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Peatland fertilization

Short-term Chemical Effects of Runoff Water

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Abstract

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In peatland forestry, fertilization is often needed to reach a good yield. Phosphorus and potassium are mainly used, but on nutrient poor fens and bogs nitrogen also has to be added. These fertilizers affect the environment and thereby influence the runoff waters.

This essay concerns the first three months after fertilization, of which the first two weeks have been paid particular attention.

As the mires of the sub-basins were sedge fens, partly poor fens, with a pine stand in some areas but mostly treeless, the fertilizers used were ammonium nitrate (100 kg N), rock phosphate (50 kg P) and potassium chloride (100 kg K). The fertilization was performed from the air.

During the very first hours after fertilization, drastic changes in water chemistry were found. In one area pH dropped 0.3 units while at the other no immediate change was seen. For the whole three months of the investigation period the decreases in pH were in the range 0.1–0.5 units.

Nitrogen concentration reached a peak of 260 mg/l, phosphorus 5 mg/l and potassium about 60 mg/l. These high values were of short duration but the concentrations were considerably increased during one week. Later, partly due to decreasing discharge, the water chemistry became almost similar to that measured under unfertilized conditions.

The main loss of fertilizer occurred during the first two weeks and amounted to 22% of the applied nitrogen, about 1% of the phosphorus and 5–9% of the potassium.

High concentrations of ammonium and nitrate may occur after fertilization and together with drops in pH may be hazardous to fish. Increased concentrations of aluminium dissolved from stream bottoms due to decreased pH may also be toxic to fish. In this investigation no fish kill or changes in fish populations were found. In runoff waters with pH around 7 the high ammonium concentrations found in the Siksjöbäcken study could cause lethal or sublethal effects on fish due to increased concentrations of ammonia (NH_3).

Key words: Fertilization, peatland, runoff, water chemistry.
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Introduction

Increased drainage and fertilization of peatlands have been proposed as means of increasing forest production in Sweden. Such utilization of peatlands has already been in progress in a large scale in both Finland and the USSR. As the increased utilization of peatland is expected to cause changes in the natural environment of wetland ecosystems, the National Swedish Environmental Protection Board initiated and supported a research program in 1977 to investigate the effects of such utilization.

The Siksjöbäcken area was chosen for investigations into the effects of drainage and fertilization on hydrology and limnology. The choice fell on this area because of the fish in the streams and the presence of peatland areas suitable for drainage and fertilization. The effects of drainage were followed for a period of two years (March 1981 – March 1983), and the results are given in a separate report (Bergquist et al., 1984). In May 1983, the drained mires were fertilized, and this report deals with the effects of fertilization on the chemical composition of runoff during the first three months.

In modern silviculture the peatlands that are to be used for increased forest production are foremost smaller peatlands close to mineral and clear-cut areas, i.e., peatlands with a thin cover of peat above mineral soil.

Most mires have shown good possibilities for a fairly large production of wood, >5 m^3 sk/ha and year (Skogsarbeten, 1980). To reach this yield there is a need of drainage and often also fertilization. Fertilization with phosphorus and potassium is generally needed on peatlands if the yields are to be increased to any great extent, but on nutrient-poor peatlands there may also be a need of nitrogen fertilization.

In all fertilization of peatlands and mineral land there is a loss of fertilizer in runoff (Tamm et al., 1974). This occurs more strongly when air fertilization is used in combination with the presence of numerous brooks and open ditches in the fertilized area, than when ground fertilization is done in a landscape with few open drains. On peatlands, the drainage systems often increase the fertilizer outflow. The water flow in peat is very small and the water storage capacity is often enhanced by drainage, so the outflow of fertilizer from the strips between the ditches will be correspondingly small. With precipitation and elevated groundwater levels and increased outflow of fertilizer will occur. Nitrate is the most mobile fertilizer compund in peat, while ammonium, potassium and phosphorus are more retained.

Only a few investigations into nitrogen fertilization of peatlands have been made, and these show a minor leaching of fertilizer (Paavilainen, 1976; Braekke, 1977). Small losses for phosphorus were generally found but several authors (Paavalainen, 1976; Kenttämies, 1977, 1981; Lehmusvuori, 1981) found that increased leaching occured for more than one year after fertilization. These investigations also report long-lasting increases in the leaching of potassium.

The aims of this investigation were to determine the concentrations of fertilizer compounds in runoff water downstream from the fertilized mires and to calculate the losses of applied fertilizers. Consequences on pH and biota, primarily fish, from increased concentrations of fertilizers in the runoff waters were to be investigated.

The Study Area

Location and sampling stations

The investigation area, the Siksjöbäcken basin, is situated in central Sweden (N60°00', E14°27') in the western parts of the Bergslagen region, about 30 km north of Hällefors municipality (Fig. 1). The drainage area of the basin is 15 km^2 and contains four subbasins. Two of the subbasins were chosen as references, while the other two were selected as impact basins with drained and fertilized mires. The reference basins are the drainage areas of the brooks Hamptjärnsbäcken (HA) and Saltbäcken (SA), and impact basins are the drainage areas of the brooks Särkalampibäcken (SÄ) and Letjärnsbäcken (LE).

The Letjärn impact basin is situated close to the Hamptjärn reference basin at relatively high elevation (325 m above m.s.l.). These two basins are similar with respect to physiography, mire type and chemical composition of runoff water. Both basins have a peatland area that is 25% of the basin area. The water sampling stations are situated at the discharge stations close to the peatland areas, and also further downstream (1 000 m) in Letjärnsbäcken (Fig. 1).

