Distribution of Alpine Tundra in the Adirondack Mountains of New York, U.S.A

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Abstract

The distribution of alpine tundra in the Adirondack Mountains of New York was investigated through a combination of field mapping and GIS analysis. Alpine tundra vegetation covers 26.3 ha (65 acres). Tundra patches are rare below an elevation of 1350 m although significant differences exist in mean tundra elevation between summits reflecting overall summit morphology. Tundra is generally more abundant, and extends to lower elevations on windward slopes with northerly and northwesterly aspects. Tundra patches on leeward slopes are found at higher elevations and are considerably larger, reflecting increased fragmentation on windward slopes and development of snowbank communities on leeward slopes. At a regional scale, the percentage of high-elevation land covered by tundra decreases from the northwest to southeast across the study area, suggesting that mountains upwind along the prevailing winter wind vector shield downwind summits, underscoring the role of exposure in limiting the upward growth of trees. Because exposure exerts a fundamental control over patch boundaries, shifts in the balance between arboreal and non-arboreal vegetation over time could be expected if changes occur in the frequency of icing events, the severity of winter storms, temperature, cloudiness, or prevailing wind directions.

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Introduction

A handful of mountain summits rise above the krummholz in the northeastern United States, supporting islands of alpine vegetation in an otherwise thickly forested region. These alpine outposts have long fascinated naturalists who recognized early on that the plants found on these summits are more typical of tundra environments at much higher latitudes (e.g. Bliss, 1963; Miller and Spear, 1999). Studies have identified a series of alpine plant communities in these environments including cushion-tussock tundra, heath-shrub-rush complexes, sedge meadows, alpine bogs, and snowbank communities, which is broadly consistent among separate summits throughout the region (e.g. Bliss, 1963; LeBlanc, 1981). It is generally accepted that these communities are remnants of lowland tundra that migrated upward in response to post-glacial climate amelioration and became stranded on mountain summits (Miller and Spear, 1999). Paleobotanical evidence indicates that climate changes shifted the relative dominance of herb-shrub tundra, bog vegetation, and krummholz during the post-glacial period and these fluctuations may have caused the extirpation of some species (Spear, 1989; Miller and Spear, 1999; Munroe, 2008). Changes in the elevation of alpine treeline may also have impacted the overall extent of alpine environments over time (Miller and Spear, 1999). However, the presence of these plants on so many widely scattered summits suggests that these environments have persisted at the highest elevations in the region throughout the Holocene.

The climatic significance of alpine summits in this region, where treeline is notably low (~1300 m) for a mid-latitude location (~44°N), remains unclear. Growing season temperature is classically considered an overriding control on the elevation of alpine treeline, with trees giving way to alpine vegetation as mean summer temperatures drop below 10 °C (e.g. Daubenmire, 1954). However, other studies have stressed the influence of landscape position as a factor in exposure (e.g. Allen and Walsh, 1996; Elliott and Kipfmueller, 2010), and previous studies in the northeastern U.S.A. (e.g. Bliss, 1963; LeBlanc, 1981; Kimball and Weihrauch, 2000) have posited that exposure is the primary factor limiting the extent of trees on summits in this region. Measured rates of rime ice accumulation increase exponentially above ~800 m in this region (Ryerson, 1990) and trees at higher elevations can become encased in rime during winter. Under these conditions, trees are subject to severe mechanical damage when strong winds snap frozen limbs. Thus, plants of low stature, including tundra species common throughout the circumarctic, are at a competitive advantage in these locations.

The largest areas of alpine habitat in the northeastern U.S.A. are found in New Hampshire (11.3 km^2) and Maine (7.3 km^2; Kimball and Weihrauch, 2000) where they are clustered in a few, widely separated massifs of sustained high elevation (Fig. 1, inset). Previous work has evaluated the role of exposure in these environments and has suggested that long-term monitoring could be a useful tool for documenting climate change impacts (Kimball and Weihrauch, 2000). However, because this work focused solely on the two most extensive alpine areas in the northeastern U.S.A. it is unclear how its interpretations bear on the numerous, smaller alpine areas in this region. The Green Mountains of Vermont, for instance, contain three similar alpine outposts (Thompson and Sorenson, 2000), and the High Peaks region of New York's Adirondack Mountains contains numerous summits that support small areas of tundra, usually covering <1 ha each (Fig. 1; Slack and Bell, 2006). The large number and wide distribution of tundra communities in the High Peaks in particular provide the opportunity to evaluate the environmental factors responsible for tundra occurrence through analysis of tundra patch distribution. Because these plant communities are located at high elevations that were not logged and are rarely, if ever, subjected to fire, this information could illuminate aspects of the natural history of these environments, including their origin and evolution over time. Improved understanding of the controls on the

