Polarforschung 49 (1): 70—79, 1979

Interaction of Bryophytes and Thermal Cracking in the Genesis of Hummock and String-like Microtopography in High Arctic Tundra Meadows

By Paul Barrett *

Summary: Observations of hummock and string-like microrelief features were made in High Arctic hydric meadows. Thermal shearing of thick bryophyte mats, and subsequent roll back during spring flooding, appears to be one way in which this topography is formed. Hummocky and non-hummocky (flat) meadows show distinct floristic differences which may in part be due to observed differences in temperature, nutrient concentrations and moisture relations.

Zusammenfassung: Spezielle Erscheinungsformen der Oberfläche hocharktischer Flachmoore und Sumpfwiesen — kleine Bülten (hummocks) und wulstartige Erhebungen (string bogs, Strangmoore) — wurden untersucht. Bei der Entstehung dieser Geländeformen scheinen durch Temperaturschwankungen verursachte Risse in der Moosdecke sowie deren anschließendes Aufrollen während des Frühjahrshochwassers eine Rolle zu spielen. Flache Wiesen (Flachmoore) und solche mit Bülten weisen deutlich anders geartete floristische Zusammensetzungen auf, die zumindest zum Teil auf beobachtete Unterschiede in Temperatur, Nährstoffkonzentration und Feuchtigkeitsgegebenheiten zurückzuführen sind.

INTRODUCTION

Topographic gradients are known to produce substantial diversity of vegetation in arctic and alpine tundras. So common are these topographically induced gradients that they have recently been generalized under the term "mesotopographic gradients" (BILLINGS, 1973). Gradients may range in scale from tens of meters, as the raised beach to meadow gradients of many arctic coastal areas (TEERI, 1972) to thousands of meters in upland to valley systems (BILLINGS, 1973). Smaller microtopographic gradients have also been noted to produce similar vegetation responses in arctic and alpine systems (BILLINGS & MOONEY, 1959; JOHNSON & BILLINGS, 1962).

String-bogs are distinctive topographic features of boreal and subarctic regions which have long been known to produce vegetation discontinuity (SCHENK, 1966; SJORS, 1959). BROWN & PÉWÉ (1973) have recently pointed out, however, that their mode of origin and relationship to permafrost in north latitudes are only poorly understood.

During the course of a study of the plant ecology of a coastal lowland on the northeastern portion of Devon Island (BARRETT, 1972; BARRETT & TEERI, 1973) observations of hummock and string-like microrelief features in hydric tundra sedge meadows were recorded. The purpose of this paper is to relate these observations to past research on string-bog features noted at more southern latitudes and to present observational evidence for a hypothesis of the genesis of string-like microtopographic features in these high arctic coastal meadows.

THE NATURE OF STRING-BOGS AND THEIR ORIGIN

True string-bogs appear to be best developed near the southern limit of permafrost (BROWN & PÉWÉ, 1973), although well defined bogs have also been reported from

---

* Dr. Paul Barrett, Department of Botany, University of Maryland, College Park 20742 (USA).

Minnesota (HEINSELMAN, 1963) and near the boundary of widespread permafrost in Schefferville, Québec (THOM, 1972). Descriptions of string-bogs are variable. All however are characterized by sinuous surface ridges (Stränge) alternating with long water filled swales (flarks) (BROWN & PÉWÉ, 1973). HEINSELMAN (1963) distinguishes true string-bogs from patterned fens. In the former, ridges cover up to half the ground surface and are vegetated primarily by bog species including trees (Tamarack, Black Spruce). Patterned fens on the other hand have hollows or flarks covering the màjority of the ground surface and ridges are dominated by fen species (grasses and sedges) rather than bog species. The scale of ridge and hollow topography varies and few actual field measurements are available from the literature. BROWN & PÉWÉ (1973) indicate that ridges are 1 to 3 m in width and up to 1 m in height. HEINSELMAN (1963) reports ridges of only 6 to 12 inches (0.15—0.3 m) in typical patterned fens in Minnesota. The latter are frequently discontinuous but occasionally may coalesce to form nets. In all cases, string features are formed on slopes where ridges lie at right angles to surface water movement (HEINSELMAN, 1963).

