ELSEVIER

Catena 36 (1999) 233–254

CATENA

The importance of topographic factors on the distribution of bog and heath in a Newfoundland blanket bog complex

Phil A. Graniero [a,1], Jonathan S. Price [b,*]

[a] *Department of Geography, University of Toronto at Mississauga, 3359 Mississauga Road N, Mississauga, Ontario, Canada, L5L 1C6*

[b] *Department of Geography, University of Waterloo, Waterloo, Ontario, Canada, N2L 3G1*

Received 17 June 1998; received in revised form 8 January 1999; accepted 8 January 1999

Abstract

It is commonly assumed that the development of blanket bogs is governed more by climatic factors than by topography, but no quantitative studies have been undertaken. The primary aim of this research was to quantitatively assess the extent and nature of the topographic influence of both the surface and the underlying substrate on the distribution of bog and heath communities within a blanket bog complex. Three blanket bog sites on the southeastern lobe of the Avalon Peninsula, Newfoundland, were studied. Terrain shape characteristics such as slope, plan and profile curvature, and upslope catchment area were derived from digital elevation models (DEMs) of surface and mineral substrate, and analysed using Partition d'un Ensemble Géographique pour l'Analyse Spatiale Ecologique (PEGASE), a procedure based on concepts from information theory. The analysis showed that topography accounted for approximately 22% of the structure underlying the distribution of bog and heath communities within the blanket bog complexes studied. Furthermore, only substrate morphology, which represents the topographic conditions at the initiation of peat accumulation, strongly affected the present pattern of bog and heath at the sites. Although lower elevations were more favourable for bog development, bog communities persisted in upper elevations in areas where the topography assisted in detaining water. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Blanket bog; Peatland; Topography; Heathland

---

[*] Corresponding author. Fax: +1-519-746-0658; E-mail: jsprice@watserv1.uwaterloo.ca

[1] Fax: +1-905-828-5273; E-mail: graniero@eratos.erin.utoronto.ca.

PII: S0341-8162(99)00008-9

1. Introduction

Peatland development has been studied for many decades, and early research suggested that climate, nutrient supply, and topography were important controlling factors (von Post and Granlund, 1926). Peatlands, particularly bogs, require an adequate amount of atmospheric moisture to exist, primarily dictated by the balance of precipitation and evaporation (Romanov, 1968). If there is sufficient water available due to the balance of atmospheric controls, the topography must also conform to limiting conditions to keep this water at the surface so peat may develop. Favourable conditions include, but are not limited to, gentle slopes and convergent curvatures (Lindsay et al., 1988; Heathwaite et al., 1993).

Blanket bogs are extensive peat deposits, which occur fairly uniformly over hill and valley (Zoltai, 1988) and appear on the southeastern portion of the Avalon Peninsula in Newfoundland (Wells, 1981). Blanket bogs have not been documented elsewhere in eastern North America (Davis, 1984), but they appear in other climatically cool and wet areas such as Alaska (Siegel, 1988), coastal Ireland (Barry, 1954), northern Scotland (Lindsay, 1996), some areas of England (Osvald, 1949), and Wales (Moore, 1972).

It is commonly assumed that the development of blanket bogs is governed more by climatic factors such as high precipitation and low evaporation than by topography (Wells and Pollett, 1983; Davis, 1984). In the Avalon Peninsula blanket bog zone, Price (1992a) demonstrated that frequent advection fog deposition provides a significant amount of water input and reduces evapotranspiration losses, thereby favouring high water table conditions within the area. However, there have been no quantitative studies done to assess the relative influence of climate and topography on the observed spatial pattern of peat development within a blanket bog complex at the community scale. Quantitative analyses of the spatial distribution of peatlands have mainly focused on climatic influences at a regional scale, though incorporation of regional relief and model validation at more local scales is under investigation (Kirkby et al., 1995).

A blanket bog complex is dominated by extensive tracts of bog, interspersed with patches of drier heath communities as well as scattered pools, all of which have no obvious pattern (Wells, 1981). For instance, in the 9.4 ha basin studied in the Cripple Cove Creek area (Price, 1991, 1992a,b, 1994), heath represents 10% of the ground cover, ponds cover an additional 11% of the basin area, and bog constitutes the remainder. There, the transition between bog and heath is very sharply defined, clearly visible even on 1:17,000 scale air photos. The transitions occur over distances as short as 1 m. These abrupt changes suggest that some factor or factors controlling the local hydrological regime exert a strong influence on the locations of the communities and the boundaries between them. While meso-scale atmospheric processes are common at the community scale, local conditions, including upslope drainage area, flow convergence or divergence, substrate slope and hydraulic conductivity, control the local water table elevation, thus the requisite condition for peat accumulation. Again, there have been no attempts to identify a pattern at the community scale particularly in terms of topographic shape.

The primary aim of the research presented in this paper was to assess the extent and nature of the topographic influence, of both the surface and the underlying substrate, on the distribution of bog and heath communities within a blanket bog complex. This was accomplished by meeting the following objectives:

1. Identifying the distribution and extent of bog and heath communities within the landscape;
2. Characterizing the topographic relationships using digital elevation models (DEMs) of the landscape and information theory modelling techniques; and
3. Interpreting the influence of topography on the community distribution.

1.1. Hydrological effect of topographic characteristics

At the scale of individual communities, local hydrologic conditions combine to provide the sustained level of saturation required for peat accumulation. Many terrain shape characteristics have a direct effect on the local hydrologic conditions and are easily measured from DEMs. These include: (1) slope, which in blanket bogs closely approximates the water table (Price, 1992b); (2) profile curvatures, where the deceleration of water at the bottom of a concave slope will cause the water table to rise (Hewlett and Hibbert, 1967); (3) plan curvatures, which control the convergence or divergence of flow, and (4) upslope contributing area, which acts as the ‘capture zone’ for flows into a localized area.

1.2. Information theory and the PEGASE procedure

It would be informative to determine which topographically defined hydrological characteristics have the most controlling influence upon the observed distribution of bog in the landscape. Partition d’un Ensemble Géographique pour l’Analyse Spatiale Ecologique (PEGASE) is a procedure derived from the concept of entropy used to explore the organizational structure underlying a complex pattern (Phipps, 1981). It has been used to model the organization of forest landscapes in Mont-Ste-Marie, Quebec (Morin, 1979), and to model landscape-driven redistribution of snow in Saskatchewan (Lapen, 1991), for example.

1.2.1. Entropy and ecological order

The spatial pattern of community types within a landscape can be viewed as a *system*. The particular observed spatial arrangement of community types in the area of study is the *state* of the system. *Entropy* represents the uncertainty attached to the state of the system, or the freedom for the system to take various states (i.e., spatial arrangements). In this case, entropy represents the freedom for the spatial pattern of bog and heath communities to vary within a particular blanket bog complex, i.e., the freedom of the system to have alternate patterns of bog and heath communities given the current arrangement of hydrologic controls imposed by topography and climate.

The PEGASE procedure considers the spatial pattern of m communities in a given region, where the region is divided into F grid cells. The community pattern may be viewed as a system whose *macro-state* is defined by a description of the frequency distribution of community types in the region. The macro-state only describes the community distribution in an aggregated manner; two different systems with the same community frequencies but different spatial arrangements have the same macro-state.

A *micro-state* of the system is any particular spatial arrangement of the F cells distributed among the m community types, so as to satisfy the observed frequency distribution. Without considering any other influencing factor, any one of these micro-states is equally probable; the entropy H, or uncertainty as to which micro-state the system is currently in, is represented by:

$$H = \frac{1}{F}\left[F \ln F - \sum_{j=1}^{m} f_j \ln f_j \right], \tag{1}$$

where f_j is the number of cells of community type j. H is zero if all grid cells in the region are dominated by one single community type, since there is only one possible spatial arrangement of the community pattern in that case.

