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Release of inorganic N, P and K in peat soils; effect of temperature, water chemistry and water level

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Abstract. In the Netherlands, fens that are fed by polluted river water are often eutrophic, whereas fens fed by calcium-rich groundwater often are mesotrophic. Differences in trophic status can not always be attributed to differences in the nutrient load of the water.

In this paper we try to determine if the inflow of river water in fens, in fact, accelerates the soil nutrient release, thereby creating more eutrophic conditions ('internal eutrophication'). For this purpose, we compared nutrient release rates (N, P and K) in soil cores from *Sphagnum* peat and *Carex* peat saturated with different media, that were artificially created to mimic the three basic water sources: polluted river water, unpolluted calcium-rich groundwater and rainwater. In addition, we studied the effect of temperature and water level on nutrient release rates.

The experiments proved that *Sphagnum* peat released much more P and ammonium than *Carex* peat. The strong site effect proved consistent throughout the water chemistry treatments, which indicates that soil quality may be the most important agent determining nutrient release rates. Nevertheless, it was established that water chemistry and water level are of significant influence on nutrient release rates in peat soils. In particular, river water stimulated P release by the peat, most notably in the *Sphagnum* peat. P-release in both soils was only minor when the soils were incubated in clean Ca-rich groundwater. It is suggested that P release is strongly associated with soil chemical processes, and that high P release rates after incubation in river water are due to the high sulphate content of the water.

The net release from the soil of ammonium, potassium and phosphate increased with increasing temperature. A freezing treatment significantly increased nutrient availability.

The results of the experiments are examined in the context of hydrologic management strategies for the conservation of fens in agricultural landscapes.

Introduction

Eutrophication is one of the most important contemporary anthropogenic disturbances and its detrimental effects on wetland vegetation have been

reported in numerous cases (Klötzli 1986; Wheeler 1983; Verhoeven et al. 1988). The nutrient availability in wetlands is determined by external nutrient inputs and by soil biogeochemical processes (mineralization, chemisorption), the latter processes being strongly regulated by environmental conditions (water chemistry, redox potential, temperature, etc.) and substrate quality (e.g. *Carex* peat vs. *Sphagnum* peat) (Verhoeven et al. 1990).

Eutrophication of wetlands can thus be attributed to (1) increased external inputs of nutrients ('external eutrophication') and/or (2) acceleration of nutrient cycling within the wetland soil associated with a change of environmental conditions ('internal eutrophication'). In the latter case we are dealing with nutrients that were already present in the wetland ecosystem, but in organic-bound or chemically bound forms, and thus unavailable to the wetland vegetation.

So far, eutrophication studies did not attempt to establish the relative importance of external and internal eutrophication, and until recently processes involved with internal eutrophication hardly received any attention (but see Curtis 1989; and Caraco et al. 1989, 1990). This is unfortunate, as strategies towards conservation or restoration of nutrient-poor ecosystems can only be successful, if the processes responsible for eutrophication are understood.

In the Vechtplassen area, The Netherlands, numerous small quaking fens are situated in a matrix of pastures used for dairy production. Most of the fens in recharge areas have been seriously affected by eutrophication, whereas those located in areas with discharge of clean Ca-rich groundwater are relatively undisturbed (Beltman & Verhoeven 1988; Verhoeven et al. 1988). As there were no major differences in the nutrient mass balance of fens under constrasting hydrological conditions (Koerselman et al. 1990a), it was postulated that internal eutrophication was responsible for the observed increase of nutrient availability in recharge fens. Differences in trophic status between discharge fens and recharge fens were more specifically attributed to the inflow of polluted river water in recharge fens that was thought to accelerate internal nutrient release processes (Koerselman et al. 1990b). The mesotrophic character of fens is generally attributed to the steady inflow of unpolluted calcium-rich groundwater, resulting in a strong fixation of P (Wassen et al. 1990; Boyer & Wheeler 1989; Kemmers 1986; Koerselman et al. 1990b; Van Wirdum 1991).

In this paper we try to determine whether the inflow of polluted river water in fens, in fact, accelerates the soil nutrient release, thereby creating more eutrophic conditions. For this purpose, we compared nutrient release rates in soil cores from *Carex* peat and *Sphagnum* peat saturated with

polluted river water with those saturated with non-polluted calcium-rich groundwater and rainwater. In addition, we studied the effect of water level and temperature on nutrient release rates. The results are examined in the context of hydrologic management strategies for the conservation of fens in agricultural landscapes.

Methods

Study area

The study sites are located in the Vechtplassen area, The Netherlands (5°7′E, 52°9′N). The peat soil consists of a floating root mat that supports vegetation and moves up and down with fluctuations of the water table. Therefore, water tables are near the soil surface during most of the year (Koerselman 1989). One fen is dominated by *Carex diandra, Potentilla palustris, Menyanthes trifoliata, Caltha palustris* and *Equisetum fluviatile.* The plant community belongs to the mesotraphent Scorpidio-Caricetum diandrae (Westhoff & Den Held 1969), and can be classified as transitional rich fen vegetation (*sensu* Sjörs 1950).

