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BOG DEVELOPMENT AND LANDFORM DYNAMICS IN CENTRAL SWEDEN AND SOUTH-EASTERN LABRADOR, CANADA

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SUMMARY

(1) Stratigraphic analysis, detailed surveying, and radiocarbon dating were used to document the development of Hammarmossen a raised mire in central Sweden, and to contrast the structure development and dynamics of landforms there with those on Gilbert bog in south-eastern Labrador, Canada

(2) A series of basal radiocarbon dates from transects of peat cores across Hammarmossen shows that peat started to accumulate approximately 5500 years B P and spread radially across a glacial outwash plain throughout the late Holocene The implications of this pattern of development for models of bog hydrology and growth and for interpretations of the process of paludification, e g by Malmstrom, are discussed

(3) On both Swedish and Labrador mires the distribution shape and development of open-water pools are closely controlled by the topography of the peat surface The largest and deepest pools occur on the flattest surfaces, where water outflow is slow Pool development results from hydrological controls on relative rates of peat accumulation in hummocks and hollows

(4) Pools were initiated throughout the last 4000 years of bog development On Hammarmossen a deep layer of algal gyttja partly fills the pools whereas on Labrador bogs algal sediment is absent, and the pool floors are degrading peat and peat detritus This contrast in stratigraphy of bog pools in Sweden and Labrador follows a similar pattern for pools on minerotrophic mires (fens) in the two areas

(5) Once formed, pools undergo similar dynamics in the two regions Pool depth increases as peat accumulation on hummocks exceeds sedimentation in pools Lateral expansion of pools occurs through marginal flooding, controlled by differential rates of accumulation and by the breakdown of peat ridges separating adjacent pools Pools may be drained through surface erosion or through subsurface piping Erosion of the bog from the mire margin towards the centre may gradually fragment the peat mass Under very wet conditions raised bogs are inherently unstable systems on which water-dominated landforms increase through time until stream erosion gradually dissects the mire

INTRODUCTION

Results from recent stratigraphic investigations of patterned fens (aapamires) in central Sweden (Foster & Fritz 1987) corroborate elements of a hypothesis for mire development based on examples from Labrador, Canada (Foster *et al* 1983, Foster & King 1984) The Swedish research highlights the value of comparative study of mires in different geographic regions for, although the general developmental pattern and the dynamics of surface landforms on fens in the two areas are strikingly similar, some notable differences permit refinements in the original hypothesis and suggest approaches for additional study

The key predictions of the hypothesis investigated in the studies on patterned fens are that (i) paludification is an important continuing process in the lateral expansion of the mires, (ii) pools develop through a gradual process of surface differentiation controlled by rates of peat accumulation that are ultimately governed by hydrological factors, and (iii) once pools are formed they are dynamic systems that deepen, enlarge, coalesce, and may drain Results of the studies emphasize the similarities among widely separated sites On both Swedish and Labrador fens, upslope and lateral paludification throughout the late Holocene is documented by radiocarbon dates of the basal peat (Foster & King 1984, Foster & Fritz 1987) Pool formation throughout the last 4000 years is also dated, and the surface patterns and stratigraphy support the general concepts of pool formation and dynamics One surprising observation is that, on all sites observed to date, fen pools in Sweden have a thick layer of algal gyttja in the bottom whereas in Labrador the pool bottoms have a thin layer of woody detritus over the peat and appear to be degrading

Many of the elements of this hypothesis for patterned fen development should presumably apply to ombrotrophic raised bogs as well, despite their contrasting hydrology, chemistry, and vegetation (Foster & Glaser 1986) Research on raised bogs in Scotland (Ratcliffe 1964, Boatman, Goode & Hulme 1981, Boatman 1983), Canada (Sjors 1959, 1961), and the Soviet Union (Botch & Masing 1979, Ivanov 1981, Mets 1982) supports this view of pool formation and dynamics However, uncertainty remains concerning the role of paludification and mire expansion in raised-bog development (Auer 1928, Granlund 1932, Birks 1972, Clymo 1984)

The present study of two ombrotrophic mires in Sweden and Labrador was comparative in two ways First, it was intended to determine the extent to which common processes were involved in the development of these two bogs and the patterned fens previously studied Secondly, the study focused on similar bog types in contrasting geographic locations with different flora, landscape history, and regional chemistry, in order to evaluate current theories of bog formation

Specific methodology to test the hypotheses in this study includes (i) transects of long cores across Hammarmossen, which is favourably situated on a nearly level outwash plain, to investigate the process of bog development and expansion, (ii) detailed surveying of the morphology and stratigraphy of bog landforms (pools, hummocks, drainage streams) to examine their developmental history, and (iii) observations of mire drainage features to investigate pool dynamics and the formation and function of streams within the peat

METHODS

Maps of Hammarmossen in Sweden and Gilbert bog in Labrador were compiled from low-level aerial photographs At each site the surface and subsurface topographies were surveyed with a theodolite by recording the elevation of each open-water pool and by probing with a thin metal rod to determine the peat depth At Gilbert bog each pool was examined to determine whether the water table had been lowered as a result of stream erosion The highest water level was identified by the position of stranded banks and highest shoreline and the difference between this and the current water level was measured as the decline in water level

At each site the morphometry and stratigraphy of between five and eight pools and their adjoining hummocks were determined on transects along the width and length of the pools A rope marked off in metre intervals was strung tautly across the pool and used to control a small inflatable raft Water depth was measured at 1–5-m intervals, depending on the size of the pool Cores of the surface sediments were obtained with a plastic piston-corer, whereas deeper sediments and peats were cored with a metal piston-corer (Wright 1967) or a Russian corer, 5 cm in diameter Cores were extruded and described and then wrapped in plastic film for transport to the laboratory

At Hammarmossen, long cores were taken along transects running the length and width of the bog (Figs 1 and 2) and closely following the survey lines of Granlund (1932) Duplicate cores of the basal peats were taken with the Russian corer to provide ample material for radiocarbon dating at the Department of Quaternary Geology, Lund University

RESULTS

Macrostructure

Hammarmossen is a concentric raised bog with steep, treeless margins that rise 3–4 m up to a broad centre (Fig 3) The mire is elongated north–south along the slope of the underlying glacial plain and is approximately 2 5-km long by 1 0-km wide The elongated central plain of the mire consists of two gently sloping areas separated by a steeper slope in the middle of the mire (Fig 3) The lagg is poorly developed and the mire is surrounded by pine (*Pinus sylvestris*)* forest, much of which is planted and managed

Gilbert bog is a plateau bog (*sensu* Foster & Glaser 1986) consisting of a broad, central plain and steeply sloping margins (Figs 4 and 5) The mire is approximately 1 5 by 2 5 km and is bounded by Gilbert Lake to the east, streams to the north and south, and mineral uplands to the west The northern and southern halves of the mire are separated by a secondary (endotelmic, *sensu* Ivanov 1981) stream that has cut westward from the lake across the bog plateau A steep ice-push ridge 2-m high borders Gilbert Lake and separates the bog from the shore (Fig 6) Adjacent to the ice-push ridge the mineral substratum underlying the bog is barely raised above the lake level

Mire development

At Hammarmossen the dates of basal peat in sixteen long peat cores decrease consistently from the centre of the mire (5820–5190 years B P) to the margins, where modern dates were obtained in pine forest below 20 cm of humus (Fig 1, Table 1) A plot of depth versus age for the basal radiocarbon dates shows a nearly linear relation (Fig 7) Isochrones of mire expansion therefore closely approximate the contours of peat depth on the mire (Fig 1) Forestry activity in marginal areas may inhibit further expansion of the mire

