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Distribution of bog and heath in a Newfoundland blanket bog complex: topographic limits on the hydrological processes governing blanket bog development

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Abstract

This research quantified the role of topography on hydrological processes within and, hence, the development of, blanket bogs. Topographic characteristics were derived from digital elevation models (DEMs) developed for the surface and underlying substrate at three blanket bog sites on the southeastern lobe of the Avalon Peninsula, Newfoundland. A multinomial logit (MNL) model of the probability of bog occurrence was constructed in terms of relevant topographic characteristics. The resulting model was then used to investigate the probabilistic boundary conditions of bog occurrence within the landscape. Under average curvatures for the sites studied, substrate slopes up to 0.065 favoured blanket bog development. However, steeper slopes could, theoretically, be occupied by blanket bog where water is concentrated by convergent curvatures or large contributing areas. Near community boundaries, bog and heath communities both occupied similar topographic conditions. Since these boundary locations are capable of supporting the hydrological conditions necessary for bog development, the heath is likely to be encroached upon by bog.

Introduction

Blanket bogs, extensive peat deposits that occur uniformly over hill and valley in the local landscape, appear on the southeastern portion of the Avalon Peninsula in Newfoundland (Wells, 1981) and are not documented elsewhere in eastern North America (Davis, 1984). Peatlands, particularly bogs, require an adequate range of atmospheric moisture dictated, primarily, by the balance of precipitation and evaporation (Romanov, 1968). Thus, the distribution of peatlands is limited by climatic variables (Damman, 1979) but subject to local topographic and geological constraints. The model of Kirkby *et al.* (1995) integrated large scale climatic conditions with a peat growth algorithm to predict the potential distribution of peatlands in Europe. However, to explain the actual pattern of peatland occurrence a better understanding of local topography is needed (Wells and Hirvonen, 1988).

Blanket bogs form initially by infilling small pools or by primary peat production directly on top of moist soils, made possible by a wet climate. The peat then develops outward by paludification, or gradual waterlogging of upslope areas and, eventually, peat forms in the newly wetted areas. Paludification normally occurs upslope (Frenzel, 1983) but, in areas with supporting topographic characteristics, peat also paludifies downslope from upland bog plateaux (Graniero and Price, in press). The influence of topographic shape on hydrological conditions, therefore, is particularly important in the early stages of peat production (Wells and Hirvonen, 1988).

If, due to the balance of atmospheric controls, sufficient water is available, the topography must also conform to limiting conditions to retain this water at the surface so peat may develop (Price, 1992b). The necessary conditions include, but are not limited to, gentle slopes and convergent curvatures (Lindsay *et al.*, 1988; Heathwaite *et al.*, 1993), due to their effect on the gravitational movement of water. More specifically, no one topographic characteristic dominates the conditions favourable for peat development, but rather a combination of topographic variables function together, suggesting that their interrelationships should be investigated further. The threshold conditions of these topographic characteristics are recognized qualitatively, but quantitative understanding is less developed. Further quantification of threshold or boundary topographic conditions within blanket bogs can provide theoretical insights into the complex processes involved in both formation and perpetuation of these wetland areas.

The purpose of the research presented in this paper was to quantify the role of topography in hydrological processes which influence the development of blanket bogs, using a multinomial logistic regression (MNL) model of the probability of bog occurrence.

THE LOGISTIC REGRESSION MODEL

The logistic regression model (also known as a binomial logit model) describes a nonlinear probability curve (McFadden, 1973) and was originally used in geographical research primarily for transportation analysis and human choice models (Aldrich and Nelson, 1984; Ben-Akiva and Lerman, 1985). However, the model may also be applied to the physical sciences, and ecological analysis.

The derivation of the more general multinomial logit model was reviewed in Anas (1983). In the present study, only bog and heath communities are possible alternatives; therefore, the simpler logistic regression model may be used, which has the form:

$$p = \frac{e^{\beta_0+\beta_1 x_1+\ldots+\beta_k x_k}}{1+e^{\beta_0+\beta_1 x_1+\ldots\beta_k x_k}} \qquad (1)$$

where p is the probability of bog occurrence in a particular location (assigning heath as alternative 0 and bog as alternative 1), x_i is the value of the ith attribute at that location, and the βs are the calibrated model parameters.

The probabilities under a binomial model follow a logistic curve. The logistic shape implies that more extreme values of an attribute are more strongly identified with a particular community type. This is consistent with the general patterns described earlier, i.e. bogs generally occur in *flat* (low slope) areas with *concave* (increasingly negative) profile curvatures and convergent (increasingly positive) plan curvatures.