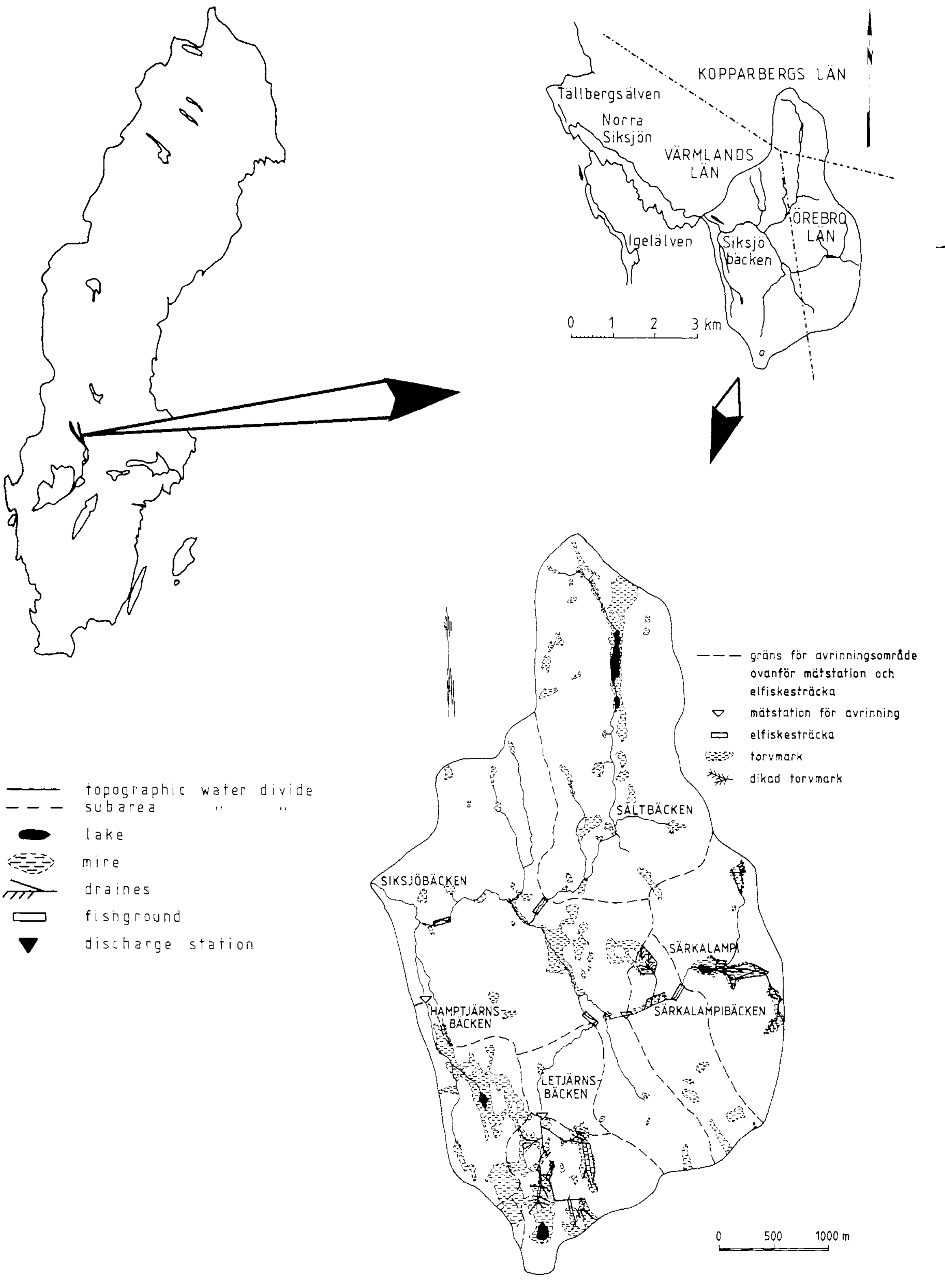

Fig. 1. Location of Siksjöbäcken basin with subbasins.

The Särkalampi impact basin, together with the Saltbäcken reference basin, are situated in the lower parts of the terrain at 285–300 m above m.s.l. The basins are similar in respect of groundwater outflow and peatland area (10% of basin area). The groundwater outflow in these basins in more extensive than in the Letjärn and Hamptjärn basins. A water sampling station was placed close to the fertilized mires in the impact basin and upstream the small lake Särkalampi, and another is located further downstream (1 000 m) at the discharge station in the brook Särkalampibäcken.

The sampling station in the brook Saltbäcken is situated just above the junction with the main stream Siksjöbäcken. In the main stream, at a distance of about 5 km downstream from the fertilized mires, there is also a sampling station for water chemistry. The drainage area and impact area of the different basins are given in Table 1, and the locations of the different basins are shown in Figure 1.

Climate and hydrology

The Siksjöbäcken basin is situated at realtively high altitude, 250–400 m above m.s.l., and has a cold climate during winter. The mean annual temperature is 4.1°C, and the growing period (>5°C) is 180 days (Odin et al., 1983).

The mean annual precipitation is about 900 mm (Eriksson, 1980), with high precipitation during July and August (100 mm each). The period with snowcover is about 160 days, and the mean of the greatest snow depth is 50 cm (Bergquist et al., 1984).

The mean annual runoff in the Siksjöbäcken area is calculated, from streamflow records given by SMHI (1979), to 12–13 l/s and km^2. Measured values from the Särkalampi and Hamptjärn basins were somewhat higher as compared to the Letjärn basin. The variation in runoff during the year is typical for this region, with high discharge during spring and autumn, low during winter and variable during summer.

Table 1. *Drainage area and impact area above the different sampling stations*

Station B	Basin area, ha	Peatland area, ha	Impact area ha	Impact area %
LE	140	34	20	14
LEN	170	35	20	12
SÄI	142	11	11	8
SÄ	265	25	18	7
SA	390	36	–	–
HA	110	31	–	–
SII	1 440	150	38	3

Geology and peatlands

The bedrock consists of reddish subjotnian granites (Lundquist, 1953), and is covered by sandy fine-sandy till of varying thickness. Along the streams of Saltbäcken and Siksjöbäcken there is also glacifluvial gravel.

The mires of the Siksjöbäcken basin are oligotrophic to mesotrophic sedge fens of mainly minerogenic origin. The peat thickness of the mires varies between 2 and 3 m. The mires in the Letjärn basin are small (<5 ha) and frequently mixed with till hummocks. The mires in the Särkalampi basin are long and narrow, and are found along the brooks.

The many small or narrow mires caused increased ditch length as compared to few and integrated mire areas and implied that many lagg ditches had to be excavated at the boundary between peatland and mineral soil. These ditches penetrated the mineral soil. In the Letjärn basin 20 ha were drained mainly in March and April 1981 but with 25% complementary draining in April 1982. The total ditch length amounted to 8 000 m which gives a ditch density of 400 m/ha. Corresponding values at the Särkalampi basin, which was totally drained in 1981, were 18 ha, 8 000 m and 444 m/ha. There was, however, an attempt here to accomplish 0.7–1.0 m deep ditches 40 m apart. On the actual peatland area the spacing was 40 m but the many lagg ditches and small mires increased ditch density values.

Assuming a ditch width of 0.8 m, the area consisting of ditches is about 0.6 ha in each basin, i.e. 3–4% of the drained area. The width of open water in the draines is estimated to only 0.3 m, i.e. 1% of the drained area.

The tree vegetation on the mires is sparse and the mires are mainly treeless. In both basins there are, however, scattered trees of mainly pine but in the central part of the Särkalampi basin there is a Pine stand of mean density covering 5 ha, i.e. 28% of the drained area, and with a tree height of 10–12 m.

Chemical composition of runoff

The brooks in the Siksjöbäcken basin have a physical-chemical composition that is typical of waters in forest areas on till. The water has a low conductivity, relatively high water colour and low concentrations of nutrients such as nitrate, ammonium and phosphate (Table 2). Due to different influences of groundwater and peatland, the alkalinity, pH, conductivity and water colour values vary between the brooks. Särkalampibäcken is similar to Saltbäcken because of the extensive groundwater outflow, and Letjärnsbäcken is similar to Hamptjärnsbäcken because of the great peatland area in the drainage basin.

