Journal of Ecology 1997, **85**, 3–16

Regional linkages between raised bogs and the climate, groundwater, and landscape of north-western Minnesota

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Summary

1 Landsat imagery was used to map the distribution of 127 raised bogs in north-western Minnesota. Bogs collectively cover 1236 km^2 (16% of the study area) despite the relatively dry regional climate and periodic droughts.

2 The physical, chemical, and biotic properties of these bogs have no apparent relationship to the westward climatic gradient indicating a high degree of buffering from changes in moisture stress.

3 Most bogs are located where groundwater discharge moderates moisture losses to the atmosphere and may decouple bogs from a direct climatic control. Bogs are also consistently related to physiographic features, such as drainage divides, interfluves of tributary streams, and beach ridges that constrain the surface and groundwater hydrology.

4 During droughts groundwater moves upward through the peat column toward the depressed water table, which is located 1–2 m below the peat surface. During moist periods, however, water-table mounds within these bogs drive surface water downward deflecting the deeper upwardly moving groundwater laterally to the bog margins.

5 Such short-term reversals in flow have little effect on the pore-water chemistry of major cations, which reflect the predominant downward flow over the past decade. Several chemical species, however, behave nonconservatively and respond more directly to climatic change.

6 Discharge zones for groundwater seem to be an essential prerequisite for bog formation in arid regions. Peat accumulation should be most rapid over discharge zones, which can maintain water table mounds, even during droughts Once a peat mound has formed, its higher water table will drive local recharge cells, which isolate the vegetation from groundwater and facilitate the development of a raised bog.

Keywords: climatic gradients, groundwater, pore-water chemistry, raised bogs, species diversity

Journal of Ecology (1997) **85**, 3–16

Introduction

The Glacial Lake Agassiz region of northern Minnesota is noted for its extensive peat cover and intricate systems of raised bogs and patterned fens (Heinselman 1963; Glaser *et al.* 1981; Glaser 1992). Peatlands cover over 60% of the regional landscape and some of the raised bogs reach impressive dimensions (Glaser 1992b). The peatlands, however, have accumulated within a relatively dry region, which is characterized by only a slight moisture surplus and also by extreme droughts. Although fens may persist in dry regions because of groundwater inputs, raised bogs are generally assumed to be disconnected from groundwater and fed solely by atmospheric precipitation (Von Post & Granlund 1926; Ingram 1982, 1983). The presence of raised bogs within this dry region is therefore anomalous and requires some special mechanisms to maintain positive water balances.

The distribution of raised bogs was therefore determined across the sharp climatic gradient in north-western Minnesota. The size, abundance, and surface patterns of bog land-forms were mapped within a 7000 km^2 study area. The regional variation in veg-

Contribution no. 493 of the Limnological Research Centre.

etation assemblages, surface-water chemistry, peat depth, and basal ages was determined to analyse the response of the bogs to climate and landscape features. The hydrogeology of these bogs was measured over a drought cycle to identify mechanisms that would permit bogs to form in such a dry climate.

STUDY AREA

The study area is located within the Glacial Lake Agassiz region of north-western Minnesota between 48°3′ and 48°35′N. Latitude and 94°3′ to 95°40′W. Longitude (Fig. 1a). The landscape is a nearly flat plain, which has a gradient of less than 20 cm per kilometre (Wright 1972). The plain is underlain by 20–60 m of unconsolidated glacial deposits that cover the metamorphic bedrock. Peatlands cover nearly 5000 km^2 or ≈61% of the study area (Glaser 1992b). The peatlands average 2–3 m in depth and began forming less that 5000 years ago in response to climatic cooling (Janssen 1968). The extensive peat cover is locally interrupted by sandy beach deposits that rise up to 20 m above the peat and also by areas of ground moraine. The study area spans 3 regional watersheds (Fig. 1b) that ultimately drain into Hudson Bay (Bidwell *et al.* 1970: Helgesen *et al.* 1975; Lindholm *et al.* 1976).

The regional climate is more arid to the west and colder to the north (Baker *et al.* 1967, 1985). Average precipitation declines from 63.5 cm in the eastern part of the study area to 55.8 cm in the west. Evapotranspiration, in contrast, increases to the west (Baker *et al.* 1979), and the entire region is subject to extreme multiyear droughts. The annual mean temperature ranges from 2.2 to 2.7°C, and the region is typically covered by at least 15 cm of snow for 70–100 days.

Methods

REMOTE-SENSING IMAGERY

The distribution of raised bogs within the study area was mapped from Landsat TM imagery (scene 5130116371 taken 23 September 1987) on the basis of the peat land-forms. The location of local and regional drainage divides was also mapped from the peat-landform patterns, which are consistently orientated either parallel or perpendicular to the prevailing slope. The drainage divides could not be mapped as accurately from the topographic maps because of the low regional gradient. The areas of bog, fen, mineral soil, and water were then delineated with a digital planimeter.

FIELD SAMPLING

The regional hydrogeological survey began at the height of an extreme 3-year drought in August 1990 and continued until after the return of normal precipitation patterns in July 1991. A Hughes 500 helicopter provided access to 16 bogs and bog complexes during the field expeditions, each of which lasted 2 weeks (Table 1). The sites were selected from the Landsat imagery to obtain an even distribution across the study area. The vegetation was described by the relevé method as modified in Glaser *et al.* (1981). Peat cores from each bog were collected with a piston sampler that is 10 cm in diameter and has a serrated cutting edge (Wright *et al.* 1984). Radiocarbon dating was supplied by Beta Analytic, Inc.

HYDROGEOLOGY

At each site two nests of piezometers were installed within the peat and mineral soil at depth intervals of either 50 or 100 cm according to methods described by Chason & Siegel (1986), Siegel & Glaser (1987), and Romanowicz *et al.* (1993). The piezometers were made from 1.25-cm-diameter PVC pipes. Hydraulic head recovery was recorded at 1-m depth intervals with a digital data logger and a 10 psi pressure transducer. Hydraulic head was measured in piezometers installed at 0.5-m depth intervals. Pore-water samples were collected at 50-cm intervals from the piezometers with a peristaltic pump and stored in 30-mL bottles. One set of samples was collected for analysis of major cations; these were filtered through 0.2-mm Gelman filters in the field and acidified with quartz-distilled nitric acid. The other set of samples for anions was untreated. Raw samples were analysed in the field for pH with an Orion field pH meter and Ross electrode. Water samples for metal analysis were analysed by Direct Current Plasma Spectrometry, whereas anions were analysed on a Waters HPLC ion chromatograph.

