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Spatial interrelationships between terrain, snow distribution and vegetation patterns at an arctic foothills site in Alaska

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A multidisciplinary approach combining field surveys, aerial photographic techniques, digital terrain modelling, and GIS technology was used to analyze spatial interrelationships at a study site in the northern foothills of the Brooks Range. The sensitivity of snow drifting to topography at the site is pronounced. The drift patterns indicate winter winds are predominantly from the south with a major secondary component from the southwest. These southwest winds are likely in conjunction with storm events. The deepest snow beds are found on the steeper, north-facing slopes. Snow also has an effect on vegetation that is evident at the scale of mapping (1:6000). Communities dominated by *Cassiope tetragona* are associated with deeper snow regimes, and may be useful indicators of deeper snow regimes even at much smaller scales because of their unique spectral signatures. The analyses conducted to date demonstrate the power of the GIS for analyzing terrain-geobotanical interrelationships, which will increase as we add new layers for other variables, and are able to correlate these with satellite data.

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Introduction

The "landscape ecology" is a useful method of evaluating spatial interrelationships between various ecosystem components. As defined by Risser et al. (1984), "landscape ecology considers the development and dynamics of spatial heterogeneity, spatial and temporal interactions and exchanges across heterogeneous landscapes, influences of spatial heterogeneity on biotic and abiotic processes, and management of spatial heterogeneity." Historically, many ecologists have conducted studies under the assumption that ecosystems are more or less homogeneous and, in some cases, at approximate equilibrium. Because of the spatial patterning of landscapes, however, flows and transfer among spatially-related components (e.g. terrain, vegetation, soils and hydrology) can take on special importance. The process of redistribution of materials, energy, and/or individuals among landscape elements is an essential feature of landscape ecology. Part of the problem in recognizing spatial dynamic processes has been the difficulty of collecting and analyzing the large volume of spatial data needed to describe complex land processes. Recent advances in remote sensing and computerized geographic information systems, however, now allow researchers to address these dynamic ecological processes.

In this paper, we examine the spatial interrelationships between landform geometry, snow distribution and vegetation patterns in the vicinity of the R4D study area (Fig. 1). Climatic data, aerial photographic techniques, digital terrain modelling, and GIS technology were combined in a multidisciplinary fashion to map and analyze spatial interrelataionships among these terrain variables.

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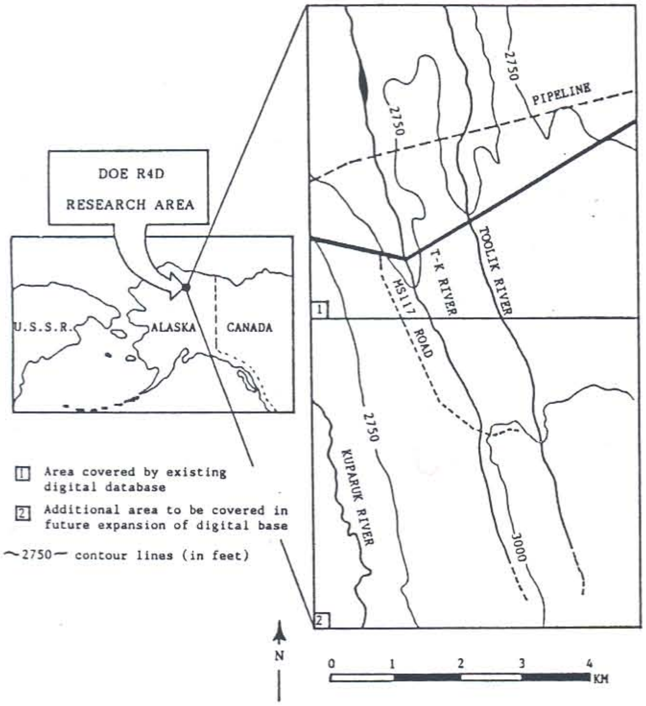


Fig. 1. R4D study area location.

The nature of a geographic information system

In situations where complex environmental relationships exist, data concerning different aspects of the physical environment can be used more effectively in combination than separately. A geographic information system (GIS) is a computerized database consisting of spatial information registered to some type of geographic coordinate system (e.g. latitude/longitude, UTM, State Plane, etc.) with software that permits complex spatial analyses, including facilities for inputting spatial (map or image) data, manipulating the data, and outputting various map and tabular products. Three of the primary functions of a GIS are the combination and evaluation of disparate spatial data sets for the purpose of providing "new" composite information, the production of high-quality maps, and the generation of statistical summaries.

