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THE PALEORECORD OF GEOCHEMISTRY AND HYDROLOGY IN NORTHERN PEATLANDS AND ITS RELATION TO GLOBAL CHANGE

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Evidence is presented to show the utility of peatland paleorecords in determining (1) variations in the time of initiation as well as the rate of accumulation of peat and biophilic elements, (2) the history of changes in surface-water acidity and water-table depth, (3) shifts in ground-water influence upon plant communities and the chemistry of the water in which they grow, and (4) alterations in the rate of deposition of diverse pollutants from the atmosphere. This evidence constitutes background information of great value for investigations of the ecological and biogeochemical consequences of global change.

Keywords: Geochemistry, global change, hydrology, paleorecord, peatlands

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INTRODUCTION

Paleorecords in peatlands can be derived from diverse sources and used for a variety of purposes. Here we shall examine paleorecords in northern peatlands for the information they can provide concerning (1) initiation of peat deposition, (2) rate of accumulation of biophilic elements in peat deposits, (3) sequential changes in pH, (4) alterations over time in the height of the peat surface above the mean water table, (5) elucidation of spring-fen formation by ground-water upwelling, and (6) accumulation of anthropogenically produced toxins.

DATING THE LONG-TERM RECORD OF PEAT ACCUMULATION

Initiation of peat accumulation

A graph of the cumulative frequency — from oldest to youngest — of 418 radiocarbon dates for basal peats in North America (E. Gorham, J.A. Janssens, S.C. Zoltai & P.H. Glaser, unpublished data) indicates (Fig. 1) that peatlands began to form about 14 000 B.P., but did not spread rapidly across the landscape until about 10 000 B.P. After that time they spread rather steadily until 4 000 B.P. The apparent slowdown after that time may be real, but may equally well be an artifact of undersampling shallow and — in most cases — relatively young deposits.

Rate of accumulation of biophilic elements

Basal radiocarbon dates can be used to calculate the overall (top to bottom) rates of accumulation for individual chemical elements; in the present case, we shall focus upon three biophilic elements — carbon, nitrogen, and sulfur.

Carbon

The overall rate of carbon accumulation in northern peatlands has been estimated (Gorham 1991) as 96 Tg yr^{-1}, or 29 g m^{-2} yr^{-1}. Clymo's (1984) model of peat–bog growth suggests that current accumulation is likely to be less than this, and