STATISTICAL AND MULTIVARIATE ANALYSIS

The vegetation and pore-water data were analysed by standard statistical and numerical methods with SYSTAT version 5.2.1 and JMP programs. The regional variation in the species assemblages, surface-water chemistry, peat depths, and basal peat ages were analysed by box-plots (Tukey 1977; McGill *et al.* 1978) and by linear regression. The underlying relationships within the pore-water chemistry were first explored with a scatter-plot matrix that contained all variables. Linear regressions were used to test the hypothesis that the pore-water chemistry conformed to a simple linear mixing-model between precipitation and groundwater of the calcium-magnesium-bicarbonate type. This model was also tested by cluster analysis to determine if the pore-water samples from each of the study sites could be assigned to (1) recharge derived from precipitation, (2) groundwater, or (3) an intermediate mixing zone. The clustering routine was based on a Euclidean distance measure and included

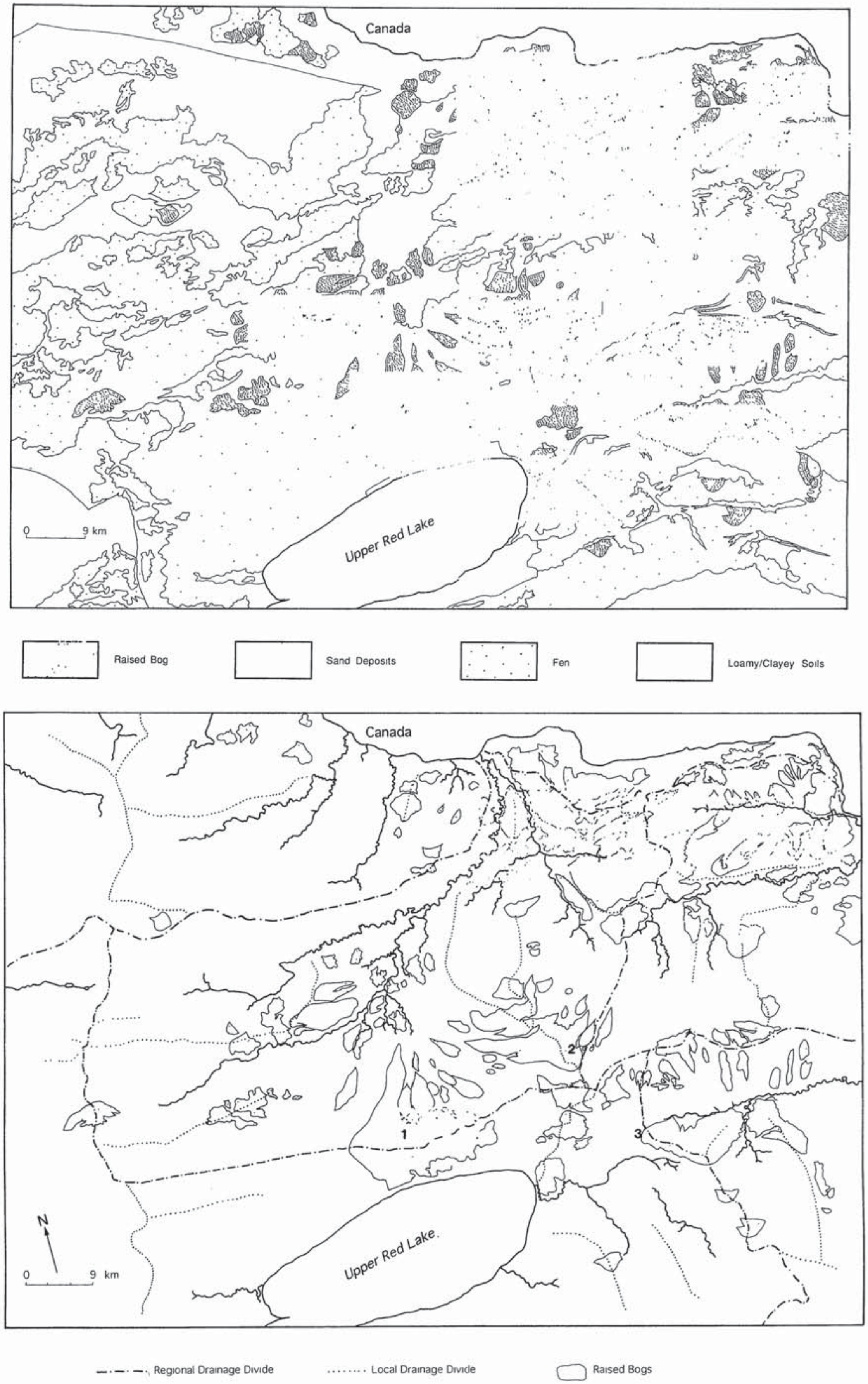

Fig. 1 Glacial Lake Agassiz study area: (a) peatland types and upland soils, and (b) distribution of raised bogs in relation to watershed divides and the drainage network. The sites referred to in the text are (1) Red Lake II, (2) Red Lake IV, and (3) Lost River.

Table 1 Physical properties of raised bogs within the Glacial Lake Agassiz region. The landform symbols are bog crest (BC) and internal water track (INT). The flow system refers to measurements of hydraulic head. I.D. indicates that insufficient time was available for the head values to equilibrate, whereas N.D. indicates the site was not sampled at that time

Site	Site name	Lat.	Long.	Area (km)	Landform	Basal age	Lab. no.	Basal depth (cm)	Mineral substratum	Flow System 1990	Flow System 1991
9112	Red Lake II	48°15′	94°43′	151.4	BC	3780 ± 95	SI-5990	341–345	Clayey gravel	Discharge	Recharge
9004	Red Lake IV	48°20′	94°18′	96.7	BC	3530 ± 100	Beta-53043	365–369	Gravel	Discharge	Recharge
9021	Fairland	48°23′	94°01′	17.0	BC	2590 ± 60	Beta-53056	252–257	Gravel	Discharge	Recharge
8104	Lost River	48°12′	94°17′	16.3	BC	8295 ± 105	SI-5997	320–325	Silty Clay	Discharge	Recharge
9008	Sturgeon River	48°10′	94°14′	28.4	BC	4870 ± 70	Beta-53033	540–545	Clayey Gravel	Discharge	Recharge
9016	Ridge	48°05′	94°02′	6.1	BC	4610 ± 60	Beta-53036	427–432	Gravel	Lateral	Discharge
9118	Gates Corner	48°10′	94°01′	34.5	BC	3570 ± 60	Beta-53052	236–241	Silty Sand	Lateral	Recharge
9009	Oakes Corner NE	48°18′	94°46′	22.9	BC	—	—	231	Clayey Sand	Lateral	I.D.
9018	Pine Island	48°10′	94°14′	16.2	BC	—	—	240	Gravely Clay	I.D.	N.D.
9122	North Black River	48°30′	94°01′	19.7	BC	2070 ± 70	Beta-53058	242–247	Silty Sand	N.D.	N.D.
9113	Red Lake II	48°18′	94°43′	17.1	INT	3905 ± 55	SI-5442	300–305	Sand	Discharge	Discharge
9003	Red Lake IV	48°20′	94°18′	24.3	INT	2910 ± 60	Beta-53048	280–295	Silty Sand	Discharge	Discharge
9011	Oakes Corner NE	48°18′	94°46′	0.6	INT	—	—	230	Sandy Clay	N.D.	N.D.
9123	North Black River	48°30′	94°01′	0.1	INT	3500 ± 100	Beta-66730	372–377	Silty Sand	N.D.	N.D.
9014	Gates Corner	48°10′	94°01′	7.8	INT	—	—	228	Silty Sand	Lateral	Lateral
9022	Fairland	48°23′	94°01′	1.3	INT	—	—	181	Silty Sand	Lateral	N.D.

those chemical variables that the regressions indicated behaved conservatively within the pore waters.