Two possible methods of string-bog initiation have been proposed in the literature. SCHENK (1966) concluded that the typical ridge and hollow pattern results from frozen turf layers being broken into disconnected sections. These are subsequently tilted to form a rib-like pattern by thawing of underlying permafrost and subsurface drainage of melt water through existing ice lenses. The lack of string-bogs within regions of present continuous permafrost is suggested as correlative evidence for this hypothesis. RAPP & ANNERSTEN (1969) and THOM (1972) have commented on the lack of evidence confirming this hypothesis.

The fluvial transport of detritus has also been suggested as an initial cause of ridge formation (DRURY, 1956; THOM, 1972). MIDDENDORF recognized the importance of lemming harvested detritus accumulations in this respect as early as the late 1800's, and TIKOMIROV's later descriptions of these features emphasize the similarity between these and string-bog microtopography:

> Held up and accumulated in banks, these masses of hay lead to the formation of lengthy peaty mounds measuring from 10—15 m in length, 20—30 cm in width and 20—40 cm in height. This peculiar small mound microrelief characteristic for regions at the foot of gentle slopes of central taimyr, we have singled out calling it small mound microrelief of zoogenous descent (TIKOMIROV, 1959).

DRURY's (1956) studies in the Kuskokwim River Region of Alaska emphasized the role of detrital deposition in the formation of patterned fens. Briefly, organic debris is flushed across the surface of bogs during spring melt. Debris lines remain after the melt and are preferred sites for plant growth since they are relatively better drained. At this point the process becomes self-accelerating since organic residues accumulate more rapidly beneath the incipient hummock. Hummocks grow by lateral extension and as they coalesce, act as dams for the further collection of transported detritus. Frost-push from winter ice in the hollows narrows and elevates the ridges and prevents downslope expansion.

More recently THOM (1972) has studied string-bogs near Schefferville, Quebec, and described several stages in the melt-transportation process. His observations indicate that two sorts of debris accumulation processes operate simultaneously. Tide-like lines of accumulation develop at the margins of open pools and damming occurs behind obstacles protruding above the frozen surface of the bog. In each case, deposition occurs at right angles to water movement and deposits tend to be sinuous in form. Ice-push appeared important only after pronounced ridges were formed.

TUNDRA MEADOWS ON DEVON ISLAND

Extensive tundra sedge meadows cover coastal strandflats on the northeast coast of Devon Island (75° N, 86° W) (BARRETT, 1972; BARRETT & TEERI, 1973; MUC, 1972).