Table 2. *Water chemistry of the brooks in the Siksjöbäcken basin before drainage and fertilization. Arithmetic means for the period 1979–1980*

	Sampling stations						
Element	LE	LEN	SÄI	SÄ	SII	HA	SA
Cond. (us/cm)	28	27	35	33	32	27	35
pH	5.3	5.5	5.9	5.6	5.8	5.1	5.8
Colour (mg Pt/l)	110	86	44	75	73	163	74
NH_4-N (mg/l)	0.035	0.028	0.025	0.031	0.026	0.037	0.034
NO_3-N (mg/l)	0.052	0.104	0.037	0.104	0.105	0.065	0.169
Total-N (mg/l)	0.43	0.44	0.27	0.44	0.46	0.57	0.54
PO_4-P (mg/l)	0.007	0.008	0.006	0.007	0.002	0.003	0.007
Total-P (mg/l)	0.015	0.014	0.010	0.014	0.017	0.023	0.014
K (mg/l)	0.53	0.60	0.41	0.41	0.58	0.61	0.74

Material and methods

Study technique

The investigation was performed as a comparative study, the impact basins being compared with the reference basins. During the calibration period a relationship was established between the impact basin and the reference basin. The relationship had the form of an equation with the values of the reference as the independent value. Later during the impact period, the measured values in the reference basins were put into these relationships, thereby making it possible to calculate values for undrained and unfertilized conditions in the impact basins. Deviations between these calculated values and the measured values in the impact basins were considered as effects of drainage or fertilization. A problem with this technique is that a high similarity between impact and reference area is essential. The advantage is that time dependent changes due to natural fluctuations are eliminated if the calibration period is similar to the impact period. In this investigation a short impact period is compared with a considerably longer calibration period. The differences in period extensions do not actually matter since the impact period is within the range of the calibration period.

Fertilization

The drained mires of the Letjärn and Särkalampi basins were fertilized in May 1983, two years after drainage. The fertilization was performed by helicopter on two consecutive days. The fertilizer compounds were ammonium nitrate (16.7% NH_4 and 16.7% NO_3), apatite (rock phosphate with 13% P and potassium chloride (50% K). The Särkalampi basin was fertilized with ammonium nitrate on May 25, and with phosphorus and potassium on May 27. The Letjärn basin was fertilized with ammonium nitrate, phosphorus and potassium on May 26. The amount of fertilizer supplied was 100 kg N/ha, 50 kg P/ha and 100 kg K/ha.

Runoff

The runoff in the research area was monitored continuously with three discharge stations (each with a Thomson weir and a registrating gauge) sitauted close to the mires in the impact basins Särkalampi and Letjärn and in the Hamptjärn reference basin (Fig. 1). During winter, when the gauge wells were frozen, readings were made manually at weekly intervals.

Water chemistry

Water samples were taken monthly at the different sampling stations (Figure 1). At the fertilization event the sampling was intensified, and during the first four days (May 25–29) water samples were taken every second hour in the impact brooks. During the following three days samples were taken daily, and thereafter twice a month until August.

During the intensified sampling period the chemical analysis of the water comprised the parameters ammonium, nitrate, phosphate, potassium, chloride, pH, conductivity and, with the less intense sampling also total phosphorus and nitrogen. The analyses were performed according to Swedish standards (SIS).

Results

Runoff

During the investigated period, from May to August, runoff decreased from 19 l/s and km^2 at fertilization to 0.2 l/s and km^2 in August, apart from two discharge peaks in early June and July. The discharge peak in June was 56 l/s and km^2 and the peak in July 15 l/s and km^2. Only in the first half of June was the water flow comparably high, the rest of the investigation period being characterized by a low flow.

Water chemistry

pH

The pH of the brook water within the investigation area varies normally between 5.0 and 6.5. Just before fertilization, the impact brooks had pH values of 5.2 (LE) and 5.9 (SÄI).

During the first hours after fertilization a pH drop of 0.3 units was noted at the LE sampling station, while no immediate decrease was found at the SÄI station. Instead, the pH was 0.2 units higher during fertilization than just before. The following 3–4 days showed no change in pH for the impact brooks, but in the references the pH steadily increased by 0.2–0.5 units. It was thus concluded that during this period the fertilization effect on pH in both impact brooks was a decrease by 0.2–0.5 units (Fig. 2). Lower pH values were also noted at the downstream stations (LEN and SÄ), the change there amounting to 0.1–0.3 pH units.

For the whole investigation period the impact brooks still showed a lower mean pH than the reference brooks. The runoff water at the upstream stations showed a decrease in pH from 5.8 to 5.3 for LE and from 6.2 to 6.0 for SÄI. At the downstream stations, LEN and SÄ, the decrease was 0.3 and 0.1 pH units respectively.

Nitrogen

The nitrogen content in runoff water from the Siksjöbäcken subbasins is normally about 0.5 mg/l. In normal cases the organic fraction dominates with 70% of total nitrogen, while nitrate contributes 20% and ammonium 10%.

During the nitrogen fertilization of the drained mires in the Särkalampi basin the nitrogen concentration reached a maximum of 260 mg/l one hour after fertilization. The increase in concentration was com-

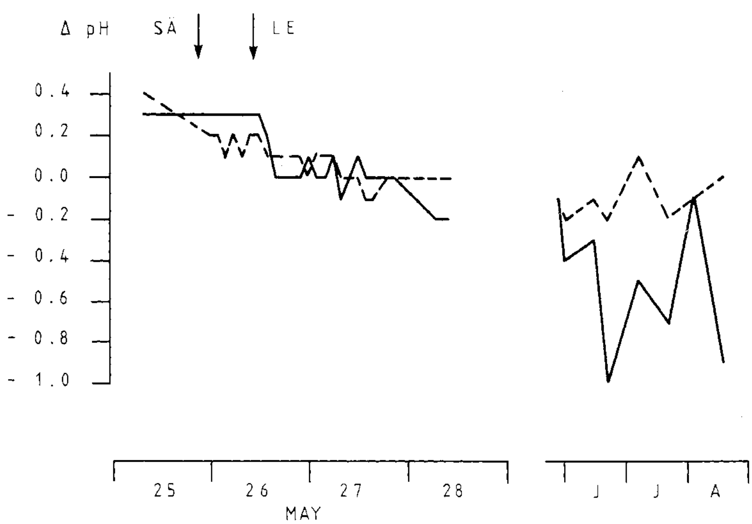

Fig. 2. Changes of pH values in runoff from fertilized mires of the Letjärn and Särkalampi basins during May 25 to August 18, 1983.

Δ pH = difference between measured pH and calculated pH as unfertilized

——— = LE, the Letjärn basin

– – – = SÄ, the Särkalampi basin

↓ = time of nitrogen fertilization (100 kg N/ha)

(Observe the change in time scale at the end of May).

posed of equal shares of nitrate and ammonium. The huge increase lasted only a short while, and two hours later the concentrations of nitrate and ammonium were about 10 mg/l each.

In the Letjärn basin the increase was slower. After 6 hours the nitrogen concentration had reached 40 mg/l with equal shares of nitrate and ammonium. Twelve hours later, the increase was in recession and stabilized at levels below 10 mg/l, but remained at that level for one week. Four weeks later the increase was negligible (Fig. 3).

Further downstream from the fertilized mires (1 km) at the SÄ and LEN stations, increased concentrations were noticed 2–5 hours after fertilization. These increases were much smaller (only 5–15 mg/l)) than at the upstream stations, but the increase above 1 mg/l lasted for one week. Two weeks later the ammonium concentration was back to normal level, but the nitrate concentration remained raised for two months after fertilization (Fig. 3).