BOUNDARY ANALYSIS

If the probability of bog occurrence generated by the logistic regression model is greater than 0.5 for a particular location, then there is a greater than 50% chance that the area is topographically suitable for bog. If the value is less than 0.5, it is more likely that heath will occur under those topographic constraints. A location with a 0.5 probability of bog occurrence is weighted towards neither community type; that location may then be interpreted as lying on the boundary between bog and heath communities. For a given logistic regression model, the probability changes most rapidly at probability 0.5, and the rate of change is calculated by:

$$\left\|\nabla p(x_1, \ldots x_k)\right\|_{p=0.5} = \tfrac{1}{4}\sqrt{\beta_1^2 + \ldots + \beta_k^2} \qquad (2)$$

This value may be interpreted as an indicator of the boundary sharpness within the modelled system. Higher values indicate a sharp boundary between bog and heath communities, i.e. a narrow transition zone. Under boundary ($p = 0.5$) conditions, the relationship between the values of the attribute is represented by the equation:

$$\beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k = 0 \qquad (3)$$

This expression describes a family of attribute combinations; any change in an attribute value along the boundary necessitates a balancing change in one or more of the other attributes. By using Eqn. (3) with the parameters of a calibrated model and a set of observed representative values for all but one attribute, the theoretical range in which bog may exist under those conditions may be identified for the remaining attribute.

Study sites

The study was conducted at three sites on the south-eastern lobe of the Avalon Peninsula in Newfoundland (Fig. 1): Cripple Cove Creek (CRIPP) and Bristy Cove Creek (BRIST), near Cape Race; and Rocky Island Pond (ROCKY) near Colinet. These sites are representative of the regional topography, and the hydrological processes at Cape Race have been investigated in depth (Price, 1991,1992a, 1992b and 1994; Lapen *et al.*, 1996).

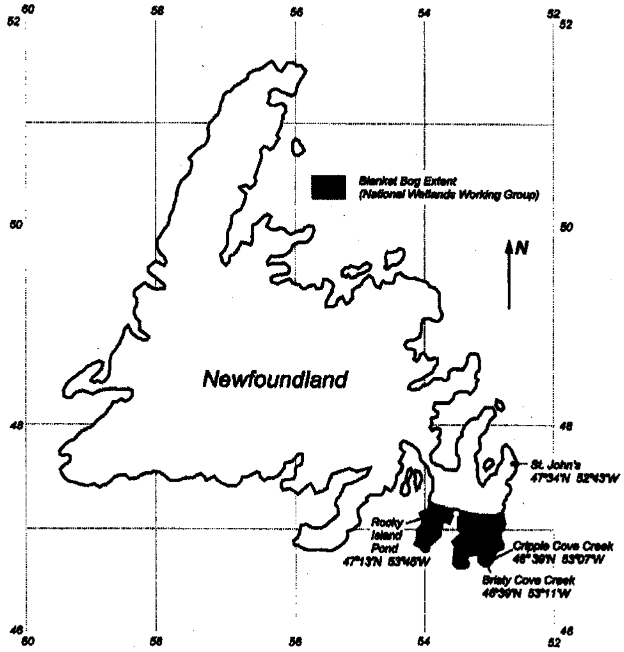

Fig. 1. *Newfoundland study sites: Cripple Cove Creek (CRIPP; 46° 39′ N, 53° 07′ W), Bristy Cove Creek (BRIST; 46° 39′ N, 53° 11′ W), and Rocky Island Pond (ROCKY; 47° 13′ N, 53° 45′ W).*

Cripple Cove Creek (CRIPP) and Bristy Cove Creek (BRIST) lie approximately 750 m inland from the Atlantic coast, and BRIST lies 4.6 km west of CRIPP. These two sites are visually similar in both topography and community pattern. CRIPP and BRIST are simple bog/heath mosaics in the foggiest southern extent of the Newfoundland blanket bog zone (Hare, 1952; Wells, 1981). The terrain is gently undulating, with average slopes of 0.037 at CRIPP and 0.040 at BRIST; the total relief within the surveyed area at CRIPP (65.3 ha) was 14 m, and at BRIST (23.9 ha) was 6.5 m. The bog surface is predominantly *Sphagnum fuscum*, with patchy cover of *Empetrum spp.*, *Rubus spp.* and *Cladonia spp.* (Price, 1991). Heath communities comprised *Kalmia spp.*, with some low *Scirpus spp.* (Price, 1992a) and cover 29.3% and 27.5% of CRIPP and BRIST, respectively. The transition between bog and heath communities is very sharply defined, clearly visible even on 1:17 000 scale air photos. The transitions occur over distances as short as 1 metre. Small ponds and pools occupy local depressions, with open water covering an average of 10.2% of each site.