The peatland expanded to the south down the gently sloping outwash plain more rapidly than across or up this slope The basal peat is extremely well-decomposed and contains abundant charcoal The reconstruction of the vegetation that occupied the site before mire development is therefore uncertain

Microstructure and vegetation

At both mires the microrelief and distribution of landforms is correlated with the topography of the peat surface On Hammarmossen gently sloping surfaces in the mire centre are coverd with broad pools arranged in a concentric pattern paralleling the surface

* Plant names follow Lid (1974) and Nyholm (1954) for Sweden and Fernald (1970), Ireland *et al* (1980) and Hale & Culberson (1970) for Labrador

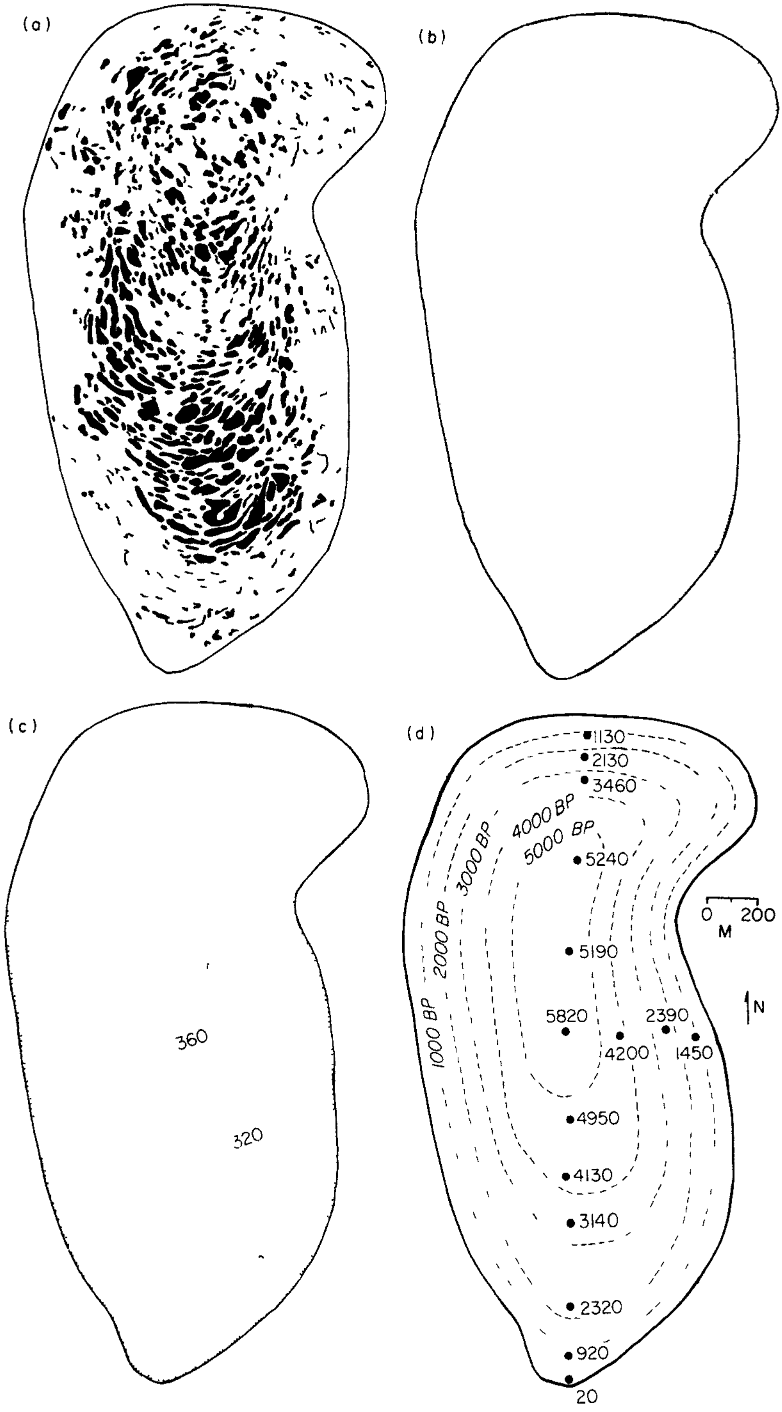

FIG 1 Plan view of Hammarmossen showing (a) pattern of pools (black) (b) tree heights on the mire surface as < 5-m tall (light shading), 5–10 m tall (medium shading) and > 10-m tall (heavy shading), (c) contours of water table altitude for the southern two-thirds of the mire in cm above the substratum, and (d) radiocarbon dates of the basal peats (years B P) and approximate isochrones of mire expansion

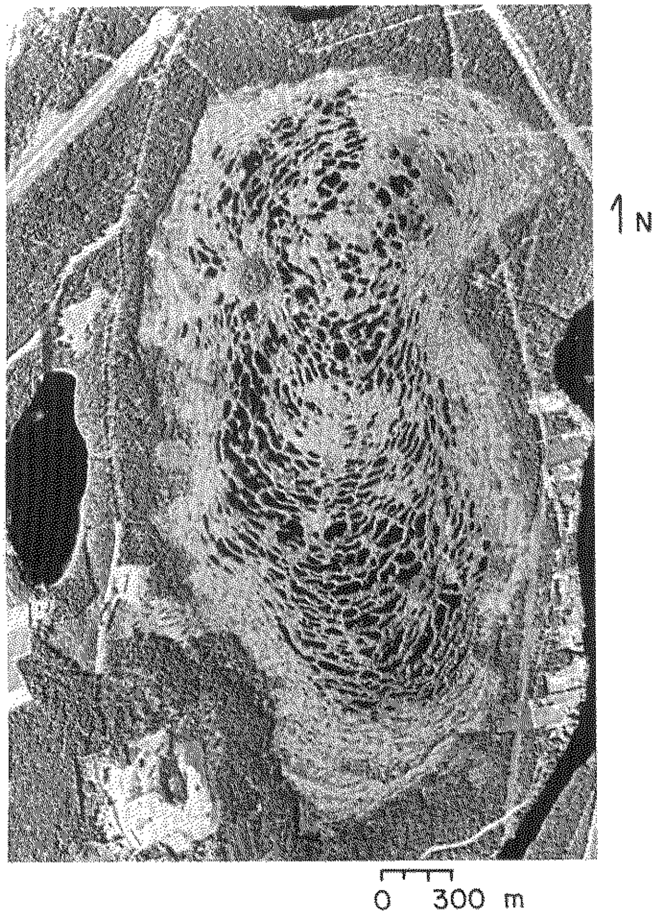

FIG. 2. Vertical aerial photograph of Hammarmossen. The concentric pattern of pools along the contours is continued towards the margins of the bog in the alternating pattern of linear hummocks and hollows.

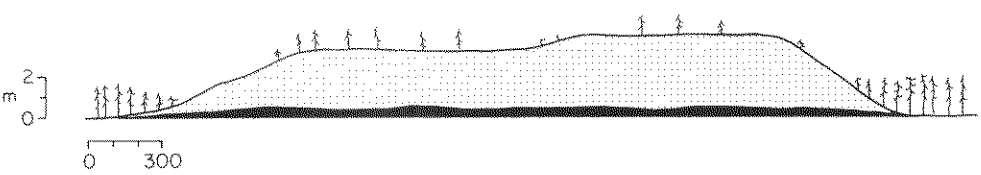

FIG. 3. Cross-sectional profile of Hammarmossen along north–south transect showing the approximate thickness of sedge peat in black and *Sphagnum* peat as stippled, and the relative height of trees on the mire surface.