In the main stream, Siksjöbäcken, about 5 km downstream from the fertilized mires, the first concentration peak was observed 12–18 hours after fertilization. This peak reached a maximum of 3–4 mg/l and was composed of 1.2 mg/l of ammonium and 1.9 mg/l of nitrate. At a discharge peak 1–2 days later a second concentration peak appeared, with a maximum of 13–14 mg N/l. After one day the concentration decreased to 1 mg/l and after 2–3 weeks the concentration reached normal values (Table 3).

During fertilization, and during the following 3–4 weeks, the inorganic fractions dominated the total nitrogen, while organic nitrogen only composed about 10% of total nitrogen.

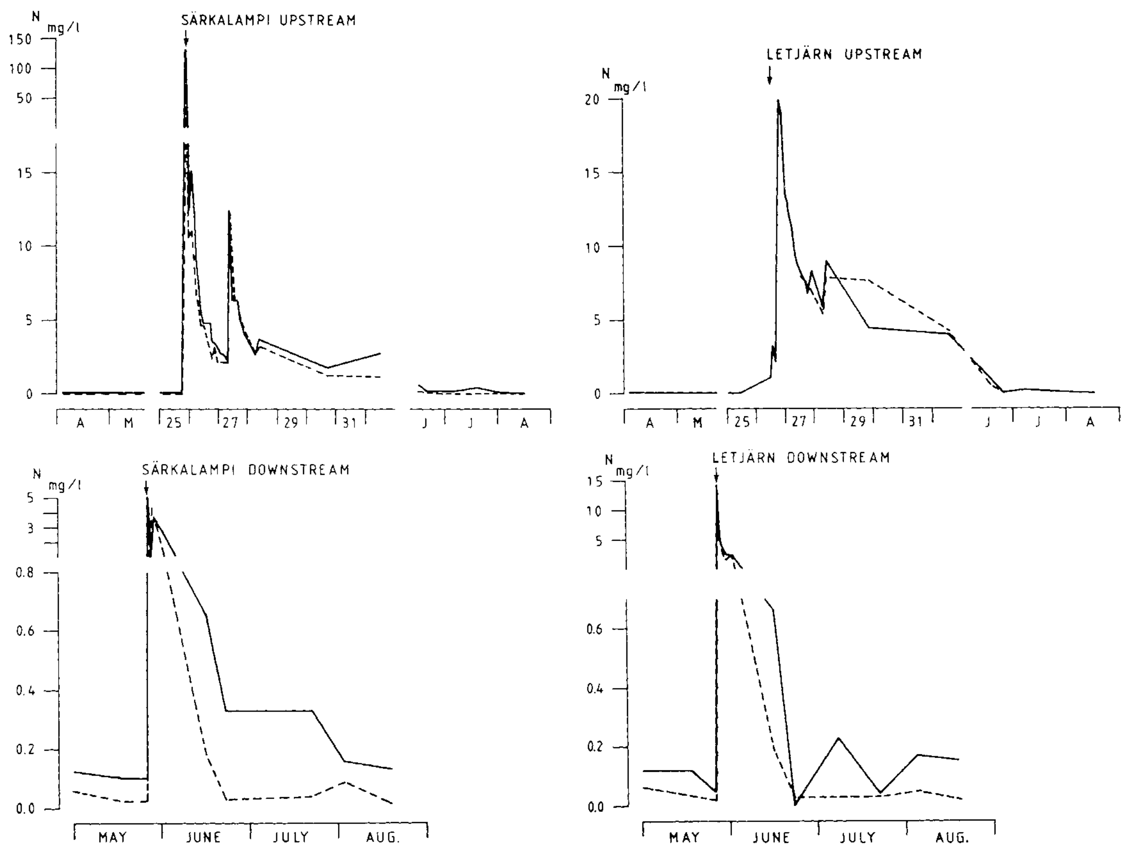

Fig. 3. Concentrations of nitrate and ammonium in runoff from the fertilized mires of Letjärn and Särkalampi basins during April/May to August 1983.
Above: the two upstream stations
Below: the two downstream stations
——— = NO_3-N; – – – = NH_4-N; ↓ = fertilization
(Observe the differences and changes in time and concentration scales).

Table 3. *The concentrations of nitrogen in the Siksjöbäcken basin shortly after fertilization* (Arithmetic means)

Station	Distance from the fertilized mires	Nitrogen fraction	Concentrations, mg/l			
			Before	Max.	Mean. 1 day	Mean. 1 week
LE	0–500 m	NO_3-N	0.07	20	11	6
		NH_4-N	0.05	20	11	7
LEN	1 000–1 500 m	NO_3-N	0.05	14	9	4
		NH_4-N	0.04	13	7	3
SÄI	0–500 m	NO_3-N	0.03	131	21	6
		NH_4-N	0.02	129	19	5
SÄ	1 000–1 500 m	NO_3-N	0.03	5	2	2
		NH_4-N	0.02	5	2	2
SII	4 500–5 000 m	NO_3-N	0.02	13	1	5
		NH_4-N	0.02	2	1	1

Before = concentration just before fertilization.
Max. = highest measured value.
Mean 1 day = mean value after 1 day.
Mean 1 week = mean value after 1 week.

Phosphorus

The mean annual concentrations of phosphorus in the brook waters of the Siksjöbäcken basin are normally within the 0.01–0.02 mg/l range. After fertilization, an almost immediate increase in total concentrations of phosphorus was found at the upstream stations, SÄI and LE. The concentrations reached a peak level of 5 mg/l, but this elevation was of short duration. After 6 hours the values were below 1 mg/l. After 3–6 days, the concentration was at the same level as before the fertilization (Fig. 4).

At the downstream stations, SÄ and LEN, the concentrations increased to a peak of 1.9 mg/l, but decreased after one week to the level found before fertilization. In the main stream, 5 km downstream from the fertilized mires, no change in phosphorus concentration was found.

The phosphate fraction dominated the total concentration of phosphorus only during the first week after fertilization and later the fraction of organic bound phosphorus again dominated the total concentration.

Potassium

The concentration of potassium in the different brooks in the Siksjöbäcken basin vary normally between 0.4–0.8 mg/l. At fertilization the concentration of potassium increased almost immediately in

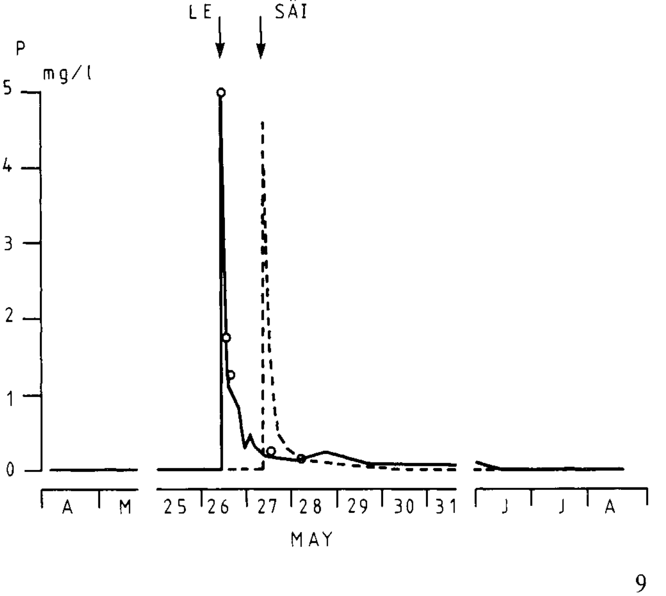

Fig. 4. Concentrations of phosphate and total phosphorus in runoff from the fertilized mires of the Letjärn and Särkalampi basins during April to August 1983.
——— = LE, Letjärn upstream;
– – – = SÄI, Särkalampi upstream
○ = total phosphorus at Letjärn basin
(Observe the different time scales).

the brooks. The concentration peaks at the SÄI and LE stations reached levels of 57 and 65 mg/l respectively (Fig. 5).