In the entropy calculation presented in Eq. (1), each possible spatial arrangement of the bog and heath community cells is considered equally likely. However, this is rarely the case in a natural system. Different sites within the region of study vary in characteristics such as nutrient availability, topography, and microclimate. Bog or heath tend to occur under certain types of conditions, and therefore the probability of finding either bog or heath varies from one location to another. Thus we can say that within the landscape there is some ecological ordering. The probability of a particular location bearing a particular community type is not equal for all locations. Therefore, locations may be distinguished and classified into groups with similar probability distributions.

The PEGASE procedure merges the concept of ecological order with that of entropy. If the number of possible spatial patterns is reduced by ecological ordering, then the entropy, or uncertainty as to which state currently exists, must also be reduced. In the context of topographic constraint on the blanket bog system, the presence of an extremely steep slope would preclude the possibility of encountering bog communities at a particular location, thus reducing the number of possible patterns. The purpose of the PEGASE procedure is to seek out and identify sources that reduce entropy (i.e., introduce order) in the community pattern through a statistical analysis of the system.

1.2.2. Information channels and redundancy

In seeking out sources that reduce entropy, the initial set of cells may be split into subsets on the basis of some thematic ecological factor, such as soil type. In the case of an interval-scaled or ratio-scaled factor, such as ground slope, the variable must be rescaled into nominal or ordinal classes, such as the set {*flat*, *gentle slope*, *steep slope*}. If the initial set of cells is split into subsets according to slope class, and the frequency distributions of community types for the subsets are significantly different from the frequency distribution of the initial set (Fig. 1), then slope represents a differentiation of the community pattern, and an ecological organization of space has been revealed. The ecological characteristic, in this case slope, is called an *information channel*, due to its influence on the order in the pattern and the reduction of entropy in the system.

After the initial set of cells has been subdivided by some information channel, a new entropy measure for the system, H_s, can be computed that takes into account the organizing influence of the information channel (Phipps, 1981). The difference between the original entropy H, without the information channel, and the new entropy H_s, with

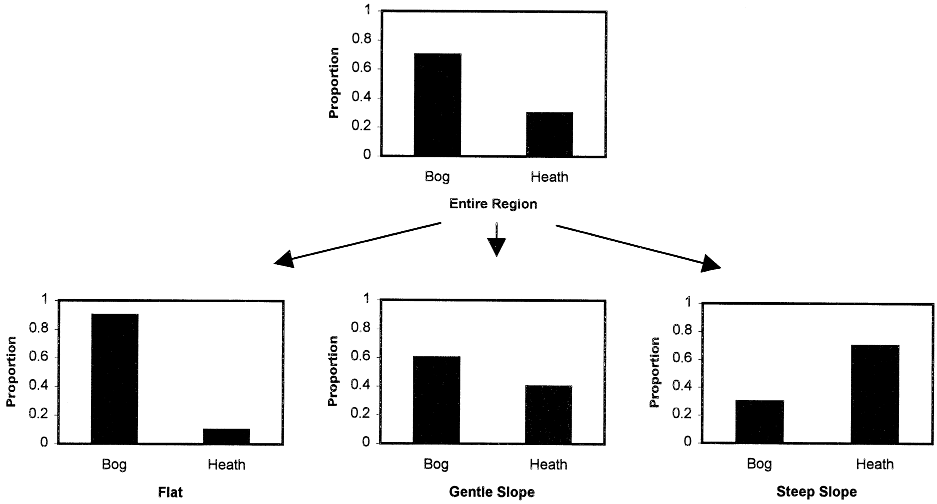

Fig. 1. Frequency distribution for a hypothetical blanket bog region with 70 bog grid cells and 30 heath grid cells, and resultant frequency distributions when the region is subdivided by three slope classes. The emergence of distinct distributions and increased homogeneity in the flat class indicates that slope exerts some control over the community pattern; that is, slope is an information channel.

the information channel, represents the reduction in entropy introduced by the information channel, or *redundancy*, *R*:

$$R = \frac{H - H_s}{H}. \tag{2}$$

A high redundancy value indicates that the ecological factor has a strong controlling influence on the community pattern. The significance of the redundancy value may be evaluated by applying a chi-squared test to the quantity $2F(H - H_s)$. It is also possible to subdivide the original set of cells based on a combination of two or more ecological factors, and compute the total redundancy due to this combined set of information channels.

The end-product of the PEGASE analysis is a number of subsets, which cannot be further subdivided and are related to each other in a tree structure. Each terminal subset represents a group of cells that are homogenous with respect to the ecological characteristics used along the branch of the tree ending at that particular subset, and with respect to the distribution of community types within the subset. The theoretical basis of the procedure suggests that the cells within a particular terminal group are indistinguishable from one another, whereas cells from one group are not comparable to the cells of another group.

2. Study sites

The study focused on three bog sites on the southeastern lobe of the Avalon Peninsula, Newfoundland (Fig. 2): Cripple Cove Creek (CRIPP; 46°39′N, 53°07′W) and

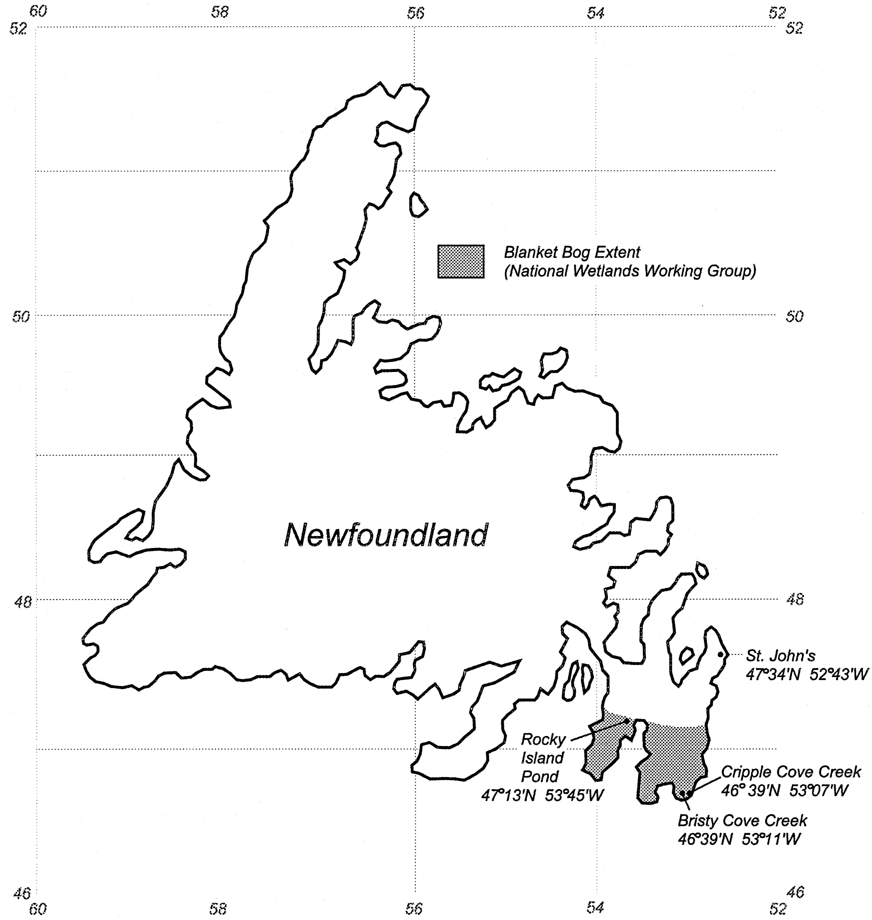

Fig. 2. Newfoundland study sites: Cripple Cove Creek (CRIPP; 46°39′N, 53°07′W), Bristy Cove Creek (BRIST; 46°39′N, 53°11′W), and Rocky Island Pond (ROCKY; 47°13′N, 53°45′W).

Bristy Cove Creek (BRIST; 46°39′N, 53°11′W), near Cape Race; and Rocky Island Pond (ROCKY; 47°13′N, 53°45′W), near Colinet. At all three sites, the blanket bog extended over a considerably larger area than the extent of the surveys.