Rocky Island Pond (ROCKY) is a blanket/slope bog complex approximately 75 km northwest of Cape Race, at the northern extent of the blanket bog zone. Fog is less frequent at this site. The topography is more varied, with occasional patches of exposed bedrock. The relief range of the area surveyed (14.9 ha) was 6.8 m and the average slope was 0.039 but, nearby, hills and rock outcrops had slopes estimated at 0.20 to 0.25. The bog/heath boundaries are less sharply defined at ROCKY and more ericaceous vegetation is present. Patches of evergreen shrubs in the area are typically taller than those found near Cape Race. Stands of *Abies spp.* and *Picea spp.* appear along the slopes of the large hills, with many individuals reaching several metres in height. Heath covers 30.6% of the study area, and open water covers 0.9% of the site.

CRIPP was the primary site of investigation, and the other two sites were used to test the results obtained there, over a range of conditions. CRIPP and BRIST had similar climatic conditions, and were visually similar with respect to topography and community patterns. This allowed testing of the validity of the modelled relationships over a broader region; ROCKY had different climatic characteristics, and was visually different from CRIPP in terms of topography and community patterns.

Methods

PEAT SURVEY

Peat depth surveys were conducted at the three sites between August 28 and September 10 1995; 225, 128, and 598 sample points were surveyed at the CRIPP, BRIST, and ROCKY sites respectively. The substrate at ROCKY was quite variable, so more points were sampled to ensure adequate representation of its shape. At each sample point, peat surface elevation, thickness, geographic position and community type (bog, heath or transitional) were recorded. The intended goals of the survey were i) to capture the full representative range of surface and substrate topography, and ii) to create a relatively uniform and complete coverage, within each study area. The sample points were chosen *ad hoc* in the field; the hidden nature of the substrate extrema and breaking conditions required interpretation of the landscape shape to judge their locations as closely as possible. The range pole was consistently placed on the surface of larger hollows within bog areas, and hummocks or narrow crevices were avoided.

PHOTOGRAMMETRIC ANALYSIS

Northway Map Technologies Ltd. in Downsview, Ontario performed standard photogrammetric analyses on 1:17 000 air photographs marked for ground control. Totals of 5606 points were acquired over 205.6 ha at CRIPP, 5771 points over 209.6 ha at BRIST, and 9386 points over 166.7 ha at ROCKY. Most data points traced pond and stream outlines, break lines, and other identifiable topographic features. The remainder were sampled on a regular grid spaced at 2 mm on the air photos, or 34 m ground distance. The area covered by each photogrammetric analysis was considerably larger than the area surveyed at each site in order to minimize potential edge effects on the terrain analyses conducted on the study areas.

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, giving an average RMS error of approximately 2.8 pixels, or 2 m on the ground. The surveyed points were overlaid onto the air photos as a guide, and the study extent and community boundaries were digitized. As mentioned previously, the community boundaries appeared quite sharply on the air photos. Boundary placement was likely to be affected more by rectification error than by digitization accuracy.

DEMs were then created for both the ground surface and the substrate within each bounded study area using a triangulated irregular network (TIN) structure and further interpolation to a gridded elevation model. The interpolation at the centre of each grid cell used a local quintic polynomial estimation as implemented in ARC/INFO's TIN module. Experimentation showed that the distribution of topographic measurements was relatively unaffected by resolution at these sites and scales, so a grid resolution of 10 m was chosen to reduce spatial autocorrelation. Areas outside the study boundary and within ponds were recorded as of unknown elevation.

Slope (SLP), profile curvature (PFC) and plan curvature (PLC) were calculated for both the ground surface (GSLP, GPFC, GPLC) and substrate (SSLP, SPFC, SPLC) at each grid cell, using the surface and substrate elevations (GELV and SELV) respectively. The shape measures were computed using a partial quartic equation fitted to the 3 × 3 window centred on each grid cell, as described by Zevenbergen and Thorne (1987). 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.

Upslope contributing areas (GUPA and SUPA) were calculated using a variant of the multiple flow direction algorithm (Quinn *et al.*, 1991). Equal fractions of a cell's upslope contributing area were added to each neighbouring cell of lower elevation, working from cells of highest elevation to those of lowest elevation. Pits and flat areas in the DEM were left intact when running the algorithm.