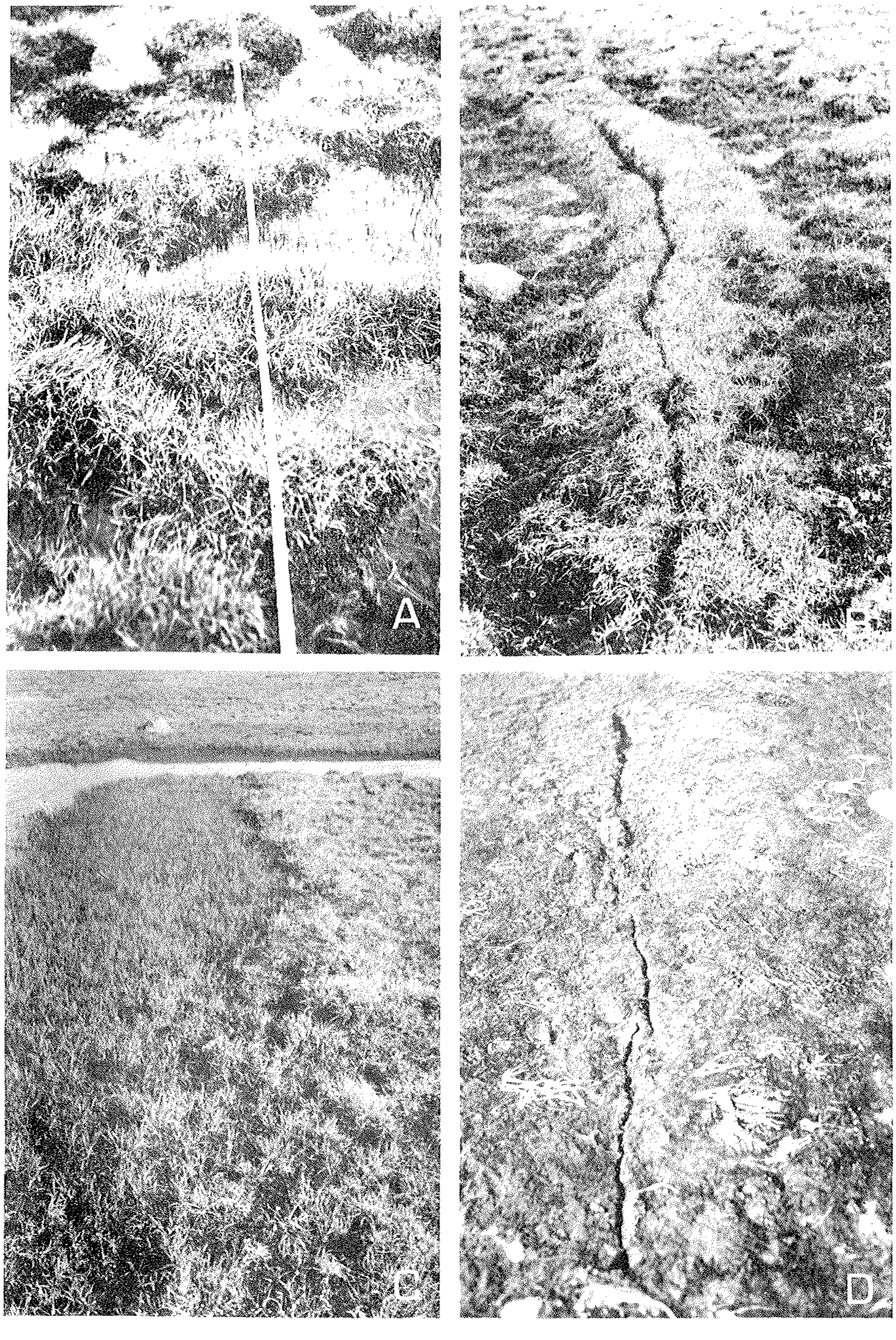
Fig. 1: Current raised beach formation along shoreline of northern Devon Island. Note sea ice (left) against the currently forming beach ridge. Behind lies lagoon (foreground, right) with breached outlet to the ocean in the foreground. Raised beach, slope and hydric meadow communities will eventually be established along the resulting topographic gradient.

Abb. 1: Gegenwärtig bestehende gehobene Strandformation entlang der Küste im nördlichen Devon Island. Meereis (links) drückt gegen den sich bildenden Kieskamm; hinter dem Strand liegt eine Lagune (Vordergrund rechts) mit enger Mündung ins Meer. Der gehobene Strand und die für seine Hänge und Sumpfwiesen charakteristischen Pflanzengesellschaften werden hier schließlich eine neue Geländeoberfläche bilden.

Initially these areas were tidal lagoons, enclosed behind emerging beaches during isostatic uplift (Fig. 1). The emergent beach ridges, foreslopes and meadow systems now form a repeating series of mesotopographic gradients across the present lowland surface. During the course of synecological studies in this area (BARRETT, 1972) it became apparent that floristic differences occurred between meadows with pronounced hummock topo-

Fig. 2: A. Hummock and depression topography in *Carex stans* dominated meadow.
B. String-like hummock with thermal crack which has sheared through the entire vegetation mat to mineral soil beneath.
C. Distinct boundary between flat meadow (a) at the margin of a pond and the start of a hummocky terrain (b) forming further from the open water.
D. Thermal crack shearing through an almost pure bryophyte mat. The mat in this picture lies beneath 10 to 30 cm of water.