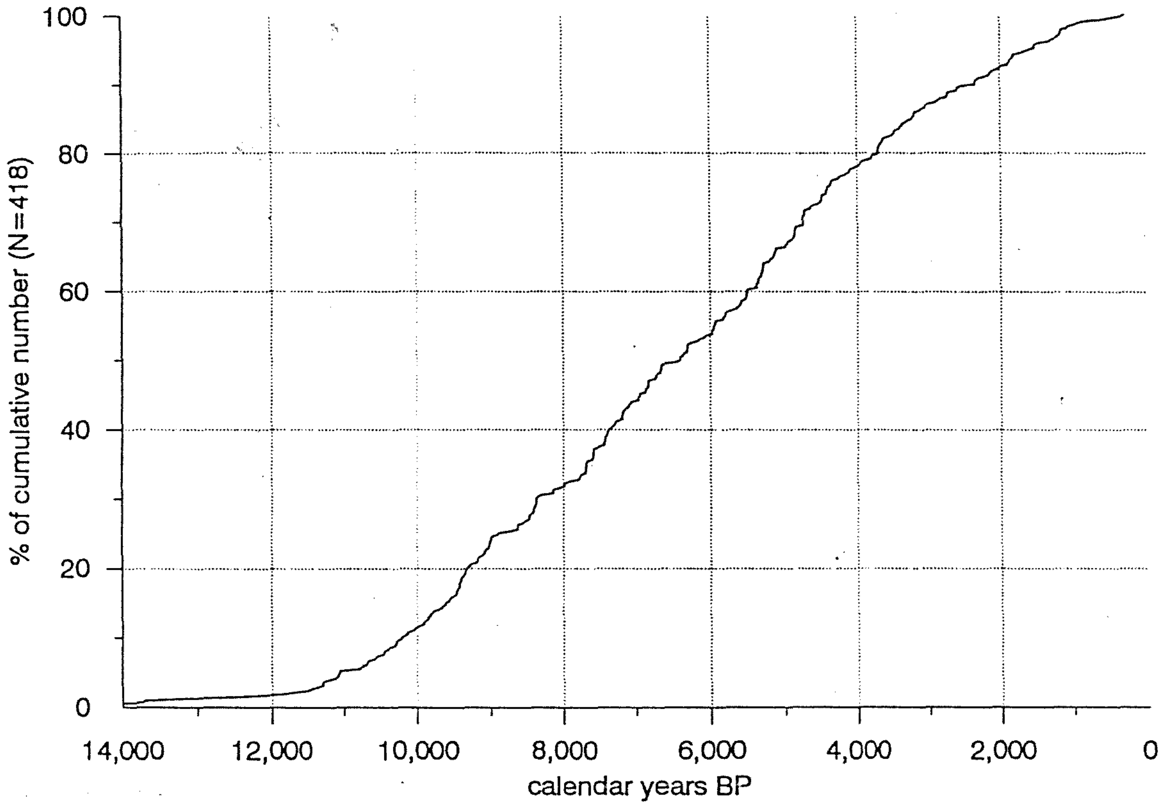


Fig. 1. Cumulative number — oldest to youngest — of North American radiocarbon dates for basal peats, excluding basal lake muds (= gyttja).

— making several simplifying assumptions — it has been estimated (Gorham 1991) as 76 Tg yr^{-1}, or 23 g m^{-2} yr^{-1}, which is about 7.5% of annual net primary production, estimated recently (Gorham 1990) as 307 g m^{-2} yr^{-1}.

Nitrogen

Data similar to those used by Gorham are not available for nitrogen. However, Riley (1987) and Riley and Michaud (1989) provide very extensive data on C/N ratios in peat cores (top to bottom) from a wide variety of peatlands in northern Ontario that are characteristic of northern peatlands in general. Dividing the carbon data given above by the average C/N ratio of 28.7 yields an overall accumulation rate of 3.3 Tg yr^{-1}, or 1.0 g m^{-2} yr^{-1}. The same ratio cannot be applied to the estimate for current carbon accumulation because the average C/N ratio of surface (0–10 cm) peat in northern Ontario is distinctly greater (45.0) than the overall ratio. Applying this greater ratio yields a current accumulation rate of 0.51 g m^{-2} yr^{-1}.

Sulfur

Calculations similar to those above for nitrogen, using an overall C/S ratio of 350, yield an overall accumulation rate for sulfur of 0.27 Tg yr^{-1}, or 0.083 g m^{-2} yr^{-1}. Current accumulation, using a surface (0–10 cm) C/S ratio of 417, is about 0.18 Tg yr^{-1}, or 0.055 g m^{-2} yr^{-1}.

Relevance to global change

The slow annual rates of carbon sequestration in peat, both past and current, indicate that peat formation is a very minor factor in opposing "greenhouse" warming by fossil-fuel combustion, which amounts to more than 5 x 10^{15} g yr^{-1}. Similarly, the rate of sulfur accumulation is much slower than its rate of ionic (SO_4–S) wet deposition in areas subject to severe air pollution, which is often in the range of 1.0–1.4 g m^{-2} yr^{-1} (NADP/NTN 1990). However, the estimated current rate of nitrogen accumulation is a substantial fraction of ionic (NH_4-N+NO_3-N) wet nitrogen deposition in such areas, which is often in the range of 0.7–1.2 g m^{-2} yr^{-1} (NADP/NTN 1991). Whether increased nitrogen deposition will lead to increased long-term storage in peat is uncertain. In the case of sulfur, long-term storage in a coastal Newfoundland bog subject to seaspray deposition of sulfate was about 3.5 x that in a Minnesota bog with a similar rate of nitrogen storage (E. Gorham, unpublished data).

Another point to be made in connection with global change is that peatlands represent a large reservoir for all three elements. In areas of the southern boreal zone where climatic warming becomes sufficiently strong to increase substantially the frequency of severe droughts, it seems possible that peat fires (Wein 1983, Wein et al. 1987, Maltby et al. 1990) could release at least locally significant amounts of all three to the atmosphere and perhaps, as the peat in burned areas erodes and oxidizes further, to streams draining the peatlands. However, as Hogg et al. (1992) point out, the deeper peats exposed by burning to oxidation may be relatively resistant to further decomposition, at least in the short term.

THE USES OF BRYOPHYTE FOSSILS IN PALEOECOLOGY

Relationships of bryophytes to environmental factors

Patterns of distribution of species and communities along gradients of pH and water-table depth have been studied for a long time (Kotilainen 1928, Lumiala 1944, 1945, Du Rietz 1949, Sjörs 1950), but it is only recently that new techniques of stratigraphic analysis (Janssens 1983) and sophisticated statistical methods (Jongman et al. 1987, Birks et al. 1990) have allowed (1) a relatively clear picture of bryophyte species distribution in relation to the interaction of these environmental factors, and (2) the historical reconstruction of inferred pH and water-table profiles in peatlands (Janssens 1988, 1990a, b, 1992, Gorham & Janssens 1992).