Results

REGIONAL DISTRIBUTION

Bog land-forms in north-western Minnesota are characterized by (1) a forested crest with radiating lines of stunted trees, (2) unforested lawns down-slope from the crest, and (3) sharp streamlined margins trimmed by fen water tracks. Subtle drains usually originate near the bog crest and channel acidic runoff toward the perimeter of the landform. All bogs larger than 20 km^2 also contain fen water tracks that arise within the continuous mass of ombrotrophic peat. These internal water tracks widen down-slope and fragment the lower bog flanks into streamlined lobes and ovoid islands. The regularity of the forest patterns are occasionally interrupted by angular fire scars and by circular infection sites for dwarf mistletoe (*Arcethrobium*).

The study area contains 127 bogs that cover 1236.4 km^2 or 16% of the study area (Fig. 1a,b). Most bogs are smaller than 10 km^2, but these smaller bogs account for less than 30% of the regional bog cover. The largest bogs, in contrast comprise more than half of the total area for all bogs and tend to be clustered in the central and west-central portions of the study area (Fig. 1b). Otherwise there is no significant relationship between the size of the bog land-forms and the regional climatic gradients. The frequency of bogs is also relatively constant along east-to-west and north-to-south transects.

The regional distribution of bog land-forms, however, is related to physiographic features particularly (1) major drainage divides (19 bogs covering 544.6 km^2), (2) interfluves of tributary streams (31 bogs covering 296.4 km^2), and (3) sandy beach ridges (34 bogs covering 298.2 km^2). The largest bogs straddle major drainage divides, whereas the smaller bogs are more likely to be associated with the edges of the beach ridges or interfluves of small streams.

VEGETATION

The ombrotrophic bog vegetation in north-western Minnesota is distinguished by (1) low species richness, (2) the absence of fen-indicator species *sensu* Sjörs (1963) and Wheeler *et al.* (1983), and (3) a nearly continuous carpet of *Sphagnum*. The regional bog flora contains 24 species of vascular plants and 19 bryophytes, but only a few species are dominants (Glaser 1992c). The vegetation types are (1) *Picea mariana* forests at the bog crests (*Carex trisperma-Vaccinium vitis-ideae* nodum *sensu* Glaser *et al.* 1981), (2) lawns on the lower bog flanks (*Carex oligosperma* nodum *sensu* Glaser *et al.* 1981), and (3) small *Sphagnum cuspidatum* hollows (*Rhynchospora alba- Scheuchzeria palustris* nodum *sensu* Glaser 1992c). These noda grade into two types of poor-fen that are found at the perimeter of the large bog complexes and the lower margins of all bog land-forms. These poor-fens may be distinguished from the true bogs by the appearance of a few fen indicator species and by their higher pH (>4.2) and Ca concentration ($>2\,\mathrm{mg\,L^{-1}}$).

The three bog noda are remarkably similar across the region with respect to species richness, species dominance, and floristic assemblages. For example, the total species richness for the large forested plots (400 m^2) consists of only 9–14 species of vascular plants and 4–8 species of bryophytes (Fig. 2a,b). The interquartile range (25–75% interval) of these distributions is less than 3 species per plot, and the whiskers ($\pm 1.5 \times$ interquartile distance) are similarly narrow. The species richness distributions are nearly identical for the forested and nonforested bog noda, although the nonforested noda have a slightly lower median. These noda share very similar floristic assemblages, although the dominant species are different. *Sphagnum cuspidatum* hollows, in contrast, are very rare in Minnesota and are found on only three bogs within the study area. No changes in these bog noda are discernible that can be related to the regional climatic gradients.

SURFACE-WATER CHEMISTRY

The surface waters on bogs consistently have a pH below 4.2 and Ca concentrations less than 2 mg L^{-1} (Glaser 1992c). The pH has a narrow range from 3.8–4.2 in both the forested and nonforested bog vegetation (Fig. 2c). The range in pH is also small in the 2 types of bog-like poor fens, although these poor fens have a slightly higher median value. The distributions for Ca are similarly narrow, although the median values clearly separate the bogs from the various types of poor fens (Fig. 2d). These increasing median values for Ca provide the best chemical indicator for separating the various types of bog and poor-fen noda.

PEAT DEPTH AND BASAL AGE

The peat depth for raised bogs ranges from 181 to 545 cm with a median depth of 308 cm. Bogs tend to be deeper than fen water tracks, although the median depth for these fens is only slightly lower (Table 1). Basal peat dates tend to be more variable, although the median value for most bog and fen land-forms coincides at 3500–3700 year B.P. The difference between these median values falls within the range of the error bars for the radiocarbon dates. No significant trend is apparent with respect to basal dates and the location of the bogs along the climatic gradients. However, the basal ages of the bogs and fens are significantly related to the peat depth ($r^2 = 0.672$).