LOGISTIC REGRESSION MODELING

Graniero and Price (in press) indicated that substrate characteristics were the most important controls on the bog/heath community structure at CRIPP and BRIST, whereas surface topographic characteristics had a greater influence at ROCKY. To reflect these findings, an initial logistic regression model was calibrated for each site using the substrate shape characteristics available, namely SSLP, SUPA, SPFC and SPLC:

$$p = \frac{e^{\beta_0+\beta_1(SSLP)+\beta_2(SPFC)+\beta_3(SPFC)+\beta_4(SPLC)}}{1+e^{\beta_0+\beta_1(SSLP)+\beta_2(SUPA)+\beta_3(SPFC)+\beta_4(SPLC)}} \tag{4}$$

For each site, the substrate characteristics at 1000 sample points, and the model specified in Eqn. (4), were input into the Generalized Linear Model solving system in S-Plus (Statistical Sciences, 1995), set for the binomial logit family of equations. An additional logistic regression model was calibrated for ROCKY using GSLP, GUPA, GPFC and GPLC:

$$p = \frac{e^{\beta_0+\beta_1(GSLP)+\beta_2(GUPA)+\beta_3(GPFC)+\beta_4(GPLC)}}{1+e^{\beta_0+\beta_1(GSLP)+\beta_2(GUPA)+\beta_3(GPFC)+\beta_4(GPLC)}} \tag{5}$$

The calibrated parameters were interpreted in terms of blanket bog topography and hydrology. The rate of change at probability 0.5 was calculated for each logistic regression model, and the values were compared between sites and interpreted. The probability of bog occurrence was calculated for each model at every grid cell for which all topographic variables were defined, and probability isolines were constructed.

To test the validity of the models, the probability of bog occurrence was calculated at each survey point using the calibrated models. Bog points were considered to have an actual probability of 1.0, and heath points a probability of 0.0. Goodness of fit was determined for each model using Akaike's Information Criterion (AIC) (Akaike, 1973).

Results and discussion

Table 1 summarizes the resulting substrate models (SSLP, SUPA, SPFC, SPLC) calibrated for each site, and the ground surface model (GSLP, GUPA, GPFC, GPLC) calibrated for the ROCKY site. The AIC for the substrate model calibrated at CRIPP was 11.69, the AIC for the substrate model calibrated at BRIST was 9.35 and the AIC for the surface model calibrated at ROCKY was 12.63. The mean accuracy for community type prediction on the basis of substrate shape was 71.2% at CRIPP and 72.8% at BRIST, and the accuracy of prediction on the basis of ground surface shape was 74.2% at ROCKY.

The substrate model parameterization at BRIST was generally similar to that at CRIPP, indicating that the underlying topographic structure (in terms of the variables included in the model) was similar but not identical at both sites. Numerically, the model calibrated for CRIPP performed as well at BRIST as at the calibrated site; when applied to BRIST, the AIC of the CRIPP model was 7.73. Visually, the performance of the CRIPP model at the two Cape Race sites was also consistent (Fig. 2). Therefore, the

Table 1. Calibrated parameters, the rate of change in probability at p=0.5, and Akaike's information criterion (AIC) or the logistic regression model at each study site.

Substrate Topography Model

Calibration Site	β_0 (SSLP)	β_1 (SUPA)	β_2 (SPFC)	β_3 (SPLC)	β_4	$\|\nabla p\|_{p=0.5}$	AIC
CRIPP	1.714	–27.91	0.00786	–121.6	149.2	48.62	11.69
BRIST	1.091	–14.57	0.03061	–120.0	149.5	48.05	9.35
ROCKY	1.154	–8.319	0.05472	–47.63	–0.347	12.09	25.44

Ground Surface Topography Model

Calibration Site	β_0 (GSLP)	β_1 (GUPA)	β_2 (GPFC)	β_3 (GPLC)	β_4	$\|\nabla p\|_{p=0.5}$	AIC
ROCKY	1.682	–31.33	0.02477	–78.45	–140.4	40.97	12.63

