

Alpine Vegetation Communities and the Alpine-Treeline Ecotone Boundary in New England as Biomonitors for Climate Change

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Abstract—This study mapped and analyzed the alpine-treeline ecotone (ATE) boundary and alpine plant communities on the Presidential Range, New Hampshire and Mount Katahdin, Maine. These are sensitive biomonitoring parameters for plant community responses to climatic change. The ATE boundary spans a considerable elevational range, suggesting that shorter growing seasons with increasing elevation only partially explain the upper limits for this boundary. This ecotone boundary may be influenced by topographic exposure factors related to mechanical damage caused by winter ice events and wind. Climatic changes that alter cloud frequency, wind, precipitation and ice loading at the upper elevations could influence shifts in the ATE boundary.

The ecological and societal implications of major geographic shifts in vegetation as a response to climatic change are profound. There are many competing hypotheses about whether climatic change is occurring and the reasons for it. These include natural events such as variations in solar irradiation (Karlan 1998) to the increased accumulation of greenhouse gases of anthropogenic origin (Gates 1993). The long-term objective of the National Oceanic Atmosphere Administration's (NOAA) Climate and Global Change Program is to provide reliable predictions of global climatic change and associated regional implications on time scales ranging from 10 to 100 years. This study establishes a biomonitoring baseline for plant community shifts due to climatic variability, based on the alpine-treeline ecotone (ATE) boundary in the Northeast. Long-term climatic conditions have altered since the retreat of the Pleistocene glaciers and climatic changes will continue to affect the ecotone boundary between the alpine zone and treeline in this region.

In the United States east of the Mississippi River, alpine habitat is currently a relatively rare habitat, occurring mostly as isolated islands on higher peaks. In total, it is estimated to occupy at most about 34 km². The majority of this alpine habitat is located on New Hampshire's Presidential Range (11.3 km²), and Mount Katahdin, Maine (7.3 km²) (fig. 1). The remaining Eastern alpine areas are limited to

several hundred hectares or less in size in northern New York, Vermont, New Hampshire, Maine and southward along the Appalachian Mountain Range. There are characteristics that make northeastern "alpine" mountains suited to the monitoring of vegetation responses to climatic change. They are mostly in public ownership and have relatively undisturbed histories. Their alpine plant communities have been relatively stable for extended periods of time because the dominant species are mostly long-lived perennials. The isolated nature of these particular alpine zones limits disease and herbivore impacts. Proximate weather data are also available to describe existing climatic conditions.

Spatial Changes in the Alpine-Treeline Ecotone as a Barometer of Climatic Change

Spatial changes in the ATE boundary and the alpine vegetation communities have the potential to be sensitive indicators of vegetative response to climate change. In 1941, Griggs (1942) gave an address at a "Symposium on Alpine Ecology" to the Ecological Society of America, in which he

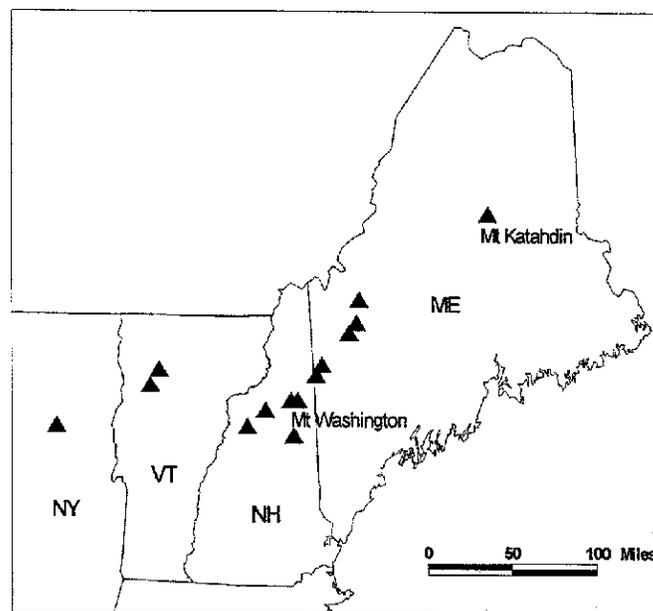


Figure 1—Study area and alpine areas in the northeastern United States.