The second fen has a sparse phanerogam vegetation and is dominated by *Carex acutiformis* and *Phragmites australis.* A thick *Spahgnum* carpet (mainly *S. squarrosum, S. fimbriatum* and *S. fallax*) covers the soil completely. The plant community at this site is a transition between the eutraphent Thelypterido-Phragmitetum (borders) and the oligotraphent Pallavicinio-Sphagnetum (central part; Westhoff & Den Held 1969), and can be classified as a poor fen (*sensu* Sjörs 1950).

Selected soil characteristics of the two fens are given in Table 1. The soils will be referred to as *Carex*-soil (site 1) and *Sphagnum*-soil (site 2). Differences in fen water chemistry and vegetation of the two fens (Table 1) are strongly related to the contrasting hydrologic regime. The *Sphagnum* fen is fed mainly by precipitation (874 mm) and receives additional river water inputs of 309 mm. Discharge of Ca-rich groundwater is the main input the *Carex* fen (1001 mm), that further receives 865 mm of precipitation and 115 mm of polluted river water (Koerselman et al. 1990a and b for details).

Soil sampling

Soil material was obtained from the 5—15 cm stratum in the central part of the fens at 4 occasions during the summer and the autumn of 1989. Hand-augered material was transported to the laboratory, where coarse

Table 1. Selected soil characteristics of the *Sphagnum* and *Carex* soils.

Site	*Carex*	*Sphagnum*		*Carex*	*Sphagnum*
Soil (5–15 cm)			Soil water* (5–15 cm)		
pH	5.96	4.17	pH	6.3	4.4
organic matter (%)	89	98	EC_{20}	238	108
bulk density (g/l)	69	49	IR	0.94	0.22
water content (%)	93	95			
C/N ratio	15	36	Fe	0.7	0.4
			Ca	37.8	6.6
Total nutrients			Mg	3.3	1.1
(mg/g dry wt)			Al	< 0.1	0.2
N	25.1	11.2	HCO_3	96	19
P	1.3	0.7	SO_4	10	13
K	0.5	0.8	Cl	25	24
			NO_3-N	0.08	0.02
Available nutrients			NH_4-N	0.54	0.30
(mg/kg dry wt)			PO_4-P	0.03	0.04
BAP	24.7	23.7	K	2.13	5.4
P-water	0.1	1.0	Na	13.6	10.6
NH_4-N	12.8	8.3			
NO_3-N	0.1	2.5			
K	58.6	345.1			

* Concentrations in mg/L., EC_{20} in µS/cm. Ionic Ratio (IR) after Van Wirdum (1991): IR = 2[Ca]/(2[Ca] + [Cl]), molar concentrations.

plant parts and white roots were removed from the material. In addition, soil water was collected from the peat for chemical analyses, and for application in the incubation experiments.

Incubation procedures

Peat samples were incubated in glass tubes (diameter: 4 cm) provided with a bottom outlet. The tubes were filled with 10 cm of soil material on top of a layer of glass pearls.

Experiment 1: effect of temperature

The soil columns were inundated with water that had been collected at the sites. The water level was maintained 1 cm above soil surface, which mimics *in-situ* summer water tables. The tubes were loosely capped with foil to reduce evaporation, and were then incubated in dark chambers at 0 °C, 10 °C and 20 °C for 6 weeks followed by extraction of NH_4, NO_3, ortho-P and K following procedures explained below. Similar extractions

were performed with fresh peat at the start of the incubation. All treatments were performed with 5 replicates.

To estimate the effects of freezing on nutrient transfers in the peat, soil samples were frozen at −15 °C for 1 week, then thawed at 5 °C for 24 hous. Immediately before and after the freezing treatment soil samples were analyzed for nutrients using methods described below.

Experiment 2: effect of water chemistry and water level

Soil columns were percolated intermittently for 16 hours with 500 ml of an incubation medium (5 times the volume of the tube) to exchange the original water volume by three different artificially created solutions (Table 2). The amount of solution needed to replace the original water volume had previously been determined in an experiment in which soil columns were percolated with salt solutions until the ionic content of the drain water was similar to that in the salt solution (Van Winden 1987).

The three incubation media used in the experiment (rainwater, clean calcium-rich groundwater and polluted river water) were artificially created from salts. The water found in wetlands is a mixture of these three water types, their relative quantities being determined by the hydrologic regime (cf. Koerselman et al. 1990a, b).

Before and after the percolation procedure, the soil columns were extracted for NH_4, NO_3, ortho-P and K. The second step of the experiment involved the incubation of the pre-percolated soil columns at two water levels. Part of the soil columns were inundated with simulated solutions (water level 1 cm above soil surface), and part of the soil columns were incubated at a lower water level (10 cm below soil surface). The tubes were loosely capped with foil to reduce evaporation, and were then incubated in dark chambers at 20 °C for 6 weeks, followed by extraction of NH_4, NO_3, ortho-P and K.

All treatments were performed with 5 replicates.