With regard to species distribution, Table 1 shows the pH and water-table optima and tolerances of a variety of common bryophyte species sampled from numerous plots in 5 major regions across northern North America; Fig. 2 shows the optima in a 2-dimensional diagram (Janssens 1990b). It is clear that they cover a broad range of both pH and water-table depth, and canonical correspondence analysis (CANOCO, Jongman et al. 1987) indicates that no significant correlation exists between pH and water table; in other words, they exhibit independent gradients. They also account for most of the ecologically relevant variance (Janssens 1990b).

The bryophyte plots can also be segregated, by detrended correspondence analysis (DECORANA, Jongman et al. 1987) of their floras, into a variety of ecotopes: physically uniform parts of wetland ecosystems that are dependent upon the same hydrologic and minerotrophic influences. Examples are open bogs, forested bogs, poor fens, forested rich fens, poor and rich fen water tracks, etc., which correspond closely to landform units (Glaser & Janssens 1986) characterized by topography, hydrology, vegetation structure, flora, water chemistry, and type of substrate. In this way stratigraphic analysis of a peat core (Fig. 3) allows the tracking over time of any given site through a series of ecotopes or landform units (Janssens et al. 1992).

Constructing the paleorecord of pH and water table

Birks et al. (1990) concluded that the statistical calibration technique of weighted averaging (WACALIB) is an excellent tool for inferring paleoecological profiles of ecotope acidity, and Janssens (1990b) developed the technique for inferring also the height of the peat surface above mean water table (HMWT). Table 1 summarizes the data employed, and Fig. 4 illustrates an application of bryophyte–fossil analysis to a pair of peat cores, RLP8112 and RLP8104, in the Red Lake Peatland of northern Minnesota (Janssens et al. 1992). RLP8112 (Fig. 4A) was taken near the open center of an ovoid bog "island" with spruce forest around its margins; RLP8104 (Fig. 4B) was taken at the southern, outer margin of the island close to the adjacent fen water track that defines the "island" border.

Peatland development started at these sites, possibly by paludification of a prairie landscape, around 3 300–3 500 years ago. In nearby sites to the south, a large (now crested) bog was already developing and encroaching to the north. At both coring sites aquatic or emergent bryophyte populations were present initially but were rapidly re-

Table 1. Optima (o = weighted average), tolerances (t = weighted average S.D.), and number of occurrences among all plots for pH and height of the peat surface above mean water table (HMWT, cm), calculated with WACALIB 2.1 (cf. Line & Birks 1990) for the most common bryophyte species of the combined North American reference data-sets (total n = 431, and 217, respectively). Reprinted, with permission of the authors and the University of Minnesota Press, from Janssens et al. (1992).

		pH			HMWT	
Species	o	t	n	o	t	n
Sphagnaceae						
S. fallax	4.27	0.68	32	12.5	10.2	22
S. fuscum	4.35	0.73	46	27.5	9.5	25
S. capillifolium	4.33	0.71	83	19.3	7.4	41
S. majus	4.40	0.44	20	6.6	4.7	18
S. angustifolium	4.69	0.89	99	19.5	8.9	58
S. papillosum	4.33	0.38	59	12.0	6.8	41
S. magellanicum	4.39	0.65	103	19.4	8.3	65
S. centrale	5.68	0.99	27	19.9	6.9	10
S. teres	5.78	0.88	24	12.7	8.5	6
S. subsecundum	5.29	0.43	31	10.0	4.9	22
S. warnstorfii	6.77	0.47	33	19.2	8.7	9
Amblystegiaceae						
Drepanocladus fluitans	4.66	0.70	12	3.7	7.0	8
Calliergon stramineum	5.03	0.72	46	11.9	8.2	25
C. cordifolium	6.17	0.62	15	7.4	7.5	4
Calliergonella cuspidata	6.19	1.05	14	–	–	0
*Calliergon giganteum**	6.91	0.35	11	6.0	3.1	7
Campylium stellatum	6.56	0.78	29	10.8	5.9	2
*Scorpidium scorpioides**	6.65	0.71	16	3.3	2.4	8
*Drepanocladus revolvens**	6.88	0.54	10	8.7	4.2	6
Amblystegium riparium	6.79	0.44	17	3.6	–	1
Others						
Mylia anomala	4.11	0.26	25	20.7	8.4	12
Pleurozium schreberi	4.95	1.34	73	26.9	9.7	37
Polytrichum strictum	4.71	1.01	36	29.7	9.2	18
Dicranum undulatum	4.91	1.31	22	24.3	8.2	8
Cladopodiella fluitans	4.39	0.30	32	6.5	3.6	22
Aulacomnium palustre	5.47	1.15	86	19.5	8.5	40
Helodium blandowii	6.96	0.41	26	11.2	11.7	3
Plagiomnium ellipticum	6.88	0.61	22	13.0	11.4	6
Hylocomium splendens	5.90	1.38	21	19.4	13.4	11