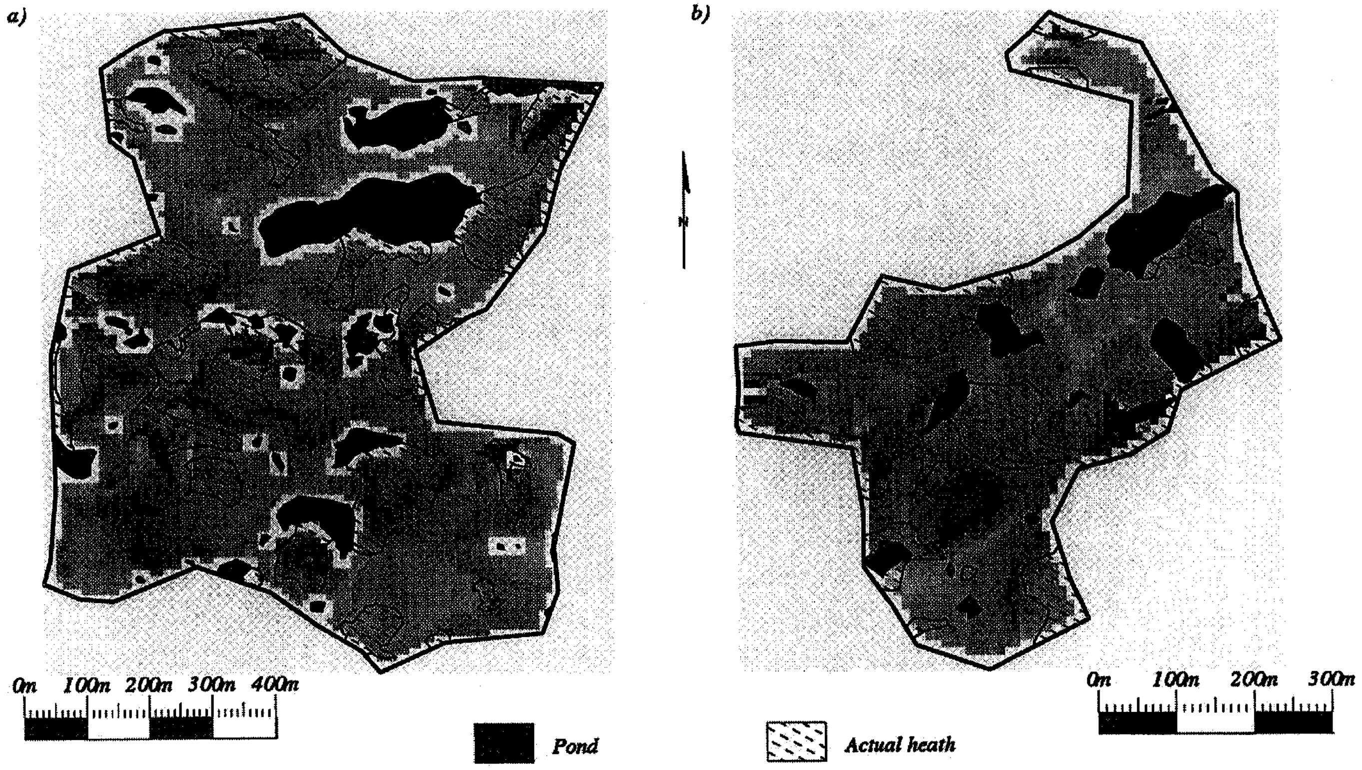

Fig. 2. *Probability of bog occurrence as predicted by the substrate model calibrated at CRIPP, compared to actual bog/heath distribution. Darker shades indicate lower probability of bog occurrence, i.e. greater probability of heath occurrence. White grid cells immediately adjacent to the ponds and the study site boundary were not included in the analysis; topographic characteristics were not computed for these cells due to edge effects. a) CRIPP study site; b) BRIST study site.*

CRIPP model was considered representative of the topographic structure underlying the blanket bogs in that geographic region.

The CRIPP substrate model did not perform well at the ROCKY site; the AIC was 97.37, considerably higher than at either CRIPP or BRIST (Table 1). Visually, the dense, intricate pattern of intermediate-valued probability contours across the site indicated that the CRIPP model could not identify particular community types with any certainty at ROCKY (Fig. 3). The ground surface model constructed for ROCKY achieved a level of accuracy much closer to those obtained by using the CRIPP substrate model at CRIPP and BRIST, and the spatial distribution of probabilities more accurately reflected ROCKY's observed community pattern. It appears that the relationship between topography and community type was consistent through the blanket bog area near Cape Race, but the role of topography was different in the Colinet area.

Overall, regions of low probability of bog coincided with the interiors of actual heath patches, but the predicted areas tended to be smaller than the actual heath extent. The higher bog probability in the heath fringes indicated that throughout the areas under study, both bog and heath exist under the topographic conditions observed in the heath fringe. Bog communities have encroached onto the heath in some of the locations, but not in others. In some transitional locations, peat had accumulated to a greater depth under heath vegetation than is usually found in the heath interior or near the community boundary. Since the topography is capable of supporting the hydrological conditions required for bog growth, there is no reason why, on the basis of topography, some of these locations have not been encroached upon; this implies that the study areas have not reached a steady state in terms of community succession.