Chemical analyses

Wet equivalents of 1 g dry peat were extracted with 100 ml of medium. Samples were shaken with distilled water (1 hour, for analyses of NO_3 and water soluble ortho-PO_4; 'P-water'), 0.2 M KCl (1 hour, for analyses of NH_4 availability) and a 0.04 M acetic acid and 0.1 M ammonium lactate solution of pH = 3.75 (4 hours, for analyses of K and biological available ortho-P: BAP; Egnér et al. 1960). The extract solution was filtered through 1.2 μM glass fibre filters and then analyzed on a Skalar continuous flow analyzer using colorimetric methods for NH_4 (indophenol

Table 2. Chemical composition of artificial rainwater, groundwater and river water that was used in the experiments. Concentrations in mg/L., EC_{20} in µS/cm, Ionic Ratio after Van Wirdum (1991): IR = 2[Ca]/(2[Ca]+[Cl]); molar concentration).

Water type	SO_4	NO_3-N	Cl	Mg	Ca	Na	K	NH_4-N	PO_4-P	Fe	Al	HCO_3	pH	IR	EC
Rainwater	7	0.8	4	0.2	1	2	0.2	1.5	0.00	0.0	0.0	0	4.4	0.2	51
Groundwater	3	0.9	14	3.5	54	9	0.4	0.4	0.03	0.2	0.0	25	6.8	0.9	199
River water	61	4.3	113	9.6	60	70	6.9	2.2	0.68	0.2	0.1	157	7.1	0.4	533

blue method; Bietz 1974), NO_3 (sulfanylamide/naphtyl-ethylene-diamine method; Downes 1978) and ortho-P (ammonium-molybdate method; Lennox 1979), and flame emission spectrophotometry for K. In addition, total-P and total-N were determined using a wet acid-digestion following a salycylic acid thiosulphate modification of the Kjeldahl method (Page et al. 1982). Soil pH was determined potentiometrically before and after the extraction procedure using a PHM 84 pH meter. Redox potentials were measured with a calomel electrode, and changed to standard hydrogen cell values at pH 7 (Eh_7) using correction factors given by Clymo (1983).

Expression of results and statistical techniques

The amount of nutrients extracted after incubation minus the amounts extracted directly after the percolation procedure will be referred to as 'released nutrients', and represent the net-result of mineralization, microbial immobilization and chemisorption processes.

The statistical significance of differences in nutrient content between time intervals was tested with Student's *t*-test (Sokal & Rohlf 1981). The statistical significance of differences between sites and treatments was tested with the General Linear Models procedure of the Statistical Analyses System (SAS Institute Inc. 1985). The overall level of significance used is $p < 0.05$, unless otherwise stated.

Results

Experiment 1: effect of temperature

Redox potentials

Measurements of the redox potentials after the 6 weeks incubation period revealed no significant difference between the two soils when corrected for differences in pH (Table 3).

Table 3. Redox potentials (Eh_7, mV) at 3 soil depths in the incubation tubes after 6 weeks incubation at 20 °C. Values are means ± s.e. for 5 replicates.

Soil	Depth (cm below soil surface)		
	0	5	10
Carex	143 ± 14	118 ± 16	100 ± 19
Sphagnum	116 ± 16	93 ± 8	72 ± 7

Nutrient release rates

Both site and temperature significantly affected the release of all parameters except nitrate (Table 4). In every case, interaction factors are significant as well, indicating that the effect of the factor temperature was different for both soils.

Table 4. Values of p of a two-factor analysis of variance of the amounts of nutrients released by the soils after 6 weeks incubation at 20 °C. Site and temperature are independent variables. p values < 0.05 are considered statistically significant.

	P values				
	BAP	P-water	Ammonium	Nitrate	Potassium
Site	0.0001	0.0001	0.0001	0.2081	0.0001
Temp	0.0001	0.0001	0.0001	0.8819	0.0001
Site*temp	0.0257	0.0374	0.0074	0.1522	0.0131

More than 95 percent of the nitrogen release was in the form of ammonium (data not shown). The relation between temperature and ammonium release (Fig. 1c) was approximately linear for both soils. Ammonium release in the *Sphagnum*-soil significantly ($p < 0.05$) exceeded that in the *Carex*-soil at 10 ° and 20 °C. At 0 °C ammonium release still proceeded at a significant rate, but differences between the two soils were not significant.

BAP and P-water release rates in the *Sphagnum*-soil significantly exceeded those in the *Carex*-soil at every temperature ($p < 0.05$; Fig. 1a, 1b). There was a marked difference between the two extraction procedures used. P-water release occurred over the whole temperature range in both soils (Fig. 1b). Unlike P-water, BAP extractions indicated phosphorus immoblization at the lower temperatures, most particular in the *Carex*-soil (Fig. 1a).

At all temperatures, potassium release in the *Carex*-soil significantly exceeded that in the *Sphagnum*-soil ($p < 0.05$; Fig. 1d). In the *Sphagnum*-soil, net potassium immobilization occurred at 0 ° and 10 °C.

Effect of freezing

Amounts of nutrients in the soils after the freezing procedure are significantly increased ($p < 0.01$) compared to amounts in fresh soil samples, except for P-water release by *Carex* peat (Fig. 2).