In most GIS systems, data are stored using either a vector or grid-cell data structure. With vector-based systems, the geographic coordinates associated with points, lines or polygons that comprise a given feature are explicity stored. With grid-cell-based systems, the location of various map features are implicitly stored via a row/column (i.e. matrix) structure. Both vector-based and grid-cell-based systems have their advantages and disadvantages, which are often a function of their intended uses. In general, vector-based systems are better-suited for producing cartographic-quality output. Grid-cell-based systems, on the other hand, because of their similarity to algebraic matrices and FORTRAN arrays, are more amenable to mathematical modelling and statistical analyses.

For this study, both vector and gridded data have been compiled and analyzed. The vector-based applications were handled by the North Slope Borough's ARC/INFO system in Anchorage. Grid-cell-based applications were handled primarily by systems housed at the Office for Remote Sensing of Earth Resources at Penn State University.

Methods

Field work and aerial surveys

Topography

A photogrammetric survey was conducted during the summer of 1984 to ensure that geobotanical and snow features were accurately mapped in the study area. Fifty ground control points were surveyed and stereoscopic aerial photographs were acquired at several scales. As a result of these activities, orthophotos and topographic contour maps were created at scales of 1:6000 and 1:1000 with 5-cm and 2-m contour intervals, respectively.

Snow distribution

The distribution of snow across the area was determined using several techniques (Liston 1986). Snow depth was probed along selected traverses, and pit studies were made to examine extremes of snow types. Photographs of the ground were taken with automatic cameras (both 35 mm black and white cameras and 8 mm color movie cameras) set up to record the progression of snow melt. Oblique aerial photographs were also taken from a light aircraft. From this combination of air and ground photographs, as well as measurements of snow properties, several snow cover maps were made. These maps, in turn were used to prepare maximum snow water equivalence maps for two consecutive snow seasons.

Vegetation

The vegetation, terrain units, and other surface features existing at the R4D research site were mapped at a scale of 1:6000 using an integrated mapping approach developed for tundra ecosystems in northern Alaska (Walker et al. 1980, Walker 1983, Walker et al. 1989). Intensive geobotanical surveys were conducted during the summers of 1984 and 1985. The vegetation was classified into separate community types using sorted table analysis procedures described by Mueller-Dombois and Ellenberg (1974). These community types were grouped into units that are appropriate for airphoto interpretation at a scale of 1:6000. These photo-interpreted units correspond to Level B of the hierarchical approach of Walker and Acevedo (1987).

The results of the intensive ground surveys were used in subsequent airphoto interpretation conducted for the purpose of preparing geobotanical maps of the entire site. During this phase, 1:6000-scale maps were prepared using mid- and low-altitude color infrared aerial