In: McCool, Stephen F.; Cole, David N.; Borrie, William T.; O'Loughlin, Jennifer, comps. 2000. Wilderness science in a time of change conference—Volume 3: Wilderness as a place for scientific inquiry; 1999 May 23–27; Missoula, MT. Proceedings RMRS-P-15-VOL-3. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

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reviewed the dynamic history of treeline on Mount Washington, New Hampshire since glacial retreat. His concern was the change in the climate towards a repeat of colder conditions again causing a “further” retreat of treeline on this mountain. Today, more than a half century later, changes in our earth’s atmosphere create the possibility of a very different scenario, global warming due to ‘greenhouse’ gas emissions.

Temperature-limited environments, such as boreal and arctic regions, are thought to be very sensitive to global warming. Grabherr and others (1994) reported an upward elevation migration of the alpine-nival (uppermost) flora from their 1992 field work in the mountains exceeding 3,000 m of western Austria and eastern Switzerland, compared to 70–90 years before, a change they linked to climatic warming. They concluded that an upward altitudinal shift in the alpine vegetation belt could theoretically be occurring at a rate of 8-10 m per decade. Myneni and others (1997) reported increased plant growth from 1981 to 1991 in the northern arctic latitudes and related it to increased CO₂ levels and warmer temperatures. Similarly, Gottfreid and others (1998) hypothesized that the alpine-nival ecotone boundary in the European Alps will probably be affected by climatic change, but that the vegetation patterns at this interface zone will also be related to topographic relief.

Relationship of Alpine Vegetation Communities to Topographic Exposure Factors

Topographic relief can modify a mountain’s climate considerably. In Northeastern alpine areas, topographic features of exposure may interact with climate as a dominant factor in treeline and the distribution of alpine plant communities. Climate change probably takes place more quickly than major overall topographic changes on Northeastern mountains. Climate change could, therefore, significantly alter the distribution of alpine plant communities. Determinants for the distribution of alpine plant communities and the ATE boundary should include climate, as well as topographic features of exposure including elevation, aspect, slope and slope shape, e.g. concavity (valley) or convexity (ridge). Clearly, there are other factors as well, including edaphic conditions and the biogeography of species in island habitats.

The Presidential Range is located at the convergence of weather derived from three different air masses, which give rise to frequent cloud events and strong winds. For the Presidential Range, the frequency of clouds by elevation commonly approximates the treeline boundary. The summit of Mount Washington is in the clouds over 55% of the time. During the winter, rime ice deposition, caused by enshrouding clouds propelled by strong winds, can give rise to heavy mechanical loading and subsequent damage to the vegetation. Blowing snow on the mountains has considerable abrasive action before it is blown off the more exposed alpine zone and deposited in the ravines and snowfields.

Bliss (1963) attributed the distribution of nine plant community types on Mount Washington to two gradients: 1) an increasing snow depth and late spring melt gradient,

and 2) increasing summer atmospheric and soil moisture and fog. Bliss suggested that these moisture gradients are strongly influenced by topographic features of aspect and elevation. The first objective of this study is to quantify the availability of different topographic features and how they relate to the frequency and distribution of different alpine plant communities on the Northeast’s higher mountains. A second objective is to better understand how the ATE boundary and alpine plant communities, as biomonitoring parameters, may respond to climatic change.

Study Sites

Protected within the White Mountain National Forest, the highest peak of the Presidential Range is Mount Washington, at 1917 m. Though the alpine zone of this range has seen considerable human use over two centuries (Randall 1983), it is still relatively undisturbed. It is the largest and most ecologically diverse alpine zone in the Northeast. The Great Gulf and Presidential Dry River Wildernesses extend upwards into this alpine zone. There have been earlier studies on vegetation patterns and forest migration on the lower slopes of the Presidential Range (Foster and Reiners 1983; Leak 1975; Leak and Graber 1974; Kimball and Keifer 1988; Worrall and Harrington 1988); Spear’s (1981) attempt to reconstruct the post-glacial changes in the high-elevation vegetation also provides considerable insight. Although logging occurred on the lower slopes at the turn of the century (Belcher 1980), the upper slopes of the Presidential Range for the most part were not logged due to difficult access.