The downstream stations, SÄ and LEN, showed concentration maxima (12–15 mg/l) two to six hours later. In the main stream, 5 km downstream from the fertilized mires, there was a slight increase of 2.5 mg/l on one occasion, but otherwhise the concentration did not increase more than 50% of the background values.

The duration of the concentration peaks at the upstream stations was short and lasted only one day. After 2–4 weeks the concentrations were normal again. At the downstream stations the concentration decreased below 5 mg/l after one day, and three weeks later were only 0.5 mg/l higher than normal values.

Losses

Nitrogen

The losses of nitrogen from the different subbasins in the Siksjöbäcken basin were 2–5 kg/ha and year in the pristine state. The flux of nitrate was about 0.2 kg/ha and year and the flux of ammonium 0.1–0.2 kg/ha and year.

The first two weeks after fertilization showed increased nitrogen flux. The flux was 0.1 kg/ha and day, compared to 0.01 kg/ha and day for unfertilized conditions. During the following two months the flux was lower and amounted to 0.03 kg/ha and day, compared to 0.008 kg/ha and day as unfertilized.

The nitrogen loss, as compared to the total amount of applied nitrogen fertilizer, from the Letjärn basin during the first two weeks after fertilization was 19% with equal shares of nitrate and ammonium. After three months the loss was 404 kg, i.e. 20% of applied fertilizer. In the Särkalampi basin the nitrogen loss during the first two weeks was 22%, and after three months 504 kg, i.e. 26% of applied fertilizer (Table 4).

The main part of the nitrogen loss took place during the first two weeks and the following period contributed very little to the total loss (Fig. 6). Part of the immediate loss after fertilization is caused by fertilizer that falls directly in the ditches. This part, however, contributes only 1–3% of the total fertilizer applied (cf. Geology and peatlands). The loss during floods is greater than during low flows and the lack of such floods during the second period (mid-June–August) is one reason for the small loss during this period.

Phosphorus

The flux of phosphorus increased almost immediately after fertilization and as a mean for the first two weeks from 0.00002 kg/ha and day under unfertilized

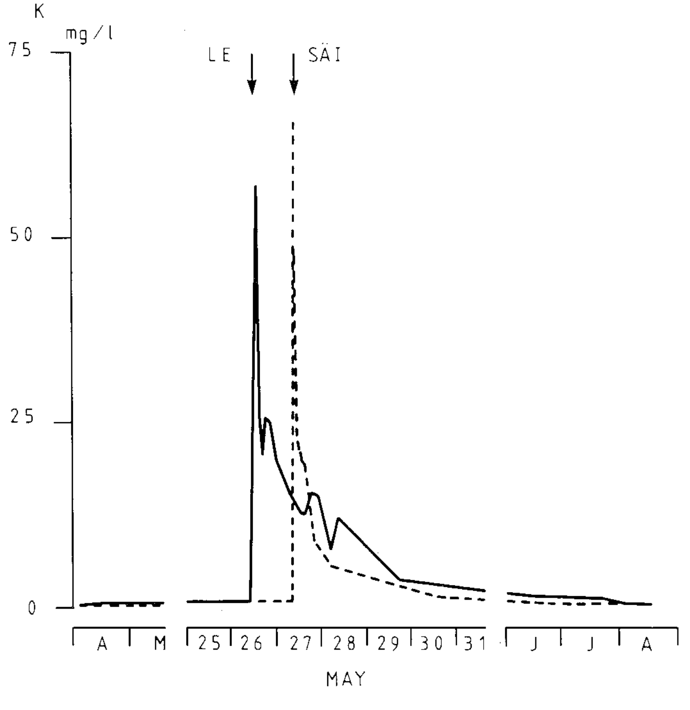

Fig. 5. Concentrations of potassium in runoff from fertilized mires of the Letjärn and Särkalampi basins during the period April to August 1983.
——— = LE, Letjärn upstream;
– – – = SÄI, Särkalampi upstream
↓ = fertilization.

Table 4. *Flux and loss of nitrogen from the Letjärn, Särkalampi and Hamptjärn basins. The mean flux is given in kg/ha and day. The loss is given in kg/ha and in per cent of applied fertilizer*

Basin	Period, days	Mean flux	T-loss basin	E-loss basin	T-loss mires	E-loss mires	%
NH_4-N							
Letjärn	0–14	0.101	1.41	1.40	9.8	9.8	10
	0–90	0.018	1.49	1.46	10.2	10.2	10
Särkalampi	0–14	0.040	0.56	0.55	8.2	8.2	8
	0–90	0.007	0.61	0.59	8.6	8.6	9
Hamptjärn	0–14	0.0006	0.01	–	0.01	–	–
	0–90	0.0002	0.02	–	0.02	–	–
NO_3-N							
Letjärn	0–14	0.091	1.27	1.25	8.8	8.7	9
	0–90	0.017	1.40	1.38	9.7	9.7	10
Särkalampi	0–14	0.066	0.93	0.91	13.4	13.4	13
	0–90	0.013	1.12	1.10	16.2	16.2	16
Hamptjärn	0–14	0.0007	0.01	–	0.01	–	–
	0–90	0.0001	0.01	–	0.01	–	–
Total-N							
Letjärn	0–14	0.129	2.8	2.7	12.0	18.9	19
	0–90	0.037	3.1	2.8	20.0	19.7	20
Särkalampi	0–14	0.120	1.7	1.5	22.6	22.4	22
	0–90	0.024	2.0	1.7	25.9	25.6	26
Hamptjärn	0–14	0.0011	0.15	–	0.15	–	–
	0–90	0.0003	0.27	–	0.27	–	–

T-loss basin = total loss from the basin.
E-loss basin = fertilizer loss from the basin.
T-loss mires = total loss from the drained and fertilized mires.
E-loss mires = fertilizer loss from the drained and fertilized mires.
% = fertilizer loss in percentage of applied fertilizer.

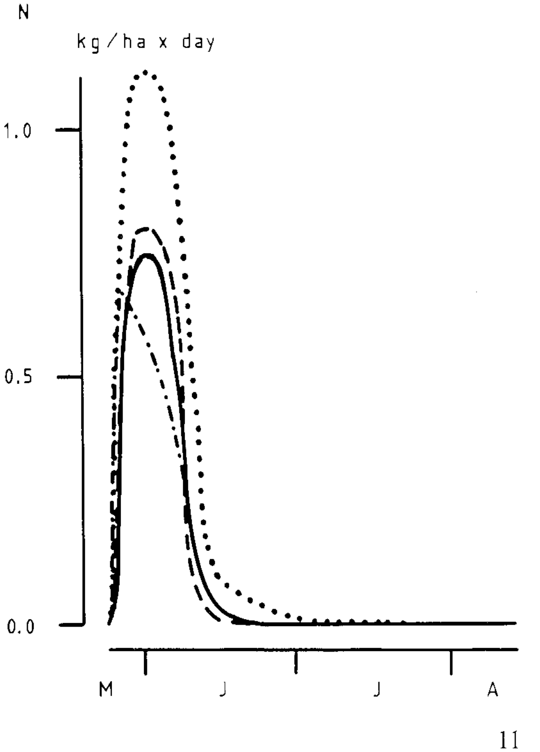

Fig. 6. Excess flux of nitrate and ammonium due to applied fertilizer at the mires of the Letjärn and Särkalampi basins during May 25 to August 18, 1983.