Cripple Cove Creek was chosen as the primary field site, due to its familiarity (Price, 1991, 1992a,b, 1994; Lapen et al., 1996) and its regionally representative topography. Bristy Cove Creek was chosen due to its proximity and similarity to Cripple Cove Creek, to validate the models. Rocky Island Pond was chosen to test the model's range of applicability, due to its distance from Cripple Cove Creek and visibly different topographic character. In addition, Cripple Cove Creek and Bristy Cove Creek lie in the heart of the blanket bog zone (Wells, 1981), whereas Rocky Island Pond is at the border of the blanket and slope bog zones.

The two Cape Race sites lie approximately 750 m inland from the Atlantic coast, separated by 4.6 km in the E–W direction. The topography at both sites is gently undulating, with small ponds and pools occupying local depressions. The surveyed area covered 65.3 ha at Cripple Cove Creek and 23.9 ha at Bristy Cove Creek. Total relief is 14 and 6.5 m, with an average slope of 0.037 and 0.040, at the Cripple Cove Creek and Bristy Cove Creek sites, respectively. The bog surface is composed primarily of *Sphagnum fuscum*, with patchy cover of *Empetrum* spp., *Rubus* spp., and *Cladonia* spp. (Price, 1991). The heath areas are covered by *Kalmia* spp., with some low *Scirpus* spp. present as well (Price, 1992a). The heath covers 27.5 and 29.3% of the Cripple Cove Creek and Bristy Cove Creek sites, respectively, and open water is 10.3 and 10.1%, respectively.

The Colinet site is a blanket/slope bog complex approximately 75 km northwest of Cape Race. Rocky Island Pond, with an area of 14.9 ha, lies approximately 14 km inland from St. Mary's Bay, a small drowned valley that cuts nearly 50 km into the interior of the Avalon Peninsula. The topography is slightly more variable at the Colinet site than at the Cape Race sites. The relief range is 6.8 m and the average slope is 0.026 throughout the study area, but there are large, steeper hills scattered throughout the area surrounding the study site. Patches of exposed bedrock are occasionally observed throughout the region. The community pattern is more complex than at the Cape Race sites, with more ericaceous vegetation present, and the bog/heath boundaries are less sharply defined. Patches of evergreen shrubs reaching varying heights, typically larger than near Cape Race, appear throughout the area. Stands of *Abies* spp. and *Picea* spp. reach several metres in height along the slopes of the large hills. Heath makes up 30.6% of the study area, comparable to the Cape Race sites, but open water only comprises 0.9% of the site.

3. Methods

3.1. Peat survey

Between August 28 and September 10, 1995, 225, 128 and 598 points were surveyed at the CRIPP, BRIST and ROCKY sites, respectively, to determine peat surface elevation, thickness and geographic position. A 1/2-in.-diameter metal rod was plunged through the peat until it struck the bedrock substrate. The community type (i.e., bog, heath, or transitional) was noted at each point.

The sample points were chosen ad hoc in the field, attempting to locate points that fairly represented the full range of topographic conditions. Sampling of substrate extrema and breaking conditions was less certain due to their hidden nature, but interpretation of the landscape shape was used to judge their locations as closely as possible. Points that were readily identifiable as either bog or heath were preferentially chosen. However, for topographic completeness, some points of transitional land cover were surveyed. On bog sites, the rod was only placed on the surface of larger hollows, avoiding hummocks and crevices between closely neighbouring hummocks.

3.2. Photogrammetric analysis

Standard photogrammetric analyses were performed by Northway Map Technologies in Downsview, Ontario on 1:17,000 air photographs, on which ground control points were marked. Data points were measured on a grid spaced approximately every 2 mm on the air photos, or 34 m on the ground. Pond and stream outlines were traced, and break lines and other topographic features were identified. A total of 5606 points were acquired over 205.6 ha at Cripple Cove Creek, 5771 points over 209.6 ha at Bristy Cove Creek, and 9386 points over 166.7 ha at Rocky Island Pond. The area covered by each photogrammetric analysis was larger than the respective study sites to reduce potential edge effects on terrain analyses done within the study areas.

3.3. GIS pre-processing

All survey and photogrammetric data were imported into ARC/INFO point coverages. The air photos were scanned at 600 dpi, geo-registered to the point coverages, and rectified. An average RMS error of approximately 2.8 pixels, or 2 m on the ground, was achieved. The study area extent and the community boundaries were digitized for each site, using the surveyed points overlaid onto the digital photos as a guide. Once the study site was bounded, DEMs were created for the surface and the substrate at each site using the triangulated irregular network (TIN) structure, as implemented in ARC/INFO's TIN module. Gridded elevation models were created from each TIN model. The elevation was interpolated for the centre of each grid cell using a local quintic polynomial estimation, as implemented in ARC/INFO. The elevations for grid cells lying outside the study boundary or within the ponds were recorded as unknown.

Interpolation at a number of different grid resolutions showed that the distribution of topographic measurements was relatively unaffected by resolution at these sites, so a 10 m resolution was chosen to minimize spatial autocorrelation.

3.4. Topographic variables

Slope (SLP), upslope contributing area (UPA), profile curvature (PFC) and plan curvature (PLC) were calculated for both the ground surface (GSLP, GUPA, GPFC, GPLC) and substrate (SSLP, SUPA, SPFC, SPLC) at each grid cell, using the ground surface and substrate elevations (GELV and SELV), respectively. A 3×3 window, centred at the grid cell of focus, was extracted from the appropriate elevation grid. If any one of the nine elevations was missing, such as at the study boundary or within a pond, all variables were recorded as unknown. Otherwise, a partial quartic surface equation for the elevation Z was fitted to the window:

$$Z = Ax^2y^2 + Bx^2y + Cxy^2 + Dx^2 + Ey^2 + Fxy + Gx + Hy + I. \tag{3}$$

The nine parameters $A, \ldots, I$ were determined from the nine elevations of the window using Lagrange polynomials, as described by Zevenbergen and Thorne (1987).

Specifically, the parameters were derived from the nine grid elevations, as shown in Fig. 3, by:

$$\begin{aligned}
&A = [(Z_1 + Z_3 + Z_7 + Z_9)/4 - (Z_2 + Z_4 + Z_6 + Z_8)/2 + Z_5]/L^4,\\
&B = [(Z_1 + Z_3 - Z_7 - Z_9)/4 - (Z_2 - Z_8)/2]/L^3,\\
&C = [(-Z_1 + Z_3 - Z_7 + Z_9)/4 + (Z_4 - Z_6)/2]/L^3,\\
&D = [(Z_4 + Z_6)/2 - Z_5]/L^2,\\
&E = [(Z_2 + Z_8)/2 - Z_5]/L^2,\\
&F = (-Z_1 + Z_3 + Z_7 - Z_9)/4L^2,\\
&G = (-Z_4 + Z_6)/2L,\\
&H = (Z_2 - Z_8)/2L,\\
&I = Z_5, \qquad (4)
\end{aligned}$$

where the Z_n are the grid elevations and L is the distance between grid points, or grid resolution. Three topographic measurements were then determined from the parameters:

$$\text{SLOPE} = (G^2 + H^2)^{1/2}, \qquad (5)$$

$$\text{PROFILE CURVATURE} = -2(DG^2 + EH^2 + FGH)/(G^2 + H^2), \qquad (6)$$

$$\text{PLAN CURVATURE} = 2(DH^2 + EG^2 - FGH)/(G^2 + H^2). \qquad (7)$$

The upslope contributing areas (GUPA and SUPA) were calculated using a variant of the multiple flow direction algorithm (Quinn et al., 1991). An equal fraction of a cell's upslope contributing area was allocated to each lower neighbour, working from the cells

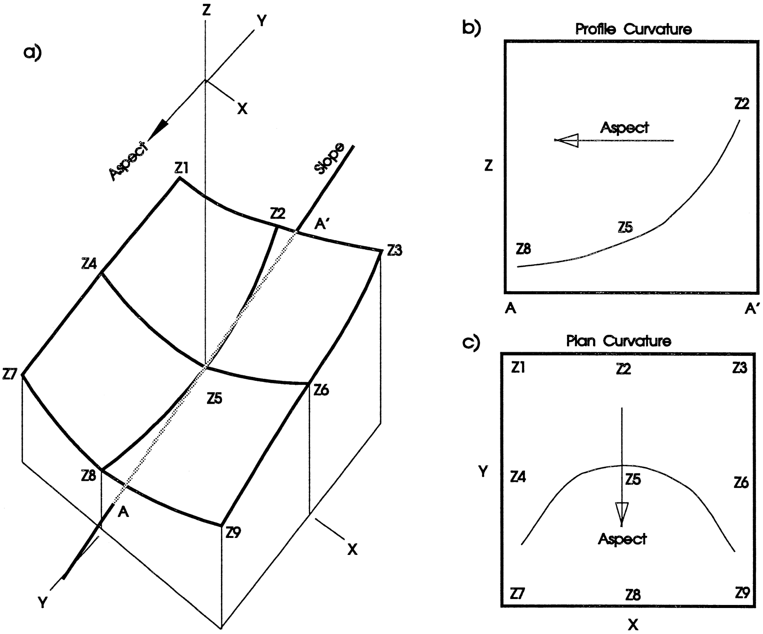

Fig. 3. Derivation of topographic variables from a gridded DEM. Adapted from Zevenbergen and Thorne (1987).