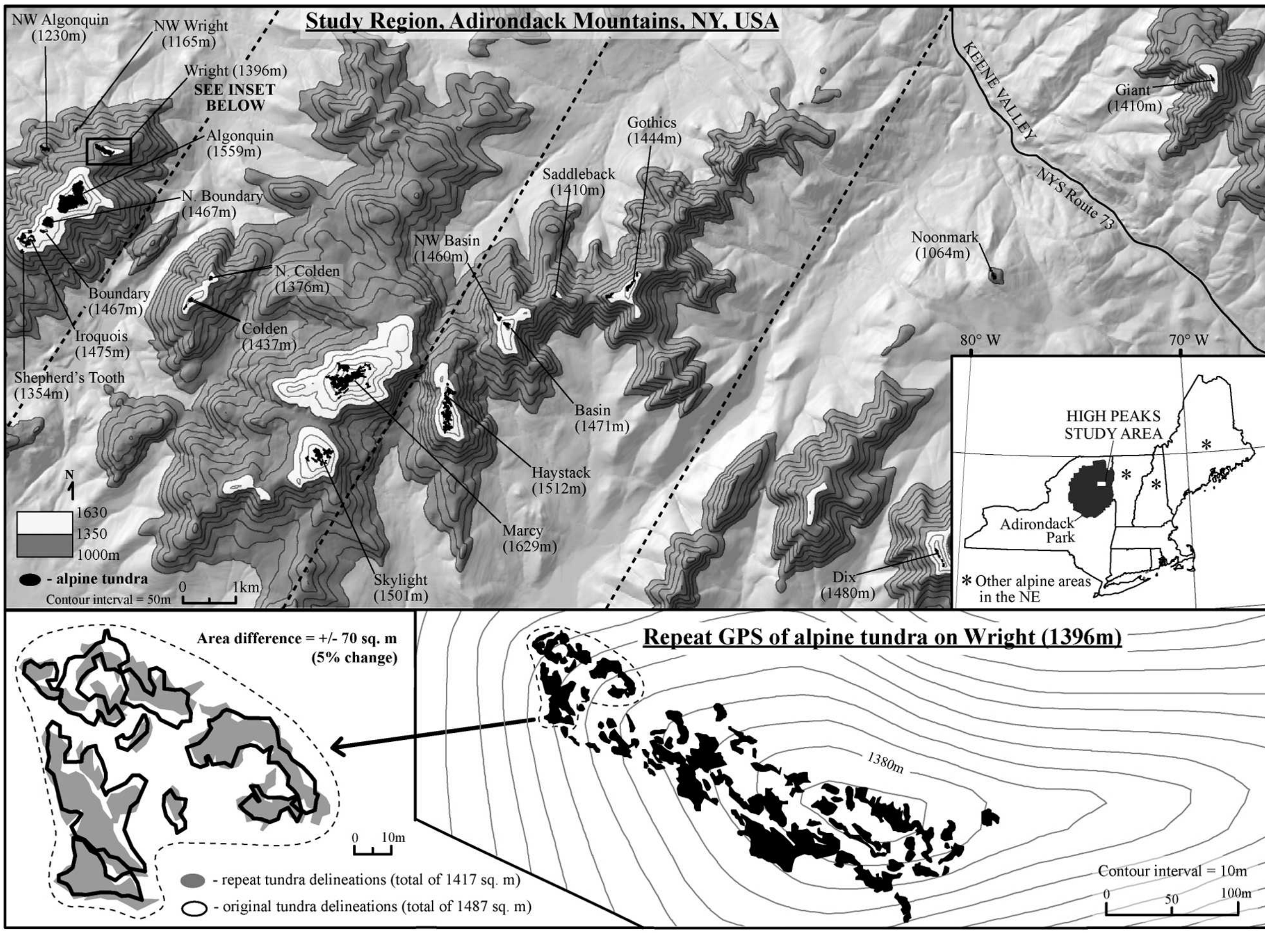

FIGURE 1. Inset: Location map of the High Peaks region in northeastern New York. Stars mark other major concentrations of alpine tundra in the region. Large map: major summits considered in this project (elevations in meters). Alpine tundra polygons are shown in black. Dashed lines delineate four swath groupings of summits discussed in text and later figures. Inset lower right: example of alpine tundra polygons mapped on Wright, enlarged to show detail. Inset lower left: results of remapping effort on Wright by same operator illustrating reproducibility of mapping.

distribution of these environments might also be useful for predicting their vulnerability to future climate change.

The overall goal of this study was to delineate, with high spatial resolution, the patches of alpine vegetation in the High Peaks region of the Adirondack Mountains. Unlike previous work in the region, which relied heavily on the interpretation of aerial photographs, mapping for this project was conducted entirely in the field using a GPS-enabled approach combined with a Geographic Information Systems (GIS) analysis. The project had three main objectives, including:

(1) calculate the total area of alpine tundra in the High Peaks,
(2) determine the distribution of tundra patches in the High Peaks, and
(3) evaluate the possible effect of environmental variables, including elevation, slope, aspect, and exposure on tundra patch distribution.

Methods

FIELD METHODS

Previous studies attempting to calculate the area of alpine tundra on high summits in the northeastern U.S.A. combined interpretation of high-resolution aerial photographs with limited field mapping. For instance, Kimball and Weihrauch (2000) utilized this approach to map the alpine zone in New Hampshire's White Mountains and on Maine's Mount Katahdin with a minimum mapping unit of 100 m^2. The Adirondack region, however, is not covered by aerial photographs of sufficiently large scale to allow for precise demarcation of alpine vegetation in the absence of field investigations. Furthermore, alpine tundra in the High Peaks forms small patches rather than extensive, contiguous units as in the higher mountains of New Hampshire and Maine. As a result, an approach that relied heavily on aerial photogrammetry would be insufficient to adequately measure the fine-scale distribution of Adirondack alpine tundra unless the imagery was of sufficiently high resolution (sub-meter) and was accurately orthorectified and documented. Instead, a new methodology based heavily on field measurements was developed for this study.

In the summer of 2009, twenty summits in the High Peaks region were visited with the goal of comprehensively mapping the boundaries between alpine vegetation, bare rock, and krummholz. These summits include all of the major concentrations of alpine tundra in the Adirondack Mountains with the exception of Whiteface, which has been heavily impacted by development. All of the studied summits have been impacted to some degree by foot traffic; however, away from the main trail corridor these impacts are relatively minor.

Field procedure involved walking the perimeter of tundra patches carrying a Trimble GeoExplorer GPS unit that traced a polyline with nodes at ~2-m intervals. Tracing polylines was more efficient than mapping polygons in the field, and allowed mapping of patch borders in segments rather than as continuous loops. After experimentation and evaluation of the field mapping procedures, and consideration of the limitations of the GPS hardware, a minimum mapping unit of 9 m^2 was established. By this standard, patches of tundra smaller than 9 m^2 were neglected, and patches of bare rock or krummholz less than 9 m^2 in area that were surrounded by tundra were included as part of the surrounding tundra. Islands of bare rock, krummholz, or gravel >9 m^2 contained within a larger patch of tundra were traced to form non-tundra "donut holes" within larger tundra polygons and were later subtracted.

Defining clear boundaries amidst the jumble of gravel, bare rock, krummholz, and plant communities typical of Adirondack summits proved to be a consistent challenge. However, generally the boundary between bare rock and tundra was sufficiently clear to make GPS error the primary source of uncertainty. Other edges, such as the krummholz-tundra ecotone, were characterized by varying degrees of clarity. To minimize subjectivity, krummholz of the same height as neighboring tundra vegetation and with an understory of *Vaccinium uliginosum* was considered part of the alpine vegetation, while krummholz taller than adjacent tundra vegetation and lacking a heath understory was excluded.

Perimeter tracing was occasionally hampered by the presence of cliffs. Although vegetation was not observed growing on slopes exceeding 45°, patches of tundra that abutted a precipitous drop were encountered. In these instances, several different options were employed. In some cases, the perimeter of an equivalently sized area in a less exposed setting was traced. Alternatively, the safe side of a tundra patch was walked and traced with the GPS and the exposed edge that ran along a cliff was incorporated by freehand drawing. In rare instances when it proved excessively dangerous to even reach a patch of tundra, entire polygons were drawn freehand from an appropriate vantage point.

On two summits, Algonquin and North Boundary (Fig. 1), tundra was the primary alpine surface cover. Accordingly, the mapping scheme was inverted and patches of bare rock, gravel, and krummholz were mapped instead of tundra, with the goal of later erasing these features in a GIS. The tundra area calculated with this approach was then added to the sum of the patches mapped on the other summits to yield an estimate of total tundra area in the region. These summits were not, however, included in the analysis of relationships between tundra patch distribution and environmental variables because their large alpine areas covered too wide a range of elevations, slopes, and aspects.

Finally, to evaluate possible bias in the field-mapping, the summit area of Wright was remapped by another individual familiar with the study but not previously involved in the fieldwork. A portion of the alpine zone on Wright was also remapped by the original mapper as a test for consistency.

GIS AND STATISTICAL ANALYSIS

To calculate the total area and distribution of tundra patches, polylines were connected into polygons in ArcGIS 9.3. Two-dimensional areas of each polygon were determined using the Calculate Geometry function, and three-dimensional areas were determined with a TIN created from a 10-m Digital Elevation Model (DEM) using the Interpolate Polygon to Multipatch function. Zonal statistics were applied to the DEM to determine a mean elevation and mean slope for each tundra patch. To determine the mean aspect of each patch, an aspect map was created from the DEM and then reclassified into eight cardinal directions. The Tabulate Area function was then used to determine the number of pixels within each tundra patch facing each of the cardinal directions. An average aspect value was then assigned manually to each polygon based on the cardinal direction containing the maximum number of pixels. Descriptive statistics for elevation, slope, aspect, and area were calculated for the 18 summits on which individual tundra patches were mapped (excluding Algonquin and North Boundary). Patch abundance was tallied, and mean patch elevations and slopes were determined for each aspect class. Tundra area as a percent of total tundra area (including Algonquin and North Boundary) was also calculated for each aspect class. Summits were also grouped into four swaths arranged from northwest to southeast along the prevailing wind direction to facilitate identification of regional trends in tundra abundance.

Patch distribution was considered within the context of topography on the six summits that exhibited a consistent presence of tundra across multiple aspects and an elevation range of at least 80 m: Marcy, Algonquin, Haystack, Wright, Iroquois, and Skylight (Fig. 1). For each of these mountains, the 10-m DEM was clipped to the elevation of the lowest tundra patch, yielding separate DEMs for the alpine zone on each summit. To determine the shape and slope of each summit cone, the Tabulate Area function was used to generate a pixel count for elevation bands above the lowest tundra patch at 10-m vertical intervals. Tabulate Area was also used to compute the area of tundra falling into each of these elevation bands, which were expressed as both a raw total and a percentage.