The weather has been well documented on Mount Washington’s summit; meteorological observations occurred there from 1870-1887 and then in summer only until 1892. Daily weather observations have now been taken since 1933 by the Mount Washington Observatory. The Appalachian Mountain Club has also maintained a weather station on the eastern slope at 620 m since 1933. Both sites are part of the National Weather Service network.

The Mount Katahdin Range lies within Baxter State Park with Mount Katahdin as its highest peak at 1605 m. This State Park is managed under a forever “natural wild state” mandate according to the wishes of its donor, Governor Percival Baxter. Similar to the Presidential Range, timbering encroached on the lower slopes of the Kathadin Range prior to its purchase in 1930 (Clark 1996), but the upper slopes were less affected (Hudson and others 1985). A meteorological record does not exist for Mount Katahdin and must be inferred from surrounding low-elevation monitoring sites.

Methods

Field Mapping

The subalpine and alpine vegetation communities of the Presidential Range were field-mapped during 1991-1993. Seventeen, uncorrected, color aerial photographs (Aug. 19, 1978 at 1:12,000 scale, then enlarged to 1:5,000) were used as the mapping base layer. In the field, mappers outlined and coded the dominant vegetation community types on the mylar-covered photos. The minimum mapping unit was 100 m². Vegetation community classifications were krummholz,

Table 1—Area for each community type within the alpine zone for the Presidential and Katahdin Ranges.

	Presidential Range		Katahdin Range	
	Area (ha)	% total	Area (ha)	% total
Krummholz	73	7	23	3
Birch-alder	2	<1	6	1
Heath-shrub-rush	115	10	245	34
Cushion-tussock	94	8	34	5
Sedge meadow	80	7	2	<1
Herbaceous snowbank	3	<1	4	1
Fellfield	759	67	312	43
Cliff	N/A	—	102	14
Other	6	1	0	0
Total	1132	100	728	100

birch-alder, fellfield, sedge meadow, heath-shrub-rush, herbaceous snowbank and cushion-tussock. The dominant plant species and a comparison to related natural community nomenclature in the literature are given in table 1.

Field mapping on the Mount Katahdin Range was conducted during 1998 using 1991 color infrared, aerial photographs (1:40,000 scale, then orthorectified to a scale of 1:3,000). Vegetation community classification units were the same as those from the Presidential Range, with the exception of an additional cliff category.

Vegetation Mapping and Orthorectification

For the Presidential Range, vegetation polygons were digitized in vector form using Atlas Draw, and rasterized to 3 m pixels in IDRISI. Geometric rectification of these vegetation maps was necessary. To orthorectify the Presidential Range vegetation maps, latitude, longitude, and elevation of ground control points were collected with a global positioning system, and with United States Geological Survey Digital Elevation Model (USGS DEM) data run through an orthophoto procedure. Orthorectification accuracy of the Presidential Range vegetation maps (aerial photos) is estimated to be 15 m. Katahdin Range vegetation polygons were digitized with CartaLinx and rasterized to 3 m pixels, similar to the Presidential Range study.

In this study, krummholz and birch-alder occur in both the subalpine and alpine zone. We define the lower limits of the subalpine forest as areas where the trees are less than 2.5 m in height. Accurately mapping the lower elevation subalpine forest boundary was problematic: It was difficult to define the boundary where trees were 2.5 m high, and the field mappers were unable to accurately locate themselves on the aerial photos in the dense cover. Reference points along hiking trails and other easy access points were used to define the lower subalpine forest zone, and professional judgement was used to interpolate.

Where birch-alder and krummholz community types abut or merge with the true alpine zone and extend down into the subalpine forest, we arbitrarily excluded them and used their uppermost limit as the start of the alpine zone boundary for purposes of calculating the area of the alpine zone. If these community types were totally enclosed within the alpine zone, they were included as alpine. Where cliff and

fellfield were totally contained within the subalpine zone, they were included as part of the subalpine zone.