*The height optima and tolerances for these three species are above the local water table, because no plots with these species were available in the data-set for mean water table standardized to *Sphagnum angustifolium*.

placed by carpet-forming species. The initial low pH and high local water table at site RLP8104 is inferred from the abundance of *Drepanocladus fluitans*, a quite acidophilous species. This is another indication of the nearness of the large, *Sphagnum*-dominated bog to the south. By 2 500 to 2 000 years ago the bog reached the coring-site locations. A sharp drop in pH is recorded; first at the RLP8104, then at the RLP8112, site; RLP8104 is farther south and nearer to the crested bog. Around 2 000 years ago bog expansion halted and the large expanse of forested bog started to

Fig 3 (Below right). Detrended correspondence analysis of Minnesota bryophyte populations classified by ecotope, with a superimposed trace of fossil assemblages in a peat core (RLP 8104) from the Red Lake Peatland in northern Minnesota (see also Fig. 4B). Reprinted, with permission of the authors and the University of Minnesota Press, from Janssens et al. (1992).

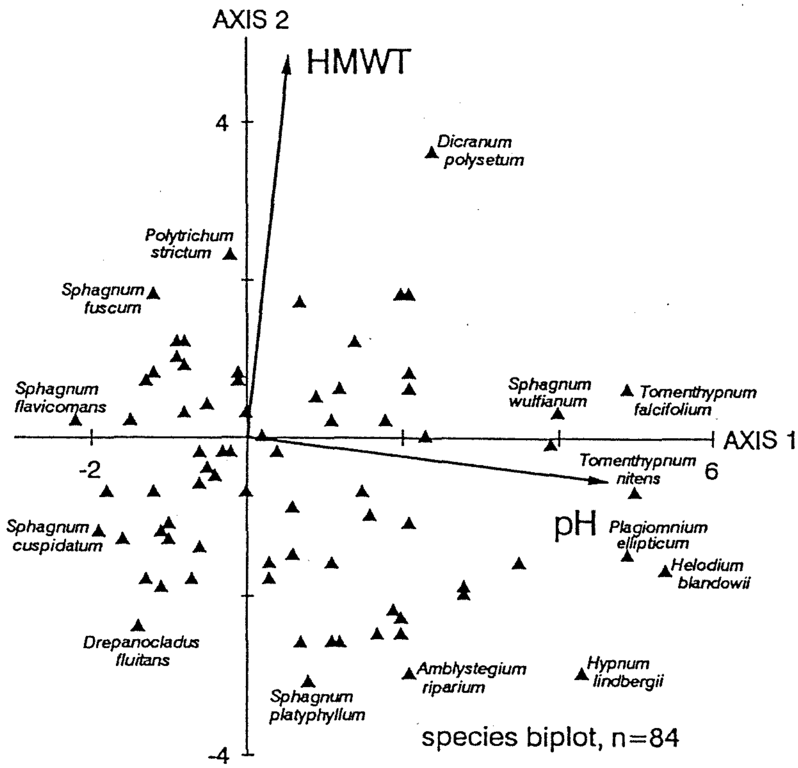
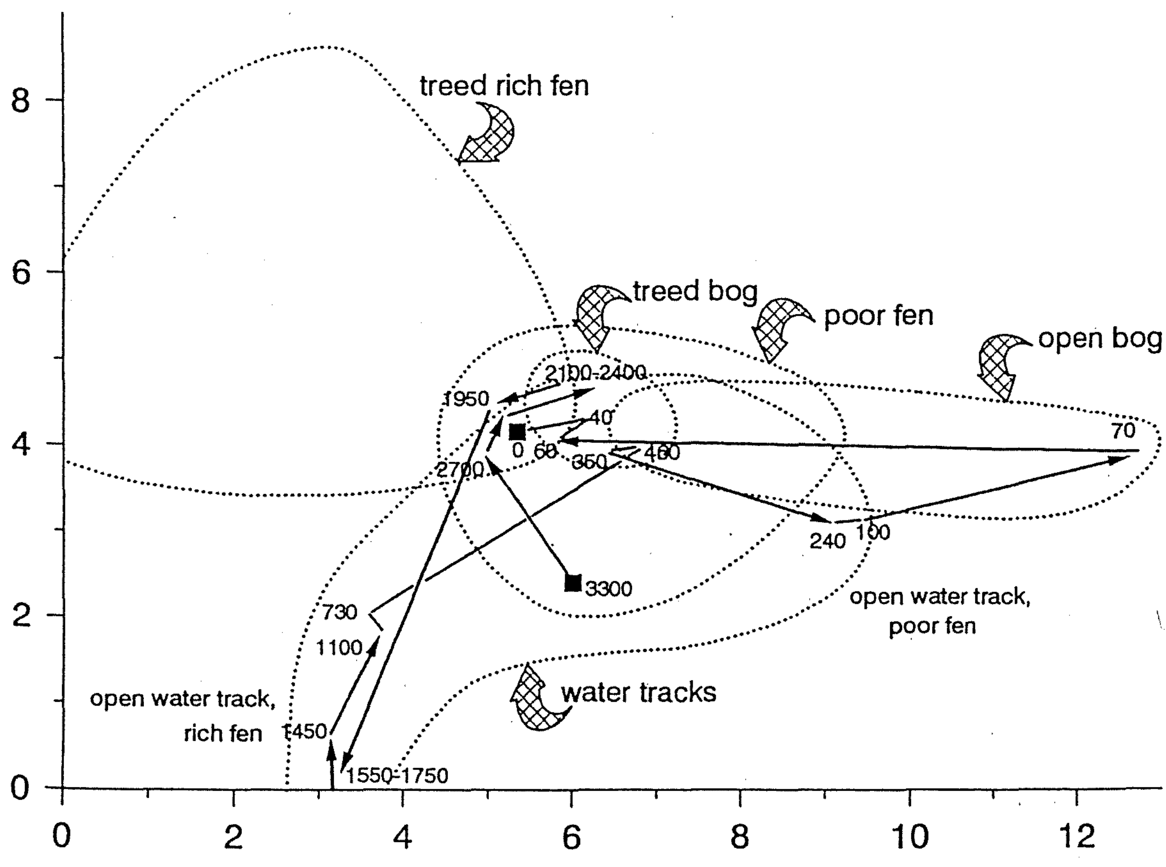
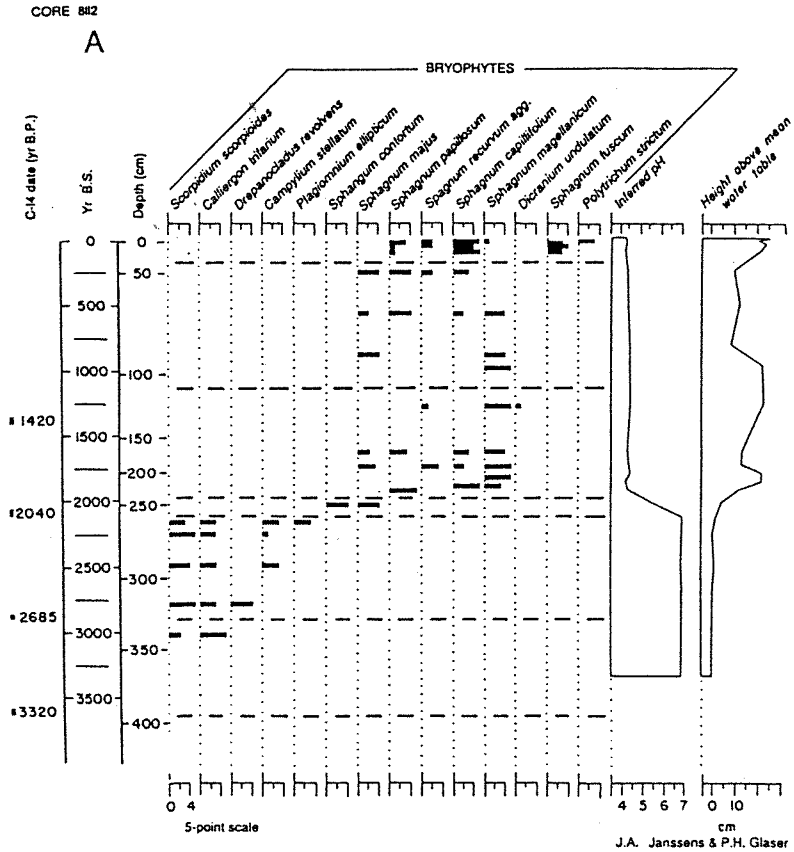


Fig. 2. Species–environment biplot, calculated by canonical correlation analysis. The environmental variables are represented by arrows. Eigenvalue for axis 1 = 0.55, for axis 2 = 0.39.