Table 1 Radiocarbon dates from Hammarmossen, Sweden

Laboratory number	Sample description	Depth of sample (cm below peat surface)	Radiocarbon date (years B P)
Lu-2539	Drained pool—algal gyttja	215–220	2040 ± 50
Lu-2540	Drained pool—*Sphagnum* peat	225–230	2390 ± 50
Lu-2541	Pool no 2—algal gyttja	305–310	3770 ± 60
Lu-2542	Pool no 2—*Sphagnum* peat	315–320	4200 ± 60
Lu-2543	Pool no 1—algal gyttja	290–295	2580 ± 50
Lu-2544	Pool no 1—*Sphagnum* peat	300–310	4010 ± 60
Lu-2545	Pool no 1—*Sphagnum* peat	310–315	4130 ± 60
Lu-2537	Drained pool no 2—algal gyttja	90–100	1300 ± 45
Lu-2538	Drained pool no 2—*Sphagnum* peat	110–120	1940 ± 50
Lu-2526	Basal peat	25–30	20 ± 45
Lu-2527	Basal peat	105–110	920 ± 45
Lu-2546	Basal peat	115–120	1130 ± 50
Lu-2536	Basal peat	130 140	1450 ± 45
Lu-2533	Basal peat	170–180	2130 ± 50
Lu-2528	Basal peat	215–220	2320 ± 50
Lu-2535	Basal peat	235–245	2390 + 50
Lu-2529	Basal peat	300–305	3140 ± 50
Lu-2530	Basal peat	300–309	4950 ± 60
Lu-2531	Basal peat	375–385	5190 ± 60
Lu-2532	Basal peat	365–375	5240 + 60
Lu-2534	Basal peat	385 395	5820 ± 60

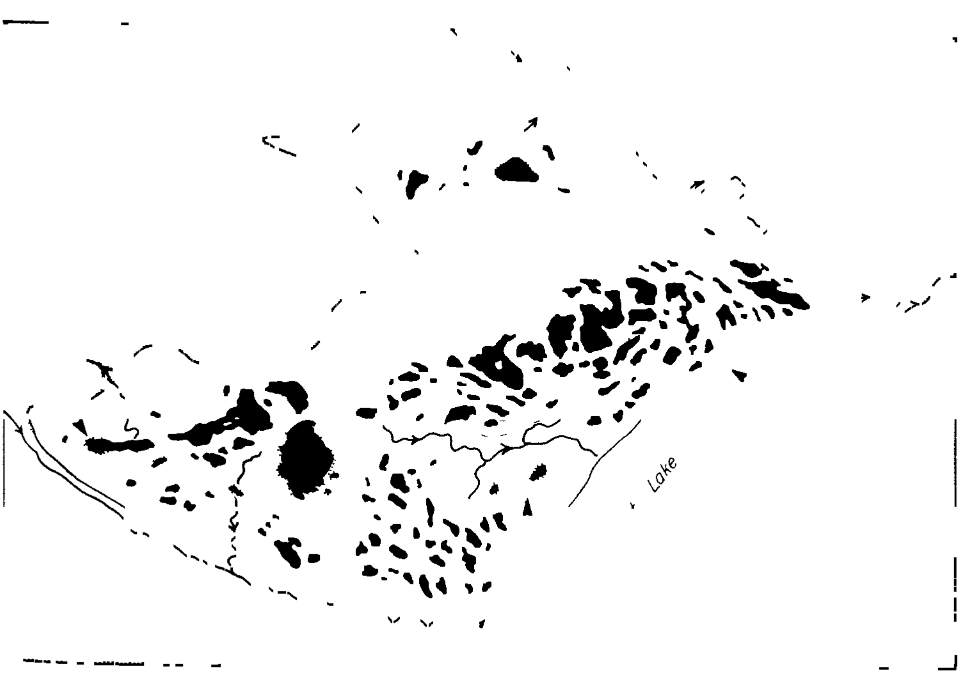

Fig 4 Map of Gilbert bog showing the pool pattern endotelmic streams contours of water table altitude in centimetres above the lake surface and the former extent of drained pools as stippled shadings The approximate orientation of Fig 5 and location of Figs 13 and 14 are indicated by arrows

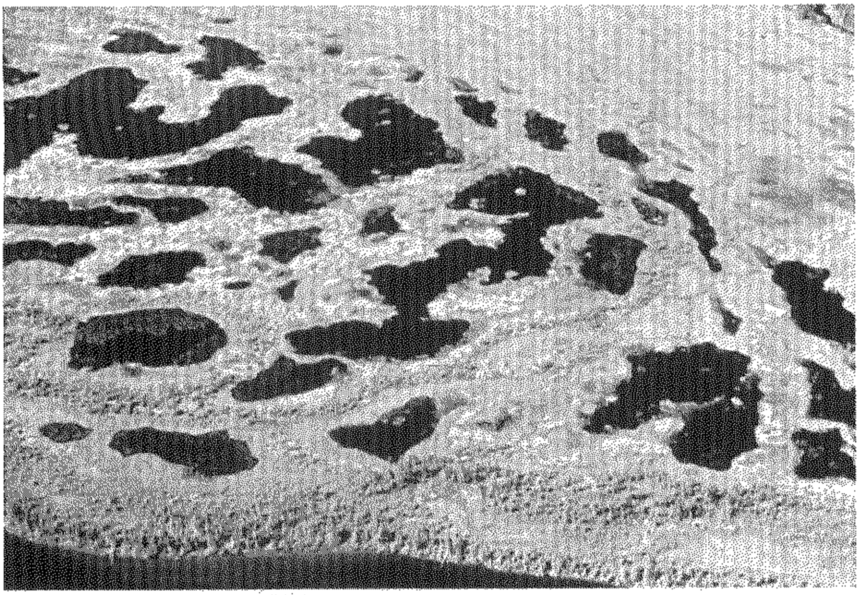

FIG. 5. Oblique aerial photograph of Gilbert bog showing coalescence of adjacent pools and the robust hummocks covered by *Cladonia* lichens. The 10-m tall black-spruce trees along the shore of Gilbert Lake at the bottom of the photograph provide scale.

contours (Fig. 1). Pools are narrower across steeper slopes and then are replaced towards the margins by shallow hollows that are only seasonally inundated. Broad pools are separated by robust hummocks 40–80 cm above the water table and 3–15 m across that are covered by lichens and shrubs. Hummocks are narrower and more linear on the steeper slopes.

Tree height and density on the mire expanse are correlated with surface morphology (Fig. 1). Tall (>10 m) and straight, well-formed *Pinus sylvestris* occupy the broad hummocks adjacent to the largest pools (Fig. 8). Tree height decreases in areas where the surface features are less pronounced. Stunted (<3 m), poorly-formed pines occupy the marginal slopes and unpatterned centre. Towards the extreme margin of the bog, tree height increases as the peat thins onto the mineral soil (Fig. 3).