Abb. 2: A: Wiese mit Bülten und Vertiefungen. Vegetation: überwiegend *Carex stans*.
B: Wulst- oder strangartige Erderhebungen mit gerissener Pflanzendecke. Der Riß wurde durch Temperaturschwankungen verursacht und reicht bis auf den Mineralboden.
C: Deutlich erkennbarer Übergang zwischen flacher Wiese (a) am Ufer eines Teiches und Wiese mit kleinen Erhebungen (b), die sich etwas weiter vom Wasser entfernt gebildet haben.
D: Durch Temperaturschwankungen verursachter Riß in einer fast reinen Bryophytendecke, die im Foto 10—30 cm unter Wasser liegt.


A
B
C
D

graphy and those without. While both sites had a number of species in common, meadows with hummocks included in their floristic composition additional species found also in more mesic environments. In nearly all cases these species were localized primarily on the hummocks. Conversely, a small number of species found principally in environments with standing or running water, were preferentially located in meadows lacking hummocks (Tab. 1).

In some meadows, sinuous ridges or groups of coalesced hummocks were observed (Fig. 2 A, B). Visually these features appear similar to string-bogs pictured by THOM (1972) from Québec and strikingly like string-bogs noted on meadows over Kellet soils from Banks Island in the western arctic (TEDROW & DOUGLAS, 1964).

Where small ponds have not yet completely become closed meadows, sharp ecotones may mark the boundary between level meadows at the margin of the open water and incipient hummock formation further outward (Fig. 2, C).

Species	No Hummocks (5 quadrats)		Prominent Hummocks (7 quadrats)	
	Constancy class	Avg. species significance	Constancy class	Avg. species significance
Saxifraga cernua	V	1.5	I	—
Cardamine pratensis	III	0.6	—	—
Hippuris vulgaris	III	0.6	—	—
Ranunculus hyperboreus	III	0.3	—	—
Calliergon giganteum	V	6.8	III	1.0
Carex membranacea	II	0.2	V	4.1
Equisetum variegatum	—	—	V	2.3
Carex misandra	—	—	V	1.8
Draba lactea	—	—	IV	0.9
Pedicularis hirsuta	—	—	IV	0.6
Melandrium apetalum	—	—	IV	0.6
Dryas integrifolia	—	—	III	1.3
Saxifraga foliolosa	—	—	III	0.5
Saxifraga oppositifolia	—	—	III	0.3
Stellaria longipes	—	—	III	0.2
Orthothecium chryseum	III	0.7	V	5.1
Catoscopium nigritum	—	—	V	3.5
Tomenthypnum nitans	—	—	V	2.7
Pogonatum alpinum	—	—	V	2.0
Aulacomnium turgidum	—	—	IV	1.3

Tab. 1: Constancy classes and mean species significance values for species found preferentially in hummock or non-hummock tundra meadows. Species with a constancy class below III are omitted even though found in only one area. Braun-Blanquet constancy classes and Domin-Krajina species significance scale from 10 x 10 m quadrats.

Tab. 1: Konstanzklassen und durchschnittliche Signifikanzwerte für Arten, die bevorzugt in Tundrawiesen mit und ohne Bülten auftreten. Konstanzklassengrößen unter III bleiben unberücksichtigt, auch wenn die Arten in nur einem Gebiet auftreten. Konstanzklassen nach Braun-Blanquet und Signifikanzwerte nach Domin-Krajina auf der Grundlage von 10 x 10-m-Quadraten.

ORIGIN OF HUMMOCK AND STRING-LIKE MICROTOPOGRAPHY

During initial lagoon entrapment, surface drainage occurs through gaps in the emergent beach ridges (Fig. 1). These gaps are formed initially by tidal entrances to the lagoons (MÜLLER & BARR, 1966). This drainage pattern remains evident in certain instances, even though marsh vegetation is well established behind the present beach crests. During early spring thaw, melt water flows parallel to the empounding beach and then through the tide gap to the next marsh further down slope.