Basin	NO_3-N	NH_4-N
Letjärn	———	— —
Särkalampi	. . .	— · —

conditions to 0.003 kg/ha and day. During the following two months only a minor increase in the flux of phosphorus occurred, and the excess loss of phosphorus during this period was therefore negligible.

The total loss of applied fertilizer from the fertilized area amounts to 0.35 kg/ha for the Letjärn basin and 0.54 kg/ha for the Särkalampi basin. These values correspond to about 1% of the fertilizer applied in each area (Table 5).

Potassium

The annual mean flux of potassium from the different subbasins in the Siksjöbäcken basin was about 2 kg/ha and year, i.e. 0.02 kg/ha and day in the pristine state. After fertilization, during the first fortnight, the flux increased to 0.06 kg/ha and day. During the following 2 months the increased flux only amounted to 0.015 kg/ha and day but was still higher than for unfertilized conditions (0.005 kg/ha and day) (Table 6).

The losses of applied fertilizer during the first two weeks were 0.6 kg/ha in the Särkalampi basin, and 0.8 kg/ha in the Letjärn basin. This corresponds to 9% and 5% respectively of the total amount of applied fertilizer. For the whole investigation period the loss increased to 0.9 kg/ha and 1.1 kg/ha respectively, i.e. 13% and 7% of the applied fertilizer in the Särkalampi and Letjärn basins (Fig. 7).

Table 5. *Flux and loss of phosphorus from the Letjärn, Särkalampi and Hamptjärn basins. The mean flux is given in kg/ha and day. The loss is given in kg/ha and in per cent of applied fertilizer*

Basin	Period, days	Mean flux	T-loss basin	E-loss basin	T-loss mires	E-loss mires	%
Letjärn	0–14	0.0036	0.050	0.050	0.35	0.35	0.7
	0–90	0.0006	0.052	0.051	0.36	0.36	0.7
Särkalampi	0–14	0.0025	0.035	0.035	0.52	0.52	1.0
	0–90	0.0005	0.040	0.037	0.54	0.54	1.1
Hamptjärn	0–14	0.00003	0.0004	–	0.0004	–	–
	0–90	0.00004	0.0031	–	0.0031	–	–

T-loss basin = total loss from the basin.
E-loss basin = fertilizer loss from the basin.
T-loss mires = total loss from the drained and fertilized mires.
E-loss mires = fertilizer loss from the drained and fertilized mires.
% = fertilizer loss in percentage of applied fertilizer.

Table 6. *Flux and loss of potassium from the Letjärn, Särkalampi and Hamptjärn basins. The mean flux is given in kg/ha and day. The loss is given in kg/ha and in per cent of applied fertilizer*

Basin	Period, days	Mean flux	T-loss basin	E-loss basin	T-loss mires	E-loss mires	%
Letjärn	0–14	0.08	1.11	0.76	5.6	5.3	5
	0–90	0.02	1.48	1.11	7.5	7.0	7
Särkalampi	0–14	0.07	0.94	0.64	9.7	9.4	9
	0–90	0.02	1.29	0.88	13.4	13.0	13
Hamptjärn	0–14	0.02	0.31	–	0.30	–	–
	0–90	0.01	0.43	–	0.40	–	–

T-loss basin = total loss from the basin.
E-loss basin = fertilizer loss from the basin.
T-loss mires = total loss from the drained and fertilized mires.
E-loss mires = fertilizer loss from the drained and fertilized mires.
% = fertilizer loss in percentage of applied fertilizer.

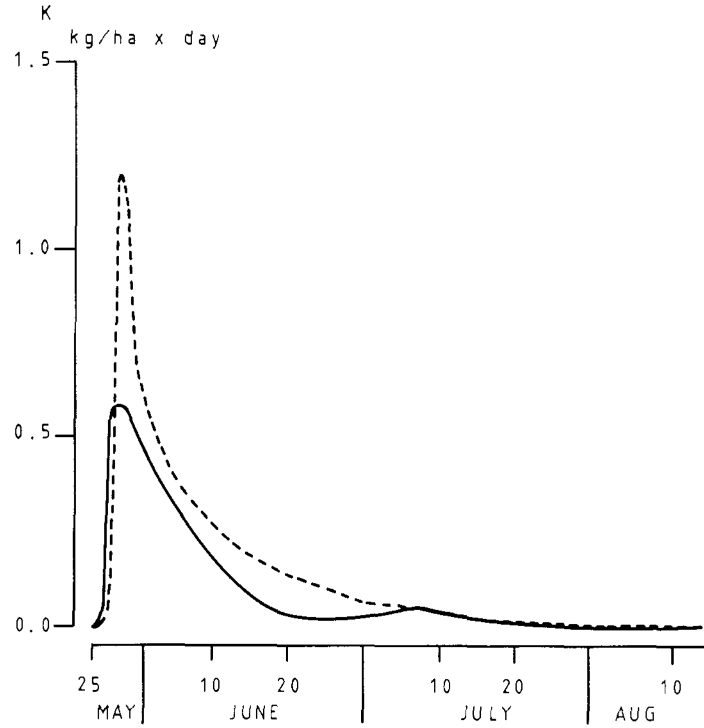

Fig. 7. Flux of potassium from the fertilized mires of the Letjärn and Särkalampi basins during May 25 to August 18, 1983. The fluxes are calculated due to drained and fertilized areas only.
——— = LE, Letjärn;
– – – = SÄI, Särkalampi.

Discussion

Comparison with other investigations

The almost immediate concentration increases of nitrogen, phosphorus and potassium in runoff after fertilization are due to fertilizer having fallen directly into the ditches and the streams. These types of concentration peaks normally have a very short duration, only a few hours, and are often missed when sampling is conducted on a daily basis. The transport velocity of the fertilizer compounds varied in this investigation between 250–350 m/h.

The very high concentration peaks (130 mg/l) for ammonium and nitrate nitrogen in the Särkalampi basin during fertilization are greater than the concentration increases reported by Wiklander (1974), while the increase (20 mg/l) in the Letjärn basin is about the same size. Wiklander reported concentration peaks between 5–30 mg/l for ammonium, and between 2–12 mg/l for nitrate after peatland fertilization with ammonium nitrate. Braekke (1979) reported increased nitrate concentrations up to 10 mg/l after ammonium nitrate fertilization of a bog in Norway. With regards to forest (mineral soil) fertilization, increases between 2–70 mg/l have been reported for both ammonium and nitrate (Ramberg et al.l, 1973; Edlund & Jäger, 1977; Grip, 1982; Möller, 1983) (Table 7). The large difference in concentration increase between the Särkalampi basin and the Letjärn basin is probably due to a more efficient drainage system in the Särkalampi basin than in the Letjärn basin and that the distribution of the fertilizer was more concentrated in time in the Särkalampi basin.