The sign of the parameter associated with a particular attribute indicates how the value of the attribute affects the predicted probability of bog occurrence. Positive parameters indicate that *larger* attribute values increase the likelihood of bog occurrence (e.g. upslope contributing area), and negative parameters indicate that *smaller* attribute values increase the likelihood of bog occurrence (e.g. slope and profile curvature). Bog communities were, therefore, generally associated with small slopes, larger upslope contributing areas, and concave (negative) profile curvatures, which is consistent with general knowledge (Lindsay *et al.*, 1988; Heathwaite *et al.*, 1993). Similarly, *convergent* (positive) plan curvatures were generally associated with bog

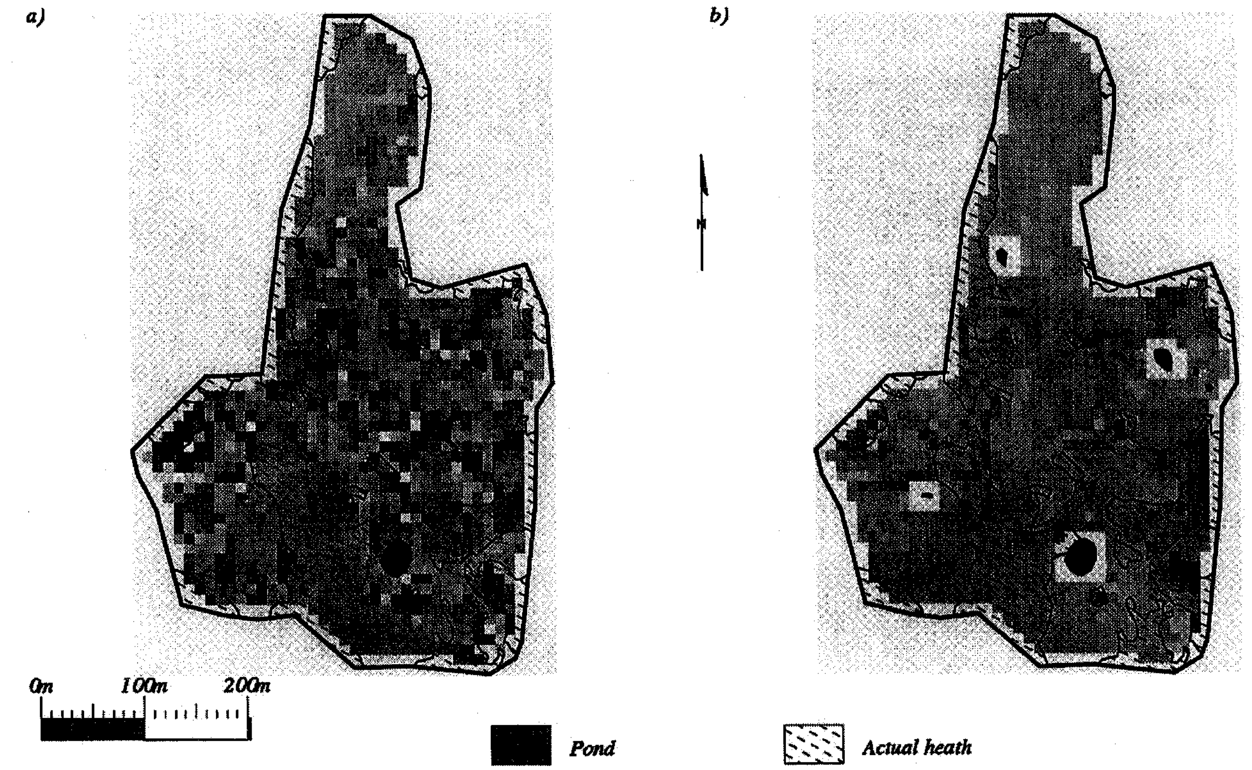

Fig. 3. *Probability of predicted bog occurrence compared to actual bog/heath distribution at the ROCKY study site. Darker shades indicate lower probability of bog occurrence, i.e. greater probability of heath occurrence. White grid cells immediately adjacent to the ponds and the study site boundary were not included in the analysis; topographic characteristics were not computed for these cells due to edge effects. a) substrate model calibrated at CRIPP, shown in Figure 3; b) ground surface model calibrated at ROCKY.*

occurrence at CRIPP and BRIST. However, *divergent* (negative) plan curvatures were generally associated with bog occurrence at ROCKY. Although the plan curvature at ROCKY is unexpected, little significance should be attached to this particular result: the relative weight of the SPLC parameter combined with the magnitudes of the SPLC is considerably smaller than that of the other parameters, and is likely to reflect the error in the elevation data. A final point to consider is that the associations described above are for the general case; there were some areas at the Cape Race sites, for example, where bog areas had divergent plan curvatures as a result of downward paludification from upland bog; this phenomenon was not observed at the ROCKY study site nor in the surrounding area.