In the majority of these meadow systems the overlying sedge canopy is underlain completely by a thick mat of hydrophytic bryophytes. The principle genera composing this highly productive component are *Drepanocladus, Meesia, Cinclidium. Mnium* and *Callier-*

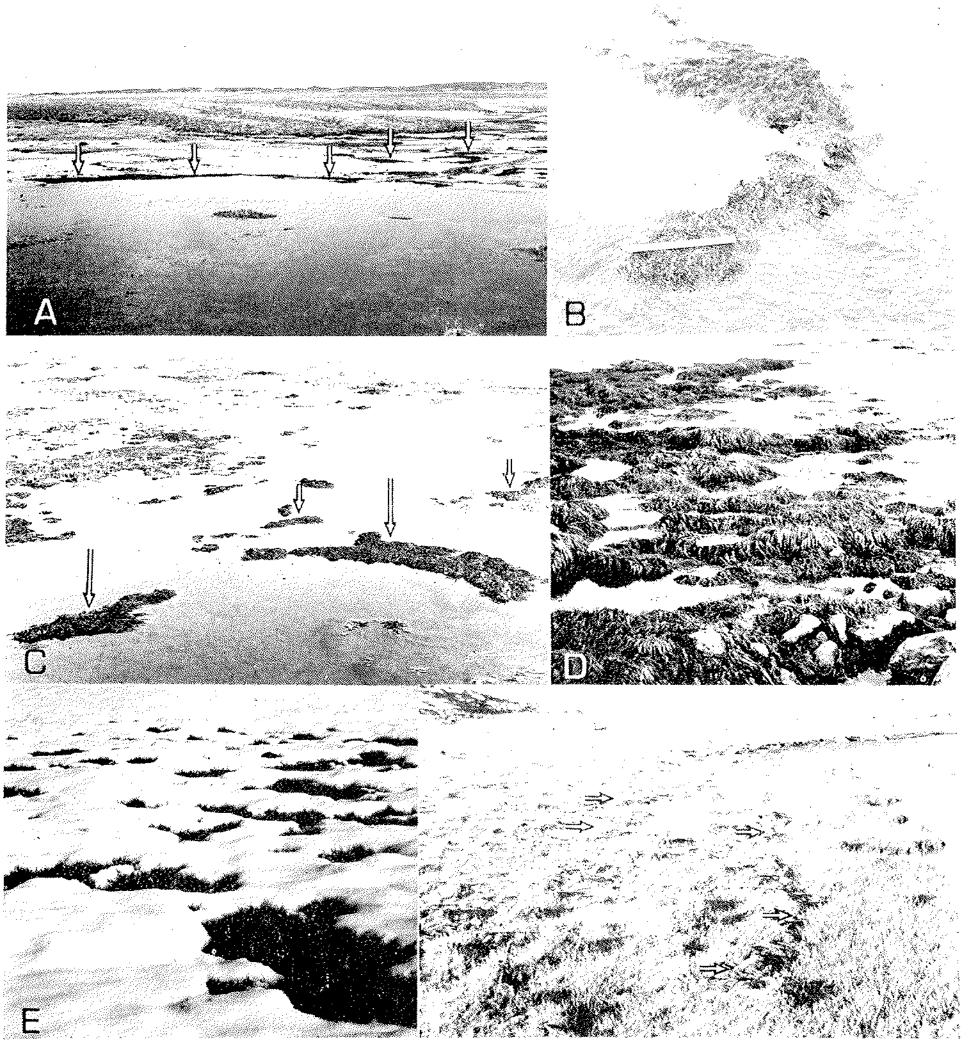


Fig. 3: A.—C. Arrows mark the rolled-up mats of nearly pure bryophyte material now above the spring melt water. Scale in 3A is 30 cm in length.
D. Collecting bryophytes, vegetation and detritus at the stream outlet of a pond behind a raised beach.
E. Differential spring snow melt between hummock (exposed) and depressions (snowfilled).
F. Bryophyte detritus (arrows) which has been washed beyond the current pond margin by spring flooding.