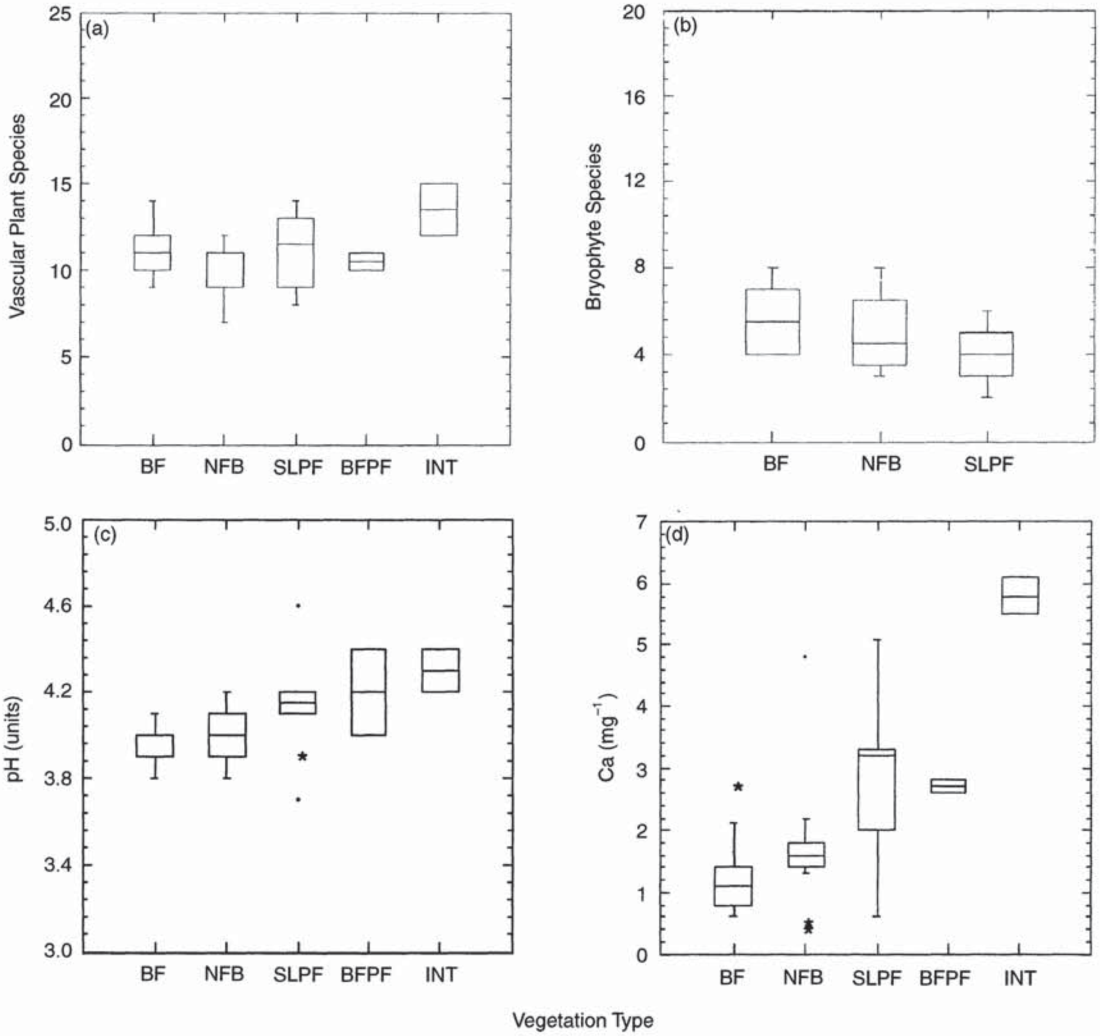

Fig. 2 The regional variability of species richness and surface-water chemistry on raised bogs across the study area: (a) vascular plant species, (b) bryophyte species, (c) pH, and (d) Ca concentrations. The symbols stand for bog forest (BF), nonforested bog lawns (NFL), *Sphagnum*-lawn poor fens (SLPF), bog-like forested poor fens (BFPF), and internal water tracks (INT). The distribution for each vegetation type is represented by boxes, the upper and lower sides of which mark the 25% and 75% percentiles of the distributions. The boxes are divided at the median. The whiskers are drawn to the largest or smallest observation within 1.5 interquartile ranges (i.e. length of the box) of the edge of the box. Values outside the whiskers are marked by an asterisk, whereas extreme values more than three interquartile ranges from the end of the bog are marked by dots. The maximum value of the *y*-axis is constrained by the upper limit of variable under consideration.

HYDRAULIC HEAD GRADIENTS

A significant change occurred in the hydraulic head gradients on most raised bogs between 1990 and 1991 (Table 1). During the 1990 drought, most raised bogs were located over discharge zones for groundwater. The upward head gradients at these sites indicated that pore fluids were moving upward from the basal peat/mineral contact toward the water table. At this time the water table was depressed 70–200 cm below the peat surface. The internal water tracks at Red Lake were also located within discharge zones for groundwater in 1990. The head gradients of the remaining bogs did not change with depth and corresponded to the elevation of the water table, indicating that pore fluids moved laterally through the peat. None of the bogs had downward head gradients in 1990 indicative of recharge (downward-flow) systems.

Recharge systems, in contrast developed on most raised bogs in 1991 after 2 months of normal precipitation. At this time the water table rose to within 20–40 cm of the peat surface. The head gradients were downward within the upper portion of the peat profile, indicating that pore waters flowed downward from the water table into the deeper peat. Only 1 bog still exhibited either lateral flow or discharge throughout the entire peat profile. The striking reversal in head gradients is illustrated by the profiles recorded from the crest of Red Lake IV (Fig. 3). In 1990 the water levels in piezometers were all higher than the water table indicating that the bog crest was located over a discharge zone. Hydraulic head also increased with depth, indicating that water was flowing upward

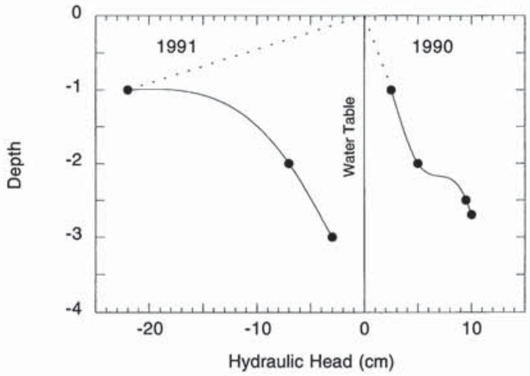

Fig. 3 Head gradients from the bog crest at Red Lake IV during 1990 and 1991.

from the basal sediment to the water table. However, in 1991 all the water levels in the piezometers were below the position of the water table. Hydraulic head decreased with depth from the water table (reference elevation = 0) to 1 m depth where the head was −22 cm. The hydraulic head then increased from −7 cm at 2 m depth to −2 cm at 3 m depth. These head measurements indicate that (1) shallow pore-water moved downward from the water table to a depth of 1 m and (2) deeper pore-water moved upward from 3 to 1 m depth).

PORE-WATER CHEMISTRY

During both years, the pore-water concentrations of the major cations consistently increased with depth with the most rapid changes occurring from 1.5–2 m depth (Fig. 4). At the bog crest at Red Lake IV, for example, Ca remained less than 5 mg L^{-1} in the uppermost m of saturated peat and then increased steadily to 64.2 mg L^{-1} at a depth of 3 m. The chemical profiles for most sites were remarkably similar, although bogs with a higher crest tended to have slightly lower concentrations for Ca for any given depth. This general trend is supported by cluster analysis, which distinguished shallow, intermediate, and deep classes of pore-water in 1990 and 1991 on the basis of 6 conservative chemical factors (Fig. 5a,b).

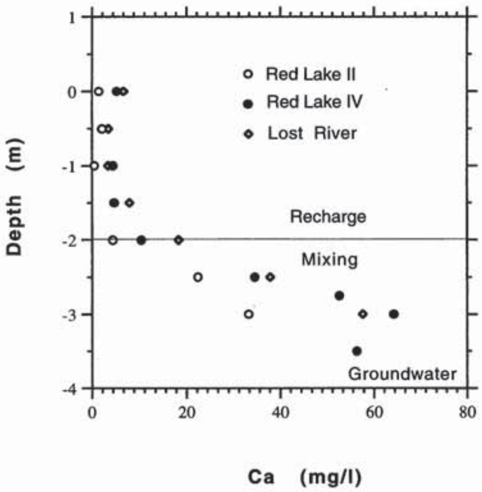

Fig. 4 Depth profile for Ca in pore waters from Red Lake II, Red Lake IV, and Lost River during 1990 and 1991.

The chemical profiles for most cations changed little between 1990 and 1991. Most of the cations were linearly related to Ca, particularly Mg, Sr, and Na (Fig. 6). The most important exceptions were K and Al. The pH profile was also similar for these 2 years, as pH is related to both Ca and Mg. Dissolved inorganic carbon (DIC), however, changed considerably, with very high concentrations in 1990 and much lower concentrations in 1991 (Fig. 7). Although DIC was significantly related to Ca, Mg, and pH for both years, the r^2 and F-values were much higher in 1991.