An assessment of the correlation between the topographic variables considered in this study showed that, at all sites, almost all of the coefficients of determination (r^2) were under 10%, which indicates nearly complete independence among the variables. The r^2 values between profile and plan curvature pairs ranged a little higher at 20% to 40%, but these values were not high enough to invalidate the assumption of independence. In fact, a portion of the correlation may be attributed to the fact that both profile and plan curvature had small values that tend to concentrate near zero. The only noteworthy correlation was between ground elevation and substrate elevation, with r^2 values between 61% and 92% at the three sites. The arbitrary elevation datum established at each site was 100 m, and the peat reached depths of up to 4 m; therefore, considerable correlation was expected. However, elevation was not used in the logistic regression models since they cannot be compared between study sites.

To determine the model's sensitivity to a particular attribute, one may compare the magnitude of the parameter associated with that attribute to the magnitudes of the other parameters. However, one must also consider the order of magnitude of the attribute itself. For example, the SPLC parameter for CRIPP is 1.49×10^2, and the SUPA parameter is 7.86×10^{-3} (Table 1). However, the order of magnitude of the mean SPLC is 10^{-5} whereas the order of magnitude of the mean SUPA is 10^1 (Table 2). When the mean attribute values of SPLC and SUPA are combined with their respective parameters, their relative weights in the probability calculation have orders of magnitude of 10^{-3} and 10^{-2} respectively. This indicates that the model is more sensitive to the value of SUPA than SPLC, or that substrate upslope area has more influence than substrate plan curvature in determining the probability of bog occurrence. Considering the parameters in this fashion,

Table 2. *Statistical summary of topographic attributes at each study site.*

		GELV (m)	GSLP	GUPA (100 m²)	GPFC	GPLC	SELV (m)	SSLP	SUPA (100 m²)	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^{-5}	3.91×10^{-5}	1.461	2.36×10^{-2}	18.5	2.24×10^{-5}	1.85×10^{-5}
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^{-5}	3.56×10^{-5}	2.073	3.36×10^{-2}	9.8	6.36×10^{-5}	5.76×10^{-5}

slope had the greatest influence in estimating the probability of bog occurrence in all models, followed by upslope area. Curvatures, with their near-zero values in the study areas, had the smallest relative influence on the calculated probabilities.

The model parameters calibrated at CRIPP and Eqn. (3), which represents the interaction between attributes at the probabilistic boundary between community types, were used to calculate the theoretical maximum substrate slope upon which blanket bog may exist. Under mean substrate conditions at CRIPP, i.e. 1233 m² upslope contributing area, a profile curvature of -8.624×10^{-5}, and a plan curvature of 7.306×10^{-5}, bog may exist on substrate with slopes of up to 0.065. Although the mean slope at the site was 0.037, the entire area was not covered by bog; either the upslope contributing areas were smaller, profile curvatures were more convex, or plan curvatures were more divergent than the mean values above, thereby reducing the maximum local slope upon which bog could exist. With supporting curvatures, even greater slopes may, theoretically, be occupied. With a contributing area as great as 3910 m² (mean + 1σ), profile curvature as concave as -2.309×10^{-3} (mean − 1σ), and plan curvature as convex as 1.590×10^{-3} (mean + 1σ), substrate slopes up to 0.074 can support the hydrological conditions necessary for blanket bog development, according to the model. For comparison, the actual maximum substrate slope measured for blanket bog at the CRIPP site was 0.071.

At BRIST, the mean substrate conditions resulted in a theoretical maximum substrate slope of 0.066. Improved conditions of one standard deviation allowed a theoretical maximum substrate slope of 0.070. The maximum slope observed in bog areas within the study area was also 0.071, confirming the similarity of the topographic relationships within CRIPP and BRIST.

Mean ground surface characteristics at ROCKY allowed a theoretical maximum ground slope of 0.065, whereas the improved conditions allowed a slope of 0.105, which was comparable to the observed bog maximum ground slope of 0.106. It appears that, although the attributes used in the ROCKY model and therefore the implied topographic structure at the ROCKY site differed from those at the Cape Race sites, the same degree of certainty about the topographic structure could be achieved.

The distribution of ROCKY's topographic characteristics often differed from the Cape Race sites, and the CRIPP model was not portable to ROCKY, though it was portable to BRIST. The use of ground surface shape rather than substrate characteristics greatly improved the accuracy of the predicted community pattern at ROCKY. Hence, the ROCKY area was more like an extensive slope bog, or a mix of blanket and slope bog, than a pure blanket bog. This possible difference in bog type was consistent with visual field observations at the sites. The topography of the Cape Race sites was gently undulating and generally homogeneous in its character. At ROCKY, the terrain was more variable in character. Outcrops of exposed bedrock and the presence of larger nearby hills gave the impression that the bog areas were filling the bottoms of gentle valleys.