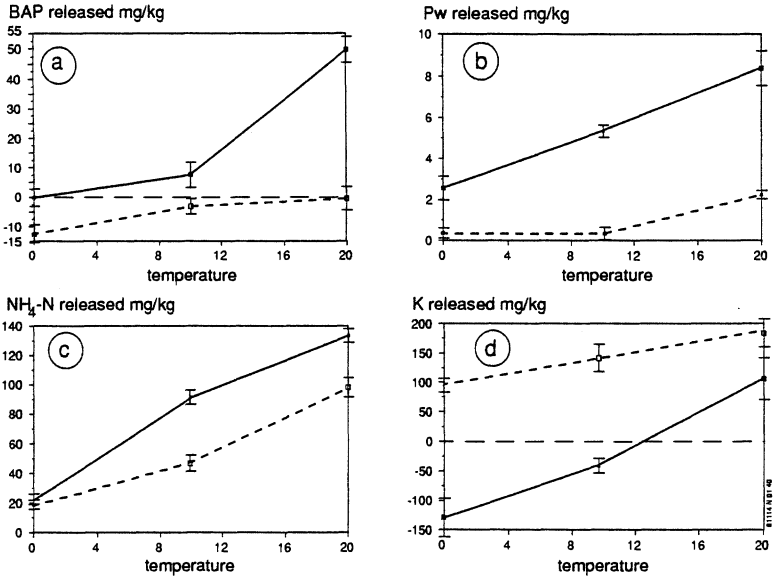


Fig. 1. Relationship between temperature and amount of nutrients released from soil cores (mg/kg) after 6 weeks incubation time. Values are means over 5 replicates (± s.e.). Black symbols: *Sphagnum* peat. White symbols: *Carex* peat. a: BAP; b: P-water; c: NH_4-N; d: K.

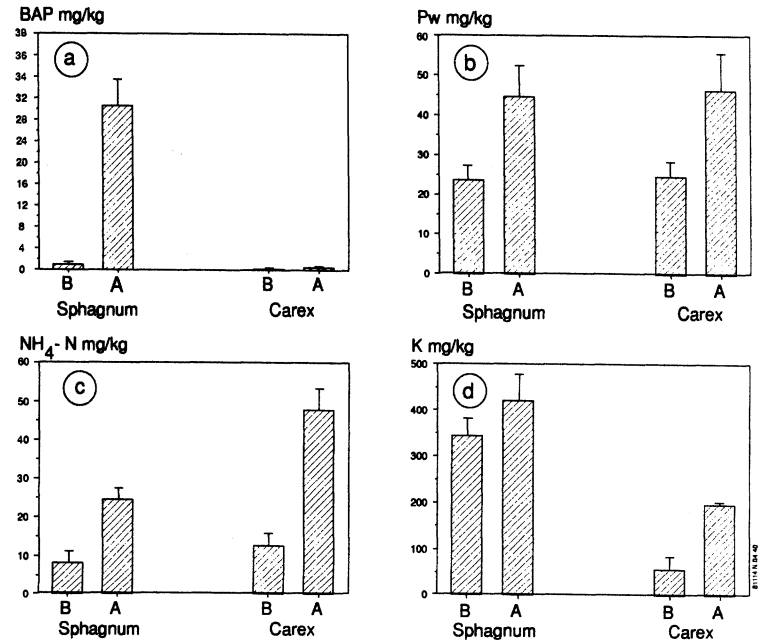


Fig. 2. Amounts of nutrients released from the soil after 1 week freezing (mg/kg). B: before freezing; A: after freezing. a: BAP; b: P-water; c: NH_4-N; d: K.