DEM and Environmental Variables

The 30 m USGS DEM images used for the Presidential Range were resampled to 3 m pixels using nearest neighbor calculation. The DEM source data contained “streaking” artifacts in the data. We tried a filtering command within IDRISI to enhance the source DEM data. This did not completely remove the artifacts within the source DEM data and, unfortunately, eliminated extreme values like steep slopes. Therefore, we used the DEM data without filtering.

The elevation model for the Katahdin Range was based on source USGS 1:24,000 contour data and constructed into a DEM with a pixel resolution of 10 m by James W. Sewall Company, which we resampled to 3 m.

The vegetation layers were geo-referenced with four environmental variables derived from Digital Elevation Model (DEM) data—elevation, aspect, slope percent and slope shape (concave to convex). These parameters are assumed to be important exposure factors that influence microclimate and alpine plant distribution. Elevation comes directly from the DEM, while aspect and slope percent were generated with the IDRISI SURFACE command (Eastman 1992).

The slope shape is a relative index that estimates concavity and convexity across 570 meters on the ground. It was calculated by applying a convolution filter to the DEM image with a 191 x 191 pixel kernel that had -1 as the coefficient at the N,S,E and W positions in the kernel (the middle of each side), 4 at the middle (target pixel), and 0 everywhere else, with a gain of 0.08772. The resulting values represent the average of the slope percentage from the target pixel in each of the four compass directions at a distance of 285 m. Negative values represent increasing concavity (valley), positive values represent increasing convexity (ridge), and a plane is represented by a zero value.

Statistical Analysis

For each alpine plant community and the entire study area, total area, as well as mean, standard deviation, minimum and maximum elevation, slope percent and slope shape were calculated. A common but often incorrect practice in the ecological literature is to treat aspect as a linear variable, instead of a circular variable. This treatment of aspect can result in incorrect results (for example, the average aspect for 350 and 10° should be 0°, not 180°). To alleviate this problem, we used circular statistics (Batschelet 1981) to calculate the mean angle and mean angular deviation (equivalent to the standard deviation of linear statistics) for aspect; minima and maxima appropriately were not calculated.

The distributions of elevation, slope percent and slope shape for each alpine plant community were compared to their total available distribution across the entire study area, using Kolmogorov-Smirnov two sample tests (SYSTAT 1996) to determine significant differences. The aspect data was placed into eight groups (N, NE, E, etc.) to moderate a bias towards all multiples of 45 degrees generated by the IDRISI aspect model. A chi-squared test was performed

comparing the grouped aspect distribution of each alpine plant community against the available grouped distribution.

Results and Discussion

Alpine Plant Communities

The Presidential Range subalpine and alpine zone covers 2,748 ha: subalpine and alpine krummholz (1,351 ha, 49%), fellfield (867 ha, 32%), birch-alder community (226 ha, 8%), heath-shrub-rush (115 ha, 4%), cushion-tussock (94 ha, 3%), sedge meadow (80 ha, 3%), and herbaceous snowbank (3 ha, <1%). The Mount Katahdin Range covers 1,697 ha: subalpine and alpine krummholz (723 ha, 43%), fellfield (349 ha, 21%), heath-shrub-rush (245 ha, 14%), birch-alder (219 ha, 13%), cliff (117 ha, 7%), cushion-tussock (34 ha, 2%), herbaceous snowbank (4 ha, <1%) and sedge meadow (2 ha, <1%). The noticeable difference between the two mountains is the greater degree of cliffs, but limited presence of sedge meadows on the Katahdin compared to the Presidential Range. Table 1 shows vegetation community-type composition only within the alpine zone. Large-scale color maps of the subalpine-alpine vegetation communities were developed for future monitoring.

The classification system used in this study is similar to other studies that have looked at plant communities found in the larger New England alpine areas (table 2), although differences exist. Due to the scale of this study, localized or narrow linear communities were not included, therefore we excluded alpine streamside vegetation. Other investigators have not included birch-alder or fellfield as alpine plant communities. Bliss (1963) refers to felsenmeer as a geological phenomena rather than an alpine plant community type, while Cogbill and Hudson (1990) do not include it in any of their transects. We included fellfield because, in addition to extensive lichen colonies on the rocks, the interstitial spaces between the rocks harbor considerable vegetation: and also fellfield occupies a dominant part of the alpine zone in our study area. Birch-alder communities are largely a result of past landslides or snowslides, which create a suitable environment for these pioneering species (Flaccus 1959). Depending on the frequency of these disturbances, the birch-alder community may be a transient alpine community on its way to being re-established as a boreal spruce-fir community, or it may be a more permanent subalpine plant community devoid of tall vegetative growth.