The distribution of tundra patches and relationships between patches and environmental variables (on all summits except Algonquin and North Boundary) were investigated by non-parametric statistical techniques given the skewed distributions of some of these variables and the highly variable sample size associated with each aspect class. Differences between the elevation, slope, and area means partitioned into aspect classes were considered using a Kruskal-Wallis test. Statistical analyses were conducted in SPSS 15.0 except for mean aspect and circular standard deviation for each summit, which were computed using directional statistics in Oriana.

Results

OVERALL DATA SET

In the course of this project, 634 separate patches of alpine vegetation were mapped. Of these patches, 26 (4%) were determined freehand, while the rest were traced by walking patch boundaries. The total area of alpine vegetation mapped with this method is 15.6 ha (38.6 acres) when taking slope into account (3D area). In addition to the patches mapped on 18 of the High Peaks, Algonquin and North Boundary were mapped as single tundra polygons with numerous "donut holes" of non-tundra subtracted from their interior. Together, Algonquin and North Boundary accounted for 10.8 ha (26.6 acres) of tundra, comprising 41% of the study area total. The overall total area of alpine tundra in the High Peaks region determined from these combined approaches is 26.3 ha (65 acres) (Table 1).

Table 1 presents summary data for the 634 alpine tundra patches measured on 18 summits in the study area (excluding the tundra complexes on Algonquin and North Boundary). Tundra patches are quite variable in size, ranging from 9 to 8267 m^2

TABLE 1

Descriptive statistics for alpine tundra patches in the High Peaks region of the Adirondack Mountains.

Summit	*n*	Statistic	Mean	Median	Std. deviation	Minimum	Maximum	Range	Skewness
Algonquin*	1	Elevation (m)	1498.4	1495.0	32.5	1435.0	1555.0	—	0.12
3D area: 9.5 ha		Slope	23.1	22.5	6.6	2.5	37.5	—	−0.60
(23.5 acres)		Aspect	N**	—	—	—	—	—	—
North Boundary*	1	Elevation (m)	1457.1	1455.0	9.6	1435.0	1475.0	—	−0.62
3D area: 1.25 ha		Slope	18.0	17.5	5.9	2.5	32.5	—	−0.06
(3.1 acres)		Aspect	NW**	—	—	—	—	—	—
All Other Summits	650	Elevation (m)	1458.4	1460.8	89.1	1013.0	1623.0	610.0	−1.07
		Slope (deg)	23.6	23.5	7.1	2.4	42.5	40.1	−0.19
		Aspect (deg)	317.0	—	87.5	—	—	—	—
		Area_3D (m^2)	240.7	72.1	603.2	3.2	8266.8	8263.7	7.72
Basin	23	Elevation (m)	1451.1	1453.6	14.6	1422.8	1468.6	45.8	−0.75
		Slope (deg)	23.2	26.0	7.1	9.6	31.3	21.7	−0.61
		Aspect (deg)	0.0	—	60.2	—	—	—	—
		Area_3D (m^2)	100.7	59.3	134.8	7.5	503.2	495.6	2.23
Boundary	10	Elevation (m)	1446.1	1447.6	3.6	1439.5	1449.7	10.2	−0.75
		Slope (deg)	10.9	12.2	3.2	5.3	15.3	10.0	−0.46
		Aspect (deg)	267.0	—	36.9	—	—	—	—
		Area_3D (m^2)	163.0	49.2	253.8	5.4	719.5	714.2	1.83
Colden	4	Elevation (m)	1404.1	1404.9	12.8	1389.1	1417.4	28.3	−0.24
		Slope (deg)	19.0	20.9	5.9	10.4	23.7	13.3	−1.69
		Aspect (deg)	262.0	—	64.1	—	—	—	—
		Area_3D (m^2)	1024.9	815.0	658.4	485.0	1984.3	1499.3	1.65
Dix	15	Elevation (m)	1457.2	1455.9	6.0	1449.8	1470.5	20.8	1.18
		Slope (deg)	27.2	29.0	6.0	14.7	36.0	21.3	−0.51
		Aspect (deg)	290.2	—	22.7	—	—	—	—
		Area_3D (m^2)	117.6	67.7	125.5	20.2	408.1	387.9	1.82
Giant	4	Elevation (m)	1399.3	1400.0	7.4	1389.9	1407.4	17.5	−0.51
		Slope (deg)	29.5	28.4	10.8	18.8	42.5	23.8	0.38
		Aspect (deg)	315.0	—	67.5	—	—	—	—
		Area_3D (m^2)	150.7	121.3	98.3	71.2	288.9	217.6	1.35
Gothics	17	Elevation (m)	1385.3	1380.7	24.0	1349.2	1431.0	81.8	0.48
		Slope (deg)	31.4	31.8	4.4	19.9	37.5	17.6	−1.12
		Aspect (deg)	343.0	—	34.7	—	—	—	—
		Area_3D (m^2)	396.9	73.0	645.5	15.7	2591.1	2575.4	2.75
Haystack	131	Elevation (m)	1447.2	1445.8	33.4	1369.6	1508.7	139.2	0.07
		Slope (deg)	26.6	28.2	6.7	7.8	38.8	31.0	−0.72
		Aspect (deg)	328.0	—	82.8	—	—	—	—
		Area_3D (m^2)	234.4	86.4	432.4	3.8	2252.0	2248.3	3.29
Iroquois	51	Elevation (m)	1433.5	1430.7	22.3	1383.4	1468.6	85.2	−0.20
		Slope (deg)	23.0	23.7	4.7	8.0	35.1	27.1	−0.51
		Aspect (deg)	292.0	—	82.2	—	—	—	—
		Area_3D (m^2)	248.1	98.4	290.3	9.3	1412.7	1403.3	1.96
Marcy	218	Elevation (m)	1545.2	1542.0	41.2	1442.8	1623.0	180.2	−0.07
		Slope (deg)	23.8	23.5	5.5	6.2	40.4	34.2	0.07
		Aspect (deg)	348.0	—	79.2	—	—	—	—
		Area_3D (m^2)	250.1	70.4	633.4	3.2	6781.7	6778.5	6.69
Noonmark	5	Elevation (m)	1038.6	1036.2	20.6	1013.0	1059.8	46.8	−0.07
		Slope (deg)	26.6	24.5	4.3	22.6	31.9	9.3	0.54
		Aspect (deg)	15.0	—	61.7	—	—	—	—
		Area_3D (m^2)	436.1	151.2	642.3	10.0	1568.4	1558.4	2.08
North Colden	1	Elevation (m)	1376.4	—	—	—	—	—	—
		Slope (deg)	20.1	—	—	—	—	—	—
		Aspect (deg)	270.0	—	—	—	—	—	—
		Area_3D (m^2)	1942.9	—	—	—	—	—	—
NW Algonquin	13	Elevation (m)	1223.9	1225.9	8.9	1201.6	1235.8	34.2	−1.37
		Slope (deg)	20.2	20.1	6.1	8.5	30.1	21.6	−0.43
		Aspect (deg)	242.3	—	58.6	—	—	—	—
		Area_3D (m^2)	221.4	30.9	408.7	12.3	1467.2	1454.9	2.78
NW Basin	7	Elevation (m)	1406.7	1404.5	8.3	1398.4	1419.6	21.2	0.81
		Slope (deg)	32.1	33.4	6.7	18.2	39.0	20.8	−1.74
		Aspect (deg)	215.3	—	58.2	—	—	—	—
		Area_3D (m^2)	94.0	91.8	74.9	5.4	207.2	201.8	0.28
NW Wright	3	Elevation (m)	1162.0	1160.6	2.7	1160.2	1165.1	4.9	1.71
		Slope (deg)	20.9	20.5	3.7	17.4	24.8	7.3	0.52
		Aspect (deg)	194.6	—	21.4	—	—	—	—

TABLE 1

Continued.