Experiment 2: effect of water chemistry and water level

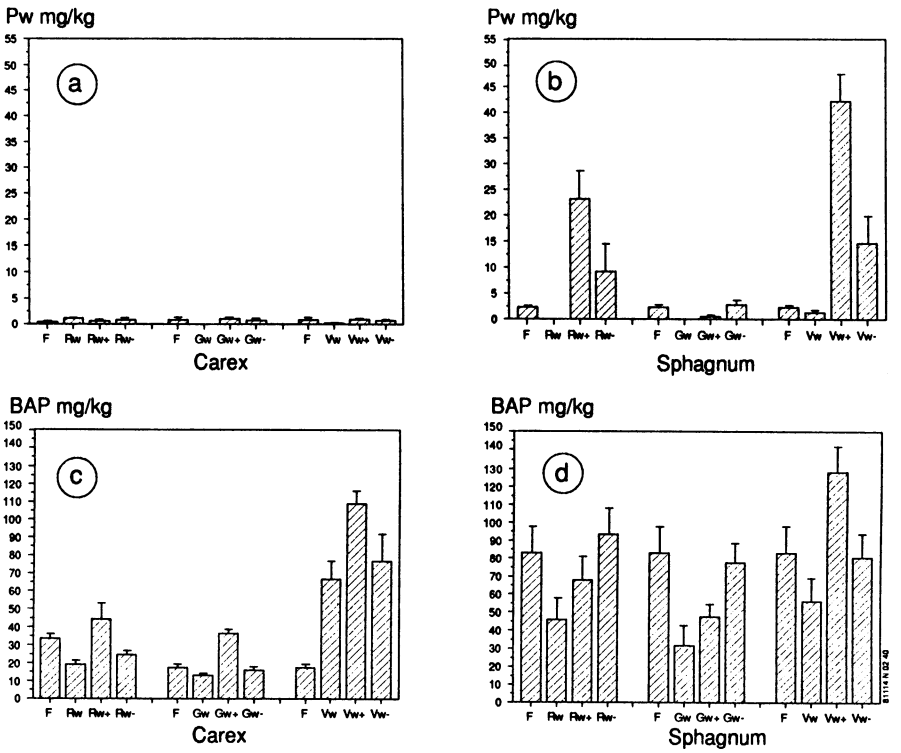
Percolation procedure

The percolation procedure greatly affected the nutrient availability in the two soils (Fig. 3). A two-factor analysis of variance indicates that the gross effect of percolation was significantly different between the two soils for all parameters. Water chemistry had a significant effect on P-water, BAP and nitrate concentrations, but interaction factors with site were significant as well indicating a soil specific effect (Table 5).

pH and redox potentials

The different treatments had a pronounced effect on soil pH in the cores (Table 6). The pH in soil cores decreased following rainwater treatment and increased following groundwater and river water treatments. Water tables also affected soil pH; in every treatment, soil pH was lower in drained cores compared to inundated cores.

Redox potentials generally decreased with depth (Table 7). In both soils and for all water types, redox potentials were higher in drained cores



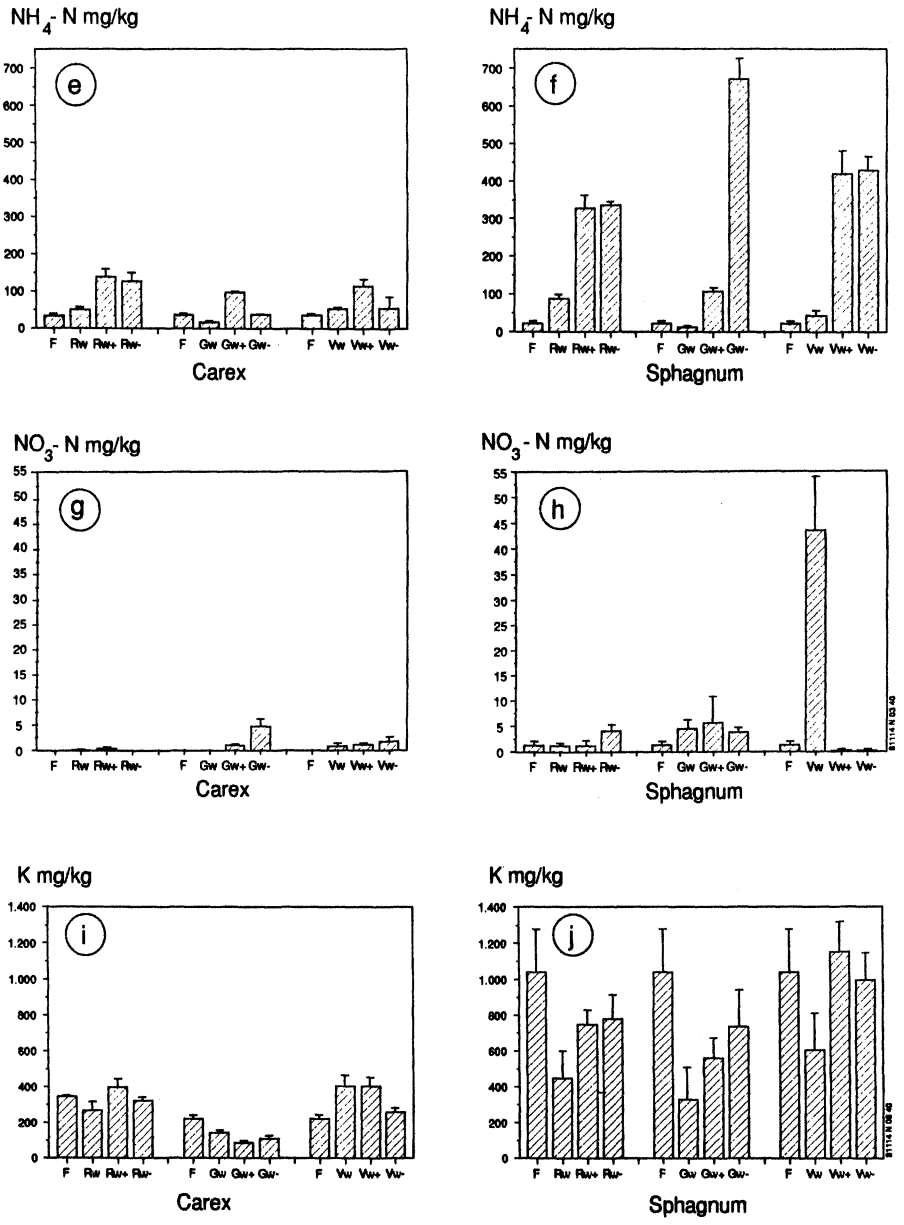


Fig 3. Nutrient concentrations (mg/kg) in fresh soil samples (F), immediately after percolation with rainwater (RW), groundwater (GW) or water from the river Vecht (VW), and after 6 weeks incubation in rainwater, groundwater or river water under inundated conditions (RW+, GW+, VW+) or with water levels 10 cm below the soil surface (RW−, GW−, VW−). Values are means of 5 replicates ± s.e. a, b: P-water; c, d: BAP; e, f: ammonium-N; g, h: nitrate-N; i, j: potassium.