CORE 8112
A
BRYOPHYTES
C-14 date (yr B.P.)
Yr B.S.
Depth (cm)
Scorpidium scorpioides
Calliergon trifarium
Drepanocladus revolvens
Campylium stellatum
Plagiomnium ellipticum
Sphagnum contortum
Sphagnum majus
Sphagnum papillosum
Sphagnum recurvum agg.
Sphagnum capillifolium
Sphagnum magellanicum
Dicranium undulatum
Sphagnum fuscum
Polytrichum strictum
Inferred pH
Height above mean water table
1420
2040
2685
3320
5-point scale
cm
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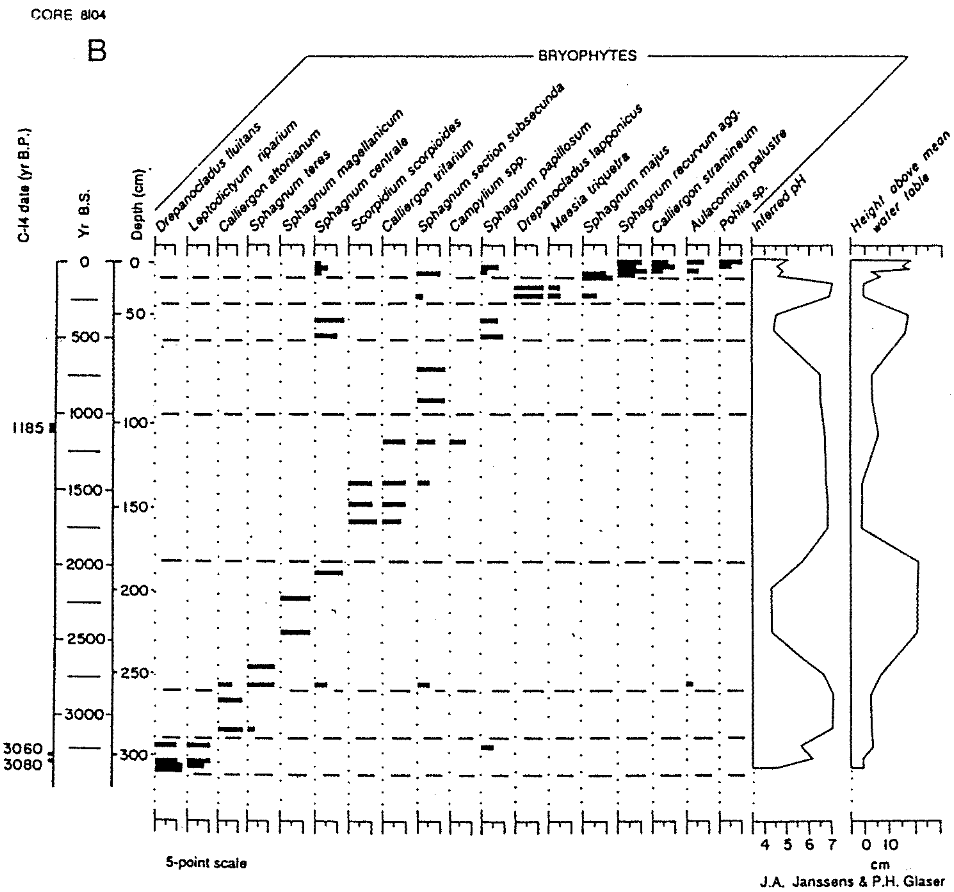
CORE 8104
B
BRYOPHYTES
C-14 date (yr B.P.)
Yr B.S.
Depth (cm)
Drepanocladus fluitans
Leptodictyum riparium
Calliergon aftonianum
Sphagnum teres
Sphagnum magellanicum
Sphagnum centrale
Scorpidium scorpioides
Calliergon trifarium
Sphagnum section subsecunda
Campylium spp.
Sphagnum papillosum
Drepanocladus lapponicus
Meesia triquetra
Sphagnum majus
Sphagnum recurvum agg.
Calliergon stramineum
Aulacomnium palustre
Pohlia sp.
Inferred pH
Height above mean water table
1185
3060
3080
5-point scale
cm
J.A. Janssens & P.H. Glaser