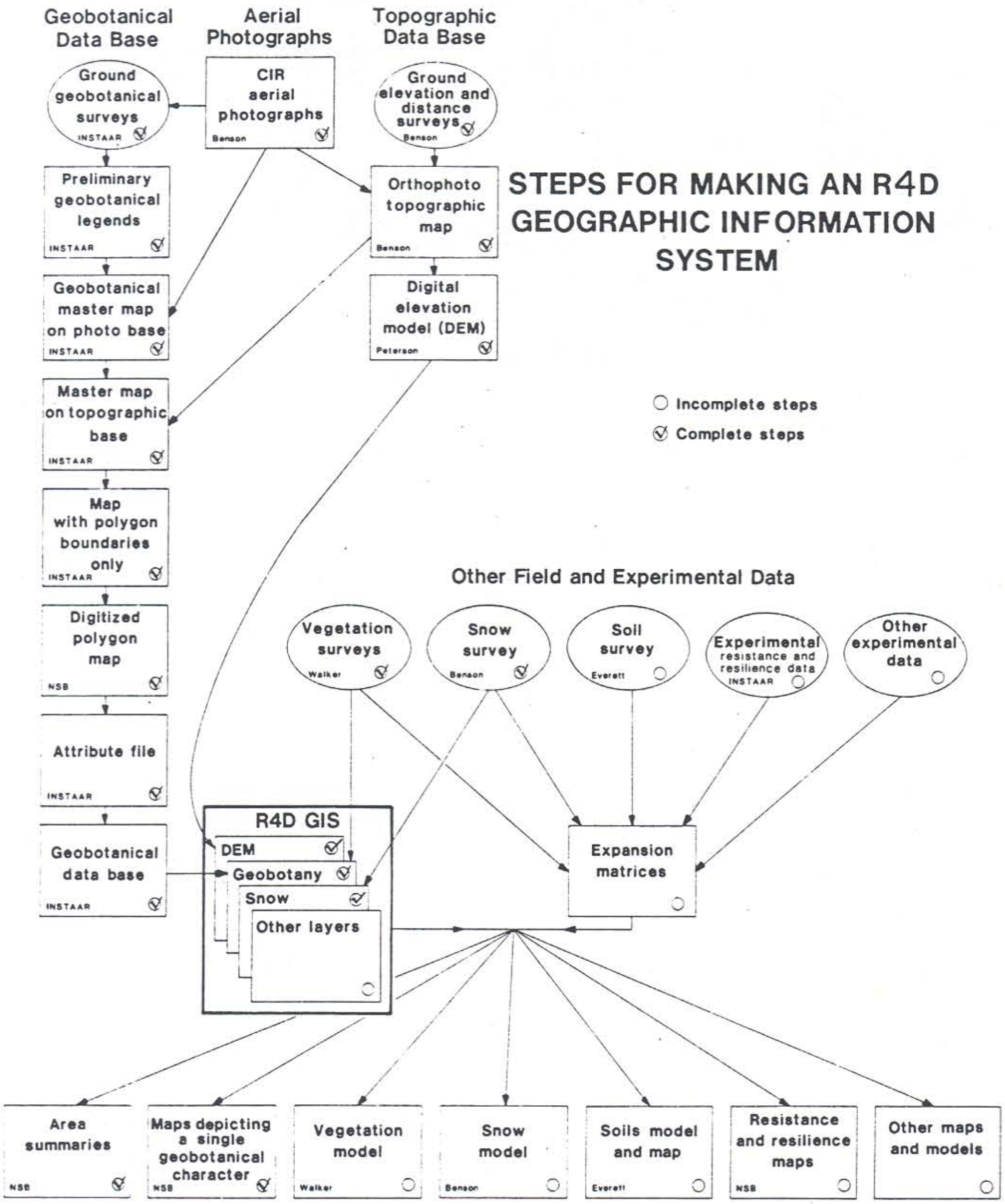


Fig. 2. Flow diagram depicting the primary steps for creating the R4D geographic database.

photographs. More detailed descriptions of the vegetation sampling and geobotanical mapping methods employed are provided by Walker et al. (1987a and 1987b), and descriptions of the terrain, vegetation, and geobotanical maps are in Walker et al. (1989).

Description of the digital geographic database

Fig. 2 is a flow diagram depicting the primary steps for developing the R4D digital database. Maps produced as a result of the field and aerial photographic work were digitized using manual and scan digitizing techniques, and were subsequently compiled in both vector and grid-cell formats. Topographic data were generated by first digitizing the elevation contours on the 1:6000-scale topographic map of the area, and then applying grid interpolation routines to this digital data to create gridded elevation, slope, and slope aspect data sets.

Most of the digital spatial analyses described in this paper were performed using the grid-cell database. Fig. 3 is a three-dimensional image of the study area (as viewed from the southwest) created with the digital elevation data, and Fig. 4 depicts the average two-year snow water equivalence for the same area. The vegetation map is in Walker et al. (1989).

The statistical analyses were performed using the grid-cell database. This database, which covers about 22 km^2, is composed of 442 rows and 458 columns for a total of 202 436 cells. Each cell represents an area of approximately 0.01 ha. Included in this database are layers depicting elevation, slope, slope aspect, snow distribution (snow water equivalence), primary (or dominant) vegetation, secondary vegetation, tertiary vegetation (secondary and tertiary vegetation are subdominant types that must cover at least 30% of a given map polygon), percent open water, landform, surface form, and terrain units.

Only slope, slope aspect, snow distribution, and pri-

Fig. 3. Perspective view of study area created with digital elevation data.