Summit	n	Statistic	Mean	Median	Std. deviation	Minimum	Maximum	Range	Skewness
		Area_3D (m^2)	253.8	207.2	237.7	42.8	511.4	468.6	0.85
Saddleback	12	Elevation (m)	1349.4	1352.9	10.8	1327.7	1358.7	31.0	−1.20
		Slope (deg)	34.3	34.1	4.5	25.8	41.7	15.9	−0.25
		Aspect (deg)	285.4	—	28.3	—	—	—	—
		Area_3D (m^2)	47.8	34.3	39.3	16.7	129.4	112.7	1.31
Shepherd's Tooth	10	Elevation (m)	1361.4	1362.3	5.6	1352.2	1369.9	17.7	−0.34
		Slope (deg)	21.8	20.8	2.8	18.8	26.8	7.9	1.00
		Aspect (deg)	256.9	—	20.8	—	—	—	—
		Area_3D (m^2)	100.7	62.0	91.1	13.8	252.9	239.2	0.94
Skylight	59	Elevation (m)	1472.6	1477.2	22.6	1409.0	1501.2	92.3	−0.96
		Slope (deg)	16.5	15.0	7.0	4.2	33.7	29.5	0.69
		Aspect (deg)	156.6	—	77.1	—	—	—	—
		Area_3D (m^2)	374.0	50.2	1277.7	5.6	8266.8	8261.3	5.34
Wright	67	Elevation (m)	1364.8	1371.6	21.5	1315.9	1393.3	77.3	−0.61
		Slope (deg)	20.8	21.1	6.2	2.4	34.7	32.3	−0.24
		Aspect (deg)	302.6	—	67.7	—	—	—	—
		Area_3D (m^2)	139.4	64.2	229.4	9.9	1630.4	1620.5	4.62

* Tundra area was determined by subtracting non-tundra patches from a larger, contiguous tundra polygon.

** Mean aspect determined from the aspect class containing the maximum area.

(Fig. 2). The mean patch size is 240 m^2 and the distribution has a strong positive skew (7.72). The average elevation of alpine tundra patches is 1458 m, with a range from 1013 to 1623 m and a slight negative skew (Fig. 2). Alpine tundra is found across a wide range of slopes, extending from 2.4 to 42°, although ~60% of the overall tundra acreage occurs on slopes from 15 to 30° (Fig. 2). The mean slope of all tundra patches is 23.6°, and the values are normally distributed with a skewness of −0.19. When Algonquin and North Boundary are included, the mean slope of all tundra is 22.3°, which is less than the mean slope of all elevations >1350 m (25.4°), although this difference is not significant ($P = 1.0$, df 106). The mean patch aspect is 317°.

INTER-SUMMIT DIFFERENCES

Several environmental variables exhibit significant differences between the 18 summits where discrete tundra patches were mapped (Table 1, Fig. 2). Overall, the mean elevation is highest on Marcy (1545 m); however, this is also the highest summit (1629 m), and the mean elevation of tundra patches is strongly correlated with summit elevation ($r^2 = 0.9684$). Thus, mean patch elevation is largely a function of topographic prominence. At the lower end, the majority of tundra patches are found above an elevation of ~1350 m, with only a few exceptions on NW Algonquin, Noonmark, and NW Wright (Table 1, Fig. 2). The lowest elevation of tundra on each summit, which could be considered a proxy for treeline elevation, ranges from 1060 m on Noonmark to 1470 on Dix. The widest range of patch elevations is found on Marcy (180 m) and the narrowest (5 m) is found between the three patches mapped on NW Wright. Patch area also varies between the summits, with most summits having means between 100 and 400 m^2. Colden has the largest mean patch area (1025 m^2); however, the total number of patches (4) is among the lowest recorded. Mean patch area is smallest (48 m^2) on Saddleback, roughly half the size of the next smallest value (94 m^2 for NW Basin). Mean slope values also differ between patches on separate peaks, ranging from 10.9° on Boundary to 34.3° on Saddleback. However, slope differences may reflect physical differences in the topography of individual peaks rather than actual differences inherent to the tundra patches. Given the strong control of summit morphology over the elevation range and available slopes for tundra patches it is not surprising that the Kruskal-Wallis test reveals that differences between mean values of patch elevation and slope between the separate summits are highly significant ($P < 0.005$, df 17). Fourteen of the eighteen summits have mean patch aspects in the west, northwest, and north aspect classes. No summits have mean patch aspects facing east or northeast. Circular standard deviations vary by a factor of four from 20.8° (Shepherd's Tooth) to 82.8° (Haystack).

DIFFERENCES RELATED TO ASPECT

There are notable differences between patch size and distribution with respect to aspect (Table 1, Fig. 3). Tundra patches are most numerous on slopes of northwestern (23.7%) and northern (19.2% of total) aspects and least common on slopes facing due east (5.5%). However, patches on east-facing slopes are considerably larger, with mean areas nearly twice those on north-facing slopes (455 vs. 281 m^2; Fig. 3). Mean patch elevations range from 1401 m (south-facing) to 1491 m (northeast-facing; Fig. 3). Plotting cumulative percent area vs. elevation by aspect class also highlights the uniqueness of the south-facing patches (Fig. 4), although this aspect class is strongly influenced by a single large (1568-m^2) patch at low elevation (1060 m) on Noonmark. Slopes facing west, northwest, and north begin gaining cumulative area at low elevations, underscoring the generally lower treeline in the northwest quadrant (Fig. 4). East-facing slopes gain alpine area rapidly at mid- to upper-elevations. Overall the greatest percentage of total tundra area is found in north (23%) and northwest (19%) aspect classes (Fig. 4, inset). Differences between mean elevation and mean slope between aspect classes are highly significant ($P >$ 0.001, df 7), although the slope differences may simply reflect topographic contrasts between the separate summits. Differences in mean areas between aspect classes are not significant ($P \approx 0.44$).

SUMMIT MORPHOLOGY

The results of the Tabulate Area functions for summit topography reveal two general summit shapes. Broad, gentle peaks,