differentiate slowly into the present-day landforms of ovoid islands divided by marginal water-tracks. At site RLP8112, possibly in the lee of a rise in the mineral soil, a small area of oligotrophic vegetation remained and became, 1 800 years ago, the nucleus of the present ovoid island. This landform has expanded considerably since that time. The present non-forested center of the forested island at site RLP8112 developed 1 000 years ago, indicated by a lower HMWT. At site RLP8104, however, bog vegetation disappeared and was replaced by a fen water-track, characterized by high pH and lower HMWT, around 1 700 years ago. Evidence from other cores indicates that this and other water-tracks gradually narrowed, and became more defined and patterned by the encroaching ovoid islands. String development in the water-track is indicated by the increase in HMWT after 1 000 years ago. By 700 years ago the development of *Sphagnum* clones lowered the pH. The string was replaced around 400 years ago by a flark (hollow) indicated by higher pH and aquatic moss-assemblages. The last century is characterized by the encroachment of the ovoid island over the RLP8104 site, possibly caused by a lowering of the overall water supply to the peatland caused by drier climate or an abortive attempt at ditching. Renewed *Sphagnum* hummock formation (higher HMWT) is also evident at the RLP8112 site near the center of the ovoid island.

It is evident from autecological as well as stratigraphical results that bryophytes respond rapidly to changing minerotrophic and hydrological conditions in peatlands and are excellent tools for the paleoenvironmental reconstruction of peatland development and succession.

Relevance to global change

Fig. 4 is of particular interest because it provides — for two specific sites — baselines against which to assess the possible effects of both global warming and acid rain upon peatlands. For instance, if global warming were sufficient to draw down peatland water-tables and dry out their surfaces to a degree greater than has been seen over the past several thousand years (cf. Billings 1987, Gorham 1991), HMWT values ought to transcend the highest levels evident in stratigraphic profiles such as those of Fig. 4. In this connection, northern landscapes are expected to experience especially severe warming, particularly in winter (Post 1990). If, under such warming, peatland water-tables were to fall drastically, bryophyte assemblages might eventually become those seen now only in bogs that have been deeply ditched for a long time, but not otherwise disturbed. As an example, Malmström (1952) reported a Swedish case in which the site became floristically depauperate and was invaded in many places by *Polytrichum strictum* and *P. longisetum* (*P. gracile*) along with the lichen *Cladonia deformis*.

Similarly, if in any peatland acidic deposition were to become of sufficient magnitude to lower substantially the pH of surface waters (cf. Gorham et al. 1984, 1985, 1987), then presumably inferred pH would drop below its limits over the past few thousand years as shown by a stratigraphic analysis similar to that in Fig. 4.

OTHER PALEOECOLOGICAL ASPECTS OF PEATLAND HYDROLOGY

There are many ways in which the paleohydrology of peatlands can be examined. The most direct on a very short-term basis is the use of actual long-term records from recording wells, for instance those from a small black spruce/*Sphagnum* bog in the continental climate of Marcell, northern Minnesota (Table 2). There annual precipitation averages 762 mm, 75% as rain from mid-April to early November, and average January and July temperatures are –14°C and 19°C respectively. Severe droughts occur occasionally; the 1976 water-table minimum at Marcell — 65 cm below the mean water table — followed an 18-month drought with a Palmer Drought-Severity Index of –4 (Verry 1984). Presently Kevin Vogel, a Ph.D. candidate at the University of Minnesota, is investigating the possibility that tree rings in

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Fig. 4 (Left). Selected profiles versus calendar-year age for analyses from peat cores RLP8112 (A) and RLP8104 (B) in the Red Lake Peatland of northern Minnesota. Reprinted, with permission of J.A. Janssens, B.C.S. Hansen, P.H. Glaser and C. Whitlock from Patterned Peatlands of Northern Minnesota, edited by H.E. Wright, Jr., B. Coffin and N. Aaseng, and published by the University of Minnesota Press. © 1992 State of Minnesota, Commissioner of Natural Resources.

Table 2. Water-table elevations over 22 years (1961–1982) in a hummock-hollow system of the Marcell Bog S-2, northern Minnesota. Data from Verry (1984).

	Elevation above mean water table (cm)
Hummock top	+48
Maximum	+24
Mean annual maximum	+12
Hollow bottom	+ 6
Lateral flow stops	− 4
Mean annual minimum	−12
Non-drought minimum	−22
Severe drought minimum (1976)	−65

black spruce and tamarack can provide an index of water-table fluctuations in the same Marcell bog, and in other peatlands with similar hydrological data nearby.