Elevation

The distribution by elevation of the different plant communities is summarized in table 3 for the Presidential Range and table 4 for the Katahdin Range. Most plant communities spanned an elevation gradient of 500-750 m, except the sedge meadow and cushion tussock communities on the Katahdin Range, which ranged from 172-380 m. Bliss (1963), Marchand (1987) and Sperduto (1994) have placed sedge meadow and cushion-tussock communities among the highest elevations within the alpine environment. Our data support this premise for the sedge meadow, but less so for the cushion-tussock community. The lower elevation of the birch-alder community may be part of the reason these

authors do not include it in their montane classification systems. Krummholz has the second lowest mean elevation.

There is an approximate 250 m elevation shift of all the plant communities we studied between the two ranges, with all found lower on the Katahdin Range. We attribute this to the Katahdin Range being 1°38' latitude (ca. 180 km) farther north than the Presidential Range.

Slope

The slopes of the vegetation communities for the study areas are listed in tables 2 and 3. Cushion-tussock and sedge meadow communities are generally found on more moderate slopes, whereas the birch-alder community is generally found on the steeper, slide-prone slopes.

Aspect

The Presidential Range encompasses areas facing all aspects but contains a southern bias, while the Katahdin Range has a bias towards the west (tables 3 and 4). The sedge community tends to the northwest on both mountain ranges. This directional orientation of the sedge meadow community corresponds to that described by Bliss (1963), Marchand (1987) and Sperduto (1994), which could be related to moist air masses being uplifted, cooled and then depositing greater amounts of cloud water and precipitation on the windward side of the range. On both mountain ranges, birch-alder tends somewhat to the northeast, which may relate in part to how winds deposit snow blown off the alpine area, causing periodic avalanches. The herbaceous snowbank community shows some directional orientation towards the east to southeast, which supports statements by Bliss (1963), Marchand (1987), and Sperduto (1994) that the herbaceous snowbank community is often found on east to southeast slopes. Again, this may in part be due to how leeward winds deposit snow blown off the exposed alpine area.

Slope Shape (Concave or Convex)

Overall, the mean shape index for both study areas is slightly convex (tables 3 and 4), which is to be expected for a mountain. The birch-alder and, to a less degree, the herbaceous snowbank community tend toward a concave value on both mountain ranges. Bliss (1963), Marchand (1987) and Sperduto (1994) have pointed out the importance of deep, late-melting snowbanks in protecting plants of the species-rich herbaceous snowbank community from fluctuating temperatures during the late spring. The generally concave microhabitat of the herbaceous snowbank community allows for greater accumulation of snow. All other plant community means were convex. The cushion-tussock community tends strongly towards convexity and occupies the other end of the spectrum in terms of snow depth. It is found on exposed wind-blown areas, where there is little or no snow cover (Bliss 1963; Tiffney 1972; Day 1984).

Statistical Analyses

Kolmogorov-Smirnov goodness-of-fit tests indicate that, individually, the elevation, slope and shape index distribution of

Table 2—Alpine plant community nomenclature and dominant plant species.