Discussion

The Glacial Lake Agassiz region contains some of the largest raised bogs in existence some of which exceed 100 km^2 in area (Glaser 1992a,b; Table 1). These bogs are characterized by their striking landform patterns, their acidic, dilute surface waters, and their acidophilic assemblages of vascular plants and bryophytes (Glaser *et al.* 1981; Glaser 1992). They conform to all the chemical and biotic criteria that distinguish bogs from fens across the boreal zone. Two hypotheses may be tested to explain the unexpected abundance of these bogs in such a dry region: (1) bogs adjust to the westward climatic gradient by alterations to their landform morphology or vegetation assemblages that reduce moisture loss, or (2) alternative sources of moisture are available to sustain the water-table mounds within these bogs. According to the first hypothesis raised bogs should become smaller, flatter, and less species-rich to the west as the species assemblages become restricted to the most xeromorphic forms, such as ericacious shrubs and lichens. Alternatively, bogs may be restricted to specific physiographic settings that focus groundwater discharge. This alternative hypothesis, however, conflicts with the basic premise that raised bogs are ombrotrophic and are therefore completely disconnected from groundwater (Ingram 1982, 1983).

CLIMATE

If the water-table mounds of raised bogs are sustained solely by precipitation, then their geographical limits should be directly determined by climatic factors. However, the best examples for such relationships are reported for maritime regions with minimal continental influence. Blanket bogs, for example, are consistently restricted to the most oceanic climates with greater than 1000 mm of annual precipitation, 160 annual rain days, and 15°C mean annual temperature with little seasonality (Ratcliffe & Oswald 1988). In Ireland, raised bogs replace blanket bogs in areas that receive 700–1000 mm of annual precipitation (Moore 1962; Hammond 1979). In Sweden the relationship

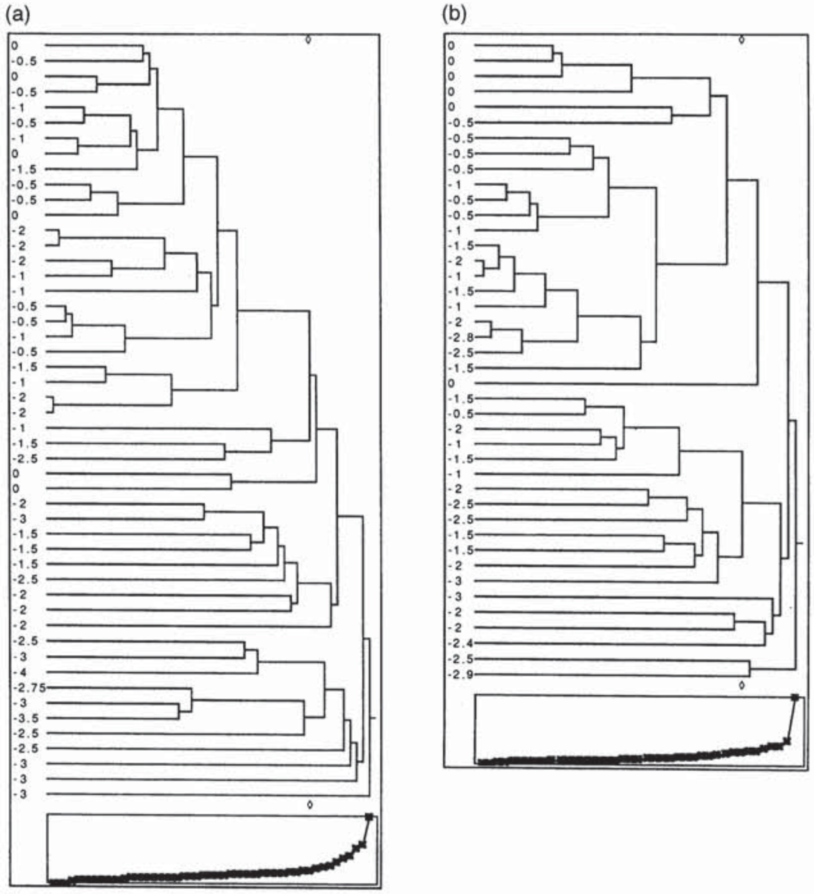

Fig. 5 Cluster analysis of pore-water samples for all raised bogs for 1990 (a) and 1991 (b). The samples were classified on the basis of the pH and five chemical species, which behaved conservatively within the peat profile. The depth intervals sampled are marked on the left side of the dendrogram.

between bogs and precipitation patterns is even closer, for the convexity of the bog land-forms decreases as the precipitation falls from over 1000 mm to 460 mm, below which bogs do not develop (Granlund 1932; Tallis 1983).

In continental regions the climatic limits for bogs are more complex because the water budget is significantly altered by evapotranspiration and increasing seasonality. Damman (1977, 1979), for example, stressed the importance of seasonal drought as a limiting factor for raised bogs in eastern North America. The southern limit for bogs in the Bay of Fundy region coincides with much higher isopleths for annual precipitation than those reported for Europe. The annual surplus of precipitation over potential evapotranspiration there, however, is 500 mm, which is comparable to the lower limit reported for Sweden by Granlund (1932). Bogs may also be limited by the length of the growing season and the accumulation of a deep winter snow-pack, which produces a flush of runoff in the spring.

In the continental climate of north-western Minnesota the relationship of raised bogs to the regional climate is more enigmatic. The regional climate becomes more arid toward the west as annual average precipitation declines from 636 to 535 mm year^{-1} (Baker *et al.* 1967). When calculated by the Thornwaite system, mean potential evapotranspiration increases east-to-west from 547 to 560 mm year^{-1}, producing a net moisture deficit in the western portion of the study area (Baker *et al.* 1979). If the pan estimates for evaporation are used, this deficit is much greater from 77 to 229 mm year^{-1} across the study area. When a water budget is calculated from gauged streams, the estimated moisture surplus is much higher (102–127 mm year^{-1}), but these values may seriously underestimate evapotranspiration because of inputs from groundwater (Helgesen *et al.* 1975; Lindholm *et al.* 1976). The moisture balance from all of these estimates seems too low to support raised bogs, particularly if these bogs are also exposed to extreme droughts.