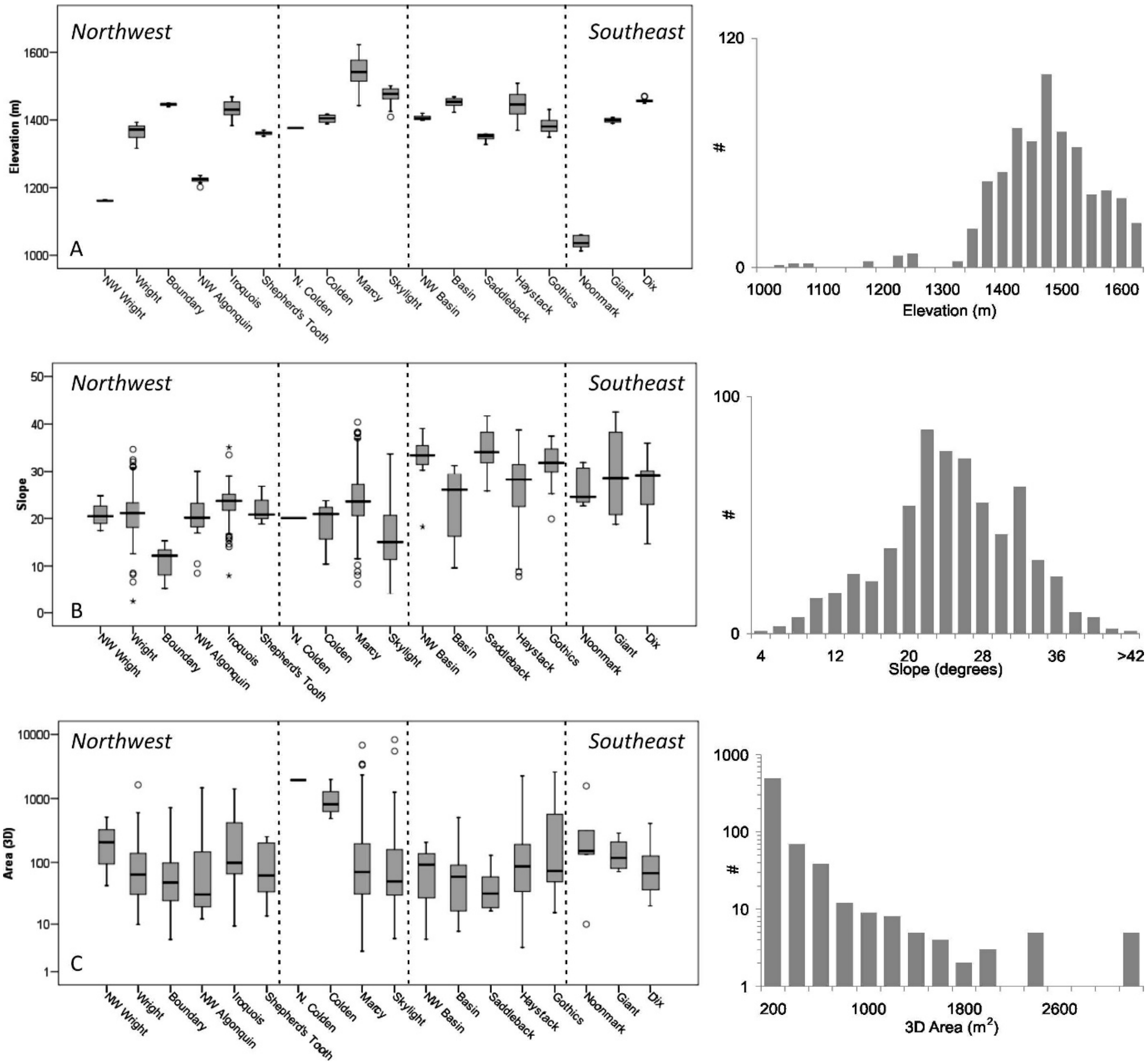

FIGURE 2. Inter-summit differences in tundra patch elevation, slope, and area (not including Algonquin and North Boundary where single large tundra complexes were mapped). Summits are listed from northwest to southeast and black dashed lines delineate swaths shown in Figure 1. For number of patches mapped on each summit see Table 1. Differences between mean values of patch elevation and slope between the summits are highly significant (Kruskal-Wallis test, $P < 0.005$, df 17). Right side shows histograms of tundra patch abundance as a function of area, elevation, and slope.

particularly Skylight, have gradual slopes in the plot of "total summit acreage" (Fig. 5). In contrast, plots from steeper summits, such as Haystack and Wright, exhibit more rapid decreases in area at higher elevations. Plots showing the percent of land area in each 10-m elevation band covered by alpine tundra are shifted among the five peaks, reflecting differences in overall summit morphology. However, with the exception of Skylight, the plot of tundra extent exhibits a bimodal pattern with maximum tundra cover occurring within discrete elevation bands below maximum summit elevations.

POSSIBLE SOURCES OF ERROR

There are several possible sources of error in the procedure employed in this study. One is user error, which was assessed through repeat mapping. Repeat measurements of tundra patches on Wright by an operator not involved in the original study yielded a total area 30% smaller than the original value. This difference is large; however, remapping of Wright by the original operator yielded a tundra area estimate within 5% of the original value, demonstrating an acceptable level of reproducibility when operator is held constant (Fig. 1). A standard protocol for future studies of this type should involve a single operator for all measurements, or employ a standardized training for multiple operators.

Overall accuracy of the GPS is another source of error that depends on many variables. Interference from canopy, ridgelines, and other obstacles in this study was minimal because the GPS data were collected in open areas above treeline. Other factors, however, were uncontrollable including satellite configurations, atmospheric disturbances, and receiver noise. Differential correction can be employed to minimize these problems, although the data used in this study were not corrected. The implications of using uncorrected GPS data were assessed by correcting a subset of the mapping using the Ray Brook, NY, base station. Uncorrected and corresponding corrected patches of alpine tundra were digitized for parts of Algonquin, Basin, Little Haystack, Marcy, and Wright. These summits were selected because the base data were available and the original mapping times varied by date and time of day, providing a diverse sample. A total of 95 patches (15% of the total number) covering 2.1 ha (5.2 acres) were compared. The total area shifted by ~1% following correction and individual patch size varied by <5%. All corrected and non-corrected patches of alpine meadow overlapped, and total coincidence was 84% by area. No corrected and uncorrected patch boundary differed more than 3 m and most differed by much less. Overall this accuracy assessment strongly supports the validity of the GPS mapping in its uncorrected form.

All of the GIS operations (aside from the calculation of 2D area) were constrained to the precision of the original 10-m DEM which was acquired from the U.S. Geological Survey National Elevation Dataset (NED) 1/3 Arc Second dataset. While there are known and documented problems with horizontal and vertical accuracy in this dataset as a whole, it was the best available at the time of the study. The smallest tundra patches mapped were 9-m^2, but most were much larger, thus it is reasonable to conclude that the vertical and horizontal accuracy of the DEM did not overly compromise the accuracy of the results for calculating the elevation, slope, and aspect of tundra patches. The most problematic tundra patches were a few large polygons draped over ridgelines that spanned multiple aspects, slope angles, and elevations. However, similar to the observations of Kimball and Weihrauch (2000) in New Hampshire and Maine, alpine tundra communities in the High Peaks are rarely found on convex ridgelines. Thus, the overall dataset is likely to be free of bias that could have been generated if a large number of polygons were found in this position.

Discussion

TOTAL TUNDRA AREA

Despite the difficulties of quantifying the extent of alpine tundra in the High Peaks, two efforts to inventory alpine areas have been undertaken over the past 40 years. Di Nunzio (1972) estimated the area of alpine tundra in the High Peaks region by using surface cover transects to quantify the relative proportions of bare rock, krummholz, and alpine tundra. This work is the basis for the widely cited estimate of "85 acres" (34.4 ha) of alpine vegetation in the High Peaks that has been adopted by conservation organizations and literature describing the natural history of this region (e.g. Slack and Bell, 2006). More recently, Howard (in preparation) used aerial photographs and GPS field checking to delineate the alpine treeline ecotone, yielding a total