AMC	Cogbill and Hudson (1990)	Sperduto (1994) NHHI	Bliss (1963)	Dominant species	Potentially common species
Krummholz	Krummholz	Subalpine Krummholz	Krummholz	<i>Abies balsamea</i> (balsam fir) <i>Picea mariana</i> (black spruce)	Highly variable. Influenced by surrounding communities and changes in microclimate and topography
Birch-Alder	None	None	None	<i>Betula papyrifera</i> (paper birch) <i>Alnus crispa</i> (mountain alder)	<i>Abies balsamea</i> <i>Picea mariana</i>
Fellfield	None	Fellfield	Felsenmeer	<i>Rhizocarpon geographicum</i> (map lichen) <i>Parmelia centrifuga</i> (ring lichen) <i>Umbilicaria hyperborea</i> (rock tripe)	Highly variable. Influenced by changes in microclimate and topography.
Sedge Meadow	Sedge Meadow	Heath-Meadow (Sedge Meadow association)	Sedge Meadow	<i>Carex bigelowii</i> (Bigelow's sedge)	<i>Arenaria groenlandica</i> (mountain sandwort) <i>Vacc. vitus-idaea</i> (mountain cranberry) <i>Vacc. uliginosum</i> (alpine bilberry)
		Heath-Meadow (Sedge-Heath-rush association)	Sedge-Dwarf Shrub Heath Sedge-Rush-Dwarf Shrub Heath	<i>Carex bigelowii</i> <i>Juncus trifidus</i> (highland rush)	<i>Vacc. vitus-idaea</i> <i>Vacc. uliginosum</i> <i>Potentilla tridentata</i> (three-toothed cinquefoil) <i>Arenaria groenlandica</i>
Heath-Shrub-Rush	Alpine Heath	Heath-Meadow (Heath-Rush)	Dwarf Shrub Heath-Rush	<i>Vacc. vitus-idaea</i> <i>Vacc. uliginosum</i> <i>Juncus trifidus</i>	<i>Potentilla tridentata</i>
		Heath Snowbank	Dwarf Shrub Heath	<i>Ledum groenlandicum</i> (Labrador tea) <i>Vacc. vitus-idaea</i> <i>Vacc. uliginosum</i> <i>Empetrum nigrum</i> (black crowberry)	<i>Cassiope hypnoides</i> (cassiope) <i>Loisleuria procumbens</i> (alpine azalea) <i>Phyllodoce caerulea</i> (phyllodoce) <i>Arctostaphylos alpina</i> (alpine bearberry)
Herbaceous Snowbank	Snowbank	Herbaceous Snowbank Meadow	Snowbank	<i>Deschampsia flexuosa</i> (hairgrass) <i>Solidago cutleri</i> (Cutler's goldenrod) <i>Vacc. caespitosum</i> (dwarf bilberry) <i>Houstonia caerulea</i> * (alpine bluets) <i>Vacc. uliginosum</i>	<i>Veratrum viride</i> (false hellebore) <i>Clintonia borealis</i> (blue-bead lily) <i>Geum peckii</i> * (mountain avens) <i>Phleum alpinum</i> (alpine timothy) <i>Castilleja septentrionalis</i> (pale painted cup)
Cushion-Tussock	Diapensia	Diapensia	Diapensia	<i>Diapensia lapponica</i> (diapensia) <i>Juncus trifidus</i> <i>Rhododendron lapponicum</i> (Lapland rosebay) <i>Loisleuria procumbens</i> <i>Vacc. Uliginosum</i>	<i>Solidago cutleri</i> <i>Salix uva-ursi</i> (bearberry willow) <i>Agrostis borealis</i> (boreal bentgrass) <i>Arenaria groenlandica</i>

(con.)

Table 2—(Con.)

AMC	Cogbill and Hudson (1990)	Sperduto (1994) NHHI	Bliss (1963)	Dominant species	Potentially common species
None	None	Alpine Streamside	Alpine Streamside	<i>Salix planifolia</i> (tea-leaved willow) <i>Salix argyrocarpa</i> (silver willow) <i>Salix herbacea</i> (dwarf willow)	<i>Calamagrostis pickeringii</i> (Pickering's reed bent-grass) <i>Cardamine bellidifolia</i> (alpine bitter-cress) <i>Saxifraga rivularis</i> * (alpine brook saxifrage) <i>Epilobium hornemannii</i> (Hornemann's willow herb) <i>Viola palustris</i> (alpine marsh violet)
Water	None	Alpine/Subalpine Bog	Alpine Bog	<i>Rubus chamaemorus</i> * (cloudberry) <i>Betula glandulosa</i> (dwarf birch) <i>Empetrum atropurpureum</i> (purple crowberry) <i>Empetrum nigrum</i>	<i>Geocaldon lividum</i> (northern comandra) <i>Vacc. uliginosum</i>
Cliff	None	Alpine Cliff Alpine Cliff/Seep	None	<i>Diapensia lapponica</i> <i>Empetrum atropurpureum</i> <i>Empetrum nigrum</i> <i>Geum peckii</i> * <i>Houstonia caerulea</i> * <i>Calamagrostis neglecta</i> (neglected reedgrass)	<i>Carex scirpoidea</i> (scirpus-like sedge) <i>Solidago cutleri</i> <i>Cardamine bellidifolia</i> <i>Saxifraga rivularis</i> * <i>Epilobium hornemannii</i>

*Not found on Katahdin Range.