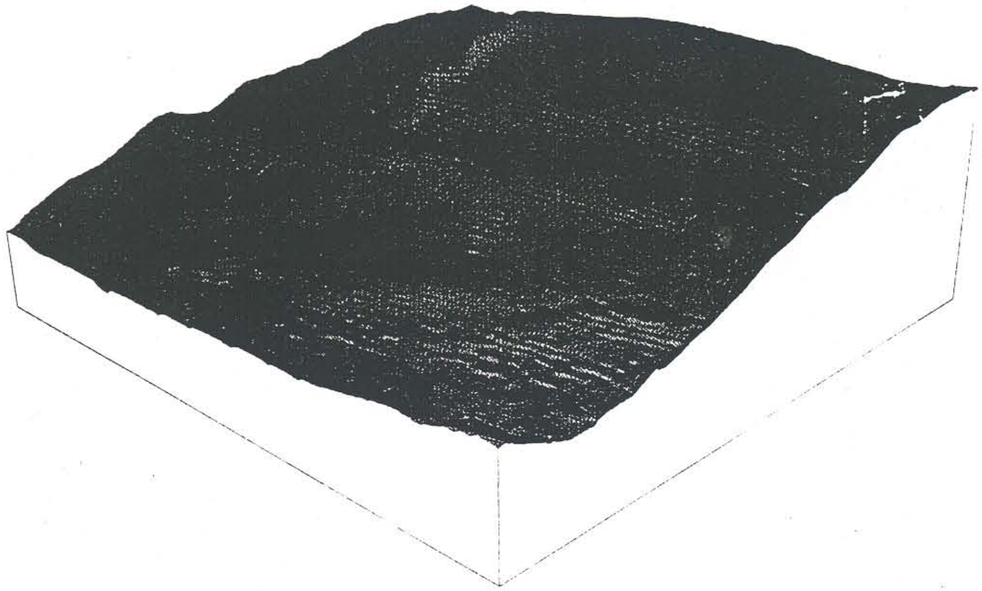
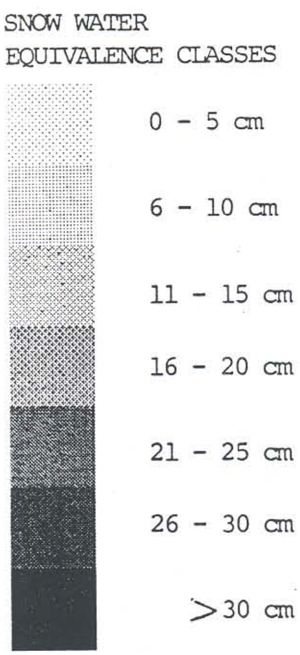


Fig. 4. Snow water equivalence map created from average 1985 and 1986 snow depth data.



mary vegetation data layers were used for the statistical analyses referred to in this paper (see Tab. 1 for synopsis). Additional descriptions of the vegetation and terrain classification systems utilized for the area are given by Walker et al. (1987b).

Statistical correlation methods

Frequency analyses were conducted to quantitatively determine the spatial coincidence between paired data layers. Specifically, a crosstabulation procedure was used to produce two-way contingency tables between

Tab. 1. Distribution of slope, slope aspect, snow depth and vegetation types within the study area.

Vegetation Type*	% in Area	Slope Class	% in Area	Aspect	% in Area	Snow Depth Class	% in Area
D1a,b	0.87	0– 3%	25.91	E	5.33	0– 5 cm	1.07
D1c	6.59	4– 8%	47.15	NE	13.73	6–10 cm	48.99
D1d	0.15	9–15%	25.37	N	6.12	11–15 cm	45.53
D1e,f,g	10.63	16–25%	1.52	NW	9.61	16–20 cm	2.03
D2	0.22	25%	0.05	W	38.14	21–25 cm	0.69
D3	0.59			SW	12.37	26–30 cm	0.62
M1a,b	0.36			S	0.56	30 cm	1.07
M2a,b,c	54.71			SE	0.89		
M3a,b	3.80			Flat	13.25		
M4a	4.86						
M4b,c,d	4.30						
W1a,b,c	3.53						
W2a,b,c	4.35						
W3	2.95						
A1a,b,c	0.09						
A1d	0.12						
A1e	0.02						
A2	0.69						
U	1.18						

* see Walker et al. (1989) for explanation of these codes.

paired data sets (e.g. snow distribution vs slope). These types of tables show combined frequency distributions for two or more variables, and are often used to estimate the degree of correlation between variables contained in separate data sets. One of the advantages of using high-resolution data contained in a geographic database is that one can assume (especially for relatively large geographic regions) that the data represent a population rather than a sample extracted from it. In the statistical analyses conducted for this study, all of the data (i.e. over 200 000 observations for each variable) were utilized in each bivariate analysis.

Most of the data analyzed for this site are categorical or count data rather than continuous data (Tab. 1). Accordingly, the observation frequencies for classes within each data layer display a nonsymmetrical distribution. Chi-square and correlation analyses were performed to test for the significance of correlations found between paired data sets on the basis of the cross-tabulation results.

Results

The map area is dominated by west-facing slopes (38.1% of the map area, upper left of Fig. 5). Flat, southwest-, northwest-, and northeast-facing slopes are moderately distributed (13.3%, 12.4%, 9.6%, and 13.7%, respectively). North- and east-facing slopes are relatively uncommon (6.1% and 5.3%, respectively), and south- and southeast-facing slopes are rare, covering only 0.6% and 0.9%, respectively.

Slopes in this location range from short, steep slopes on sandstone outcrops of the Fortress Mountain formation (Brosge et al. 1979) to relatively flat floodplain areas, and the elevation varies from about 750 to 1000 m. Although slope steepness ranges from 0 to 31%, the topography is primarily rolling to moderately steep as less than 2% of the site is covered by slopes greater than 15%.