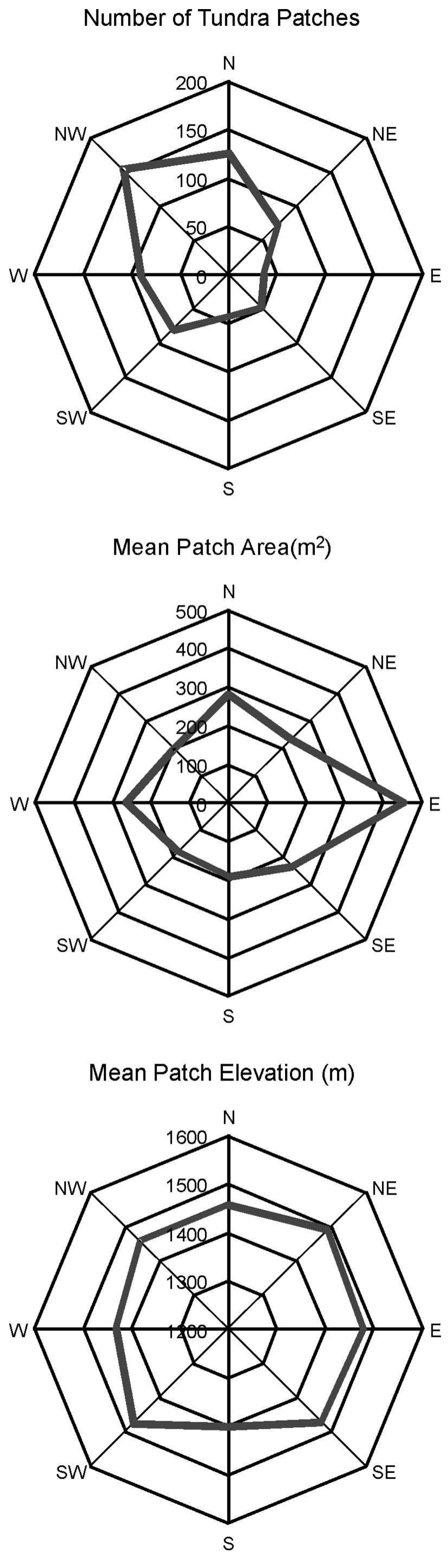

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FIGURE 3. Tundra patch characteristics partitioned by aspect class. Patches are most common on northwest-facing slopes; however, they are generally smaller in these locations. The largest patches are found on leeward slopes. The pronounced low in mean patch elevation on south-facing slopes is an artifact of a single large, anomalously low patch on Noonmark (see Fig. 2).

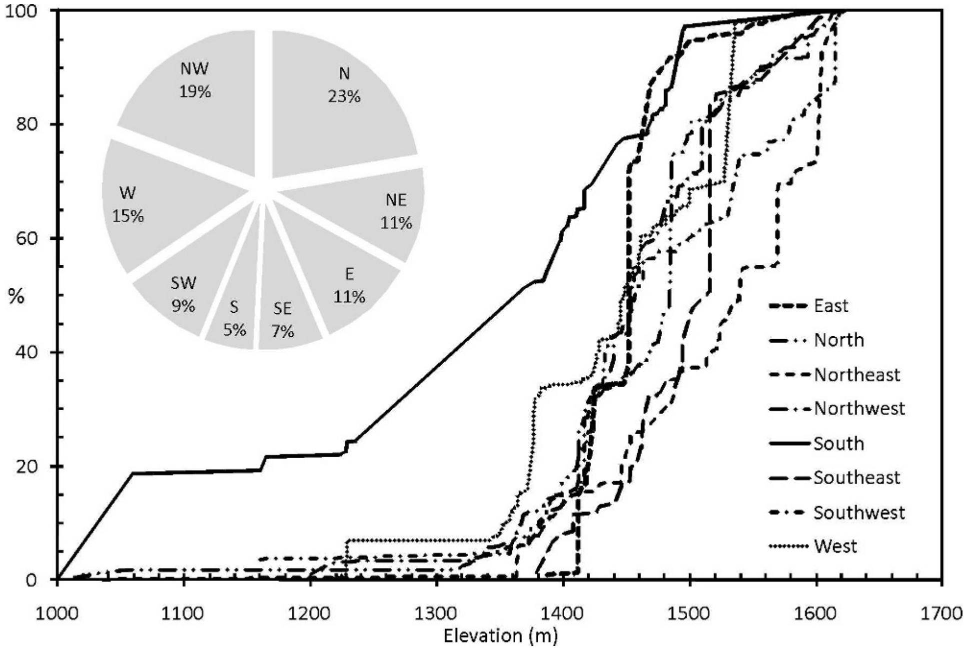

FIGURE 4. Inset: total tundra area partitioned by aspect class including Algonquin and North Boundary. Main figure: cumulative % area partitioned by aspect class (not including Algonquin and North Boundary). South-facing slopes clearly follow a different trend than slopes of other aspects, emphasizing the uniqueness of this class composed of a much smaller number of patches. Slopes facing west, north, and northwest gain cumulative area rapidly at lower elevations underscoring the lower treeline in these aspect classes. East-facing slopes gain cumulative area rapidly at intermediate elevation, perhaps reflecting the role of snow-bank communities.

"above treeline" area estimate of ~70 ha (~173 acres). This larger value can be attributed to the inclusion of all forms of alpine surface cover in addition to tundra vegetation.

Considering this history, the total of 26.3 ha (65 acres) of alpine tundra in the High Peaks region calculated by this project appears to represent a decrease from previous estimates. However, because it was determined entirely through GPS-enabled field mapping of the entire population of tundra patches, as opposed to remote sensing using relatively low resolution imagery or extrapolation from surface transects, this result may be more accurate than these prior efforts. Part of the discrepancy between this result and previous work could be due to this study avoiding the heavily impacted summit of Whiteface where a small area stands above treeline. Some areas of alpine vegetation also exist on summits not considered in this project; however, they are very small and unlikely to sum to more than a few acres. It is also possible that some areas of alpine vegetation have been lost to erosion induced by foot traffic on the most frequently visited peaks in the nearly 40 years since Di Nunzio's (1972) work. However, much of the extensive recreational damage to these areas happened before the 1970s when the Adirondack Mountain Club began an aggressive public education campaign to alert the public to the impact of unregulated foot traffic in the alpine zone (Waterman and Waterman, 1989). In fact, some alpine vegetation recovery has been documented on these stewarded peaks (J. Goren, personal communication) Overall, the decreased estimate of 26.3 ha (65 acres) most likely stems from the unique aims and methods of this study: prior research (e.g. Di Nunzio, 1972; Howard, in preparation) was geared toward a comprehensive description of alpine surface cover, whereas this work focused exclusively on the distribution of tundra vegetation.

IMPORTANCE OF ENVIRONMENTAL FACTORS

Despite extensive research, a universal theory explaining the elevation of alpine treeline on a global scale remains elusive (e.g. Dullinger et al., 2004; Holtmeier, 2003; Kullman, 2007; Körner, 1998; Malanson et al., 2007). Numerous studies have emphasized the role of temperature in controlling the position of alpine treeline (e.g. Daubenmire, 1954; Holtmeier, 2003; Körner and Paulsen, 2004), and close correspondence between average growing season temperature and treeline elevation has been noted in most settings at a global scale (e.g. Körner, 1998). The results of this study in the High Peaks reveal a threshold elevation of ~1350 m above which tundra vegetation is common (Fig. 2), which could be taken as evidence that growing season temperatures above this elevation are too cold for extensive tree growth. However, some patches at low elevation, for instance one on Noonmark (1568 m^2 at 1060 m) are quite large in area, and Figure 5 reveals that tundra does not continue to occupy increasing percentages of total land area at progressively higher elevations above treeline (with the exception of Skylight). Furthermore, the distribution of tundra patches by elevation on the different summits is non-uniform, as illustrated by Figure 2. Thus, declining summer air temperatures related to increasing elevation cannot be the sole control on the distribution of alpine tundra vegetation in the High Peaks.