Raised bogs, however, are distributed across the entire study area and also extend farther west to the edge of the presettlement prairie–forest border. The largest bogs, moreover, are located closer to the western edge of the study area, where the climate seems less suitable for their development. No regional trends are apparent with respect to the size, abundance, vegetation assemblages, surface-water chemistry, peat depth, or basal age of these raised bogs that can be related to climatic gradients. These bogs are instead

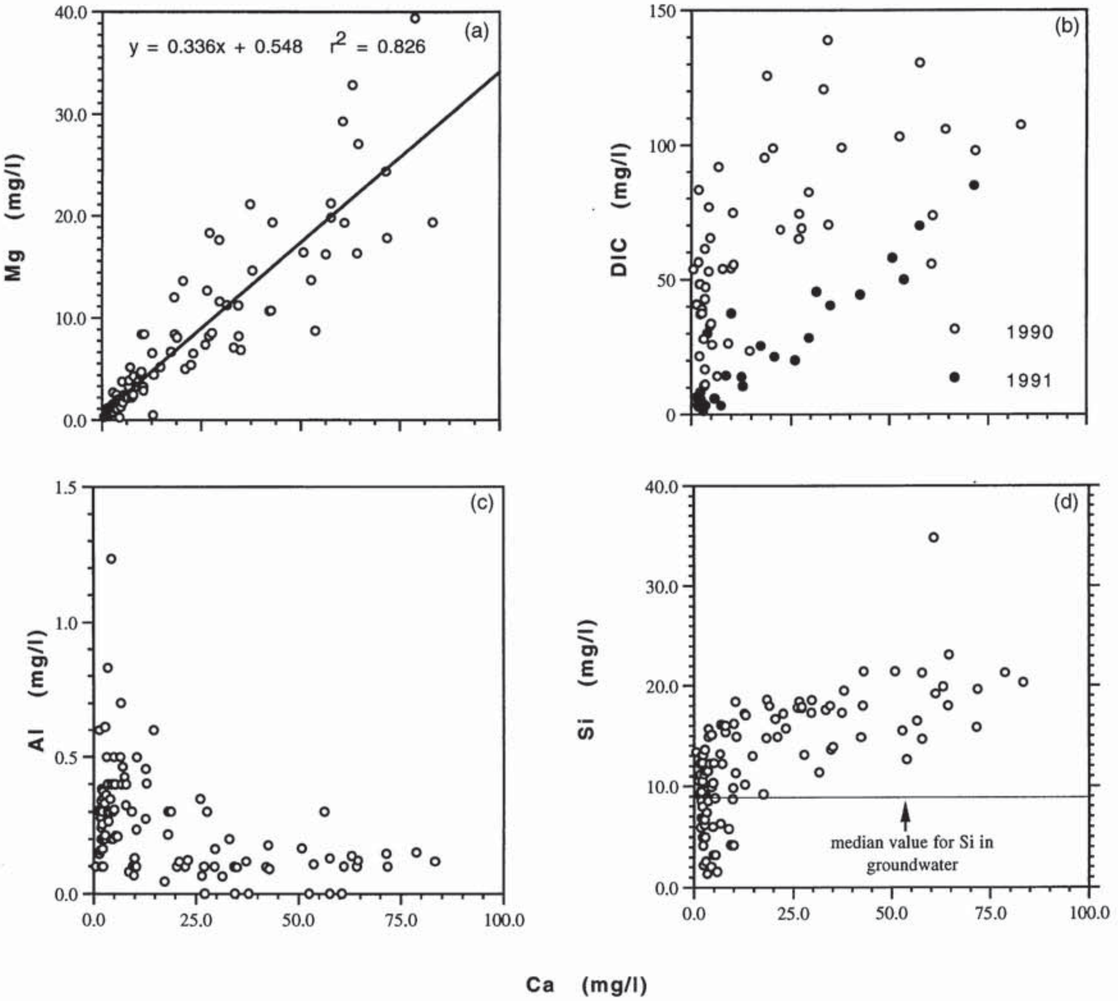

Fig. 6 The relationship of Ca to conservative and nonconservative species in the pore waters. in 1990 and 1991 (a) Ca vs. Mg, (b) DIC vs. Ca (c) Al vs. Ca, and (d) the Si vs. Ca.

remarkably similar from site to site, indicating a high degree of internal buffering to the increasing regional moisture stress. The apparently anomalous abundance of raised bogs in such a dry and drought-stressed region indicates that other factors are critical for their growth and maintenance. Kulczyńsky 1949) came to similar conclusions in his peatland survey of the Polesie in eastern Europe.

PHYSIOGRAPHIC FACTORS

Raised bogs are locally related to physiographic features that have an important influence on the surface and groundwater hydrology of the study area. The most important of these features are (1) sandy beach ridges, (2) local and regional watershed divides, and (3) interfluves of the tributary streams. Although the beach ridges are relatively stable features, the drainage system has continued to evolve in response to climatic changes during the Holocene.

The prominent beach ridges are local high points on the landscape and therefore represent sites where precipitation recharges the groundwater system. According to (Boldt 1986), these beach ridges may be connected to the raised bogs down-slope by buried sand lenses, which are confined by thick layers of silt and clay (Fig. 8). The sand lenses then serve as conduits for groundwater that originates at the beach ridges and discharges down-slope under the bogs. Groundwater discharge may also be focused by bedrock ridges located under the discharge sites. These observations are supported by the consistent occurrence of sand and gravel under the bogs sampled (Table 1) and by seismic surveys in the Lost River and Red Lake peatlands (Miller *et al.* 1992). These stratigraphic and geomorphic controls predate the formation of the peatlands.

Raised bogs also formed over drainage divides that were created by the evolving network of streams and tributaries that developed after the drainage of Glacial Lake Agassiz. This drainage system was probably poorly developed prior to 5000 years BP when the climate was much warmer and drier than at present (Janssen 1968). The shift to a wetter climate after 5000 BP probably raised the regional water-table initiating the spread of peatlands and accelerating the headward erosion of streams. Some bogs may have developed over former drainage divides that were later breached

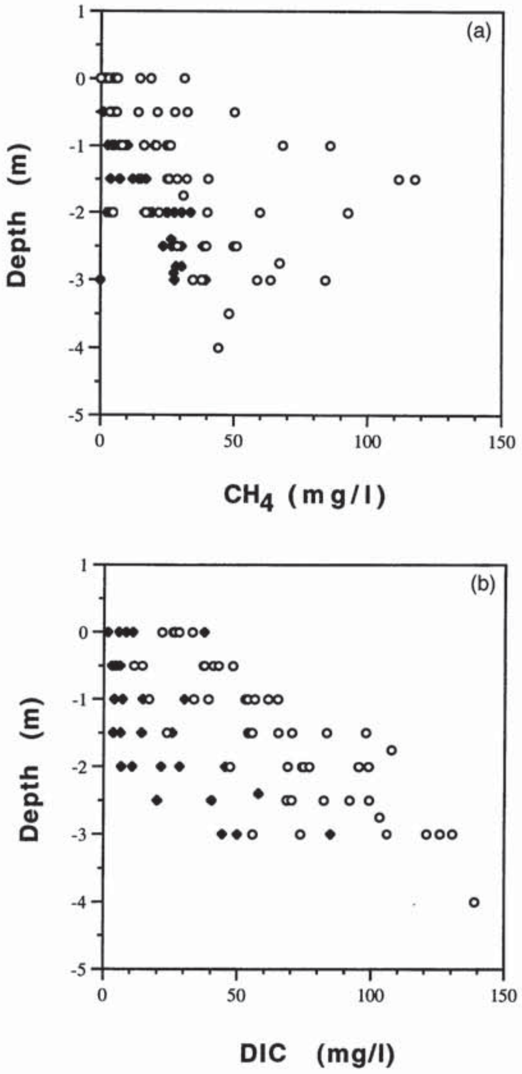

Fig. 7 The concentration of dissolved inorganic carbon (DIC) in the pore waters of raised bogs and its relationship to methane. The open symbols represent values for 1990 drought, whereas the closed symbols represent those for 1991.

by these elongating streams. However, even today the drainage network has the characteristics of a youthful system marked by its low drainage density and small number of branching tributary streams.