Table 1
Range of values included in each topographic class at each study site

Variable	Class 0	Class 1	Class 2	Class 3	Class 4
CRIPP — Cripple Cove Creek, Cape Race					
GELV (m)	95.20–95.45	95.46–97.80	97.81–99.47	99.48–100.66	100.67–105.92
GSLP	0–0.017	0.018–0.028	0.029–0.040	0.041–0.060	0.061–0.232
GUPA ($100\ \mathrm{m}^2$)	1–2.28	2.29–3.65	3.66–6.07	6.08–12.27	12.28–510.05
GPFC	(-0.023)–(-1.10×10^{-3})	(-1.11×10^{-3})–(-3.99×10^{-5})	(-4.00×10^{-5})–7.34×10^{-4}	7.35×10^{-4}–2.00×10^{-3}	2.01×10^{-3}–0.027
GPLC	(-0.026)–(-1.62×10^{-3})	(-1.63×10^{-3})–(-5.24×10^{-4})	(-5.25×10^{-4})–1.65×10^{-4}	1.66×10^{-4}–1.10×10^{-3}	1.11×10^{-3}–0.026
SELV (m)	87.67–94.39	94.40–96.34	96.35–97.77	97.78–98.46	98.47–103.98
SSLP	0–0.008	0.009–0.017	0.018–0.027	0.028–0.044	0.045–0.257
SUPA ($100\ \mathrm{m}^2$)	1–2.77	2.78–4.44	4.45–7.46	7.47–14.61	14.62–630.48
SPFC	(-0.027)–(-8.38×10^{-4})	(-8.39×10^{-4})–(-1.80×10^{-4})	(-1.81×10^{-4})–1.29×10^{-4}	1.30×10^{-4}–7.24×10^{-4}	7.25×10^{-4}–0.020
SPLC	(-0.028)–(-7.04×10^{-4})	(-7.05×10^{-4})–(-1.37×10^{-4})	(-1.38×10^{-4})–1.05×10^{-4}	1.06×10^{-4}–5.45×10^{-4}	5.46×10^{-4}–0.021
BRIST — Bristy Cove Creek, Cape Race					
GELV (m)	88.90–92.97	92.98–94.52	94.53–95.82	95.83–96.85	96.86–104.84
GSLP	0–0.013	0.014–0.024	0.025–0.038	0.039–0.066	0.067–0.637
GUPA ($100\ \mathrm{m}^2$)	1–2.53	2.54–4.13	4.14–6.80	6.81–12.60	12.61–195.24
GPFC	(-0.046)–(-1.16×10^{-3})	(-1.17×10^{-3})–(-8.19×10^{-5})	(-8.20×10^{-5})–6.86×10^{-4}	6.87×10^{-4}–1.96×10^{-3}	1.97×10^{-3}–0.049
GPLC	(-0.050)–(-1.58×10^{-3})	(-1.59×10^{-3})–(-4.53×10^{-4})	(-4.54×10^{-4})–1.64×10^{-4}	1.65×10^{-4}–1.05×10^{-3}	1.06×10^{-3}–0.041
SELV (m)	88.48–90.85	90.86–91.37	91.38–92.06	92.07–93.01	93.02–99.68
SSLP	0–0.010	0.011–0.018	0.019–0.027	0.028–0.040	0.041–0.228
SUPA ($100\ \mathrm{m}^2$)	1–2.46	2.47–4.09	4.10–6.59	6.60–11.38	11.39–248.81
SPFC	(-0.023)–(-9.39×10^{-4})	(-9.40×10^{-4})–(-3.26×10^{-4})	(-3.27×10^{-4})–4.51×10^{-5}	4.52×10^{-5}–6.31×10^{-4}	6.32×10^{-4}–0.017
SPLC	(-0.009)–(-5.89×10^{-4})	(-5.90×10^{-4})–(-1.15×10^{-4})	(-1.16×10^{-4})–1.59×10^{-4}	1.60×10^{-4}–6.16×10^{-4}	6.17×10^{-4}–0.027
ROCKY — Rocky Island Pond, Colinet					
GELV (m)	78.88–82.27	82.28–83.22	83.23–84.89	84.90–86.97	86.98–93.59
GSLP	0–0.016	0.017–0.026	0.027–0.037	0.038–0.054	0.055–0.189
GUPA ($100\ \mathrm{m}^2$)	1–2.86	2.87–5.54	5.55–9.96	9.97–19.9	20.0–230.7
GPFC	(-0.030)–(-1.65×10^{-3})	(-1.66×10^{-3})–(-4.41×10^{-4})	(-4.42×10^{-4})–2.14×10^{-4}	2.15×10^{-4}–1.41×10^{-3}	1.42×10^{-3}–0.029
GPLC	(-0.029)–(-1.46×10^{-3})	(-1.47×10^{-3})–(-3.59×10^{-4})	(-3.60×10^{-4})–3.05×10^{-4}	3.06×10^{-4}–1.22×10^{-3}	1.23×10^{-3}–0.032
SELV (m)	78.80–81.32	81.33–82.10	82.11–83.39	83.40–85.16	85.17–88.85
SSLP	0–0.025	0.026–0.040	0.041–0.053	0.054–0.073	0.074–0.277
SUPA ($100\ \mathrm{m}^2$)	1–1.66	1.67–2.56	2.57–4.16	4.17–7.98	7.99–131.3
SPFC	(-0.043)–(-4.37×10^{-3})	(-4.38×10^{-3})–(-1.32×10^{-3})	(-1.33×10^{-3})–5.33×10^{-4}	5.34×10^{-4}–3.22×10^{-3}	3.23×10^{-3}–0.041
SPLC	(-0.036)–(-3.16×10^{-3})	(-3.17×10^{-3})–(-8.04×10^{-4})	(-8.05×10^{-4})–1.03×10^{-3}	1.04×10^{-3}–3.66×10^{-3}	3.67×10^{-3}–0.030

In general, classes 0–1 are ‘below average’, class 2 is ‘average’, and classes 3–4 are ‘above average’. Positive PFC indicates convex profile curvature; positive PLC indicates convergent plan curvature.