With regard to snow depth, the map area is dominated by two snow water equivalence classes (6–10 cm and 11–16 cm) (Fig. 6). These two categories cover 94.5% of the site. Shallow snow areas (0–5 cm) cover 1.1% and snow deposition areas (>16 cm water) 5.4% of the map area.

Comparison of the distribution of vegetation types according to slope aspect (Figs 7a–7d) shows two of the dry dwarf-shrub, fruticose-lichen types (*Dryas octopetala* and *Vaccinium uliginosum*) concentrated on south- and southwest-facing slopes, whereas *Cassiope tetragona* or *Salix rotunifolia* dominated communities occur primarily on north- and northwest-facing slopes. Most of the moist and wet types do not show clear preference for specific slope aspects, and the aquatic types occur preferentially in flat areas.

Most dry vegetation types appear to be distributed mainly in the lower snow classes (1–10 cm water) (compare Fig. 6 with Fig. 7e) and in the deep snow classes associated with steep, north-facing slopes. With some exceptions, moist and wet vegetation types appear to reflect the distribution of snow classes for the entire map area, although the wet types are associated with somewhat deeper snow (compare Figs 6 and 7g). The aquatic vegetation types occur predominantly in areas having moderate snow depths.

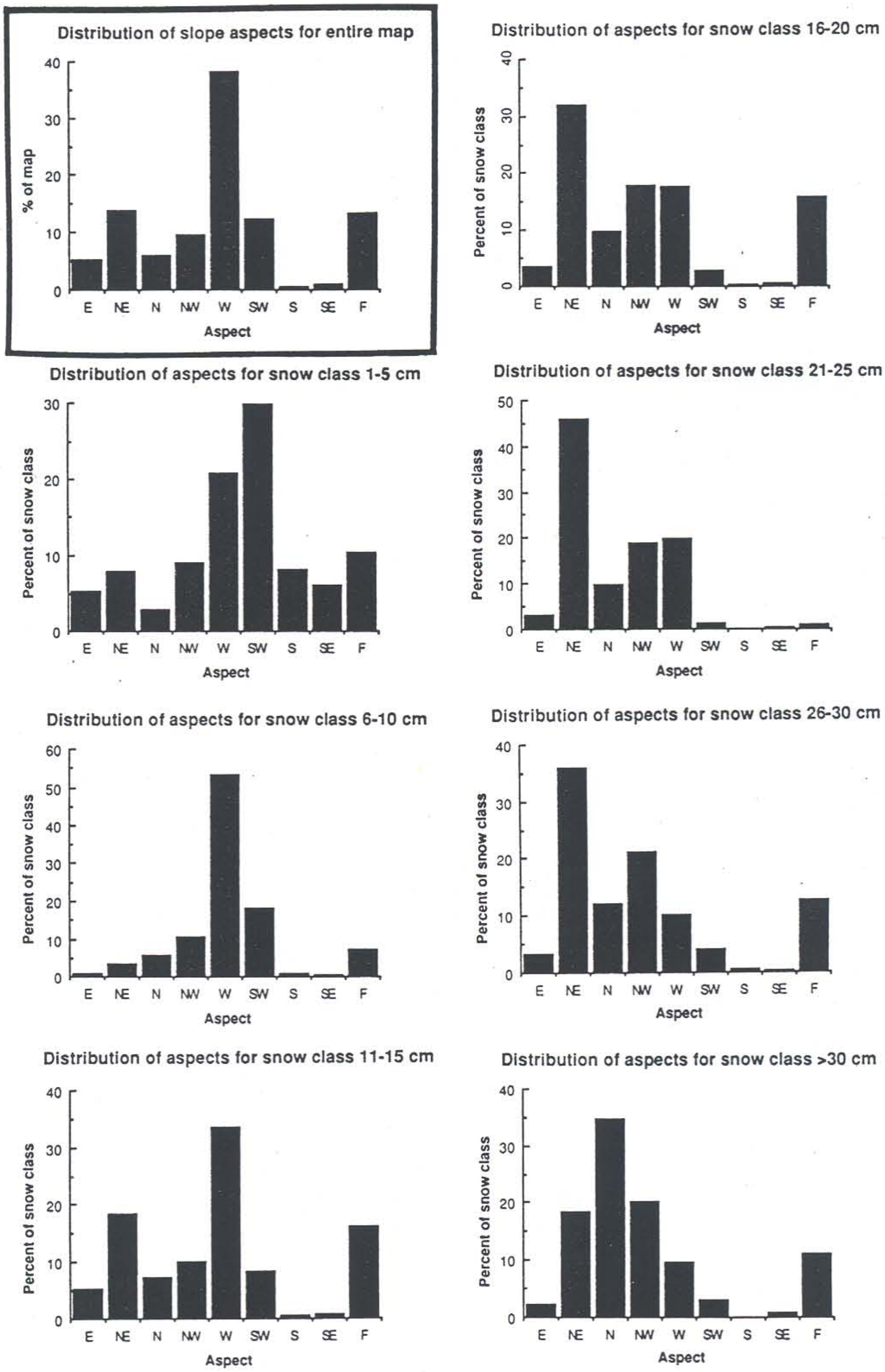


Fig. 5. Distribution of slope aspect and snow depth for the study area.