GROUNDWATER

The regional climatic gradient had no noticeable effect on the hydrology of the 14 bogs sampled across the study area. However, the head gradients reversed from discharge to recharge at the majority of sites during the shift from drought to normal precipitation in 1990–91 (Table 1). Although a majority of these sites could be classified as recharge zones in 1991, the head gradients actually indicate that pore water was flowing in opposing vertical directions at different depths within the peat profile. These converging flow-systems are clearly indicated by the head gradients at Red Lake IV (Fig. 3).

The most likely explanation for these flow reversals is the growth and decay of water table mounds within the raised bogs. During moist periods the elevation of the water table rises close to the peat surface and generates sufficient hydraulic head to drive pore fluids downward. This recharge system deflects upwardly moving groundwater toward the margins of the bogs, where it discharges into the internal water tracks. During periods of extreme drought, however, the water table may fall by as much as 1–2 m below the crest of the raised bogs, shrinking the water table mounds and halting the recharge flow. This was the hydrologic situation observed in 1990 when an extreme 3-year drought lowered the water table to depths of 70–200 cm below the bog surface. Similar hydraulic reversals have been observed by Siegel & Glaser (1987); Glaser *et al.* (1990) and Charman *et al.* (1994).

Because of these reversals, raised bogs should receive sufficient groundwater to maintain saturation even during droughts in the driest portions of the study area. From Darcy's Law ($Q = KI$), the maximum amount of groundwater up-welling into the peat column is about 60 mm $year^{-1}$, given the measured values for the maximum vertical head-gradients (≈ 0.02 m m^{-1}) and the vertical hydraulic conductivity ($\approx 10^{-5}$ cm s^{-1}) of the humified peat (Chason & Siegel, 1986; Siegel & Glaser 1987; Romanowicz *et al.* 1993). This volume of discharge is approximately double the magnitude of the moisture deficit estimated by the Thornwaite method and seems to account for the abundance of bogs in this dry region.

PORE-WATER CHEMISTRY

The hydraulic-head data are also supported by the pore-water chemistry. First, the concentration of major cations, such as Ca and Mg, were linearly

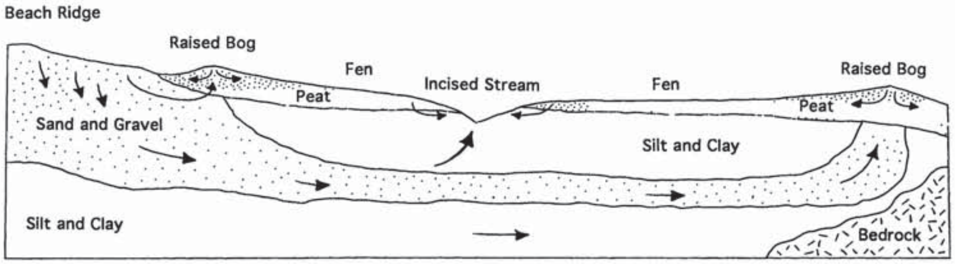

Fig. 8 Regional linkages between groundwater flow-systems and raised bogs in the Glacial Lake Agassiz region. The geological section of this conceptual model is $\approx$10 km long and 30 m thick.

related during 1990 and 1991, indicating that the pore waters are simple mixtures of groundwater (of the calcium magnesium bicarbonate type) and precipitation (Fig. 6a). Secondly, cluster analysis distinguished the populations of samples that correspond to either groundwater, surface water, or an intermediate mixing zone (Fig. 5). Thirdly, cation profiles from individual bogs clearly define the same three zones that correspond to surface water, mixing, and groundwater (Fig. 4). These profiles changed little between 1990 and 1991 indicating that the pore waters are flushed very slowly in comparison to the more rapid reversals in the vertical direction of fluid flow (Siegel *et al.* 1995).

NONCONSERVATIVE SPECIES

Several solutes deviated from the linear mixing model indicating that their chemical profiles were determined by biogeochemical processes within the peat. Aluminium for example, decreased in concentration with peat depth, pH and Ca (Fig. 6c). The concentration profiles of Al are apparently related to the enhanced dissolution of alumino-silicates embedded within the peat at low pH, and to the decreasing solubility of Al at the higher pH of the deeper pore waters.

The concentration of silica is more difficult to interpret. Si attains an asymptotic limit with respect to Ca and other cations at depths in which their concentrations are still a fraction of that found in groundwater (Fig. 6d). These relationships suggest that Si concentrations are determined by fluxes from a source/sink within the peat under the control of a coupled organic-inorganic equilibrium system. Silica may be added to the pore waters by the dissolution of diatom frustules, alumino-silicates, and quartz silt embedded within the peat. This process is enhanced by the complexation of silica to organic acid complexes under a circumneutral pH, according to Bennett & Siegel (1987) and Bennett *et al.* (1991).

Two lines of evidence indicate that the source of dissolved inorganic carbon (DIC) switched from largely biogenic CO_2 in 1990 to inorganic bicarbonate in 1991. First, DIC was weakly related to Ca in 1990 ($r^2 = 0.405$), whereas the more strongly linear trend in 1991 ($r^2 = 0.885$) indicates simple mixing of precipitation and bicarbonate-rich groundwater. Secondly, the log of DIC was also weakly related to the pH in 1990 ($r^2 = 0.396$), in contrast to the more strongly linear relationship in 1991 ($r^2 = 0.705$). High inputs of biogenic CO_2 (from fermentation and methanogenesis) can lower the pH in a nonlinear manner because of protonation and ion-pairing effects as CO_2 is added to pore waters derived from different mixtures of precipitation and groundwater (Stumm & Morgan 1981; Butler 1982; Hemond 1990; Driscoll *et al.* 1994). In 1991, however, the pore waters were mainly buffered by bicarbonate derived from groundwater (Fig. 6b). These changes in DIC correspond to those reported for methane and seem to be related to transient confining layers that alternatively trap and release biogenic gases produced within the peat (Romanowicz *et al.* 1995).

DEVELOPMENT OF RAISED BOGS IN A DRY CLIMATE

The origin of raised bogs in north-western Minnesota cannot be explained by existing models of peatland hydrology. The initial development of raised bogs, for example, has been linked to the headward erosion of streams, which create local watershed divides. This mechanism was proposed by Kulczyński (1949) for the formation of bogs in the Polesie and was later applied to the Myrtle Lake peatland of Minnesota by Heinselman (1970). According to this hypothesis, precipitation leaches inorganic solutes from the surface waters of the interfluves, facilitating the invasion of *Sphagnum* and formation of a raised bog. This hypothesis is apparently supported by the general occurrence of raised bogs on local and regional watershed divides throughout the Glacial Lake Agassiz study area (Fig. 1b) and by the topographic and stratigraphic survey of Heinselman (1970) at Myrtle Lake.