Table 5. Values of p of a two-factor analysis of variance for the amounts of nutrients sorbed by the soils following percolation. Site and water chemistry are independent factors. p values < 0.05 are considered statistically significant.

	P values				
	BAP	P-water	Ammonium	Nitrate	Potassium
Site	0.0001	0.0001	0.0418	0.0001	0.0001
Water chem	0.0001	0.0001	0.3811	0.0001	0.1704
Site*water chem	0.0041	0.0001	0.4077	0.0001	0.9335

Table 6. pH (mean ± s.e, 5 replicates) in the soil cores after 6 weeks of incubation in rainwater, groundwater or river water. pH's at the start of the experiment were 6.0 for *Carex* peat and 4.2 for *Sphagnum* peat.

Soil	*Carex*		*Sphagnum*	
water level (cm)	+1	−10	+1	−10
Water type				
rainwater	5.8 ± 0.1	5.4 ± 0.2	4.4 ± 0.0	4.2 ± 0.1
groundwater	6.7 ± 0.0	5.0 ± 0.1	5.4 ± 0.1	4.5 ± 0.0
river water	6.3 ± 0.1	5.3 ± 0.2	4.9 ± 0.1	4.5 ± 0.0

Table 7. Redox potentials (mV, Eh_7) at three soil depths in the soil cores after 6 weeks incubation in rainwater, groundwater or river water at 20 °C. Values are means over 5 replicates ± s.e.

Soil	Water type	Water level (cm)	Depth (cm below soil surface) 0	5	10
Carex	rainwater	+1	99 ± 18	−36 ± 14	−52 ± 11
	rainwater	−10	159 ± 108	47 ± 148	33 ± 145
	groundwater	+1	18 ± 6	35 ± 13	3 ± 6
	groundwater	−10	137 ± 33	148 ± 20	26 ± 18
	river water	+1	76 ± 10	14 ± 4	−8 ± 4
	river water	−10	157 ± 51	74 ± 36	17 ± 43
Sphagnum	rainwater	+1	61 ± 23	41 ± 11	28 ± 13
	rainwater	−10	188 ± 47	151 ± 72	98 ± 63
	groundwater	+1	41 ± 20	22 ± 19	7 ± 10
	groundwater	−10	163 ± 15	210 ± 14	158 ± 22
	rainwater	+1	68 ± 47	29 ± 9	23 ± 5
	rainwater	−10	257 ± 16	260 ± 10	208 ± 39

compared to inundated soil cores. In drained soil cores, redox potentials in the *Sphagnum* peat were higher than in *Carex* peat given the same water treatment. The redox potential of inundated soil cores did not differ between the two soils (Table 7).

Nutrient release

A three-factor analysis of variance shows that nutrient release rates were significantly affected by site for all parameters (Table 8). Data on nutrient release rates (Fig. 3) illustrate that the site effect was very strong indeed. *Sphagnum* peat released much more P-water, ammonium and potassium than *Carex* peat in almost every treatment. Nitrate release was very low in every case (Fig. 3g, h). Although water chemistry and water level significantly affected the release of nutrients (Table 8), interaction factors between the three factors are often significant as well, indicating interdependence of these factors.

To remove the strong site effect and separate between effects of water chemistry and water level, the data for each site were pooled, followed by a two-factor analysis of variance (Table 8).

This reveals that in the *Carex* soil, the release of BAP and ammonium

Table 8. Values of p of an analysis of variance of the amounts of nutrients released in the *Carex* and *Sphagnum* soil after 6 weeks incubation at two water levels and incubated in rainwater, groundwater or river water. Site (only in a), water level and water chemistry are independent factors. p values < 0.05 are considered statistically signficant.