Abb. 3: A—C: Aufgerollte fast reine Bryophytenschicht (Pfeile) ragt über das Frühjahrsschmelzwasser hinaus. Maßstab in 3A: 30 cm.
D: Angeschwemmte Moose, andere Pflanzen und sonstiges Getreibsel am Ausfluß eines Teiches, der hinter einem gehobenen Strand liegt.
E: Unterschiedliche Schneeschmelze zwischen Bülten (schneefrei) und Mulden (schneebedeckt).
F: Moosgetreibsel (Pfeile), das vom Frühjahrshochwasser über das gegenwärtige Teichufer hinausgespült wurde.

gon (BARRETT, 1972; PERKARINEN & VITT, 1974). The thickness of this layer is variable but in certain locations over twenty inches (50.8 cm) of undecomposed bryophyte material have been measured.

Thermal contraction cracks are a common feature of tundra surfaces being the initial stage of tundra polygon development. Recent studies by KERFOOT (1972) and MACKAY

(1974) have demonstrated that cracks may extend beneath shallow lakes or shear through vegetation to the underlying mineral soil. We have noted a number of these occurring in the sedge meadows on Devon Island. Cracks may occur along strings, shearing through the sedge and bryophyte mat to the underlying mineral soil (Fig. 2, B). In younger marshes thermal cracking through the completely submerged bryophyte mat is also apparent (Fig. 2, C). The hydric nature of these sites and the fact that shearing occurs through the vegetation suggest that these cracks are generated by frost action rather than dessication (KERFOOT, 1972).

The sharp discontinuity between the upper moss layer and underlying mineral sediments allow for easy fragmenting of the moss mat by rapidly flowing spring melt water. We have noted numerous instances both in small empounded ponds and outflow channels, of moss "stringers" apparently washed free from the mat (Fig. 3, A—C). In other instances the sheared portion remains attached to the mat but is rolled back by the flow of melt water, leaving a long sinuous moss ridge above the remaining mat and water level (Fig 3, C). Profiles across two such moss ridges show that adjacent to these elevated ridges hollows occur in the moss layer, apparently left by the rolling back of the vegetation (Fig. 4). Once established these ridges may become collection points for further flushed detritus of moss or vascular plants. We have observed striking examples of this particularly at the head of outflow streams from young marshes (Fig. 3, D). Presumably these elevated microridges are then sufficiently environmentally differentiated from the adjacent hollows to initiate with time the floristic changes noted earlier.

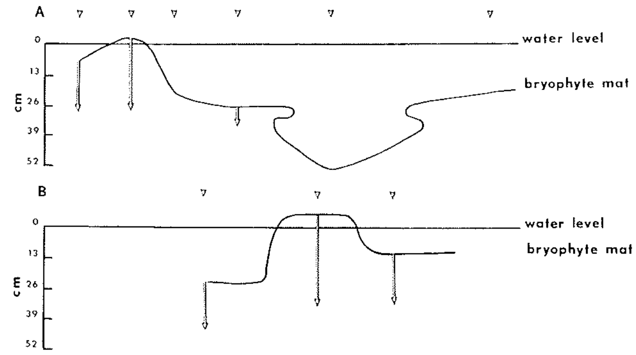


Fig. 4: Horizontal profiles from two raised bryophyte ridges in small ponds exposed to spring flooding. Long arrows indicate the permafrost table. Small arrows above indicate points of measurement along transects. In both instances depressions exist below the general level of the vegetation mat beside each ridge.

Abb. 4: Querschnitte durch zwei über das Wasser hinausragende Mooswülste in kleinen Teichen, die jeweils im Frühjahr vom Schmelzwasser überschwemmt werden. Die langen Pfeile zeigen die Tiefenlage des Dauerfrostbodens unter dem Wasser, die kleinen Pfeile die Meßpunkte entlang der Querschnitte an. In beiden Fällen bestehen neben den Mooswülsten Vertiefungen, die unter dem normalen Niveau der Pflanzendecke liegen.

Not only is better drainage evident (Fig. 2, A) but thermal and chemical differentiation of the two microsites occurs. Temperatures taken from ridge and hollow positions over a single day (Fig. 5) indicate pronounced warming of the elevated ridge soils. This feature is made more significant by the earlier exposure of the ridge sites during spring snow melt (Fig. 3, E). Chemical analyses of the upper soil horizon (H horizon) from a single ridge and adjacent hollow also highlight the separation of these microsites. While field inspection of color and morphology showed these horizons to be similar, chemical analysis shows the ridge soil to be nutritionally enhanced. Of particular significance from a botanical view is the doubling of both total nitrogen and exchangeable cations in the ridge position (Table 2).