A very interesting case where paleoecology provided useful hydrological information is that of the Lost River Peatland in northern Minnesota (Siegel & Glaser 1987, Glaser et al. 1990, Hill & Siegel 1991). There a calcareous spring-fen mound, dissected by surface streams with pH >7 and calcium concentration >20 mg L^{-1}, is located close to and separated by a poor-fen water track from a raised *Sphagnum* bog whose surface waters show values <4.2 and calcium concentrations <1.3 mg L^{-1}. Hydraulic-head gradients in the spring fen indicate upwelling into it of ground-water from calcareous substrata, but analysis of fossil remains from peat cores shows 70 cm of sedge peat above 143 cm of *Sphagnum* peat. Both the water track and the raised bog are underlain by 250 cm of bog peat. Obviously, both the spring-fen and the raised bog developed similarly for a long time, but eventually the calcareous ground-water welled up and burst through the bog peat in one site to create the spring fen. The event, dated by radiocarbon at the junction between the uppermost sedge peat and the *Sphagnum* peat beneath, took place around 1160 B.P. (Siegel & Glaser 1987). Siegel and Glaser (1987) believe that the ground-water flow system discharging to the Lost River peatland complex recharges from an exposed beach ridge about 10 km to the north. Usually, however, water flow through the surface peats of raised bogs, which usually exhibit a high degree of hydraulic conductivity (Ivanov 1981), is dominated by lateral flow of precipitation falling upon them, as shown by the profile of bomb-tritium in a peat core from the Red Lake Peatland (Gorham & Hofstetter 1971).

Relevance to global change

In assessing the influence of global change upon peatland hydrology, the very best sort of information will be actual data on water-table levels and streamflow of the kind provided by the gauged peatland watersheds at Marcell. In the Lost River Peatland, it will be of interest to see whether a drying climate provides insufficient recharge to maintain the spring-fen conditions observed there, so that the lateral flow and perched water table characteristic of raised bogs is re-established.

THE PALEORECORD OF POLLUTANTS

Several pollutants, both organic and inorganic, leave records of deposition in peatlands, but they are often difficult to interpret. For instance, the concentration of radioactive cesium-137 often exhibits a peak in peat cores, caused by the increasing deposition of radioactive fallout following atmospheric testing of nuclear weapons, and its decline after the signing in 1963 of a treaty banning tests vented to the atmosphere. However, cesium resembles the mobile, biophilic element potassium, and its 1963 peak is often blurred both by its mobility and by its liability to plant uptake (Oldfield et al. 1979, Olson 1983). Nevertheless, in some cases it has proved to be a useful marker for paleoecological purposes (Craft & Richardson 1993).

Lead is another pollutant whose atmospheric deposition increased after the onset of the industrial age, in particular following the widespread use of leaded gasoline, but it has declined in North America in recent years along with the declining use of that product. Like cesium-137, lead exhibits considerable post-depositional mobility, at least in hollows (Urban et al. 1990). This has important consequences for the use of lead-210 dating in peat deposits, which works reasonably well in hummocks but not in hollows.

In contrast to cesium and lead, chlorinated organic micropollutants are very firmly bound once deposited in peat, so that very clear input functions can be derived for DDT and toxaphene (Rapaport & Eisenreich 1986), reflecting successive patterns (Fig. 5) of increasing and decreasing use.

CONCLUSION

Smol (1992) has pointed out that resource management requires long-term environmental data, that these are rarely available, and that paleoecological data can provide a valuable proxy for them. The examples given here indicate clearly that paleoecological investigations can provide a valuable background for investigations of the ecological and biogeochemical consequences of global change in northern peatlands, and associated problems of management.

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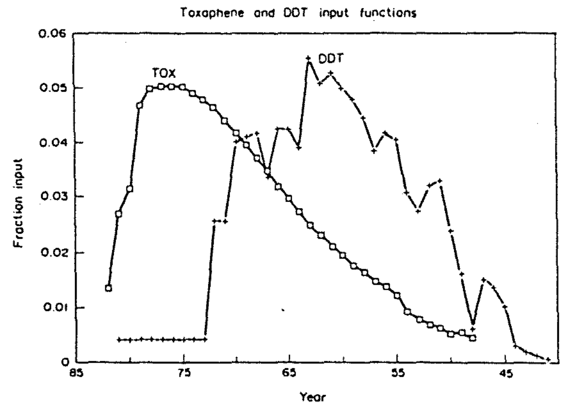

Fig. 5. Input functions (fraction of total input versus time) for toxaphene and DDT, derived from their rates of accumulation in dated North American peat cores. Reprinted from Atmospheric Environment, vol. 20, R. Rapaport and S.J. Eisenreich, pp. 2367–2379, copyright (c) 1986, with permission from Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 OBW, UK.

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