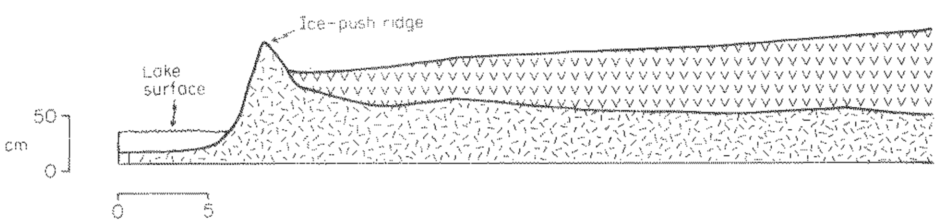

FIG. 6. Cross-section of Gilbert bog showing the ice-push ridge forming the shore with Gilbert Lake, the low elevation of the mineral substrate relative to the lake surface, and the gradual slope of the peat surface.

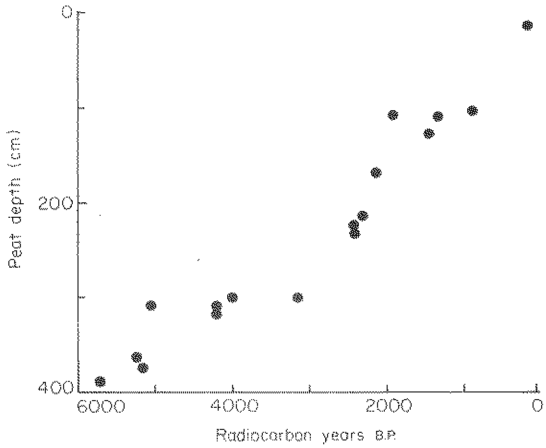

FIG. 7. Relationship between depth and age of basal samples of Hammarmossen. See Table 1 for the actual depths and dates.

FIG. 8. Photograph of a large pool in the south-central part of Hammarmossen. The trees growing on the raised margin of the pool exceed 12 m in height.

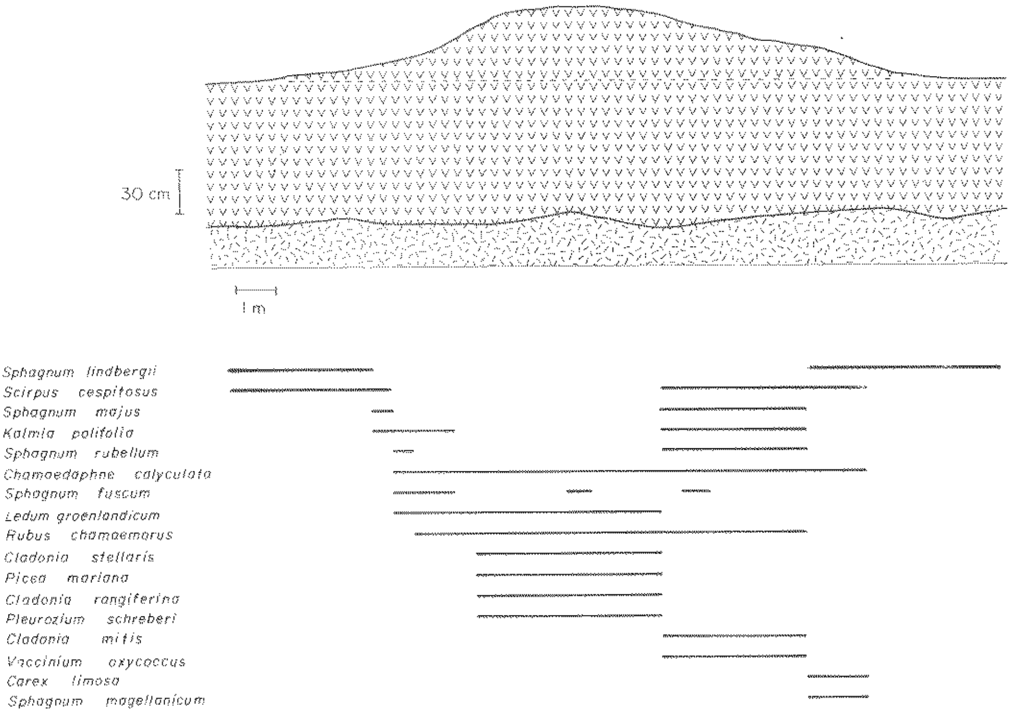

FIG. 9. Cross-section of a hummock between two hollows on Gilbert bog illustrating the distribution of species versus microtopography. The hached line indicates the level of the water table in the adjoining hollows. Mineral soil below is differentiated from peat above in the stratigraphic symbols.

On the unforested surface of Gilbert bog the most conspicuous landforms are large pools separated by broad hummocks. Across the central bog plain the pools are irregular in shape and may be more than 100 m long (Figs 4, 5). The non-oriented shape of the larger pools is accentuated by numerous islands and peninsulas of peat. On the marginal bog slopes the hollows and pools are elongated along the contours.

Large hummocks 2–10 m across rise 30–50 cm above the pool surfaces. Along the flanks of the hummocks the *Sphagnum* spp. (*S. fuscum*, *S. nemoreum*, *S. rubellum*, *S. magellanicum*, *S. tenellum*, *S. lindbergii*) and vascular plants are arranged in a zonation that is apparently controlled by the depth to the water table (Fig. 9). The hummock crests are covered by *Cladonia* spp., *Pleurozium schreberi* and *Picea mariana* krummholtz less than 1·5 m in height (Foster & Glaser 1986). In the northern section of the mire the stunted spruce were killed and the extensive *Cladonia* cover burned in a fire started by lightning in 1959 on the surrounding upland. Parts of the bog also burned in 1936 and 1898 (Foster 1983).

Pool morphometry and stratigraphy

At Hammarmossen most pools are well developed with solid peat margins and near-vertical sides that extend 1–2 m down to the mud bottom (Fig. 10). The banks are locally eroded and undercut (see Fig. 70 in Granlund 1932). Algal gyttja generally forms a smooth bottom in the pools and comprises a thick, continuous stratum 1–2 m thick.