Feature Measured	Ridge	Hollow
Color — moist	5YR2/1	5YR2/1
pH — (water)	7.2	6.1
Carbon %	31.1	14.3
Nitrogen % Total	5.50	2.80
Phosphorus p. p. m.	23	24
Potassium Me/100 gm	.31	.06
Calcium Me/100 gm	36.2	18.2
Magnesium Me/100 gm	19.8	9.7
Sodium Me/100 gm	.46	.34
Sum: exchangeable cations	56.8	28.3

Tab. 2: Chemical analysis of surface soils (0—22.8 cm) from adjacent ridge and hollow positions in a tundra meadow location, Devon Island.

Tab. 2: Chemische Analyse oberflächennaher Böden (0—22.8 cm) aus benachbarten Kamm- und Muldenlagen an einem Tundrawiesenstandort, Devon Island.

Although less frequent, we have also observed tide-like lines of bryophyte detritus deposited at the margins of open ponds (Fig. 3, F). These elongate lines of dry material showed pond bottom sediment intermixed with the stems of the bryophytes and a live layer of *Carex stans* beneath. Apparently deposited by high spring melt water, these bryophytes become stranded as water levels receded. Lying above the established meadow vegetation, they dry rapidly producing the observed detrital strings.

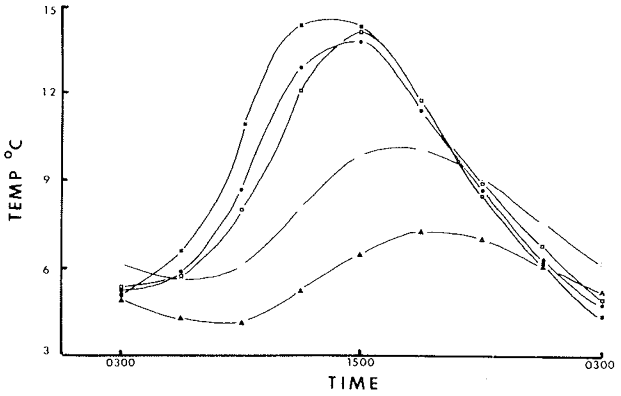


Fig. 5: Surface and subsurface temperatures in small hummock (20 cm high) and adjacent depression in a typical *Carex stans* meadow. Hummock positioned in a north-south direction.
■ Surface air temperature
● hummock temperature at —23 cm, west side
□ hummock temperature at —23 cm east side
▲ depression temperature at —23 cm, east side
○ depression temperature at —23 cm, west side

Abb. 5: Oberflächen- und Bodentemperaturen an und in einer kleinen Bülte (20 cm hoch) und einer benachbarten Mulde in einer typischen, mit *Carex stans* bewachsenen Wiese. Bülte in N-S-Richtung.
■ Lufttemperatur
● Temperatur der Bülte in einer Tiefe von 23 cm, Westseite
□ Temperatur der Bülte in einer Tiefe von 23 cm, Ostseite
▲ Temperatur 23 cm unter dem Muldenboden, Ostseite
○ Temperatur 23 cm unter dem Muldenboden, Westseite

DISCUSSION

The continuous and deep permafrost (400—600 m; BROWN, 1973) at this latitude precludes permafrost thawing as an initiator of the string-bog features found in these meadow systems. Our observations tend to support, however, the general features of fluvial-detritus origins proposed by DRURY (1956) and THOM (1972). Formation of thermal cracks shearing through a living bryophyte mat and subsequent stranding of this material appear to be one way in which microrelief is generated on certain tundra meadow surfaces. These areas in turn become collection points for detrital material flushed over the lowland surface during spring thaw. Thermal cracking and hummock formation occur commonly throughout the geographic range of string bog occurrence. WASHBURN and his colleagues (1963) noted active frost cracking and hummock microtopography from the mid-latitude climates of New Hampshire. How widespread this feature is in forming string bog topography remains to be documented. Clearly it was fortunate to observe a sequence of meadows in various stages of development. In older meadows this initiating process is obscured in the already well established vegetation. In newly forming meadows vegetation is not yet well enough established to permit this process to occur.