Table 2
Statistical summary of topographic attributes at each study site

		GELV (m)	GSLP	GUPA ($100\ m^2$)	GPFC	GPLC	SELV (m)	SSLP	SUPA ($100\ m^2$)	SPFC	SPLC
CRIPP	Maximum	105.920	2.32×10^{-1}	510.1	2.70×10^{-2}	2.56×10^{-2}	103.980	2.57×10^{-1}	630.5	1.96×10^{-2}	2.07×10^{-2}
	Mean	97.962	4.13×10^{-2}	9.6	4.46×10^{-4}	-2.10×10^{-4}	96.505	2.92×10^{-2}	12.3	-8.62×10^{-5}	-7.31×10^{-5}
	Minimum	95.204	1.51×10^{-4}	1.0	-2.32×10^{-2}	-2.56×10^{-2}	87.670	8.01×10^{-5}	1.0	-2.69×10^{-2}	-2.76×10^{-2}
	Std. Dev.	3.347	2.87×10^{-2}	17.9	3.23×10^{-3}	2.75×10^{-3}	2.681	2.52×10^{-2}	26.8	2.22×10^{-3}	1.66×10^{-3}
BRIST	Maximum	104.843	6.37×10^{-1}	195.2	4.93×10^{-2}	4.08×10^{-2}	99.675	2.28×10^{-1}	248.8	1.70×10^{-2}	2.67×10^{-2}
	Mean	94.695	5.06×10^{-2}	9.9	3.93×10^{-4}	-2.60×10^{-4}	91.867	2.85×10^{-2}	10.5	-2.24×10^{-4}	1.09×10^{-4}
	Minimum	88.899	5.60×10^{-4}	1.0	-4.62×10^{-2}	-5.05×10^{-2}	88.478	7.06×10^{-4}	1.0	-2.34×10^{-2}	-9.32×10^{-2}
	Std. Dev.	3.407	6.69×10^{-2}	13.7	5.07×10^{-3}	3.91×10^{-3}	1.461	2.36×10^{-2}	18.5	2.24×10^{-3}	1.85×10^{-3}
ROCKY	Maximum	93.594	1.89×10^{-1}	230.7	2.90×10^{-2}	3.18×10^{-2}	88.851	2.77×10^{-1}	131.3	4.06×10^{-2}	3.04×10^{-2}
	Mean	84.478	3.93×10^{-2}	13.4	-9.82×10^{-5}	-1.60×10^{-4}	83.139	5.29×10^{-2}	6.4	-3.62×10^{-4}	4.26×10^{-5}
	Minimum	78.876	6.23×10^{-4}	1.0	-2.96×10^{-2}	-2.86×10^{-2}	78.797	7.00×10^{-4}	1.0	-4.25×10^{-2}	-3.61×10^{-2}
	Std. Dev.	2.794	2.95×10^{-2}	17.5	4.04×10^{-3}	3.56×10^{-3}	2.073	3.36×10^{-2}	9.8	6.36×10^{-3}	5.76×10^{-3}

of highest elevation to those of lowest elevation. Pits and flat areas in the DEM were not removed or adjusted before running the algorithm.

Each grid representing a topographic characteristic was reclassified into five categories numbered 0 through 4 using a histogram equalization procedure (Table 1). Effectively, Class 2 contains 'average' cells, and classes 0 and 4 contain the most extreme low-valued and high-valued cells, respectively.

Fig. 4. Spatial distribution of homogeneous groups identified by the PEGASE analysis at Cripple Cove Creek (CRIPP). See Table 3 for the topographic characteristics of each homogeneous group. Grid cells located immediately adjacent to the ponds and the study site boundary that are shown as heterogeneous were not included in the analysis; topographic characteristics were not computed for these cells due to edge effects.

PEGASE was used to identify the most important topographic variables with respect to the community pattern occurring in the landscape, and to assess the degree to which these variables determine the observed pattern. For each site, all grid cells for which the cover type and all topographic variables were defined were analysed with PEGASE. The sample population for CRIPP was 4795 cells; 1534 cells for BRIST; and 1213 cells for ROCKY.

Table 3
Topographic characteristics of the homogeneous groups identified for the CRIPP study site using the PEGASE procedure, as shown in Fig. 4

Code	Topographic characteristics	Cells	% Bog	H_s
Bog community groups				
A	SUPM 0, SELV 0, GSLP 0–3	64	82.8	0.459
B	SUPM 0, SELV 1, SSLP 0–3	120	80.0	0.500
C	SUPM 0, SELV 3, SSLP 0–3	140	80.0	0.500
D	SUPM 1, SSLP 0–1	274	80.7	0.491
E	SUPM 1, SSLP 2, SPFC 1–2	65	86.2	0.402
F	SUPM 1, SSLP 2, SPFC 3, SPLC 0–2	47	80.9	0.488
G	SUPM 1, SSLP 2, SPFC 4, SELV 1–2	15	80.0	0.500
H	SUPM 1, SSLP 3, GELV 3, GPFC 4	18	83.3	0.451
I	SUPM 1, SSLP 3, GELV 4, GPFC 1–2	36	80.6	0.530
J	SUPM 1, SSLP 4, GSLP 3, SPLC 2–3	6	83.3	0.451
K	SUPM 2, SSLP 0–2	471	86.2	0.401
L	SUPM 2, SSLP 3, SPFC 0–2	129	82.9	0.457
M	SUPM 2, SSLP 3, SPFC 3, GELV 4	11	100.0	0.000
N	SUPM 2, SSLP 3, SPFC 4, GELV 0–2	16	81.2	0.483
O	SUPM 2, SSLP 4, GELV 0, SPFC 0–3	32	84.4	0.433
P	SUPM 2, SSLP 4, GELV 1	75	84.0	0.440
Q	SUPM 2, SSLP 4, GELV 3, GPFC 3–4	20	85.0	0.423
R	SUPM 2, SSLP 4, GELV 4, GSLP 0–1	15	86.7	0.393
S	SUPM 3–4	1917	83.3	0.451

Code	Topographic characteristics	Cell	% Heath	H_s
Heath community groups				
T	SUPM 0, SELV 0, GSLP 4	21	81.0	0.487
U	SUPM 0, SELV 1, SSLP 4	17	88.2	0.362
V	SUPM 0, SELV 2, SSLP 0	12	100.0	0.000
W	SUPM 0, SELV 3, SSLP 4	36	88.9	0.349
X	SUPM 0, SELV 4, SPFC 0	23	87.0	0.387
Y	SUPM 0, SELV 4, SPFC 3, GUPM 4	5	100.0	0.000
Z	SUPM 0, SELV 4, SPFC 4	249	84.3	0.434
2	SUPM 1, SSLP 3, GELV 1, SPFC 0	7	85.7	0.410
3	SUPM 1, SSLP 3, GELV 4, GPFC 0	3	100.0	0.000
4	SUPM 1, SSLP 4, GSLP 3, SPLC 4	5	100.0	0.000
5	SUPM 1, SSLP 4, GSLP 4	101	81.2	0.484
6	SUPM 2, SSLP 3, SPFC 3, GELV 2	11	100.0	0.000
7	SUPM 2, SSLP 3, SPFC 4, GELV 3	14	85.7	0.410
8	SUPM 2, SSLP 4, GELV 4, GSLP 4	8	87.5	0.377

Refer to Table 1 for the range of values associated with each topographic class.

4. Results

This section focuses on the details resulting from the Cripple Cove Creek (CRIPP) analysis. The results from the analyses at Bristy Cove Creek (BRIST) and Rocky Island