Table 3—Descriptive statistics of exposure factors for each subalpine/alpine community type on the Presidential Range, NH. The slope shape index is a relative scale where increasing positive values represent increasing convexity, increasing negative values represent increasing concavity, and a plane is represented by the value 0.

	Birch-alder	Cushion-tussock	Herbaceous snowbank	Krummholz	Fellfield	Sedge meadow	Heath shrub-rush	All
Elevation (m)								
Mean	1375	1565	1562	1450	1596	1680	1534	1504
Std. Dev.	110	77	75	98	127	97	115	136
Max.	1624	1851	1716	1735	1909	1901	1838	1909
Min.	881	1233	1183	1056	1029	1345	1170	881
Slope Shape								
Mean	-2	13	0	4	8	8	10	5
Std. Dev.	15	9	11	11	10	7	10	11
Max.	44	34	32	41	38	32	38	44
Min.	-46	-15	-43	-43	-42	-41	-31	-46
Slope (%)								
Mean	68	30	48	49	42	29	41	47
Std. Dev.	25	17	22	22	24	16	22	24
Max.	232	141	104	232	242	169	242	242
Min.	0	0	0	0	0	0	0	0
Aspect (°)								
Mean Angle	39	146	164	170	228	310	65	187
Std. Ang. Dev.	57	69	50	78	76	68	72	81

Table 4—Descriptive statistics of exposure factors for each subalpine/alpine community type on the Katahdin Range, ME. The slope shape index is a relative scale where increasing positive values represent increasing convexity, increasing negative values represent increasing concavity, and a plane is represented by the value 0.

	Birch- alder	Cushion- tussock	Herbaceous snowbank	Krummholz	Cliff	Fellfield	Sedge meadow	Heath shrub- rush	All
Elevation (m)									
Mean	1108	1376	1307	1219	1277	1283	1484	1319	1240
Std. Dev.	116	58	155	113	159	156	78	147	146
Max.	1445	1575	1507	1551	1603	1603	1576	1603	1603
Min.	783	1195	950	859	834	859	1404	934	783
Slope Shape									
Mean	-6	18	-2	2	9	7	17	12	4
Std. Dev.	14	8	18	11	22	17	6	13	15
Max.	44	43	26	48	80	60	27	79	80
Min.	-53	3	-36	-50	-45	-49	2	-35	-53
Slope (%)									
Mean	60	26	70	48	113	58	11	36	54
Std. Dev.	33	26	24	36	78	33	2	30	42
Max.	947	174	216	969	1815	1462	21	810	1815
Min.	0	0	19	0	0	0	2	0	0
Aspect (°)									
Mean Angle	60	263	97	265	20	171	302	335	263
Std. Ang. Dev.	73	72	58	73	77	72	23	74	78

all alpine plant communities have a highly significant difference ($p < 0.001$) compared to the distribution of all available habitat. Chi-squared goodness-of-fit tests indicate that the aspect distribution of all alpine plant communities have a highly significant difference ($p < 0.001$) compared to the available aspect distribution. With the large number of degrees of freedom in our analysis, the statistical power to identify these differences is not unexpected.

One area of introduced error for the Presidential Range comes from ‘streaking’ in the available DEM. Since the data for all four of the exposure factor variables is derived from the DEM, this probably added substantial error to the data set. Another factor is the scale chosen for the exposure factors. For example, shape index derived from points 285 m away is unlikely to indicate any real variation in community type caused by microtopography within, say, a 10 m radius. Conversely, slope and aspect may have a stronger affect on community type at a scale larger than the 3 m radius used in our study.