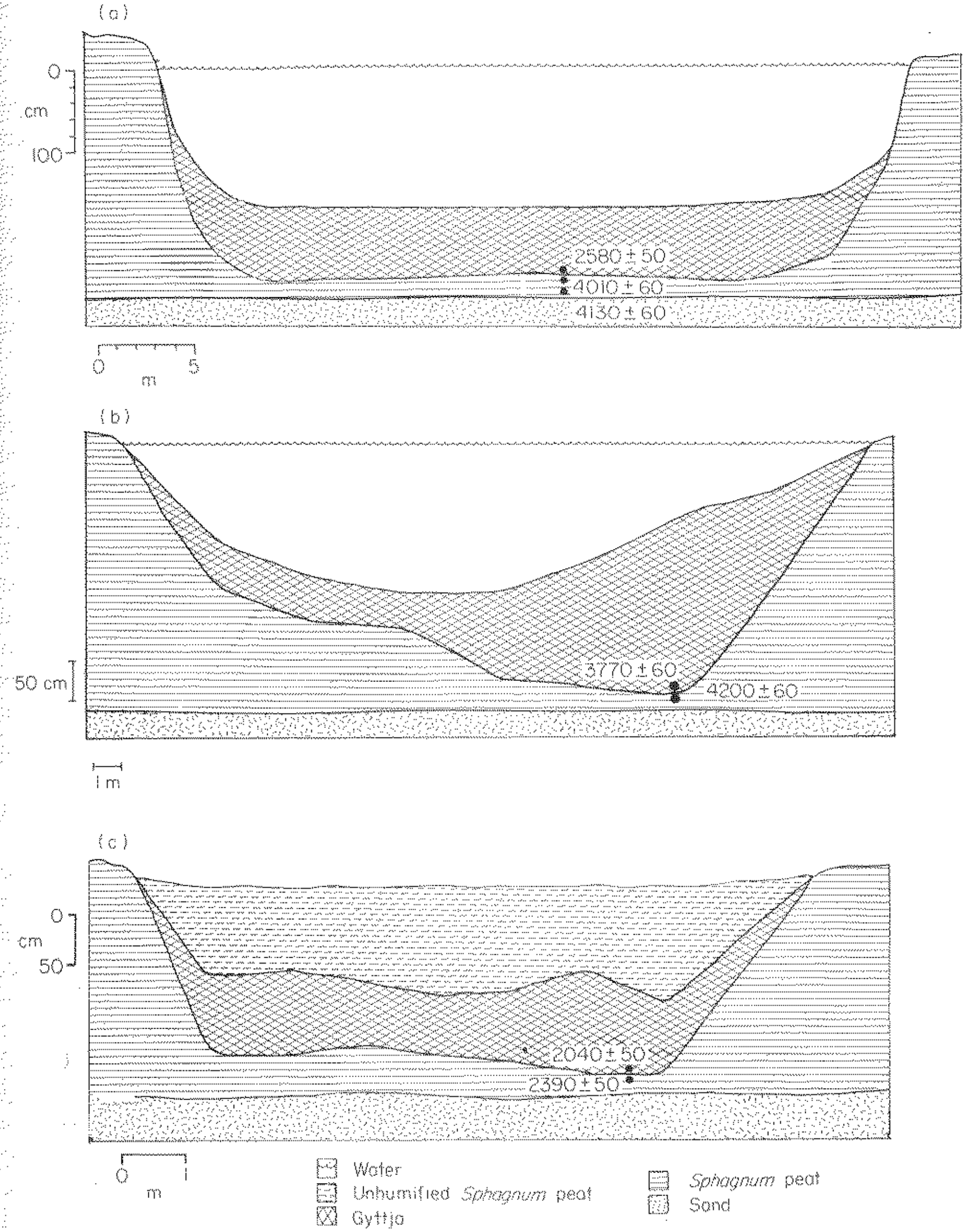

FIG. 10. Stratigraphy of two pools (a and b) and one drained and subsequently in-filled pool (c) from Hammarmossen. Locations of samples dated by radiocarbon analysis (years B.P.) are indicated by solid circles.

Detrital plant fragments in the gyttja are derived from marginal erosion, wind-blown material or floating peat masses that drift across the pools. These floating peat masses reach a maximum size of 1·5 m × 2·0 m × 2·0 m and are formed by erosion of the bank or from islands and peninsulas that have broken off and drift with the wind. Below the gyttja, a thin section of *Sphagnum* or sedge peat overlies very well-decomposed peat that is mixed with charcoal and mineral soil Deviations from this general pattern are seen in some recently coalesced or drained pools

Sediment samples (5–10 cm thickness), taken from immediately above and below the gyttja/peat interface, were dated to determine the time of pool formation and to detect any hiatus that occurred between the initial formation of pools and the subsequent onset of gyttja deposition Ages from the base of this interface range from 4200 to 1940 years B P , indicating a long period during which pools were initiated (Fig 10, Table 1) Pairs of dates from the peat/gyttja contact are 4200/3770, 4010/2580, 2390/2040, and 1940/1300 years B P The length of the hiatus represented in each pair is thus 430, 1430, 350, and 640 years For the longer intervals this hiatus may result from the removal of peat during the initial formation of the pool or from a delay in gyttja deposition

Drained pools are conspicuous landforms across Hammarmossen which are identified by (i) shallow-water depth to gyttja, (ii) the occurrence of secondary, lower shorelines below primary, higher shorelines and (iii) obvious signs of drainage, including eroded ridges or streams interconnecting adjacent pools In addition, the hummocks adjoining drained pools frequently support well-grown trees and have layers of well-decomposed peat near the surface as a result of local lowering of the water table (Foster & Glaser 1986)

Substantially lowered or fully drained pools are much reduced from their former extent and often have exposed mud bottoms (composed of gyttja and peat detritus) and *Sphagnum* carpets or sedge mats extending out from the former shorelines across this exposed substrate Drained and recolonized pools have a surface vegetation of *Sphagnum* and sedge underlain by a variable thickness of peat (Fig 10c), below which is gyttja from the former pool, followed below by *Sphagnum* and well-decomposed sedge peat overlying the mineral substratum

That widespread lowering of pools has occurred across Hammarmossen is apparent from a comparison of pool height and the general topography of the peat surface Although the overall peat surface is characterized by smooth gradients of variable slope (Fig 3), the pool heights are quite irregular (Fig 1) as a result of pool interconnections across the contours of the peat surface via streams and subsurface pipes Because of these freely-flowing hydrological connections many separate pools share the same water table

The morphometry and stratigraphy of pools at Gilbert bog are strikingly different from those at Hammarmossen, although the dynamics are closely similar In general, pools at Gilbert bog are shallow (15–120 cm) and have an irregular outline and cross-sectional profile (Fig 11) The margins slope gradually to an uneven bottom composed of solid *Sphagnum* peat or shallow (< 30 cm) accumulations of peat detritus No algal gyttja was recovered during the coring of any of the pools on Gilbert bog (or indeed on any other ombrotrophic or minerotrophic mires investigated in Labrador (cf Foster & King 1984 Foster & Glaser 1986)) Since the time of pool formation no material has been deposited in these depressions, whereas the surrounding peat surfaces have risen through peat accumulation

The dynamics of the pool systems on Gilbert bog are documented in their shape, in changes in the water-table altitude, and by general observation Pool enlargement through gradual swamping of hummocks between pools produces irregular pool bottoms Portions of the inundated hummocks form islands in the shallow pools and then remain as small peat mounds when completely submerged by the rising water table The submergence of a ridge between two pools shows up in a morphometric profile as a peat ridge separating two distinct basins (Fig 11b)