It is reasonable to assume that arctic microenvironments which are snow free at an earlier date in spring, warmer, and better drained would account for certain of the floristic and vegetational differences noted earlier between hummocky and non-hummock meadows. The causal nature of the observed nutrient differences remains to be documented. In this regard the complexity of interaction between temperature, water and nutrients has only recently received experimental attention in arctic plant biology. Clearly these areas of well expressed vegetation pattern warrant further study in the field.

Literature

Barrett, P. (1972): Phytogeocoenoses of a coastal lowland ecosystem, Devon Island, N. W. T. — Ph. D. Thesis, University of British Columbia, Vancouver, B. C.

Barrett, P. & J. A. Teeri (1973): Vascular plants of the Truelove Inlet region, Devon Island. — Arctic 26: 58—67.

Billings, D. W. (1973): Arctic and alpine vegetations: similarities, differences, and susceptibility to disturbance. — Bioscience 23: 697—704.

Billings, D. W. & H. Mooney (1959): An apparent frost hummock-sorted polygen cycle in the alpine tundra of Wyoming. — Ecol. 40: 16—20.

Brown, R. J. E. (1973): Influence of climatic and terrain factors on ground temperatures at three locations in the permafrost region of Canada. — Permafrost Second International Conference, Nat. Acad. Sci., Washington, D. C.

Brown, R. J. E. & T. L. Péwé (1973): Distribution of permafrost in North America and its relationship to the environment: a review, 1963—1973. — Permafrost Second International Conference, Nat. Acad. Sci., Washington, D. C.

Drury, W. H. (1956): Bog flats and physiographic processes in the upper Kuskokwim River Region of Alaska. — Contrib. of the Gray Herbarium, Harvard Univ. 178.

Heinselman, M. L. (1963): Forest sites, bog processes, and peatland types in the Glacial Lake Agassiz Region, Minnesota. — Ecol. Mono. 33: 327—374.

Kerfoot, D. E. (1972): Thermal contraction cracks in an arctic tundra environment. — Arctic 25: 142—150.

Mackay, J. R. (1974): Ice-wedge cracks, Garry Island, Northwest Territories. — Can. J. Earth Sci. 11: 1366—1383.

Muc, M. (1972): Vascular plant production in the sedge meadows of the Truelove Lowland. — In: L. C. Bliss, ed., Devon Island I. B. P. Project, High Arctic Ecosystem, 113—145, Dept. of Botany, Univ. Alberta, Edmonton.

Müller, F. & W. Barr (1966): Postglacial isostatic movement in Northeastern Devon Island. Canadian Arctic Archipelago. — Arctic 19: 263—269.

Parkarinen, P. & D. H. Vitt (1974): The major organic components and caloric contents of high arctic bryophytes. — Can. J. Bot. 52: 1151—1161.

Rapp, A. & L. Annersten (1969): Permafrost and tundra polygons in northern Sweden. — In: T. L. Péwé, ed., The Periglacial Environment, Montreal.

Schenk, E. (1966): Origin of string bogs. — Permafrost: Proceedings of an international conference. Nat. Acad. Sci., Washington, D. C.

Sjors, H. (1959): Bogs and fens in the Hudson's Bay lowlands. — Arctic 12: 2—19.

Tedrow, J. C. F. & L. A. Douglas (1964): Soil investigations on Banks Island. — Soil Sci. 98: 53—65.

Teeri, J. A. (1972): Polar desert adaptations of a High Arctic plant species. — Sci. 179: 496—497.

Thom, B. G. (1972): The role of spring thaw in string bog genesis. — Arctic 25: 237—239.

Tikomirov, B. A. (1959): Relationship of the animal world and the plant cover of the tundra. Transl. E. Issakoff & T. W. Barry. Ed. W. A. Fuller.

Washburn, A. L., Smith, D. D. & R. H. Goddard (1963): Frost cracking in a middle-latitude climate. — Biuletyn Peryglacjalny 12: 175—189.