The analysis of patch distribution as a function of aspect illustrated in Figure 3 provides additional information about the controls on alpine tundra in this region. Tundra patches are clearly more common on slopes facing southwest through north in the High Peaks region, and only two summits (Skylight and NW Wright) have mean patch aspects in other directions (Table 1). Mean patch elevations are also consistently lower on westerly slopes, with the exception of the south-facing aspect class that is skewed by a few, large, low-elevation patches. A similar pattern is shown in cumulative area distribution in Figure 4, where slopes facing west, northwest, and north gain cumulative area rapidly at lower elevations, and in the overall tundra area distribution plotted in Figure 4 (inset) where north and northwest aspects contain the largest amounts of tundra per aspect class. These distributions can be compared with meteorological data for prevailing wind directions. Long-term, year-round wind data are not available for the High Peaks region, although monitoring at the weather observatory on Whiteface (1500 m) in the High Peaks during January 2010 revealed a monthly average wind vector of 258° (U. Roychowdhury, personal communication). More complete data are available from the Mount Washington Observatory in New Hampshire. There at an elevation of 1917 m and at similar latitude ~200 km east of the High Peaks, annual prevailing winds

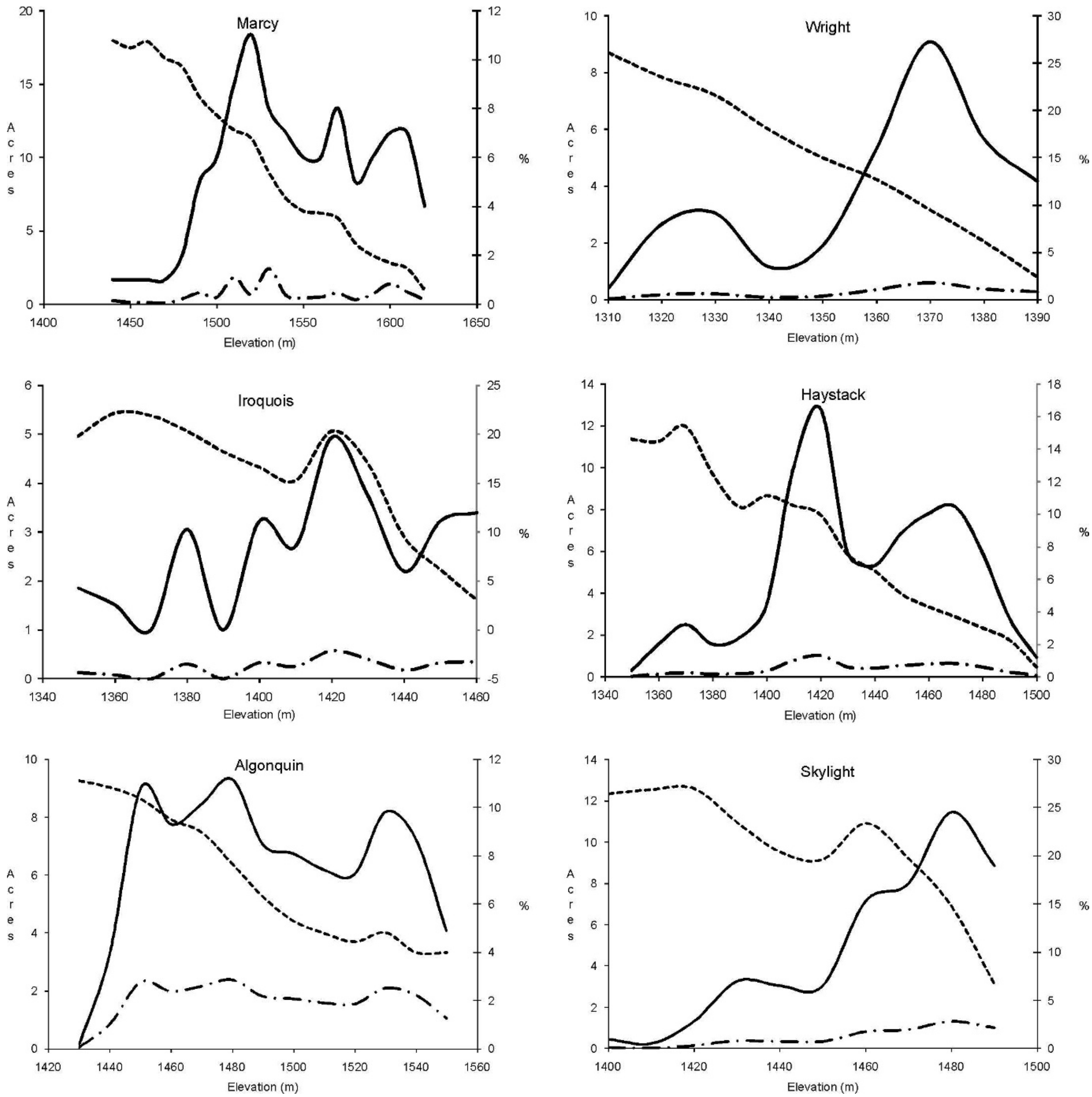

FIGURE 5. Plots showing (a) total summit area partitioned by elevation (dashed line, left axis), (b) tundra acreage partitioned by elevation (dot-dashed line, left axis), and (c) percent of summit area occupied by tundra at different elevations (solid line, right axis) for the six summits with tundra covering at least 80 m of elevation range across a wide range of aspects. Note that maximum values of tundra cover (as a percent of total area) are found at intermediate elevations within the alpine zone on all summits except for Skylight. 1 acre = 0.4 ha.

average west-northwest (290°). Together these results are consistent with the conclusions of previous studies (e.g. LeBlanc, 1981) that exposure to prevailing winds limits the growth of trees and favors the presence of low-lying tundra vegetation, explaining the unusually low treeline elevation in this understudied region.

It is also notable that while patch number and total patch area are highest on the windward slopes (Fig. 3), tundra patches found in these aspect classes tend to be individually smaller compared with the larger patches on leeward slopes. This pattern is particularly obvious in the plot of mean patch area (Fig. 3) where patches on east-facing slopes average nearly twice the size of those facing northwest. This pattern of larger tundra patches on leeward slopes may reflect the presence of snow-bank vegetation communities that flourish in settings where wind-blown snow limits the duration of the growing season. Abundant snow-bank vegetation might also explain the anomalously steep cumulative area distribution curve for east-facing slopes in Figure 4. Kimball and Weihrauch (2000) reported that snow-bank communities are typically found on leeward southeast-facing slopes in New Hampshire and Maine and it seems likely this process is operating in the High Peaks region as well. Future efforts to map vegetation assemblages in the High Peaks would allow testing of this interpretation.

Expanding the role of exposure to a larger spatial scale, the location of individual summits within the array of mountains in

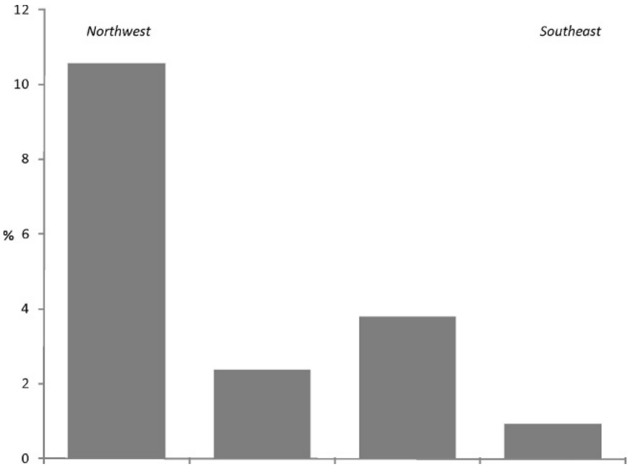

FIGURE 6. Percentage of land area above 1350 m a.s.l. in each of the four swaths (from northwest to southeast) shown in Figure 1 that is occupied by alpine tundra vegetation (including Algonquin and North Boundary). The strong regional gradient towards reduced tundra abundance towards the southeast is support for the theory that regional exposure to prevailing northwesterly winds limits tree growth at the higher elevations.

the High Peaks region might also play a role in governing the abundance of alpine tundra vegetation (Fig. 1). When the tundra complexes on Algonquin and North Boundary are considered, the cluster of alpine summits at the western end of the study area contains more than 50% of all the tundra in the High Peaks region, even though maximum elevations are greatest farther to the east around Marcy. In contrast, summits at similar elevations at the far eastern end such as Giant and Dix contain less than 3% of the total tundra area. When normalized to the area of high-elevation land, the abundance of tundra decreases markedly in the direction of prevailing winds across the study area (Fig. 6). This pattern of greater tundra abundance in the northwestern sector of the High Peaks region is consistent with varying degrees of exposure to prevailing winds from the northwest.