	P values				
	BAP	P-water	Ammonium	Nitrate	Potassium
(a) Both soils					
site	0.0106	0.0001	0.0001	0.0001	0.0001
water chem	0.9073	0.0001	0.2097	0.0001	0.0033
water level	0.0593	0.0037	0.1541	0.3361	0.0750
site*water chem	0.8732	0.0001	0.0008	0.0001	0.0005
site*water level	0.0098	0.0043	0.0001	0.7832	0.0149
water chem*water level	0.0065	0.0246	0.0263	0.8939	0.0007
site*water chem*water level	0.5272	0.0230	0.0001	0.2267	0.1429
(b) *Carex* soil					
water chem	0.9786	0.0001	0.0162	0.0047	0.0001
water level	0.0059	0.5771	0.0004	0.0791	0.0037
water chem*water level	0.3609	0.5143	0.0632	0.0567	0.0005
(c) *Sphagnum* soil					
water chem	0.7883	0.0003	0.0172	0.0001	0.4538
water level	0.5652	0.0059	0.0001	0.7100	0.6343
water chem*water level	0.0083	0.0333	0.0001	0.5944	0.3676

was significantly greater at high water table than at low water table ($p < 0.01$), the effect of water table being quite substantial in most cases (Fig. 3c, e). Ammonium release from the *Carex* soil was significantly affected by water chemistry as well, and increased in the order of river water < groundwater < rainwater. Differences, however, were relatively small. BAP release appeared not significantly affected by water chemistry (Table 8). P-water release was significantly affected by water chemistry, but the release rates were very low, as were differences between treatments and the interaction factor with water level was significant (Fig. 3a, Table 8). For potassium, both water chemistry and water level affected its release from the *Carex* soil, but the interaction factor was significant as well, indicating interdependence of the two factors (Fig. 3i, Table 8). Potassium release rates were low in some cases, whereas immobilization occurred in other cases. Nitrate release occurred at a very low rate in all cases and was significantly affected by water chemistry but not by water level (Fig. 3g).

In the *Sphagnum* soil, water level and water chemistry significantly affected the release of P-water and ammonium, but there was a significant interaction factor (Table 8). The ammonium release in the groundwater treatment significantly exceeded release rates in both other treatments at low water table ($p < 0.05$), but was significantly lower compared to river water and rainwater treatments at high water tables ($p < 0.05$). Ammonium release by *Sphagnum* peat incubated in groundwater proved strongly affected by water level. P-water release from the *Sphagnum* peat was almost absent when incubated in groundwater, while high release rates were observed in rainwater and river water treatments (Fig. 3b). BAP release in the river water treatment was significantly higher at high water level than at low water level ($p < 0.05$). Nitrate release occurred at a very low rate in all cases and was significantly affected by water chemistry but not by water level (Fig. 3h). Potassium release rates in *Sphagnum* peat were not significantly affected by water level or water chemistry (Table 8).

Discussion

Nutrient release in relation to temperature

The net release from the soil of ammonium, potassium and phosphate increased with temperature and strong site effects were observed. *Sphagnum* peat released much more BAP, P-water and ammonium than *Carex* peat. Nutrient release proceeded even when temperatures were close to freezing point. Moreover, soil nutrient concentrations typically increased by a factor 2—3 after the soil had been frozen for one week (Fig. 2). The

freezing effect is probably due to nutrient release associated with lyses of frozen microorganisms (e.g. Biederbeck & Campbell 1971).

One of the most striking results of this experiment was the observed discrepancy between BAP and P-water data, particularly in the *Carex*-soil. The fact that generally more P was extracted with acetic acid lactate than with water can be attributed to the fact that the first extraction is indicative of the P pool that is potentially available to the vegetation, whereas the second determines the immediately available phosphate occurring in the soil (Hesse 1974). The available P pool in peat generally exceeds the P in soil solution by one order of magnitude (Clymo 1983). In the *Carex*-soil the situation was very complex as the ammonium-lactate extractions indicated P immobilization, whereas water extractions indicated a slow P release (Fig. 1a, b).

Richardson & Marshall (1986) elegantly demonstrated that P fluxes from peat soil to water are primarily controlled by chemical processes. The fact that the extent to which BAP was immobilized in the *Carex*-soil decreased with increasing temperature indicates that the observed immobilization process is indeed not a biological process.

If chemisorption of P is indeed strongly regulating P availability in the peat, the most likely processes involved are the formation of complexes between ortho-P and Al and/or Fe (Stumm & Morgan 1981; Richardson 1985; Waughman 1980). pH is too low for the formation of Ca-PO_4 complexes, and in contrast to Al- and Fe(III)-P complexes, Ca-PO_4 complexes would desintegrate upon ammonium-lactat extraction (Hesse 1974; Stumm & Morgan 1981).

The question remains how to extrapolate results of the core experiments to the field situation. It is hardly realistic to postulate that P release is absent in the *Carex*-soil, as the P uptake by the vegetation at this site exceeds external P inputs by far, indicating that P release from the soil is the most important source of P at this site (Koerselman et al. 1990a). We believe, however, that chemisorption of P under field conditions may be lower than in our experiments, because P uptake by the vegetation will reduce *in-situ* P availability (water soluble and physically adsorbed), which will negatively affect chemisorption rates (Stumm & Morgan 1981).

Nutrient release in relation to water chemistry and water level

Results of experiment 2 confirm once more the strong site effect that was observed in experiment 1. This site effect proved consistent throughout the water chemistry treatments, which indicates that soil quality may be the most important agent determining nutrient release rates. To remove the strong site effect, and shed more light on the importance of other

factors, we performed an analysis of variance on the data of the separate sites. This established that water chemistry and water level are of significant influence on nutrient release rates in peat soils.