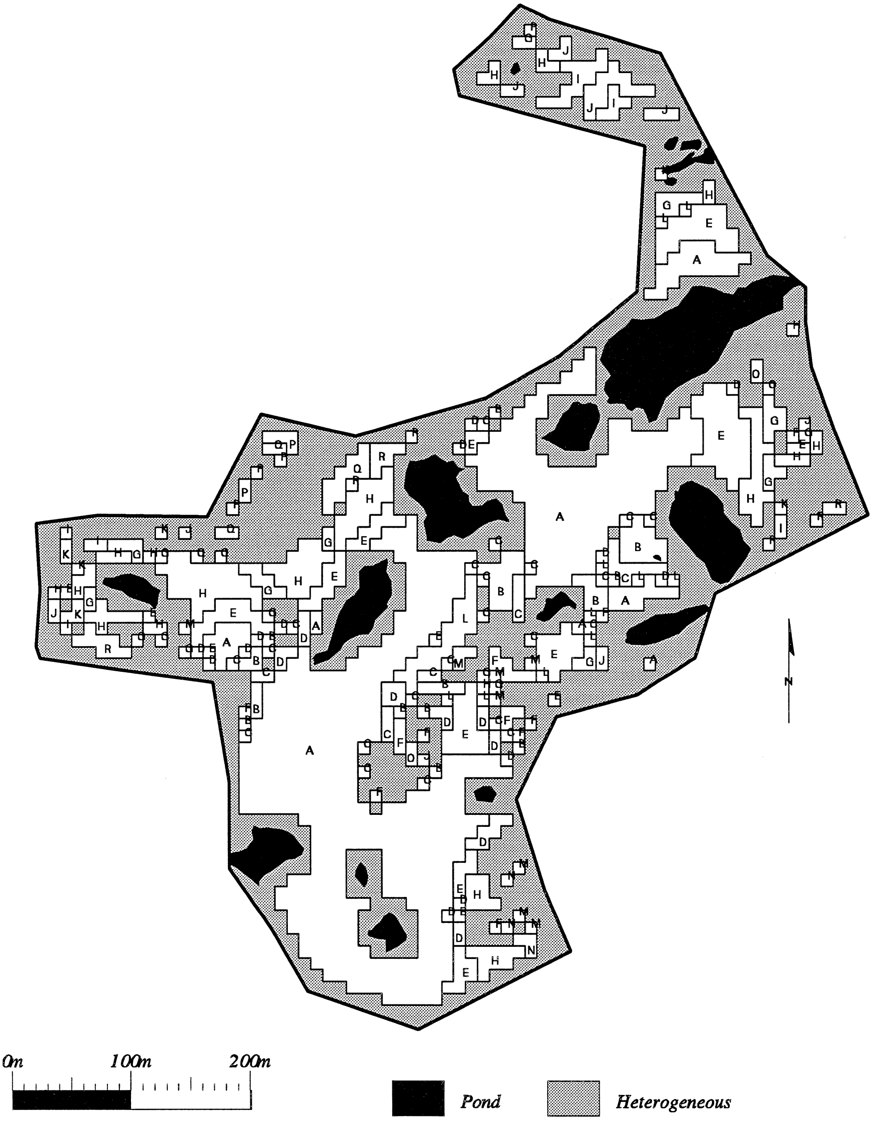

Fig. 5. Spatial distribution of homogeneous groups identified by the PEGASE analysis at Bristy Cove Creek (BRIST). See Table 4 for the topographic characteristics of each homogeneous group. Grid cells located immediately adjacent to the ponds and the study site boundary that are shown as heterogeneous were not included in the analysis; topographic characteristics were not computed for these cells due to edge effects.

Pond (ROCKY) are used as needed for comparison and for interpreting the results at CRIPP in the context of blanket bogs in general.

The distribution of topographic characteristics at CRIPP and BRIST were similar (Table 2); for all topographic characteristics, there was no indication that the means were different between the two sites at a 95% confidence level. Elevations between sites were not comparable, as an arbitrary datum was chosen at each site.

The substrate profile and plan curvatures of ROCKY differed from CRIPP and BRIST, but its surface curvatures were similar to the southern sites (two-tailed *t*-test, 95% confidence level). This is consistent with the effects of paludification and peat expansion, which causes a homogenization of the land surface. However, surface slope distribution at ROCKY differed due to the influence of steeper bedrock outcrops scattered throughout the area.

For every topographic characteristic, the range of values for bog and heath communities overlapped, almost always within one standard deviation of their respective means. This precluded a simple mapping-style classification of cover type, as bog and heath may appear under the same conditions in the context of any one particular topographic variable. Where the bog location is constrained by topography, it is a *combination* of topographic characteristics that delimits bog occurrence.

Table 4
Topographic characteristics of the homogeneous groups identified for the BRIST study site using the PEGASE procedure, as shown in Fig. 5

Code	Topographic characteristics	Cells	% Bog	H_s
Bog community groups				
A	SELV 0–1	538	85.1	0.420
B	SELV 2, SUPM 0	50	86.0	0.405
C	SELV 2, SUPM 1, GPFC 1–3	50	80.0	0.500
D	SELV 2, SUPM 2, GELV 0–1	26	88.5	0.358
E	SELV 2, SUPM 3–4	135	91.9	0.282
F	SELV 3, SUPM 0, GPLC 2	21	81.0	0.487
G	SELV 3, SUPM 2, GELV 2–3	46	95.7	0.179
H	SELV 3, SUPM 3–4	119	84.0	0.439
I	SELV 4, GSLP 0, SUPM 2–4	22	81.8	0.474
J	SELV 4, GSLP 1, GUPM 0–1	29	89.7	0.333
K	SELV 4, GSLP 1, GUPM 4	9	88.9	0.349

Code	Topographic characteristics	Cells	% Heath	H_s
Heath community groups				
L	SELV 2, SUPM 2, GELV 2	26	88.5	0.358
M	SELV 3, SUPM 1, GPLC 1	14	92.9	0.257
N	SELV 3, SUPM 2, GELV1, SPFC 2	7	100.0	0.000
O	SELV 4, GSLP 2, GELV 1	6	83.3	0.451
P	SELV 4, GSLP 2, GELV 4	10	90.0	0.325
Q	SELV 4, GSLP 3, GPFC 1–3	19	89.5	0.337
R	SELV 4, GSLP 4	23	95.7	0.179

Refer to Table 1 for the range of values associated with each topographic class.

The PEGASE analysis stratified CRIPP into 54 groups, 33 of which were considered homogeneous (at least 80% of grid cells belonging to one particular community type) (Fig. 4, Table 3). About 83% of the sample population was placed into a homogeneous group. BRIST was stratified into 32 groups, 18 of which were homogeneous, containing

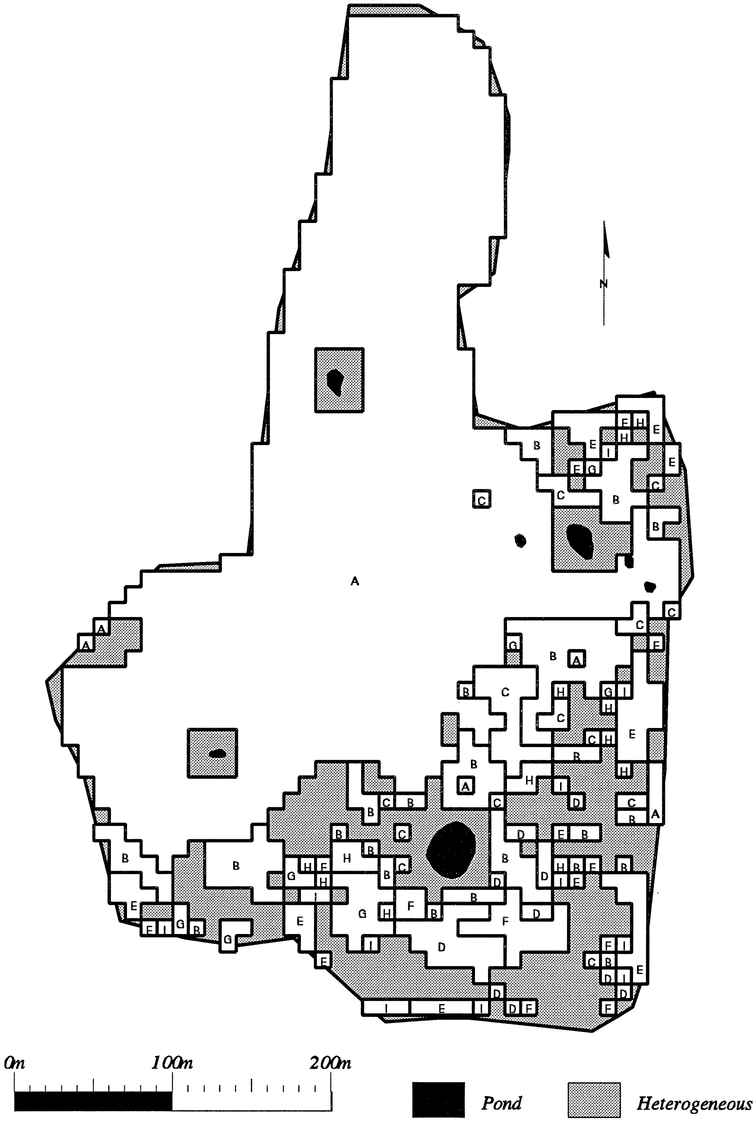

Fig. 6. Spatial distribution of homogeneous groups identified by the PEGASE analysis at Rocky Island Pond (ROCKY). See Table 5 for the topographic characteristics of each homogeneous group. Grid cells located immediately adjacent to the ponds and the study site boundary that are shown as heterogeneous were not included in the analysis; topographic characteristics were not computed for these cells due to edge effects.