The interfluvial divides should be recharge areas for local flow systems, given the nearly flat hydrogeological setting of the study area (Tóth 1962; Freeze & Cherry 1979). Recharge zones, however, are most susceptible to desiccation during droughts and thus least favourable for the genesis of bogs in dry climates. Groundwater discharge should also be focused toward the tributary streams rather than the sites where it was actually observed under the raised bogs. The only explanation for this paradox is Boldt's (1986) model in which stream incision is too shallow to penetrate through the silty lake deposits and breach the buried sand and gravel fans that serve as the major conduits for groundwater.

The moisture surplus in north-western Minnesota also seems too small to support raised bogs according to the traditional hydrological model. Ingram (1982, 1983), for example, proposed that raised bogs are maintained by the impeded infiltration of precipitation, which produces a water-table mound within the peat. Precipitation infiltrates into the uppermost layer of porous peat (acrotelm) and then flows laterally toward the bog margins because deeper infiltration is blocked by the low hydraulic conductivity of the deeper peat (catotelm). According to his model the dimensions of a raised bog are determined by the relationship:

$$(U/K) = (H^2/L^2)$$

where U is net recharge, K permeability of the deposit, H maximum height of the bog, and L maximum length.

The basic premise of this model does not hold for bogs in Minnesota because both the head gradients and pore-water chemistry indicate significant inputs of groundwater into the peat land-forms. Nevertheless, the dimensions of the Red Lake II and Lost River bogs have similar values for H^2/L^2 of 1.26×10^{-4} and 1.11×10^{-4}, respectively. The calculated values for recharge (U) would then be exceedingly small (1.11×10^{-7} to 10^{-9}) depending upon the range of values of K reported by Chason & Siegel (1986). For such small values of recharge the configuration of the water-table mound within the raised bogs should be determined by the dynamics of the regional discharge flow-system, rather than precipitation.

Discharge zones may represent an essential precursor for bogs in this arid climate (Fig. 9). During droughts the topography of the water table is altered by interactions between evapotranspiration and groundwater flow-systems. Draw-down is intensified in areas of downward or lateral flow, whereas in discharge zones draw-down is moderated by upwardly moving groundwater (Freeze & Cherry 1979). Water-table mounds will therefore form in discharge zones, producing a thinner aerobic zone and more rapid rates of peat accumulation. Peat accumulates more rapidly where the aerobic layer is thinner because organic matter is exposed to aerobic decay for shorter periods (Clymo 1984). A series of droughts should then have a cumulative effect that promotes the growth of small peat mounds over discharge zones.

During moist periods, a saturated peat mound generates sufficient hydraulic head to drive surface water downward (Siegel 1983; McNamara *et al.* 1992), which depletes inorganic solutes from the surface waters and creates an environment favourable for the invasion of *Sphagnum*. The accumulation of *Sphagnum* peat will acidify the mound either by its cation-exchange system (Clymo 1963, 1967; Clymo & Hayward 1982) or the release of organic acids during decomposition (Gorham *et al.* 1985). As the raised bog continues to grow in height its local recharge cell would also increase in magnitude during moist periods. The downward-flowing waters in these recharge cells will deflect the up-welling groundwater to the bog margins where they discharge on the surface, creating internal water tracks. Despite this close linkage to groundwater the bog vegetation remains isolated from minerotrophic water by converging flow-systems in moist periods and by substantial draw-down of the water table during droughts.

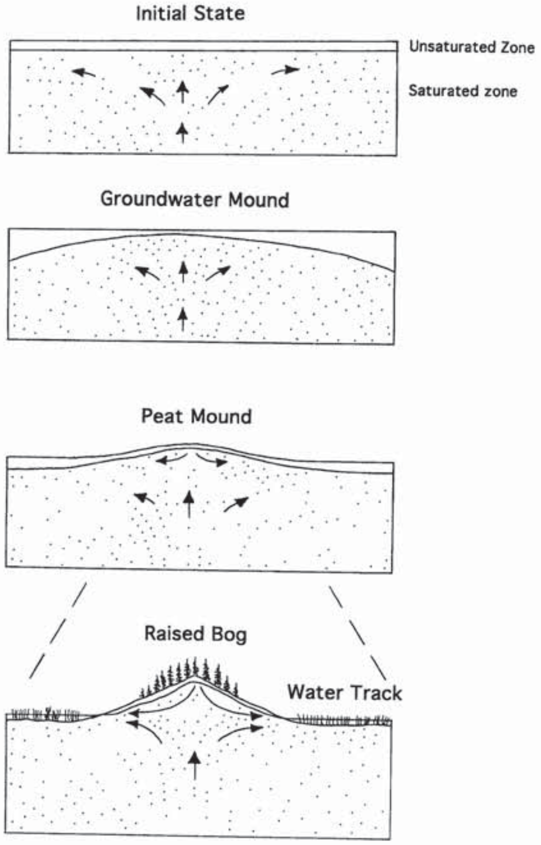

Fig. 9 Developmental model of a raised bog within the Glacial Lake Agassiz region of Minnesota. (1) Initial state: peat accumulation is uniform during moist periods when the high water table limits the residence time of organic matter in the thin aerobic layer. (2) Formation of subsurface groundwater mound. During droughts, groundwater mounds develop over discharge zones where the continuous supply of groundwater more effectively compensates for evapotranspirational losses. (3) Formation of incipient peat mound. Peat will accumulate more rapidly over groundwater mounds where the aerobic layer is thinner and organic matter is exposed to aerobic decay for shorter periods. The water table under these incipient peat mounds will drive local recharge systems depleting the surface waters of inorganic nutrients and favouring the invasion of the *Sphagnum*. (4) Formation of raised bog. The mound will continue to grow because of the lower hydraulic conductivity of *Sphagnum* peat favours the upward migration of the water table. During moist periods the higher water table under these mounds drive recharge cells that displace up-welling groundwater to the margins of the bogs where they discharge in marginal fens and internal water tracks.

Conclusions

Groundwater seems to be an essential agent for the formation of raised bogs near their climatic limits in north-western Minnesota. It is also directly responsible for internal water tracks that arise on the lower flanks of bogs larger than 20 km². These water tracks are ubiquitous features of all large bogs across the continental interior of North America, indicating a general relationship of bogs to groundwater flow-systems (Glaser 1987). The close linkage between raised bogs and groundwater flow-systems is probably responsible for the obscure relationship that exists between bogs and climatic factors in continental regions. It also has important ramifications with regard to flux of solutes and the role of peatlands as sources or sinks for carbon.

Acknowledgements

This project was supported by the US National Science Foundation and the Carbon-Dioxide Program of the US Department of Energy. We thank Lee Andrew of Brainerd Helicopter for piloting the helicopter and B. Frederick, E. Haas, E. Hetherington, P. Korth, A. Lazarus, J. McNamara, D. Nelson, S. Neuzil, D. Ours, N. Rutkowlski, M. Stone, and H. Tran for field or lab assistance. Professors J. A. Lee, N. Roulet, and H. E. Wright Jr made valuable suggestions for improving the manuscript.

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Received 14 August 1995
Revision accepted 18 March 1996