Discussion

Snow distribution and topography

The sensitivity of snow drifting to topography in the study area is pronounced. In general, snow is thickest on northern slopes and thinnest on southern slopes (Fig. 5). Snow ranging from 0 to 5 cm in snow water equivalence occurred more frequently on south-, southeast-, and southwest-facing slopes. Snow ranging from about 11 to 15 cm of snow water equivalence was not related to slope aspect, and closely mirrored the distribution of slope aspects for the entire site. The deeper snow (with the average two-year snow water equivalence ranging from about 16 to well over 100 cm) was more prevalent on north-, northeast-, and northwest-facing slopes (see Fig. 5). This was particularly evident near the sandstone

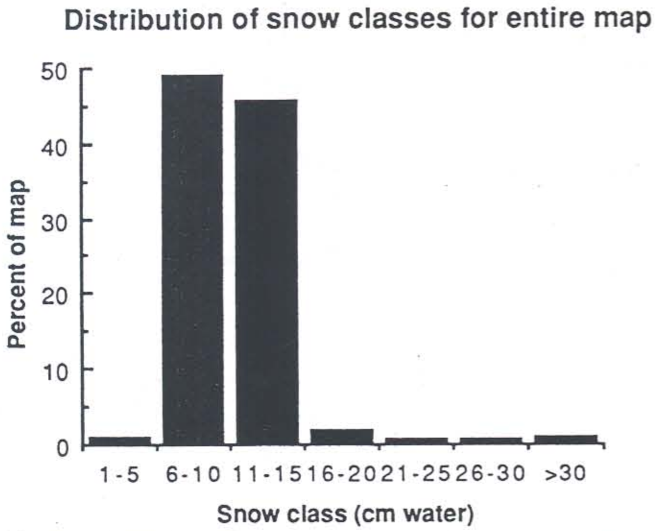


Fig. 6. Distribution of snow depth classes for the study area.

outcrops at the site. In this case, the windward (i.e. south-facing slopes leading up to the outcrops were generally blown clear of snow whereas the northfacing lee slopes had some of the largest drifts in the area.

The distribution patterns for the snow depth classes (Fig. 5) clearly show deeper snow being deposited on slopes having two primary aspects. The deepest snowbanks (>30 cm water) occur predominantly on north-facing slopes. Snowbanks of moderate depth (between 16 and 30 cm water) occur most often on northeast-facing slopes. Slopes facing these two directions also happen to be some of the steepest slopes in the area.

The deep snowbanks on north-facing slopes are a result of moderate catabatic winds that blow out of the Brooks Range during most of the winter (Liston 1986). The predominance of southerly winds near the northern front of the mountains contrasts sharply with the easterly winter winds that predominate along the arctic coast (Brower et al. 1977). The boundary on the North Slope between predominantly southerly winds and predominantly easterly winds is not well known, but it is clear that the southerly winds do not extend far north of the Brooks Range (Dingman et al. 1980). Wind data collected at the R4D site during the winter of 1985–1986 (Kelly and Foster 1986) (Tab. 2) show a predominance of winds from the southeast and south, with total winds from east-southeast to south equal to 43.2% of the total wind observations. About 23% of the observations were from the south-southwest, and 13% of the observations were from the north-northeast to east.

The snowbanks on the northeast-facing slopes are relatively shallow compared with snowbanks on the north-facing slopes, and are attributed to winds from the southwest. In the autumn of 1986 and 1987 strong winds occurred from the southwest in conjunction with major snowstorms that deposited deep snowdrifts on the northeast-facing slopes (K. R. Everett, pers. comm.). These drifts melted before the onset of winter, and it is not presently known if this same wind direction accompanied mid-winter storms. However, Conover (1960), Benson (1969) and Benson et al. (1975) have shown that although winter winds on the coastal plain are predominantly from the northeast, major snowfall events are often accompanied by stronger winds from the west, thereby resulting in the formation of deep snowdrifts on east-facing slopes. It thus appears likely that these westerly storm winds also occur near the front of the Brooks Range.