In general, the size of the concentration peaks depends on several factors such as: the total amount of fertilizer which falls directly into the water, the amount of fertilizer spread per time unit, levels and outflow of groundwater and the efficiency of the drainage system.

The amount of fertilizer falling directly into the watercourse is dependent on the stream and ditch surface area affected by the fertilization processes, and aslo on the runoff and moisture conditions during fertilization. A high groundwater table and discharge during fertilization will increase the amount of fertilizer loss in runoff. Precipitation during or shortly after fertilization will also increase the fertilizer outflow.

The high nitrogen concentrations in runoff decrease normally very rapidly, both with distance downstream and with time. In this investigation both ammonium and nitrate concentrations decreased to a few mg/l in a couple of days, but remained elevated above normal levels for about one month for ammonium and more than three months for nitrate. Wiklander (1974) (Table 7) and Möller (1983) reported peak decreases after one day, but the concentration remained above normal levels up to 4–5 months after fertilization. Ramberg et al. (1973) reported decreased peak concentrations within 1–2 weeks, but ammonium concentrations remained elevated for 5 months and nitrate concentrations were elevated for more than one year.

The losses of nitrogen from the fertilized basins were greatest during the first two weeks and amounted to 90% of the total loss (2–3 kg/ha) during the three-month period after fertilization. On a yearly basis, it corresponds to a loss of 8–12 kg/ha. This is a higher value than reported from forest fertilization. Grip (1982) reported a loss of 3.6 kg/ha and year in the first year after fertilization, and Wiklander (1977) (Table 7) reported a loss of 12 kg/ha during a two-year period. The values calculated for this investigation may be somewhat overestimated due to the short investigation period but are probably higher than the values given by Wiklander and Grip. The nitrogen loss in the Siksjöbäcken area under undrained and unfertilized conditions was within the range of 1.4–3.7 kg/ha and year, and after drainage 3.0–5.9 kg/ha and year.

The nitrogen flux at the upstream stations during the first two weeks consisted of nearly equal parts of ammonium and nitrate. Later, and further downstream, the nitrate fraction became more dominant. With regards to forest fertilization, nitrate normally dominates the flux even more. The greater nitrate dominance after forest fertilization is probably due to a more extensive nitrification in mineral soil compared to peatland. Ammonium is also retained more efficiently in mineral soil because of the stronger complexation to mineral colloids.

The main bulk of the fertilizer is retained in soil and vegetation. In mineral soil Nömmik & Möller (1981) (Table 7) reported a recovery of fertilizer in the 25 cm top soil of 25–57% while Melin et al. (1983) (Table 7) reported 39–52% in the soil and 30–37% in the vegetation. It should be noted that lower application rates increase the retention. This leaves about 20% of applied fertilizer unrecovered. The main part of this is lost in leaching. There is, though, a considerable retention also in sediment and aquatic biota. In both cases these retentions are due to geochemical sorption/precipitation and biological uptake. Nitrogen may also be lost to the atmosphere due to denitrification (Melin & Nömmik, 1983).

Nitrogen, i.e. nitrate and ammonium, is retained in soil and sediment to a minor extent. The return is generally more dependent on biological uptake and

Table 7. *A compilation of fertilization performance of referred investigations. Most of the fertilizations were performed from the air and during the summer*

Reference	Soil type	Type of fertilizer	Fertilizer dose, kg/ha
Almberger & Salomonsson, 1979	peat	rock phosphate, KCl	P = 30, K = 60
Braekke & Bjor, 1977	peat (bog)	NPK, 14:6:16	NPK = 1000–5000
Braekke, 1979	peat	NPK, 12:6:14 superphosphate	NPK = 2000
Edlund & Jäger, 1977	mineral	AN	N = 175
Gri, 1982	mineral	Urea, AN	N = 150
Karsisto & Ravela, 1971	–	PK	600–1200
Kenttämies, 1977	peat	rock phosphate, KCl	P = 120, K = 75
Kenttämies, 1981	peat	rock phosphate, KCl	P = 45, K = 85
Lehmusvuori, 1981	peat	–	–
Melin et al., 1983	mineral	AN	N = 100
Möller, 1983	mineral	AN	N = 150
Nyberg, 1977	mineral	AN	N = 150
Nömmik & Möller, 1981	mineral	AN och Urea	N = 150–600
Paavilainen, 1976	–	rock phosphate	P = 30–50
Ramberg et al., 1973	mineral	AN	N = 160
Wiklander, 1974	peat	AN, superphosphate, KCl, NPK, 12:9:16	400–500
Wiklander, 1977	mineral	AN och Urea	N = 115–175

AN = ammonium nitrate.

thus shows great variations due to season. At snowmelt there is little or no retention of the nitrogen dissolved in water. The retention is largely dependent on nitrification and denitrification processes.

In areas sensitive to acidification the areal coefficient (output/input ratio) amounts to 0.09 for nitrate and 0.07 for ammonium (Tirén, 1980). The retention in these areas is in other words, relatively high. From such an area, Grip (1982) reported a loss of 2–4% of applied ammonium nitrate during a three-year period.

The increased concentrations of fertilizer compounds in runoff also affect the concentrations of other elements, like hydrogen ions and metal ions. Fertilization with ammonium nitrate increases the flux of hydrogen ions an metal ions in runoff. The water can be acidified by exchange acidity (Tamm, 1976). There are mainly two reactions which contribute to the acidification.

1. Ammonium ions are absorbed to mineral colloids in exchange for hydrogen ions.
2. Ammonium is oxidised to nitrate by nitrification with a subsequent release of hydrogen ions.

In some cases, generally during extensive denitrification, the reverse can also occur, i.e. hydrogen ions are taken up when nitrate (nitrogen) is reduced to ammonium (nitrogen).

The effect of fertilization on the pH of the runoff water varied slightly between the two investigated basins, Letjärn and Särkalampi. In the Letjärn basin, the pH decreased by 0.3 units at fertilization, and by 0.5 units when the mean for the 3-month period was calculated. The runoff water of the Särkalampi basin showed an increased pH at fertilization, but decreased by 0.2 units when the mean for the 3-month period was calculated.

Varying effects on pH have also been reported after forest fertilization (ammonium nitrate). Möller (1983) reported a decrease of 0.1–0.2 units during the first 24 hours after fertilization but normal values occurred again within a few days. Ramberg et al. (1973) reported a decrease of 0.4 units at fertilization, but normal values afther two weeks. Edlund & Jäger (1977) reported a decrease of up to 2 units a few days after fertilization, but normal values within a week. Nyberg (1977) (Table 7) reported both increased (0.2 units) and decreased (0.3–0.6 units) pH values after fertilization.

The different responses in the change of pH may be due to factors such as differences in nitrification/denitrification activity, buffering capacity and exchange capacity in water and soil.