Table 3. Propagation of measurement error to estimates of higher-order topographic characteristics, expressed in absolute units and as a proportion of the standard deviation measured at each site.

	Max. ELV Error	Proportion of GELV	Proportion of SELV	Max. SLP Error	Proportion of GSLP	Proportion of SSLP	Max. PFC Error	Proportion of GPFC	Proportion of SPFC
CRIPP	0.021 m	0.006	0.008	0.0042	0.146	0.167	0.00084	0.260	0.378
BRIST	0.021 m	0.006	0.014	0.0042	0.063	0.178	0.00084	0.166	0.375
ROCKY	0.021 m	0.008	0.010	0.0042	0.142	0.125	0.00084	0.208	0.132

The two regions also differ climatically. The amounts of annual precipitation recorded at Cape Race and Colinet, 1379 and 1432 mm respectively (AES, 1982), are marginally within the range required for blanket bogs, which is approximately 1400 mm (Tarnocai, 1980). However, additional input to the water balance at Cape Race by deposition of advected fog is significant (Price, 1992a) and, along with suppressed evaporation losses, creates hydrological conditions that are more favourable to blanket bog development. The bogs near Colinet, such as Rocky, do not have the advantage of significant fog water deposition, as the area lies outside the high fog frequency zone (Zoltai, 1988).

Although just enough water may be input into the Colinet area to support blanket bog, the losses due to higher temperatures and consequent evaporation are likely to tip the balance in the Colinet area towards conditions that are not conducive to true blanket bog development. The average temperature at Cape Race is 4.3 °C annually and 11.2 °C June to August (AES, 1982), which is similar to typical blanket bogs, i.e. 5.0 °C and 12.5 °C respectively (Tarnocai, 1980). At Colinet, the annual average temperature is 5.1 °C and the June to August temperature is 13.2 °C (AES, 1982). The higher temperature profile of Colinet is more comparable to a typical slope bog than a blanket bog, i.e. an average temperature of 5.0 °C annually and 12.9 °C June to August (Tarnocai, 1980).

Error analysis

The degree of error in the study data was estimated to determine its influence on the results of the analysis. Graniero (1996) described the full error analysis, and a summary is given here.

The published specifications for the Pentax PX-06D EDM theodolite indicate that the instrument has an expected elevation accuracy of ±0.021 m at average sighting distances measured in this study. Repeated long range measurement tests in the field suggested that this expected error overstates the actual error. Since more than one elevation is used to compute the topographic shape variables, the errors in elevation combine either to counterbalance one another or to amplify the error. Using the average expected surveying error of ±0.021 m, the worst combination of errors was used to calculate the maximum effect on slope and profile curvature (Table 3).

The maximum effect of elevation error on the predicted probabilities of the logistic regression model was calculated, using the substrate model for CRIPP and BRIST, and the ground surface model for ROCKY. Given the opposing signs of the curvature parameters in the CRIPP/BRIST model, the curvature errors will, on average, balance. This will not be the case in the ROCKY model, since both curvature parameters are similarly signed. Hence, elevation error will have an overall maximum effect of approximately ±0.12 on the probabilities predicted by the CRIPP/BRIST model, and approximately ±0.36 on the probabilities predicted by the ROCKY model.

Conclusions

1. Gentler slopes were more favourable as an influence for blanket bog development than was the influence of upslope area, which in turn was greater than that of curvature. In conditions of average upslope areas and curvatures, slopes up to 0.065 were favourable for blanket bog development. However, steeper slopes could, theoretically, be occupied by blanket bog if the water velocity were slowed by sufficiently large upslope contributing areas and/or a concave or convergent curvature.
2. The topographic conditions observed in some heath areas were predicted by the logistic regression model to be occupied by bog and often bog occurred in areas with those same topographic conditions. Since these areas are capable of supporting the hydrological conditions necessary for bog development, they are likely to be encroached upon by bog at some time. Hence, paludification has not stopped and the region has not reached a steady state in terms of topographic influence.
3. The community structure at CRIPP and BRIST is more clearly defined by substrate topography, whereas ROCKY is more strongly influenced by surface characteristics. Furthermore, the threshold topographic conditions defining the boundary between bog and heath are not as clearly defined at ROCKY. These two factors, identified by the logistic regression model, indicate the development of different types of bog complexes at the two sites.

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