In summary, at the R4D site, storm winds appear to be responsible for moderately deep snowdrifts on steep, northeast-facing slopes, and southerly winds are responsible for redistributing the snow to form snowbanks on steep, north-facing slopes. This is in marked contrast to the coastal plain where winds from the east redistribute the snow.

Primary vegetation and snow distribution

The location of several vegetation types is clearly correlated with snow depth, and thus indirectly reflects the wind patterns. For example, moist dwarf-shrub, fruticose-lichen tundra (*Cassiope tetragona* or *Salix rotundiflora*) has 53.3% of its occurrences in areas with greater than 30 cm of snow water equivalence (Fig. 7e), although only 1.1% of the total map area is in this snow class (Fig. 6). The location of aquatic sedge marsh, aquatic grass marsh, wet sedge tundra, and wet sedge, dwarf-shrub, moss tundra coincides closely with moderately deep snow (from about 6 to 20 cm), a likely consequence of their primary locations in colluvial basins and stream drainages.

There are also distinct patterns related to low snow areas. Dry dwarf-shrub, fruticose-lichen tundra (*Dryas octopetala*) has 17.6% of its occurrences in the lowest snow class (0–5 cm snow water) (Fig. 7e), but only 1.1% of the area is covered by this snow class. This same vegetation type, however, has a relatively high percentage of its occurrences (11%) in the >30 cm class. This result is at odds with field observations which indicate this vegetation type does not occur in deep snowbeds. It does, however, occur in close proximity to deep snowbanks, such as where small wind-blown knolls are interspersed with snow accumulation sites between the knolls. The apparent presence of this vegetation type in deep snowbeds is likely due to two factors that are related to the mapping process: (1) the *Dryas*-dominated vegetation may be overrepresented on the map to include relatively narrow bands of snowbed vegetation around the margins of wind-blown sites and (2) the snow map may not have the same level of spatial resolution in areas of complex topography as the vegetation map.

Significance of the study

This study is the first analysis of snow and wind distribution patterns in the Foothills Physiographic Province,