Alpine-Treeline Ecotone Boundary

Designating a line between the subalpine krummholz and the forest is a somewhat arbitrary and subjective decision. For this study, the lower elevation limits of krummholz were defined as where vegetative growth is generally -2.5 m in height. The upper limits of continuous krummholz (the alpine-treeline ecotone or ATE boundary) can vary from a sharp boundary to a band of diminishing islands of krummholz. In other cases, it can be at an abrupt cliff or slide prone area. Therefore, the almost continuous band of subalpine krummholz extending around our study mountains is not all suitable for monitoring the alpine-treeline ecotone boundary.

We developed a map where the ATE boundary can be readily identified and is suitable for future biomonitoring purposes. On the Presidential Range, the measurable ATE boundary ranged in elevation from 1,114 to 1,687 m (range = 573 m; $x = 1513 + 93$ m), while it varied from 857 m to 1518 m (range = 661 m; $x = 1266 + 116$ m) on the Katahdin Range. The highest krummholz islands of map unit size, which are not necessarily the highest elevation of krummholz growth, are at 1,735 and 1,551 meters elevation, respectively, for the Presidential and Katahdin Ranges. Therefore, on different parts of the mountain, the upper limits of spruce-fir krummholz range from 621 to 694 m for these mountain ranges, respectively.

Biologists and climatologists have recognized that the limit of tree growth in both the alpine zone and the arctic in North America and Eurasia, north of the tropics, approximates the 10 °C isotherm for the warmest month of the year, usually July (Arno and Hammerly 1984). Temperature declines approximately 1-2 °C for every 300 m in elevation gain, due to the reduction in atmospheric pressure and expansion of the air. The wide elevation ranges we measured in the ATE and uppermost krummholz islands for both mountain ranges suggest that the concept of treeline and the upper limits of tree growth as a temperature-caused phenomena on the Northeast’s highest peaks is far too simplistic. We hypothesize that tree growth on the northeastern US mountains is strongly influenced by the climatic growing season and exposure factors.

Although elevation is recognized as an important factor in determining the location of krummholz, models that incorporate topographic exposure with elevation more accurately predict treeline for the Presidential Range (Bryant and others 1991). The extent of treeline on the Presidential and

Katahdin Range reaches higher elevations in the valleys compared to the ridges. This corresponds to the exposure factors of wind and rime ice formation in the winter. We are now using our data to adapt the models developed by Bryant and others (1991) and Allen and Walsh (1996) as a benchmark for monitoring treeline movement, if any, over time.

Summary

Topographic features that influence cloud water (summer) and rime ice (winter) deposition due to wind-driven clouds and the deposition of snow blown off the exposed alpine area onto the leeward side of the mountain probably influence the alpine-treeline ecotone boundary and distribution of alpine plant communities. The highest elevation plant communities are the sedge meadow and cushion-tussock communities; the cushion-tussock is found in more convex topography subject to the greatest wind removal of snow while the sedge meadow tends toward a northwest aspect. Birch-alder, more appropriately a subalpine community, is strongly related to steep, concave slopes with an easterly vector—where the likelihood of blown snow accumulation and resulting avalanches is greatest. The herbaceous snowbank community tends toward concave relief with a more east to southeast vector, factors that also favor snow accumulation. The krummholz, fellfield and heath-shrub-rush communities tended to have less pronounced relationships with topographic features.

The alpine-treeline ecotone boundary and upper limits of the krummholz islands vary substantially by elevation, suggesting that growing season is not necessarily the dominant factor controlling the limits of tree growth on the Northeast's highest peaks. We postulate that the Northeastern montane alpine-treeline ecotone boundary is strongly influenced by exposure factors that relate to the mechanical damage caused by winter ice events and wind, than by the growing season alone. Climatic changes that influence cloud frequency, wind, precipitation and ice loading at the upper elevations should have a strong influence on the alpine-treeline ecotone boundary.

This study developed maps of the alpine-treeline ecotone boundary and alpine vegetation communities on two mountain ranges in the Northeast. Since Wilderness areas are included, they will provide for future opportunities to measure geographic shifts by vegetation communities to climatic change.

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