The changes in phosphorus concentration in runoff after fertilization were not as evident as the changes for nitrogen. At upstream stations in the Letjärn and Särkalampi basins the concentrations increased to about 5 mg/l shortly after fertilization. The duration of the increased phosphorus concentrations was very short, however, and within one week the concentrations were back to normal levels. The increase was less than the 10–13 mg/l reported by Braekke (1979) (Table 7) and Wiklander (1974) after peatland fertilization with superphosphate but higher than the increases of 0.1–0.3 mg/l reported by Almberger & Salomonson (1979) and Kenttämies (1981) (Table 7) for peatland fertilization with apatite phosphorus.

In the Siksjöbäcken investigation, the concentration decreased very fast, both in time and with distance downstream, probably due to biological uptake of phosphorus in the streams. The duration of the elevated concentrations was only about one weak. In other investigations (Särkää, 1970; Wiklander, 1974; Paavilainen, 1976; Kenttämies, 1977; Braekke, 1979) (Table 7) the phosphorus concentrations have been reported to remain elevated above normal levels for 5 months up to several years after fertilization.

The leaching and retention of both phosphorus and nitrogen fertilizer in the streams are dependent on runoff. At low discharges there is increased retention and decreased leaching and vice versa at high discharges. This is due to a longer residence time in the watercourses during low discharges. The longer the residence time the more is retained (Meyer & Likens, 1979). This is most evident for phosphorus due to a short turnover time.

The turnover time for phosphorus in both terrestrial and aquatic ecosystems is shorter than for nitrogen. According to Likens (1974) the turnover rate of phosphorus is counted in minutes whereas for nitrogen it amounts to hours and days. In comparison with nitrogen, phosphorus is also immobilised to a greater extent through geochemical sorption. In this context the contents of Fe, Al and Ca ions in the soil and sediment are of great importance. The relatively low content of such elements in peat leads to a greater loss of phosphorus after fertilization of peatlands in comparison with mineral soils.

The loss of phosphorus to the watercourses is also dependent on the type of fertilizer used. Superphosphate is more water-soluble than rock phosphate (apatite) and is therefore less retained in the watershed.

The fertilizer loss of phosphorus was 0.04–0.05

kg/ha during the first 3 months after fertilization. Calculated on a yearly basis, these values correspond to 0.27 kg/ha. Investigations in Finland (Särkä, 1970; Karsisto & Ravela, 1971; Paavilainen, 1976; Kenttämies, 1981; Lehmusvuori, 1981) (Table 7) reported a loss of phosphorus within the range of 0.1–0.5 kg/ha and year after fertilization.

Under undrained and unfertilized conditions, the phosphorus loss in runoff normally varies between 0.025 to 0.085 kg/ha and year (Paavilainen, 1976; Kenttämies, 1977; Boetler & Verry, 1977; Bergquist et al., 1984). After drainage, the phosphorus loss can increase to 0.12–0.14 kg/ha and year (Bergquist et al., 1984), and in some cases even to 1.2 kg/ha and year (Sallantaus & Pätilä, 1983).

For potassium, peak concentrations between 57 to 65 mg/l were measured in runoff almost immediately after fertilization. After a few days the concentrations decreased to levels below 5 mg/l, but remained above the normal level for about one month. The peak increase measured is of about the same magnitude as reported by Wiklander (1974) and Braekke & Bjor (1977). Wiklander measured peak concentrations between 7–47 mg/l and the concentration remained above normal levels for about 4–5 months. Braekke & Bjor reported peak concentrations between 5–69 mg/l, and elevated concentrations above the normal levels during a 3-year period after fertilization.

The loss of potassium from the fertilized basins in the Siksjöbäcken area amounted to 1.3–1.5 kg/ha during the first 3 months after fertilization. On a yearly basis, it corresponds to 8 kg/ha, which can be compared to 2 kg/ha and year under unfertilized and undrained conditions, and 3–4 kg/ha and year under drained but unfertilized conditions. Paavilainen (1976) reported a potassium loss of 0.7 kg/ha and year under unfertilized conditions and 2.6 kg/ha and year after fertilization. Kenttämies (1977) reported a loss between 0.5–1.9 kg/ha and year for unfertilized conditions and 1.2–5.9 kg/ha and year after fertilization.

Consequences of fertilization on fish

The high concentrations of ammonium and nitrate nitrogen that occur shortly after fertilization are, together with the simultaneous pH drop, a hazardous factor for fish populations in forest brooks. In some cases fish kills have been reported downstream of fertilization areas. Nyberg (1977) reported an increased mortality for trout kept in net chambers downstream of a forest area fertilized with ammonium nitrate. The cause of the increased mortality in fish populations after fertilization has not yet been clearly solved or verified.

The most probable explanation of increased fish mortality after nitrogen fertilizations are changes in the concentrations of ammonium and ammonia ions, hydrogen ions and metal ions in runoff.

1. Even relatively low ammonia (NH_3-N) concentrations are extremely poisonous to fish. The concentration increases with high ammonium (NH_4-N) concentrations on high pH values. EIFAC (European Inland Fisheries Advisory Commission, 1973) sets the lethal concentration for salmonids to 0.2 mg NH_3-N/l. EPA (U.S. Environmental Protection Agency, 1976) sets 0.02 mg NH_3-N/l as a limit in water quality criteria for freshwater organisms.

2. Large changes in pH (>0.5 units), as well as too low or too high values, are critical to many fish populations (EIFAC 1969).

3. Metal ions, e.g. Al^{3+}, can be dissolved from the bottom of the stream during pH changes and cause toxic concentrations in stream water. Concentrations of 0.2 mg inorganic Al/l have been reported to be toxic (lethal) to salmonid fry at pH 5.0 (Dickson, 1979). Everhart & Freeman (1973) propose 0.1 mg Al/l as a probable limit for sublethal effects on salmonids.

The dissociation degree for ammonia (NH_3-N) is dependent on the pH and the temperature of the water. At pH 6.0 and a temperature of 10°C, about 0.02% of the ammonium (NH_4-N) nitrogen is ammonia nitrogen (Messer et al., 1984), which means that 130 mg NH_4-N/l corresponds to 0.026 mg NH_3-N/l. The measured ammonium concentration in the Särkalampi basin therefore corresponds to an ammonia concentration above the limit recommended by EPA (1976), but lower than the lethal limit given by EIFAC (1973).

No fish kill was detected downstream of the fertilized mires, during or after fertilization. Neither could any change in the fish populations be detected by electrofishing during the following 4 months.

Forest and peatland fertilizations concern mainly areas where the surface water has a pH lower than 7.0 Due to low dissociation degree for ammonia at these pH values and since the ammonium concentration seldom reaches levels above 100 mg/l during fertilization, it is not probable that fish kills in these waters only depend on high ammonium concentrations. In these areas changes in pH, in combination with increased aluminium concentrations are the more probable cause of increased mortality. But in waters with pH above 7.0 high ammonium concentrations can be of importance. Möller (1983) reported an ammonium concentration of 69 mg/l, after fertilization, in runoff water with pH around 7.0. This concentration corresponds to a concentration of 0.13 mg NH_3-N-l, and if the ammonium concentration had been 130 mg/l, to a concentration of 0.25 mg NH_3-N/l, i.e. above the lethal limit given by EIFAC (1973). At pH 7.0 or above, sublethal effects, such as retarded growth, are also more probable.

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