In the light of our hypothesis that river water results in extra nutrient release from the soil, its stimulating effect on P-water availability in the *Sphagnum* soil is noteworthing. In contrast, P-water release in groundwater treatments was almost negligable in both soils. We did not observe similar effects of river water in the *Carex* soil. This may be due to different soil characteristics, particularly in the amount of chemically bound P in the *Carex* soil. In the *Carex* soil we did observe a strong short-term increase of BAP availability after it was percolated with river water (Fig. 3c). Moreover, the highest BAP release rates in both soils were recorded in cores inundated in river water (Fig. 3c, d). It is therefore concluded that river water may stimulate the availability of P in peat soils.

As discussed before, phosphate-Fe or phosphate-Al complexes are the most likely compounds involved with soil chemical processes involving P. The fact that river water caused a relatively slow release of P-water and BAP in the *Sphagnum* soil at low water table, whereas it had much stronger effects in inundated *Sphagnum* cores, points to a possible role of Fe in P adsorption. The relatively high redox potentials in the *Sphagnum* soil at low water table indicate the occurrence of Fe(III) whereas Fe(II) will probably have been the dominant Fe-form in the inundated *Sphagnum* cores (Stumm & Morgan 1981). Fe(III) oxyhydroxide is capable of binding P more firmly than Fe(II) oxyhydroxide (Patrick & Khalid 1974), and an increase of P release following river water treatment may have been compensated for by P sorption onto Fe(III) oxyhydroxide in the drained *Sphagnum* cores.

Both the factor in river water that is involved with P release, and the processes involved are yet unknown. Recently, however, Caraco et al. (1989, 1990) postulated an interesting view on this subject. A correlative study in 23 aquatic systems revealed that the relative P release from sediments was strongly correlated with the sulphate concentration of surface waters, especially at low concentrations of sulphate (3—20 ppm). Caraco and co-workers postulate that sulphides (from sulphate reduction) bind Fe in anoxic sediments, and that formation of iron sulphides both prevents the re-supply of Fe-oxides and the formation of Fe(III)- and Fe(II)-oxide-phosphate compounds. This mechanism may be involved in our experiments as well: river water is much higher in sulphate than rain water and groundwater (Table 2).

In conclusion, internal eutrophication of peatlands may occur associated with the inflow of polluted river water, that particularly increases release of P. Results indicate that P release is most likely the result of chemical

soil processes and the possible role of sulphate deserves further study. It may well be that the absence of sulphate rather than the presence of high calcium contents is responsible for the observed low phosphate availability in many wetlands in the Netherlands. Earlier hypotheses on the role of calcium in the P cycling of wetlands (see Van Wirdum 1991; Kemmers 1986; Koerselman 1990b) may be restricted to alkaline wetlands with pH over 6.5 (cf. Wassen 1990).

Implications for fen management

Our results may be helpful for directing the hydrological management of peatlands. In The Netherlands, where hydrology is strongly regulated by man, water management often involves artificial recharge of water during the summer and the discharge of excess rain water and groundwater during the winter (Verhoeven et al. 1988; Koerselman 1989). The present study shows that when clean groundwater discharges into fens, nutrient availability will be low. Hydrological management operations should therefore stimulate natural groundwater discharge in nature conservation areas, that has strongly reduced over the last decades. Alternatively, unpolluted groundwater that is now discharged into lakes could be artificially supplied into fen reserve areas where water shortage occurs during the summer.

The supply of polluted river water to fen reserves must be strongly dissuaded, as this may increase P availability by its effect on P sorption processes ('internal eutrophication'). Adverse effect of river water supply on the nutrient balance of peatlands ('external eutrophication') were reported earlier (Koerselman et al. 1990a).

If polluted river water is in fact the only water source available for recharge, one has to consider the possiblity not to recharge any water at all (e.g. allowing groundwater levels in peatlands to drop during summer months). If soil pH is below 6.5, drainage may in fact reduce P availability due to fixation of phosphates onto Fe(III)-compounds, and this has in fact been observed by Grootjans et al. (1985, 1986). Unlike P, however, N availability will possibly increase, due to increased microbial activity (cf. Grootjans et al. 1985; see also Fig. 3f). The effect of drainage may thus work out differently in fens that are P limited compared to fens that are N limited. In The Netherlands, early and mid successional fen stages often are N limited, whereas late successional fen stages are P limited (Verhoeven & Schmitz 1991; Koerselman et al. 1990a). Peatland reserves often include a wide range of successional stages. A reduction of water levels may particularly affect early and mid successional stages, thereby affecting the natural cause of succession into late successional stages.

A second alternative that is sometimes advocated is to preserve the winter rainwater surplus to be used for supply purposes during the summer. Our results indicate, however, that the supply of rainwater may stimulate both N and P availability. Moreover, artificial recharge of rainwater can be expected to cause severe deterioration of base-rich fen ecosystems (Wassen 1990; Van Wirum 1991).

Thus, there are in fact no suitable options left when clean groundwater cannot be made available to fen vegetation, either by natural discharge, or via artificial recharge.

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