2013 NORTHEASTERN NATURALIST 20(4):559–577

Establishing Alpine Research Priorities in Northeastern North America

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Abstract - Research in alpine areas of northeastern North America has been poorly coordinated, with minimal communication among researchers, and it has rarely been multidisciplinary. A workshop was organized to review the state of alpine research in northeastern North America, to facilitate cooperation, and to encourage discussion about research priorities for the region's alpine habitat, which occurs in four US states and the southern part of Québec, Canada. More than 40 researchers with diverse expertise participated in the discussions, including lichenologists, botanists, herpetologists, ornithologists, ecosystem scientists, climatologists, conservation biologists, land managers, and others. Research priorities were developed through post-workshop discussions and an online survey, and they are presented here, along with a summary of the process used to organize the workshop. In addition to specific research questions, strong support was expressed for creation of a network of long-term alpine monitoring sites where a standardized protocol would be used to collect data on biotic and abiotic parameters. Researchers also strongly endorsed the creation of an organization to continue the exchange of information.

Introduction

Alpine ecosystems in northeastern North America occur on more than 60 mountains south of the St. Lawrence River, scattered across four US states and southern Québec (DiNunzio 1972, May and Davis 1977, Sperduto and Kimball 2011). Found above treeline, these regions are dominated by lichens, mosses, and perennial, long-lived graminoids, forbs, and dwarf shrubs that can survive short growing seasons, severe winter temperatures, extreme annual climatic variability, and mechanical degradation from wind, blowing snow, and icing. Alpine communities in northeastern North America occur at lower elevations (from ≈1000 m to <2000 m) than similar communities in other regions at the same latitudes. With the exception of large areas of contiguous alpine habitat

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on the Presidential Range in New Hampshire, Mount Katahdin in Maine, and the Chic-Choc Mountains on the Gaspé Peninsula of Québec, alpine communities in the region occur as discrete, isolated assemblages (Fig. 1). Although the total area of alpine habitat in the region depends in part on how the biome is defined (nomenclature for this regional biome type varies in the literature from tundra to arctic-alpine to alpine, although here we refer to it as alpine) a reasonable approximation is ≈80 km^2 (Carlson et al. 2011, Kimball and Weihrauch 2000; G. Fortin, unpubl.data See Supplemental File 1, available online at http://www.eaglehill.us/NENAonline/suppl-files/n20-4-N1158-Capers-s1, and, for BioOne subscribers, at http://dx.doi.org/10.1656/N1158.s1). These islands of habitat contribute unique elements to the region's biodiversity. Several plant and invertebrate species are endemic to the region (Fig. 2; Bliss 1963, Sperduto and Cogbill 1999, Sperduto and Kimball 2011), and the alpine habitat represents the southern range limit of a number of arctic plants (Fernald 1950, Jones and Willey 2012a, Zika 1992). Furthermore, alpine areas are important to the region's tourism industry (Royer et al. 1974, Scott et al. 2008).

Alpine and subalpine communities are among the most vulnerable to climatic change (Lenoir et al. 2008, Pauli et al. 1996, Rodenhouse et al. 2008, Walker et al. 2001, Wilson and Nilsson 2009). High-elevation and high-latitude areas have been subject to the greatest warming globally (Parry et al. 2007), and climate change has already produced observable changes in alpine plant community composition and species distributions at some sites (Lenoir et al. 2010, Parry et al. 2007, Pauli et al. 1996, 2012, Root et al. 2003, Walther et al. 2002). However, mountain ecosystems exhibit considerable horizontal and vertical variability in response to warming trends (Diaz and Bradley 1997, Weber et al. 1997). Alpine ecosystems also are threatened by changes in the timing and type of precipitation, increasing nitrogen deposition (Wolfe et al. 2003, Wookey et al. 2009), acidic pollution (Weathers et al. 1988), and long-distance transport of ozone (Fischer et al. 2004). An improved understanding of the resistance and resiliency of northeastern alpine ecosystems to ongoing changes in environmental stressors is needed.

Alpine and subalpine habitat in the northeastern United States (34 km^2) is mostly located within the White Mountains of New Hampshire, the Adirondack Mountains of New York, the Katahdin and Longfellow Mountains of Maine, and the Green Mountains of Vermont (Fig. 1). An additional 46 km^2 of alpine (>1000 m asl) and 175 km^2 of subalpine (>900 m and <1000 m asl) habitats occur on the Gaspé Peninsula of Québec (G. Fortin, unpubl. data). For the purposes of our discussion, we excluded areas north of the St. Lawrence River, where alpine tundra occurs at lower elevation and grades imperceptibly into arctic tundra, especially in coastal areas (Jones and Willey 2012a). The area on which we focus is entirely within the Greater Northern Appalachian Bioregion (Hamilton and Trombulak 2010).

Most mountains in New England and southern Québec are composed of granite and granitoid rock, mica schists, gneiss, and quartzite of Devonian age (Bliss 1963). Some clusters of alpine summits, including the Katahdin massif in northern Maine (Fig. 2), are underlain by intrusive igneous rocks (Osberg et al. 1985). All of these features are considered part of the Appalachian Mountain system. The Adirondacks High Peaks region, in contrast, is a southeastward extension of the Canadian Shield. These mountains are composed of Precambrian anorthosite and were created by domal uplift (McLelland et al. 2004). The long-term geomorphic history of these mountains is unclear, but recently published evidence suggests that unroofing and the development of kilometer-scale relief had begun by the late Mesozoic (Roden-Tice and Tice 2005, Roden-Tice et al. 2012). During the Quaternary, the form of northeastern mountains was greatly impacted by continental- and alpine-style glaciation (Davis 1999, Eusden et al. 2013).