On the scale of individual summits, the multi-modal distribution of tundra dominance (Fig. 5) may reflect zonation of alpine plant communities. In this scenario, the lower band of tundra represents the heath-meadow community, with rare instances of sedge meadow. The upper vegetation bands, in contrast, may correspond to the sedge meadow and *Diapensia* communities found on or near the actual mountain summits. The drop in tundra abundance between bands could reflect zones of steeper slopes typically present beneath the summit plateau. It is important to note that Skylight provides a clear exception to this pattern, which may be explained by its gently sloping morphology. This lack of physical impediments to the spread of alpine vegetation produces a situation in which alpine species with varying degrees of exposure tolerance are blended seamlessly into a continuous community that changes composition along an environmental gradient from lower to higher elevation. Because mapping of individual vegetation communities was not part of the fieldwork for this project it is not possible to determine if the peaks in tundra abundance in Figure 5 are composed of contrasting plant assemblages; however, this would be a worthwhile objective for future fieldwork.

IMPLICATIONS FOR TREELINE STABILITY

Given the compression of environmental gradients produced by steep topography, mountain environments should be among the first locations to illustrate effects of anthropogenic climate warming (e.g. Price and Barry, 1997). In recognition of this sensitivity, observational frameworks such as the *Global Observation Research Initiative in Alpine Environments Project* (Grabherr et al., 2000; GLORIA, 2010) aim to establish standardized methodologies for observing the evolution of biodiversity and alpine plant communities throughout a network of long-term monitoring sites. Some studies have cautioned that changes in the elevation of alpine treeline would be an imperfect proxy for climate change because of unknown lag times, the possibility that treeline position is controlled by microsite effects unrelated to climate, and variability in underlying geology (e.g. Kupfer and Cairns, 1996; Butler et al., 2007; Malanson et al., 2007). Analysis of soil properties beneath different vegetation communities was beyond the scope of this study, thus it is not possible to determine whether physical or chemical properties of the substrate exert an influence on the location of vegetation communities. Nonetheless, on a regional level, the work of Kimball and Weihrauch (2000) in New Hampshire and Maine outlined the value of using the position of alpine treeline as a biomonitor for climate change given the understanding that changes in summer temperature, frequency of ice growth, prevailing wind directions, or other environmental variables would likely impact treeline elevation. This suggestion was prescient given that recent work by Beckage et al. (2008) has documented a rise of ~100 m of the transition from northern hardwood to boreal forest vegetation in the Green Mountains of Vermont between 1962 and 2005. This rise accompanied an increase in mean annual temperature of 1.1 °C and a precipitation increase of 34%. Beckage et al. (2008) concluded that high-elevation forests in Vermont respond rapidly to climate forcing, and extrapolating from their study, it is concerning to consider what upward shifts in the range of boreal tree species might mean for the unique alpine tundra communities in the High Peaks.

The 20 summits in this project rise from 12 to 186 m above the lowest tundra patch on respective summit flanks (mean of 70 m). Given the lapse rates for summer temperature of 6.0 °C/km calculated for Vermont by Beckage et al. (2008), a relatively small temperature increase (0.07 to 1.1 °C) could be enough to drive tree growth up to the highest summits in the High Peaks. Indeed, this estimate range overlaps with the observed warming in Vermont between 1962 and 2005, indicating that temperature increases of this magnitude are possible in a relative short time period. However, results of this project in the High Peaks corroborate previous studies (e.g. LeBlanc, 1981; Spear, 1989) by indicating that alpine treeline is controlled at least as much (if not more) by winter icing and exposure to prevailing winds. Thus, increasing growing season temperature is unlikely to result in a decrease in alpine tundra area unless the frequency of winter icing events that cause physical damage to trees is reduced. Winter temperatures are unlikely to rise sufficiently to eliminate icing events in these mountains. Mean January temperatures over the past three years at the Whiteface Weather Observatory have averaged −11 °C (U. Roychowdhury, personal communication), and analysis of climate data from the Mount Washington Observatory reveals that the rate of climate warming is reduced at the highest elevations where summits project into the free atmosphere (Seidel et al., 2009). Furthermore, the pronounced exposure of these summits to prevailing winds is a function of regional topography, which is essentially constant. Thus, the higher elevations may remain uninhabitable by trees regardless of what happens with growing season temperatures lower on the mountain slopes. Indeed, there is some evidence of increasing fog and rime ice deposition over time at the Mount Washington Observatory, which would suggest that the highest elevations are not growing more amenable to tree growth (Seidel et al., 2007).

Work from other settings has underscored the non-climatic challenges faced by trees attempting to migrate upward into alpine tundra including inter-species competition, seed supply, microclimate effects, lack of exposed mineral soil, and slow growth rates (e.g. Malanson and Butler, 1994; Malanson et al., 2007). In light of these, some studies have concluded that alpine treeline has strong inertia to upward movement (Theurillat and Guisan, 2001; Dullinger et al., 2003, 2004) or that treeline is controlled so strongly by microsite characteristics that treeline could never rise uniformly at a regional scale (Malanson et al., 2007). When combined with the evidence that exposure to icing events and winter winds limits upward tree growth in the High Peaks, this interpretation raises the somewhat counterintuitive possibility that the boreal forest zone on these mountains may be more endangered by climate change than the higher alpine tundra. If northern hardwood vegetation continues to rise higher at the expense of boreal forest, as documented for Vermont by Beckage et al. (2008), but alpine treeline is unable to rise because of the frequency of icing events or other factors, then the boreal zone may be squeezed from below and reduced in overall extent (e.g. Tang and Beckage, 2010).

Conclusion

Detailed GPS-enabled field mapping reveals that the High Peaks region of the Adirondack Mountains contains 26.3 ha (65 acres) of alpine tundra. This value is less than the often presented estimate of 34.4 ha (85 acres) and is considerably less than the total estimated by a previous attempt to delineate the alpine treeline ecotone. These differences likely reflect a combination of disparate techniques and mapping subjectivity. Analysis of 634 individual patches of tundra vegetation in the context of environmental variables reveals that exposure is the dominant factor influencing the alpine vegetation distribution at regional, summit, and micro-terrain scales. This result is consistent with previous work in New Hampshire and Maine that used a related methodology with less reliance on field mapping (Kimball and Weihrauch, 2000). A major benefit of the entirely field-based approach employed in this study is the delineation of tundra patches down to 9 m^2 in area. The greatly increased presence of these patches on windward slopes and the increased dominance of tundra vegetation at the northwestern extent of the study area underscore the controlling role of exposure to winter winds in limiting growth of trees at higher elevations.

Small tundra patches such as those mapped in the Adirondacks should be particularly sensitive to changing environmental conditions. Climate changes that alter the frequency of icing events, the severity of winter storms, cloudiness, or prevailing wind directions could all be expected to shift the balance between arboreal and alpine vegetation. These changes could be detected by careful repeat mapping, and the methodology developed in this study, especially if combined with differential GPS surveying techniques, could be reapplied to monitor potential vegetation shifts over time. Given that climate change impacts on vegetation communities are likely to be felt first along ecotones and in marginal environments, alpine vegetation monitoring in the Adirondack High Peaks should be a priority for future research.

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