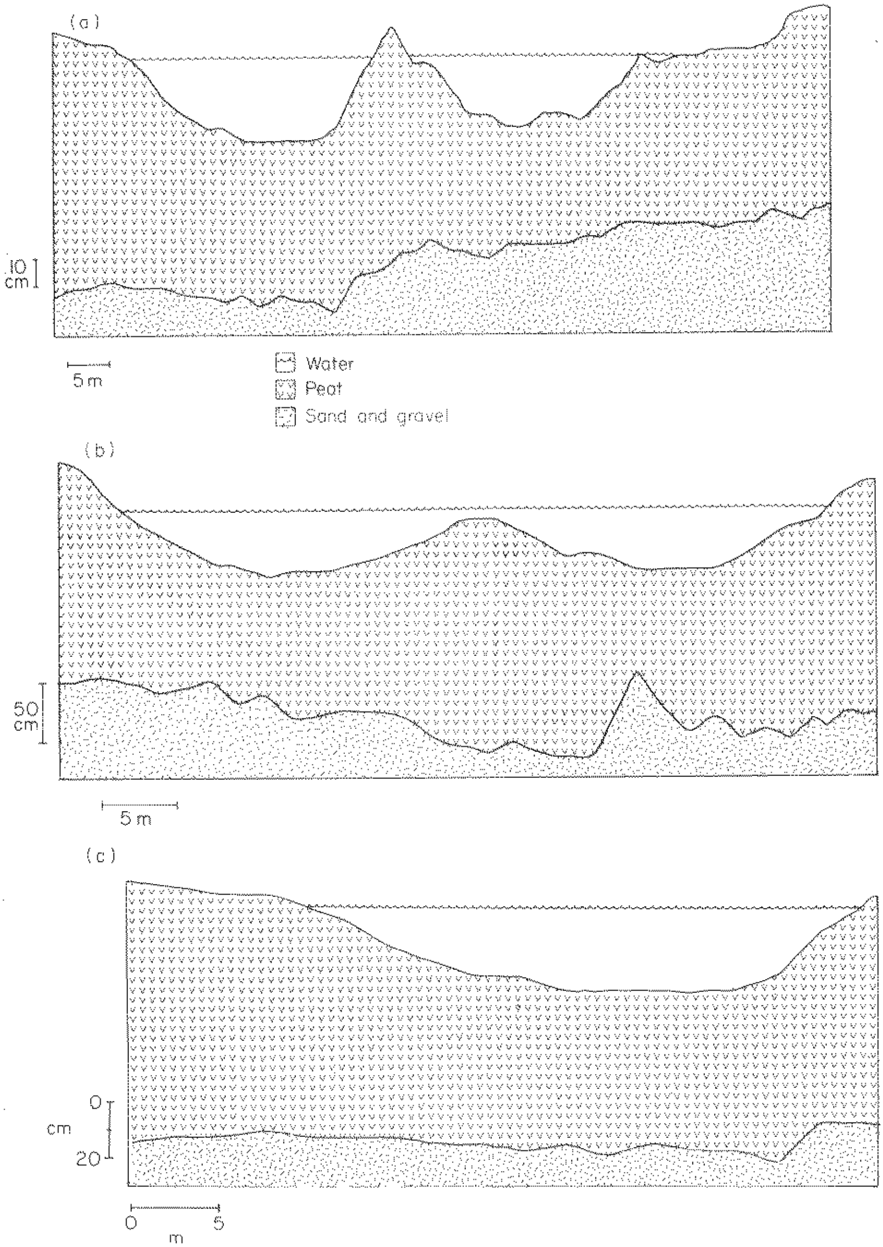

FIG. 11. Stratigraphy of pools on Gilbert bog showing (a) two adjacent pools, (b) recently coalesced pools with the submerged intervening ridge, and (c) one large pool.

Comparison of the substratum topography and pool heights from the bog margin to its crest displays the extent to which pools have been lowered. The upper limit of pools (marked by the height of the highest shoreline) parallels that of the underlying substratum, whereas the present pool heights (i.e. the present water level in the pools) deviate greatly from the highest level (Fig. 12). The greatest difference between highest

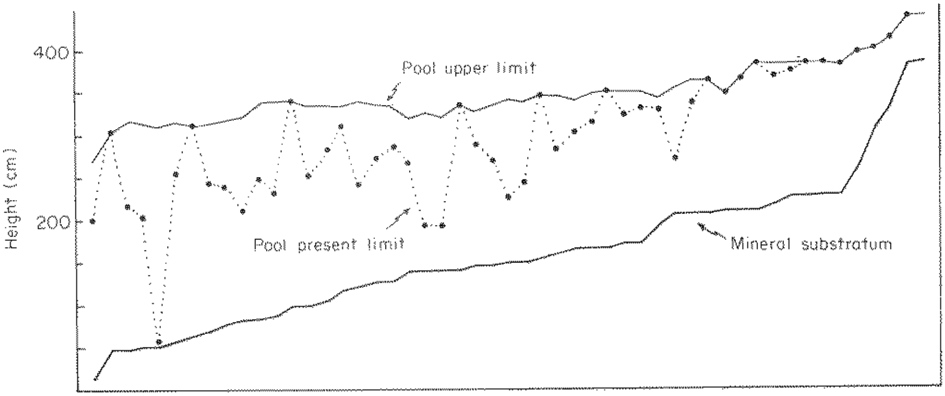

FIG. 12. Relationship between height of the mineral substratum, the present pool height and the former upper limit of pool height. Pools are arranged in their relative location on a transect from Gilbert Lake to the highest part of Gilbert bog. The majority of pools, especially near the lake, have been lowered through stream erosion or coalescence with adjoining pools.

FIG. 13. Oblique aerial view of a large lowered pool on Gilbert bog. An endotelmic stream fringed with black spruce drains to the bog margin towards the top of the photograph. The extent of pool lowering is apparent from the broad sedge and *Sphagnum* mat separating the former ridge and the present pool shore. See Fig. 4 for location.

FIG. 14. Photograph of a completely drained pool on Gilbert bog with *Eriophorum spissum* covering the former pool bottom and a robust ridge in the background covered with black spruce and shrubs. See Fig. 4 for location.

and present pool surface occurs where streams have captured pools and in some locations have eroded down into the mineral substratum (Figs 12, 13). In other cases lowering is a consequence of pool coalescence.

On Gilbert bog, the hollows containing carpet or lawn vegetation apparently result both from the draining of former pools and as a stage in pool formation. However, because of the absence of gyttja in pools the prior history of hollows is often difficult to decipher and necessarily relies on other stratigraphic and morphometric clues. Former pools frequently have a stranded and well-developed shoreline situated above the hollow floor (Fig. 14). In addition, partial drainage will result in a remnant pool in the deepest portion of the basin (Fig. 13). Recent drainage is often indicated by large expanses of exposed mud bottom and carpets of colonizing *Sphagna* lying loosely on this surface (Foster 1984). Of course active streams and obvious breaks in damming ridges are apparent on recently-drained surfaces.

Stratigraphically there may be a sharp separation between the fresh peat laid down since colonization of the exposed pool surface and the well-decomposed and often quite soft material below. In hollows not preceded by pools, the peat stratigraphy does not contain these striking breaks and the peat is generally much firmer and more compact throughout.

DISCUSSION

Mire development

In theoretical considerations of mire development a convenient and sometimes necessary simplification frequently employed is to eliminate topographic constraints from the model and to envisage peatland growth either on a flat plain or within a trough-like valley bounded by parallel ridges (Clymo 1978, 1984; Ingram 1982). Nature seldom

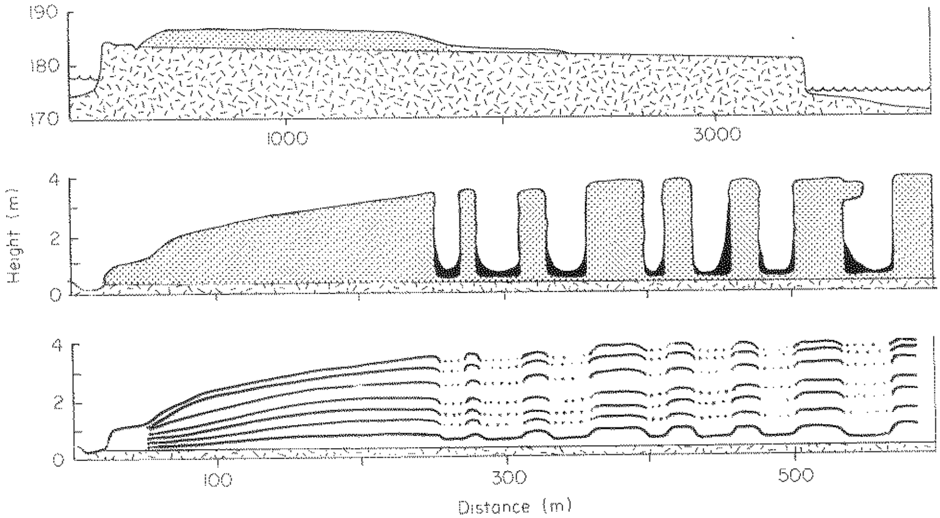

FIG. 15. Profile of Hammarmossen (Granlund 1932) showing (a) position of the bog on the gently sloping plain, (b) the north end of the mire and erroneously deep pools and (c) his (inaccurate) reconstruction of bog development with relative isochrones.

provides such simple situations; the results of many studies emphasize the heterogeneous character of mire formation in physiographic and hydrologically diverse settings (Auer 1928; Malmström 1932; Kulczynski 1949; Elina 1987). Yet it is still worth seeking topographically favourable sites that allow testing of basic assumptions concerning mire initiation, peat accumulation, and hydrological constraints on development. With such criteria in mind, Granlund (1932) selected Hammarmossen for extensive stratigraphic studies, and we followed his example. The mire is on a flat, though gently sloping outwash plain, where peatland formation could occur within a 5-km^2 area unconfined by major physiographic obstacles.