75.0% of the sample population (Fig. 5, Table 4); nine of ROCKY's 16 stratified groups were homogeneous, containing 84.5% of the sample population (Fig. 6, Table 5). The smaller number of groups for BRIST and ROCKY resulted from their much smaller sample sizes; heterogeneous groups rapidly dropped below the 40-cell stopping threshold, and therefore were not further subdivided.

As an interpretive example, Group A at CRIPP (Fig. 4, Table 3) has Class 0 (smallest) substrate upslope catchment area, Class 0 (lowest) substrate elevation, and Class 0–3 ground slope (all but the highest slopes). All 64 cells in the group have these characteristics, and all cells in the study area with these characteristics are included in this group. With 82.8% of the cells being bog, this subset has an entropy, H_s, of 0.459. The initial entropy, H, of the CRIPP site before considering any topographic stratification was 0.614. Therefore the redundancy, or reduction in entropy due to the structural influence of topographic shape, for the locations associated with Group A is equal to 25.2% (Eq. (2)). Therefore, 25.2% of the structure contributing to the pattern within locations belonging to Group A may be attributed to substrate upslope area, substrate elevation, and ground slope.

The total redundancy (reduction in entropy) was calculated for the PEGASE stratification determined at each study site: 22.0% at CRIPP; 22.7% at BRIST; and 21.5% at ROCKY. Therefore, approximately 22% of the organizing ecological structure underlying the distribution of community types within these blanket bog complexes may be attributed to topographic constraints.

To test that the redundancy due to topography was greater than that produced by random effects, 10 random test procedures were executed. For each test, 1000 grid cells were generated with random cover type (bog or heath), and a random class from 0 to 4 was assigned to each of the 10 variables. In all 10 tests, no information channel was statistically significant to a 95% confidence level. The redundancy for the random tests

Table 5
Topographic characteristics of the homogeneous groups identified for the ROCKY study site using the PEGASE procedure, as shown in Fig. 6

Code	Topographic characteristics	Cells	% Bog	H_s
Bog community groups				
A	SELV 0–2	741	85.0	0.422
B	SELV 3, GUPM 1, GPFC 1–3	38	84.2	0.436
C	SELV 3, GUPM 2–3	115	84.3	0.434
D	SELV 4, GSLP 0, GUPM 2–4	21	85.7	0.410
E	SELV 4, GSLP 1, GELV 4	34	85.3	0.418

Code	Topographic characteristics	Cells	% Heath	H_s
Heath community groups				
F	SELV 4, GSLP 1, GELV 3	16	87.5	0.377
G	SELV 4, GSLP 2, GUPM 2–4	24	91.7	0.287
H	SELV 4, GSLP 3, GPFC 0	8	100.0	0.000
I	SELV 4, GSLP 4	28	96.4	0.154

Refer to Table 1 for the range of values associated with each topographic class.

was 0%, confirming the theoretical value and demonstrating that the 22.1% figure was due to nonrandom effects.

5. Discussion

The low but significant redundancy value (22.1%) indicates that topography plays a relatively small role in defining the distribution of bog and heath communities within the blanket bog complex, compared to other factors not included in the investigation. The three main variables chosen by the PEGASE procedure at CRIPP, in terms of frequency of appearance and number of homogeneous cells identified, were substrate upslope area (SUPA), substrate elevation (SELV), and substrate slope (SSLP). Substrate profile curvature (SPFC) and substrate plan curvature (SPLC) also appeared regularly, though with less effect on the outcome. The largest homogeneous, topographically similar group contains the cells with the greatest upslope contributing areas; these are areas in which the water gradually collects as it moves due to gravitational forces. The appearance of SELV corrects for anomalies in the SUPA measure; for example, low-lying areas between ponds tend to have low SUPA values. However, they tend to be quite wet due to the influence of the ponds' collection areas. The broad range of SSLP values show that, if there is sufficient water available to a location, peat may accumulate even on steeper slopes.

One strong trend emerged at CRIPP: the PEGASE analysis rarely identified surface topographic variables as constraining the community structure. If a ground surface variable was identified as having some influence in defining a homogeneous group, the homogeneous groups it helped to define tended to be small heath areas, and emphasized steep slopes. Presumably, the homogenization caused by peat accumulation in other areas attenuates the surface topographic signal.

Only substrate morphology, which defined topographic conditions at the initiation of peat accumulation, seemed to affect the current pattern of bog and heath locations in the blanket bog complexes. Stratigraphic sequences of blanket bogs in North America (Davis, 1984) and Northwestern Europe (Iversen, 1964) tend to show a succession typically associated with paludification. The peat accumulated directly on the soil or bedrock, rather than in pond basins. This development model is in accordance with the notion that substrate shape, as indicative of the localized hydrologic conditions at peat initiation, is an important influence on the current location of peat accumulation. The relatively small explanation (22%) provided by substrate topography, however, reflects the relatively advanced state of development beyond the conditions the substrate initially presented.

Damman (1979) also suggested the importance of topography in controlling peatland development decreases as the peatland develops. Once bog communities establish themselves in areas where the substrate morphology is conducive to peat accumulation, the communities' perpetuation becomes governed more by the properties of the peat deposit and the continuation of favourable climatic conditions than by the substrate topography. Any new bog encroachment at the edges of the bog community, where little soil development in the heath community has occurred, will depend on the substrate topography considering the new moisture conditions created by the adjacent peat deposit.

Bog communities were identified throughout the entire range of substrate upslope area. A broad range of substrate slopes, profile curvatures, and plan curvatures supported bog communities. This confirms the earlier observation that no one topographic characteristic limits bog development, as long as other characteristics support water retention. For instance, in the bog groups where slopes are steeper, water would normally flow away faster. However, the profile curvatures were generally identified as concave, thereby decelerating the water and potentially 'backing it up' to some degree, counterbalancing the slope effect.

The homogeneous groups identified by the PEGASE procedure were smaller (i.e., a greater degree of subdivision occurred) where the upslope area was not as great. Where there is a large contributing area, there is a greater chance that an area can remain saturated in spite of other water retention obstacles, such as divergent curvatures. It is also likely that these areas, due to favoured water supply conditions, initiated peat accumulation at an early stage of landscape development. With a longer period for accumulation and paludification, much of the variation in drainage conditions could be overcome.

In most homogeneous bog groups, gentle slopes and convergent curvatures were identified, characteristics that are commonly attributed to bogs. Some groups, particularly at CRIPP, had substrate characteristics normally considered unusual for a bog, such as divergent plan curvature or steep slopes, particularly at higher elevations. Their spatial distributions provided some insight into their successful development as bog areas (Fig. 4, Table 3). The larger contiguous patches appeared either in the lower areas with larger upslope contributing areas, or on the upland areas towards the northern portion of the site, occupying a plateau area of flat to gentle slopes. The convex substrate surfaces supporting bog persisted in the areas directly downslope of these upland bog areas. A process similar to paludification seems to have occurred in these areas. However, rather than 'creeping up' slopes from low-lying bog areas, the bog exploited water flowing from the main expanse and 'spilled over' the edges of the plateau and expanded downslope.

The BRIST site was primarily stratified by SUPA and SELV, as at the CRIPP site. This common structure indicated that similar controls on the community pattern were present, as expected by the visible similarity of the two sites. Groups that were further stratified tended to be distinguished by ground surface variables, but this may be due to the greater number of points used to derive the ground DEM and hence greater detailed variability. The selection may also have been statistically influenced by the rapidly shrinking subsample sizes. However, the broad level pattern remains consistent with that identified at CRIPP.

