (Table 2). In both subsurface drainage and surface runoff, N and P load had a positive correlation to suspended material and TOC (Supplemental Table S3), indicating that the suspended material was mainly of organic origin. Owens et al. (2003) observed similar levels to those presented here and concluded that hay brought into the area for cattle feed increased surface runoff of TOC. In terms of pH, Field 14AC had the lowest value in subsurface drainage water of all long-term monitoring fields in Sweden (Norberg et al., 2020). There was a negative relationship between pH in subsurface drainage water and TN and NO_3–N, and lower pH gave higher N losses (Supplemental Table S3). However, this was probably because pH in drainage water was higher (5.5) when the field was dominated by ley than when dominated by barley (5.0) and losses of N were higher under barley than under ley (Supplemental Table S4). In surface runoff water, pH had a positive relationship to PO_4–P (Supplemental Table S3), probably because pH values during the 32 yr (5.8–6.7) were close to the range (~6.5) of high P availability (Penn & Camberato, 2019).

4 | CONCLUSIONS

The pattern of runoff from an agricultural field in northern Sweden, where the winters are cold and snowy, was strongly affected by snowmelt events in spring. Yearly losses of P at the site were affected by long cold winter periods with freeze–thaw events, and most P losses occurred via surface runoff. Yearly losses of N, on the other hand, mostly occurred via subsurface drainage and were less affected by snowmelt events. The crop grown at the site also affected yearly losses of N and P, but in contrasting ways, with more P losses from ley occurring via surface runoff and more N losses from barley occurring via subsurface drainage. These contrasting trends for N and P indicate that different measures are needed for mitigation of losses of these nutrients to surrounding water bodies. For mitigation of losses of P from agricultural land in northern Sweden, the focus should be on decreasing surface runoff. The most effective way of mitigating N losses is to keep the soil covered year-round by a growing crop (i.e., perennial ley).

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AUTHOR CONTRIBUTIONS

Lisbet Norberg: Formal analysis; Methodology; Visualization; Writing – original draft. Helena Linefur: Writing – review & editing. Stefan Andersson: Writing – review & editing. Maria Blomberg: Writing – review & editing. Katarina Kyllmar: Writing – review & editing.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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SUPPORTING INFORMATION

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