Granlund (1932) presented a model for bog development that was largely based on five pollen and stratigraphic profiles from the northern part of Hammarmossen. No recurrence surfaces could be satisfactorily recognized and correlated in the profiles, so his dating relied on the increase in spruce pollen resulting from the species immigration into central Sweden approximately 3000 years B.P., and on other admittedly subtle changes in the pollen stratigraphy (Granlund 1932, pp. 106–115). From this work he sketched a cross-section of the mire to show proposed isochrones for growth of the mire (Fig. 15). The bog is depicted as beginning simultaneously across its present extent and then growing slowly upwards through differential rates of peat accumulation. Decreasing rates of peat accumulation from the centre to the margin of the mire were envisioned by Granlund as giving rise to an increasingly domed surface. In the same publication he presented extensive data from the national peat inventory of Sweden to show the now well-recognized relationship between the height of raised bogs and annual precipitation. The shape and maximum height of Hammarmossen were interpreted within this context as controlled by available moisture for plant growth, which in turn was determined by precipitation (input) and slope (run-off).

A recent consideration of peat accumulation and bog growth reaches a somewhat different conclusion from that of Granlund concerning the controls and dynamics of bog development (Clymo 1984) Assuming that some limited decomposition occurs throughout the catotelm of the mire (Damman 1979), this model predicts that an equilibrium height (H_m, as dry mass on a unit area basis) is reached at $p_c/d_c = 1$, where p_c is the rate of input of material in the catotelm and d_c is the decay-rate coefficient for the catotelm (Clymo 1984) The ultimate size (height and extent) of the mire is determined by the magnitude of p_c and d_c and hydrological constraints on the lateral spread of the mire and may be modelled as an elipse with application of Child's equation for a parallel, circular or elliptical mound (Ingram 1982, R S Clymo, personal communication)

In the specific model presented by Clymo, peat accumulation starts at a central locus and spreads vertically and horizontally Water draining across the mire along a hemi-elliptical water table (Ingram 1982) and delivered to the margins promotes an increase in mire radius (Auer 1928, Osvald 1949) This feedback system between increasing mire height and length will continue until decay and the rate of material input into the catotelm limit height at H_m Hydrological constraints then restrict further lateral extension Thus, in contrast to Granlund's interpretation this model predicts that raised mires should increase in size, with the ultimate horizontal extent limited by water availability To date no field test of the predictions of the model concerning horizontal expansion have been made, although various lines of evidence suggest that predictions concerning peat accumulation and catotelm decomposition are reasonable (Damman 1979, Clymo 1984)

Stratigraphic evidence provided by sixteen basal radiocarbon dates in transects across Hammarmossen (Fig 1) contradict Granlund's interpretation of the same site (Fig 15) and provide, instead, a case where Clymo's assumptions for lateral extension of raised mires seem to hold Peat accumulation at Hammarmossen began about 5200–5800 years B P within a confined area As the mire grew vertically it expanded at a relatively constant rate until the present Lateral extension occurred most rapidly down the gentle slope to the south, presumably as a result of greater delivery of water draining off the bog crest in this direction Physiographic constraints to mire expansion were few, at present an esker to the south-west has given rise to a rather straight margin (Figs 1, 2) The north-east corner bulges in a tongue down a very gentle topographic low that promotes greater drainage and run-off

An age–depth plot of the radiocarbon dates (Fig 7), and comparison of the isochrones for basal age with the surface topography (Fig 1), indicates that age is closely correlated with the isolines of peat depth In addition these results corroborate observations recently obtained from fens in central Sweden by documenting that mire expansion has occurred continuously throughout the last 5000–6000 years (Figs 1, 7, Foster & Fritz 1987) This conclusion contradicts the long-held conviction in Sweden that expansion of peatlands essentially ceased 2000 years ago as a result of climatic deterioration (Malmstrom 1932, 1955, Sjors 1948, Lundqvist 1951) and may contribute to estimates of Holocene carbon balance in northern peatlands (Armentano & Menges 1986) Although the process of paludification is regulated in part by climate (Vasari 1962, Davis 1984), there is little indication that the rate has changed during the development of Hammarmossen or that the process has not continued to the present (Lukkala 1933, Molder & Salmi 1955) A complete vertical series of radiocarbon dates from several long cores in this transect will be needed to test other aspects of peat accumulation in Clymo's model

The results indicate that Granlund's interpretation of the development of Hammarmossen was incorrect The major intractable problem in his studies was the lack of absolute dating of peat samples The spruce pollen rise, used so effectively in other studies of lateral expansion of mires (Malmstrom 1932, 1955), provided only one datum The pollen stratigraphy during the critical 3000 years following spruce immigration on which dating might be based is relatively featureless (cf Auer 1927) Augmenting these problems was the lack of accurate maps and aerial photographs and the uncertain coring results from the use of the small-diameter Hiller corer

Development and characteristics of bog landforms

As discussed in Boatman's (1983) comprehensive review of research on the Silver Flowe in south-western Scotland, much of the confusion concerning dynamics of surface features on mires results from an inability of researchers to relate the results of their studies to other geographic or floristic systems What is needed beyond commonality of language and terminology is exposure to numerous systems The focus of the present study was to examine similarities in the structure and development of features on Canadian and Swedish mires while highlighting contrasts Similar, informative comparisons can be made, for example, between features on aapamires and raised bogs in a single region Through the analysis of analogous structures fundamental principles can be sought

The present study emphasizes that surface patterns of hummocks and pools are best developed on level surfaces and very gradual slopes (Osvald 1923, Boatman 1972, Ivanov 1981) The decreased expression of the patterns with increasing slope argues strongly against gravitational processes (e g solifluction, slippage, bog bursts) as the prevalent mode of formation as suggested in other reviews (Schenk 1966, Washburn 1979, Madsen 1985) As discussed by Sjors (1961) the inverse relationship of slope and pool development indicates that pool patterns may be the result of biological processes, controlled by hydrology, rather than purely physical mechanisms such as solifluction At Hammarmossen, for example, pools diminish to bare hollows on marginal slopes and are deep as well as broad on the level central plain of the mire Similar but even broader pools develop on the flat mire expanse of Gilbert bog This pronounced development does not result simply from the physical constraints of positioning deep pools on steep slopes and the possibility of drainage with pool expansion downslope (Gorham 1957), because such deep pools do develop on bog slopes elsewhere Rather it appears that for a given mire and hydrological conditions the most pronounced features occur where influx of moisture most greatly exceeds efflux and thereby results in ponding of water (Auer 1928, Ivanov 1981)