In contrast to CRIPP and BRIST, surface topographic characteristics were chosen almost exclusively at ROCKY. There is a possibility that the ROCKY site is an extensive slope bog, or mix of slope and blanket bog, rather than a true blanket bog. The developmental processes of slope bogs are similar to those of blanket bogs, but reduced precipitation and warmer summers reduce the amount of available water and limit the extent of paludification (Wells and Hirvonen, 1988). Slope bogs often reach blanket bog proportions in the southern Avalon, and are difficult to differentiate (Wells, 1981). The strong influence of GUPA and GSLP in the set of information channels defining its structure may indicate that paludification was limited at this site, which is true of slope bogs. Given its prevalence at ROCKY, ground slope was conspicuously absent in defining the community pattern of the southern sites.

Other factors, such as nutrient status, microclimate effects, and substrate permeability, could contribute towards a definition of the remaining variability in the community pattern at all sites. However, it would be misleading to assume that all of the entropy remaining within the community pattern was attributable to these other factors. A part of the remaining entropy may not be attributable to any known factor, and may thus reflect truly random community placement. Additional entropy, or uncertainty, may have been artificially introduced into the calculations due to error in the elevation measures and its propagation into slope and curvature measures. The upslope contributing area is particularly sensitive to the algorithmic manner of its calculation and the number of possible ways in which it may be calculated, thereby adding some uncertainty to the data. Although necessary for the proper functioning of the PEGASE procedure, the process of transforming the ratio scale variables into nominal scale variables also reduced the information available in the topographic measurements.

6. Conclusions

There were five primary conclusions reached by this study.

(1) Approximately 22% of the structure underlying the pattern was attributed to topographic constraints.

(2) Bog and heath communities could not be differentiated on the basis of any one topographic characteristic, but rather on a combination of them.

(3) Substrate morphology, rather than surface form, provided the most explanation for the present distribution of bog and heath in the blanket bog zone. Surface morphology provided little information except near the northern limit of the blanket bog zone.

(4) Lower elevations were more favourable for blanket bog development, since they receive water from a larger upslope area. However, bog communities persisted in upper elevations in areas where the flatter topography assisted in detaining the smaller supply of water contributed from upslope.

(5) The fringes surrounding upland bog areas were often divergent in plan curvature, yet were occupied by bog. It appeared that encroachment of bog onto steeper slopes by paludification was not limited to ‘creeping up’ slopes from lowland bogs, but also ‘spilled over’ upland plateaus.

This study demonstrated that topography influences the distribution of bog and heath within the blanket bog complexes of the Avalon Peninsula. However, other abiotic landscape features, such as substrate permeability, and biotic processes associated with peat accumulation must be implicated in a fuller explanation of the current distribution of bog and heath in the blanket bog zone of Newfoundland.

Acknowledgements

Comments and suggestions offered by the reviewers were appreciated. We are grateful for the financial assistance of the Natural Sciences and Engineering Research Council of Canada, and to the Department of Fisheries and Oceans for accommodation at the Cape Race site. Northway Map Technologies in Downsview, Ontario conducted the photogrammetric analysis. The field assistance of Fred Osborne Jr. and John Pike was appreciated. Thanks also go to David Lapen for direction into the PEGASE literature, provided by his Masters thesis.

References

Barry, T.A., 1954. Some considerations affecting the classification of the bogs of Ireland, and their peats. Proc. 1st Int. Peat Symp. Dublin, Ireland.

Damman, A.W.H., 1979. Geographic patterns of peatland development in eastern North America. In: Kivinen, E., Heikurainen, L., Pakarinen, P. (Eds.), Classification of Peat and Peatlands. Proc. International Peat Society. Hyytiala, Finland, pp. 42–57.

Davis, A.M., 1984. Ombrotrophic peatlands in Newfoundland, Canada: their origins, development and trans-Atlantic affinities. Chem. Geol. 44, 287–309.

Heathwaite, A.L., Göttlich, K., Burmeister, E.G., Kaule, G., Grospietsch, T., 1993. Mires: definitions and form. In: Heathwaite, A.L., Göttlich, K. (Eds.), Mires: Process, Exploitation and Conservation. Wiley, Chichester, NY, pp. 1–75.

Hewlett, J.D., Hibbert, A.R., 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: Sopper, W.E., Lull, H.W. (Eds.), Forest Hydrology. Pergamon, Oxford, pp. 375–290.

Iversen, J., 1964. Retrogressive vegetational succession in the Postglacial. J. Ecol. Suppl. 52, 59–70.

Kirkby, M.J., Kneale, P.E., Lewis, S.L., Smith, R.T., 1995. Modelling the form and distribution of peat mires. In: Hughes, J.M.R., Heathwaite, A.L. (Eds.), Hydrology and Hydrochemistry of British Wetlands. Wiley, Chichester, pp. 83–93.

Lapen, D.R., 1991. Modeling the redistribution of snow in a prairie agricultural landscape using digital terrain and spatial entropy analysis. MSc Thesis, University of Saskatchewan.

Lapen, D.R., Moorman, B.J., Price, J.S., 1996. Using ground-penetrating radar to delineate subsurface features along a wetland catena. Soil Sci. Soc. Am. J. 60, 923–931.

Lindsay, R.A., 1996. Ombrotrophic mires: the classification, ecology and conservation of bogs. Scottish Natural Heritage, Edinburgh.

Lindsay, R.A., Charman, D.J., Everingham, J., O'Reilly, R.M., Palmer, M.A., Rowell, T.A., Stroud, D.A., 1988. The Flow Country: The Peatlands of Caithness and Sutherland. Nature Conservancy Council, Peterborough, UK.

Moore, P.D., 1972. The initiation of peat formation and the development of peat deposits in mid-Wales. Proc. 4th Int. Peat Congr. 1, 89–100.

Morin, C., 1979. Modele d'organisation spatiale et ecologique des types de communautes vegetales de la region du Mont-Ste-Marie. MA Thesis, University of Ottawa.

Osvald, H., 1949. Notes on the vegetation of British and Irish mosses. Acta Phytogeogr. Suec. 26, 1–62.

Phipps, M., 1981. Entropy and community pattern analysis. J. Theor. Biol. 93, 253–273.

Price, J.S., 1991. Evaporation from a blanket bog in a foggy coastal environment. Boundary-Layer Meteorology 57, 391–406.

Price, J.S., 1992a. Blanket bog in Newfoundland: Part 1. The occurrence and accumulation of fog-water deposits. J. Hydrol. 135, 87–101.

Price, J.S., 1992b. Blanket bog in Newfoundland: Part 2. Hydrological processes. J. Hydrol. 135, 103–119.

Price, J.S., 1994. Sources and sinks of sea salt in a Newfoundland blanket bog. Hydrol. Proc. 8, 167–177.

Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modeling using digital terrain models. Hydrol. Proc. 5, 59–90.

Romanov, V.V., 1968. Hydrophysics of Bogs. Israel Progr. Sci. Transl., Jerusalem.

Siegel, D.I., 1988. The recharge–discharge function of wetlands near Juneau Alaska: Part 1. Hydrogeological investigations. Ground Water 26, 427–428.

von Post, L., Granlund, E., 1926. Södra Sveriges torvtillgånger. Sv. Geol. Undersökn, Avh. and Uppsatser C, p. 335.

Wells, E.D., 1981. Peatlands of eastern Newfoundland: distribution, morphology, vegetation, and nutrient status. Can. J. Botany 59, 1978–1997.

Wells, E.D., Pollett, F.C., 1983. Peatlands. In: South, G.R. (Ed.), Biogeography and Ecology of the Island of Newfoundland. Dr. Junk, The Hague, pp. 207–263.

Wells, E.D., Hirvonen, H.E., 1988. Wetlands of Atlantic Canada. In: Zoltai, S.C. (Ed.), Wetlands of Canada. National Wetlands Working Group, Ecological Land Classification Series No. 24, Sustainable Development Branch, Environment Canada, and Polyscience Publications, Ottawa, pp. 252–303.

Zevenbergen, L.W., Thorne, C.R., 1987. Quantitative analysis of land surface topography. Earth Surf. Proc. and Landforms 12, 47–56.

Zoltai, S.C. (Ed.), 1988. Wetlands of Canada. National Wetlands Working Group, Ecological Land Classification Series No. 24, Sustainable Development Branch, Environment Canada, and Polyscience Publications, Ottawa.