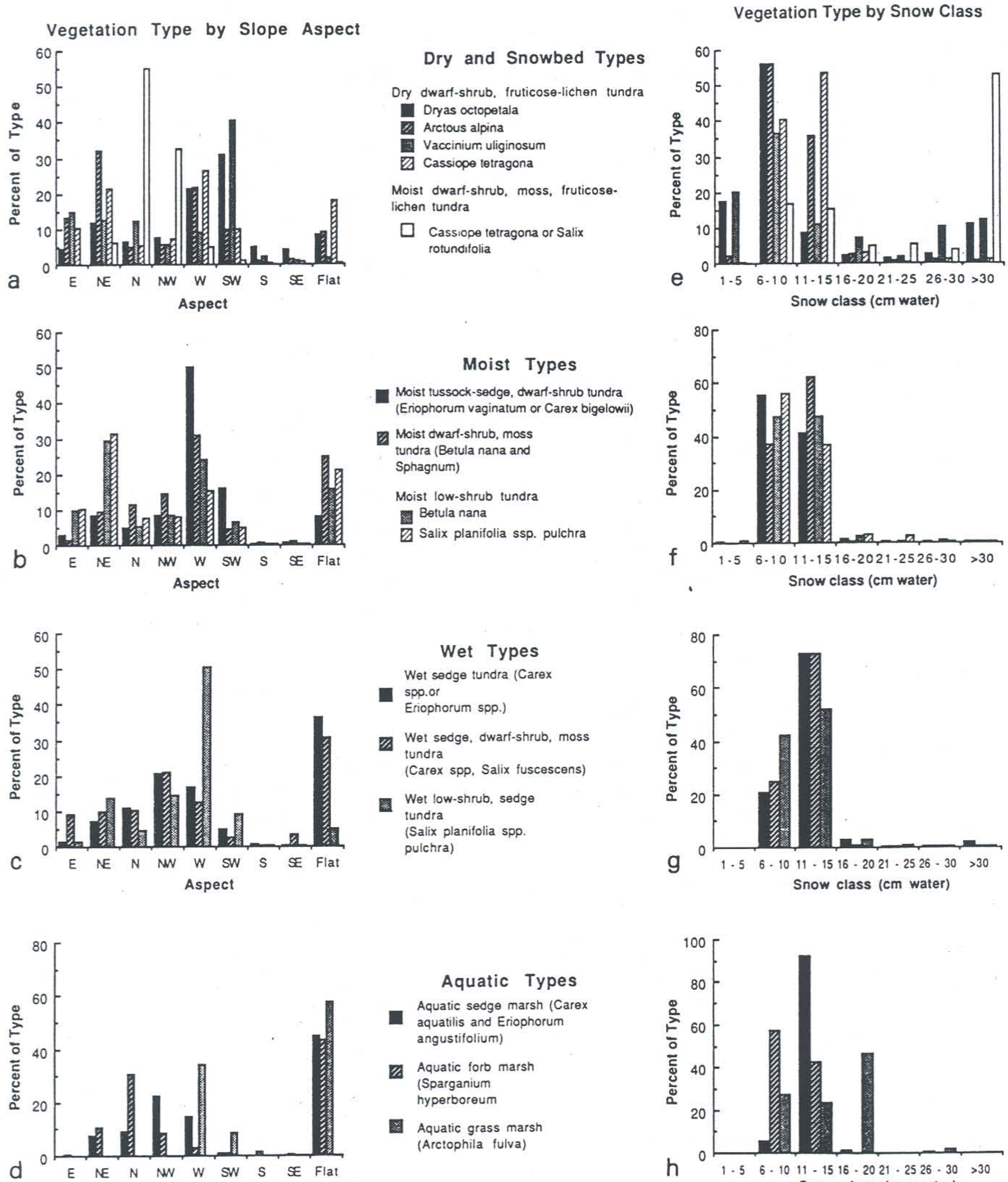


Fig. 7. Distribution of primary vegetation types for the study area.

and it reveals patterns that are distinct from those described on the Coastal Plain (Benson et al. 1975). It also represents the first attempt to correlate vegetation and snow at the landscape level.

The study revealed snow distribution patterns that were not readily apparent during field observations or in the first analysis of the wind data. The strong correlation between deep snowbeds and *Cassiope*-dominated dry dwarf-shrub, fruticose-lichen tundra is striking and could provide a useful tool for interpreting snow regimes based on 1:6000-scale summer aerial photographs. *Cassiope* has a distinctive spectral signature on

Tab. 2. Direction of winds, September–May, 1985–1986.

	Percent of observed winds										
	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Total observ.	% total observ.
N	1.4	0.3	0.3	No data	1.0	0.0	1.6	1.1	5.4	64	1.6
NNE	1.1	1.1	0.3	– –	1.1	1.0	1.6	2.4	4.0	73	1.8
NE	1.1	2.0	1.2	– –	2.1	1.0	4.0	1.4	6.9	100	2.5
ENE	4.3	3.6	1.8	– –	4.8	2.1	2.4	3.5	4.2	150	3.7
E	2.5	3.6	2.1	– –	13.1	4.4	4.8	3.8	5.7	208	5.2
ESE	5.1	3.5	10.4	– –	22.3	11.4	0.8	8.1	11.2	374	9.3
SE	10.7	6.5	23.1	– –	17.0	19.2	1.6	19.0	14.9	554	13.8
SSE	11.1	6.1	10.2	– –	6.5	11.8	1.6	9.7	10.6	364	9.0
S	19.6	10.3	15.3	– –	5.7	12.1	3.2	11.5	7.3	447	11.1
SSW	7.6	5.0	6.9	– –	6.9	7.8	16.7	9.6	2.7	277	6.9
SW	4.4	6.5	4.3	– –	4.6	7.0	16.7	7.5	2.5	233	5.8
WSW	5.6	10.3	9.7	– –	2.7	8.2	12.7	3.2	2.4	229	5.7
W	8.8	5.3	7.6	– –	2.3	7.8	4.0	2.2	3.9	203	5.0
WNW	3.4	3.2	1.0	– –	1.3	0.8	10.3	3.5	4.0	124	3.1
NW	2.5	2.2	0.2	– –	1.7	0.2	4.0	1.4	1.5	69	1.7
NNW	1.0	1.1	0.2	– –	1.7	0.2	4.0	0.8	4.8	68	1.7
Calm	9.3	29.4	5.4	– –	5.3	5.3	10.3	11.4	8.3	491	12.2
No. observ.	720.0	739.0	607.0	– –	525.0	527.0	126.0	720.0	672.0	4029	100.0

aerial photographs that is evident even at a scale of 1:6000. Large areas of vegetation dominated by *Cassiope* and other ericaceous plant species have been noted during ground surveys for Landsat mapping of other areas in the foothills of the Brooks Range (Walker and Acevedo in press). These areas, which are large enough to appear on Landsat images of the region, may be indicative of locally deep snow. Snow surveys in such areas could help determine the value of using vegetation patterns as a key to regional snow regimes.

The use of GIS technology to analyze topography, snow, and vegetation demonstrates the power of an integrated approach to analysis of arctic landscapes. The power of the system will increase in the near future as we add new layers to the GIS database, including summer thaw depths, soil types, biomass and reflected radiation measurements, and are able to correlate these with spectral and spatial data acquired from satellites.

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