Initial stages in pool formation, as seen on Gilbert bog and Hammarmossen, are derived from the gradual flooding and inundation of vegetated hollows On the flat Labrador bogs these hollows are often unorientated low spots surrounded by discontinuous hummocks or slightly elevated lawns On the sloping bogs in Sweden the irregular hummock hollow pattern that occurs on the very youngest, marginal portions of the bog become more regularly aligned across the slope as small hollows enlarge and coalesce (Fig 2) In both situations the hollows appear to accentuate as a result of differential peat accumulation and expansion along the contour At Hammarmossen radiocarbon dates indicate that pools have continuously developed on the mire surface as the mire has expanded outward Any climatic control of pool initiation (cf Aartolahti 1967, Aaby & Jacobson 1979) is not evident

Hollows apparently deepen as a consequence of greater rates of peat accumulation in adjoining ridges Many studies suggest that bryophyte production increases along the hummock-to-hollow gradient (Boatman & Tomlinson 1977, Clymo 1970, Tint 1982

Grigal 1985) but that the accumulation rate of peat may decrease along the same gradient as a result of habitat and species control of rates of decomposition (Clymo 1970, Coulson & Butterfield 1978) As hollows are inundated the vegetation dies from flooding, and the resulting mud bottoms or shallow pools may continue to expand as adjacent areas are flooded Initially the former surface vegetation of the mire breaks up, and a discontinuous pool with islands of tussocks or hummocks develops This process may be aided by warm water temperatures and high oxygen concentrations in the shallow water (Foster & Glaser 1986) that favour decomposition The deepening of pool bottoms by peat degradation is suggested by the hiatus between the peat and overlying gyttja in some pools

In Labrador the pools continue to deepen as peat accumulation proceeds in adjoining areas All allochthonous and autochthonous material delivered to or produced in the pools must be degraded or flushed out as there is no accumulation of sediment even after several millennia Some refractory materials such as wood rest on the pool floor and suggest that pool enlargement and deepening may occur through degradation of the floor and walls The same is true for all other minerotrophic and ombrotrophic mires investigated in Labrador and adjacent Quebec to date (Foster & King 1984, Foster & Glaser 1986), and may also be true for the raised mires in the Hudson Bay Lowlands in Ontario (Sjors 1963, H Sjors, personal communication)

In contrast, on the bogs in Sweden a deposit of algal gyttja and detritus accumulates even where the pools are quite shallow Although disturbance from ice action in winter and flocculation by gases must mix the material at first, the gyttja forms a thick deposit as the pool deepens Pools must deepen eventually because the rate of peat accumulation in the surrounding mire exceeds the rate of gyttja sedimentation in the pools Sediments such as these have been noted on all minerotrophic and ombrotrophic mires examined by the authors in Sweden and Norway and throughout Finland (K Tolonen, personal communication) The limnological factors preventing the deposition of algal sediments on mires in Labrador therefore remains enigmatic

In time the surface features on the mires become more pronounced as pools deepen and hummock ridges become higher and further differentiated Microtopographic differentiation may serve to explain the otherwise anomalous distribution of trees on Swedish bogs and extensive lichen cover on Gilbert bog In general, tree growth is strongly controlled by the position of the water table during the growing season (Cajander 1913, Heikurainen 1980), Soviet research on mires with *Pinus sylvestris* documents that for each 1-cm drop in mean height of the water table there is an increase of 1 m in the height of mature pines (Ivanov 1981) Trees are therefore generally common on mire margins, decreasing in height up the rand and disappearing altogether on the flat central area (Damman & Dowham 1981) In progressively more continental areas the extent of tree cover and height of trees increase On Hammarmossen the tree distribution and vigour parallels the extent of surface development trees exceeding 10 m in height occupy the central bog plain around the larger pools, whereas few trees occupy the unpatterned slopes and flanks Presumably the large trees result from the relatively great height of the larger hummocks above the water table Where pools are less developed the hummocks are less raised, and tree growth suffers In addition the natural drainage of some pools lowers the water table in the local vicinity and favours tree growth The absence of wood at depth in the peat also suggests that the development of large trees has been relatively recent, as a result of continuing differentiation of the mire surface An alternative explanation that trees are abundant around central pools primarily as a result of the effectiveness of the pools as fire breaks, although tenable for Newfoundland (Damman 1977), where upland fires occur frequently, is not appropriate in the less fire-prone area of central Sweden.

On Gilbert bog, trees are lacking, but the hummock tops are covered by lichens. Lichens are favoured over *Sphagnum* species under extreme environmental conditions, such as exposure to desiccating and abrasive winds in winter (Osvald 1923). As the hummocks develop the microtopography is accentuated, resulting in snow accumulation in hollows and exposure of the elevated hummocks (Eurola 1975, Seppala & Koutaniemi 1985). Wenner (1947) explained the widespread abundance of lichens on bogs as a result of surface drying from a temperature increase and humidity decrease following the Little Ice Age. However, there is no palaeoclimatological evidence to support that view.

Pool dynamics and mire stability

The raised bogs in both areas are located in regions with excess of moisture (precipitation vs evapotranspiration), which ultimately leads to instability of the system, as water-dominated landforms increase on the mires. As the mires expand, new hollows and pools develop on the peat surface. Progressively the individual pools expand and deepen, increasing the extent of water on the mire surface. Pool expansion occurs largely through lateral extension via flooding ('autappning = drainage through the damming string', cf. Lundqvist 1951), as well as through coalescence of adjoining pools (Boatman 1983). Coalescence is one means of establishing a common water table across broad areas, the other is through subsurface pipes that connect pools and may ultimately undermine the peat to create a surface connection (Ingram 1983). Both subsurface and surface connections may cause partial or complete drainage of pools as the upper pool assumes the level of the lower one. This inter-pool connection provides part of the explanation for the extensive number of lowered pools on Hammarmossen and Gilbert bog. The other process that lowers pools is the headward erosion and cutting of secondary (endotelmic *sensu* Ivanov 1981) streams from the margin into the centre of the mire expanse. Endotelmic streams develop when the surplus moisture draining from the bog surface becomes focused and gradually cuts erosional channels in the upper peat. Although these streams apparently develop on the Labrador mires through run-off from large pools there is evidence that similar features may start in subsurface pipes that cause the collapse of the upper peats (Smith 1918, Ratcliffe 1964). As the streams continue to cut headward they connect and lower pools, frequently to the extent of complete drainage. In extreme cases the streams cut down to mineral soil.

The continued development of endotelmic streams on the mires appears to induce irreversible, though entirely natural, change in mire development and hydrology (cf. Tallis 1985). Unlike pools, which can be stabilized at a new, though lower water level, streams once formed apparently continue to expand, extend, and deepen. As they cut into the peat they not only lower pools but they also lower the water table within the adjacent peats, gradually divide the mire into separate lobes or mire systems, and in extreme cases cause considerable erosion. Thus, the potential for substantial carbon loss arises as both enhanced decomposition and erosion may remove peat. This process is apparently a unidirectional consequence of change in mire size and hydrology and additional manifestation of the increasing role of water-dominated landforms with mire development under ample moisture surplus. Mires in moist boreal regions are inherently unstable, and dissection is the natural end-point (Ivanov 1981, Korchunov, Kusmin & Ivanov 1980).

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