The climate in the region is classified as Dfb (cool-summer, humid continental type) in the Koppen-Geiger system (Ward et al. 1938), but summits are classified as ET (tundra climate; Reiners and Lang, 1979). Summertime weather is cloudy, wet, and windy (Babrauckas and Schmidlin 1997, Bliss 1966). For the period from 1935–2006, the temperature on the summit of Mount Washington, the highest peak in the region (1917 m), ranged from (mean ± SE) -14.0 ± 1.6 ºC in the winter to 8.3 ± 0.8 ºC in the summer, while temperatures in Pinkham Notch (the valley to the east of the mountain at 619 m) ranged from -8.3 ± 1.5 ºC in the winter to 16.2 ± 0.7 ºC in the summer (Seidel et al. 2009).

In New Hampshire, alpine plant communities derived from lower-elevation tundra in the early post-glacial period were confined by forests to higher mountain elevations by about 12,000 years before present (YBP). Treeline may have extended in elevation during regional warming from 10,000 to 5000 YBP and then

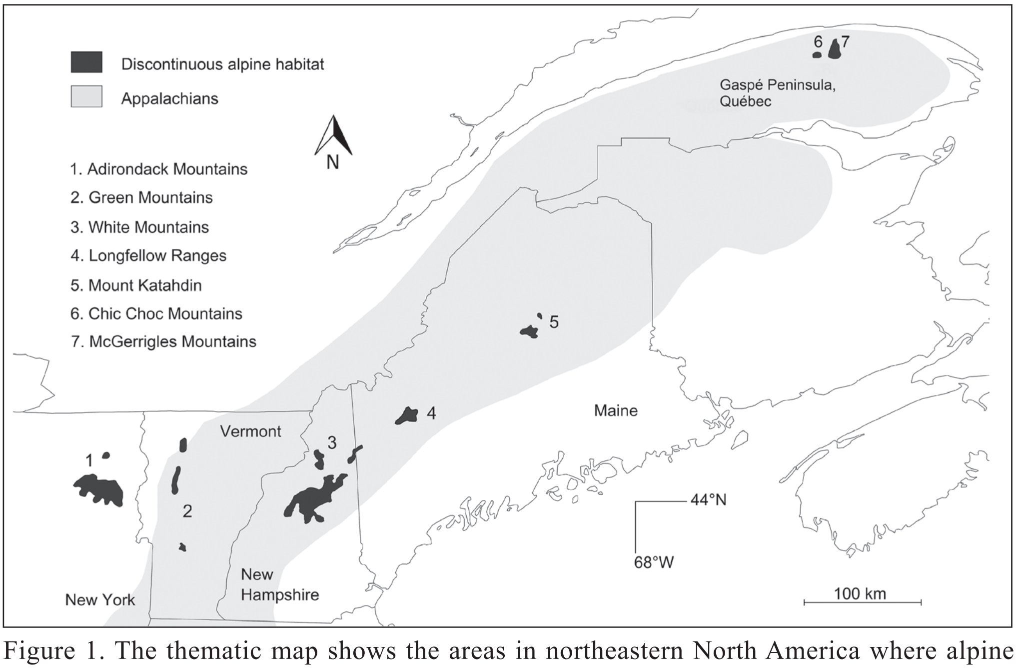

Figure 1. The thematic map shows the areas in northeastern North America where alpine habitat is found. The black-filled areas do not represent continuous alpine habitat but show the areas in which peaks with alpine communities on their summits occur and represent multiple peaks in most cases.

stabilized near current conditions, with alpine indicators increasing with cooler and wetter conditions during the past 3000 years. These post-glacial climatic oscillations likely increased the attrition of arctic-origin species isolated from their parent populations (Spear 1989). Much of the montane forest throughout the region was logged during the 19th and early 20th centuries, but disturbance in the alpine zone has been minimal (Carlson et al. 2011, Kimball and Weihrauch 2000). Domestic animals were grazed unsuccessfully on several alpine areas in the region, although not in the past 50 years, and the impacts of this practice are considered negligible (Waterman and Waterman 1989). Moose re-occupied the region in the past half-century, and they browse alpine plants occasionally, but they are thought to cause little damage. *Rangifer tarandus caribou* Gmelin (Woodland Caribou) historically occurred through northeastern North America and can influence alpine plant communities, but in this region they now occur only in the Gaspésie (Fig. 2; Jones and Willey 2012b,). Fire is not believed to be a major factor in the creation

Figure 2. Although alpine habitat occurs as small, isolated patches on many mountains in northeastern North America, most of the total alpine area is confined to a few mountain ranges (Jones and Willey 2012a). These include the Chic-Choc Mountains of Québec, which support Woodland Caribou (upper left), Mount Katahdin in Maine (lower right), and the Presidential Range of New Hampshire, where endemic taxa such as *Boloria chariclea montinus* (Scudder) (White Mountains Fritillary) (upper right) and *Potentilla robbinsiana* (Robbins' Cinquefoil) (lower left) are found. Photographs © Michael T. Jones and (upper right) Kent P. McFarland.

or persistence of true alpine areas in the region, though fire maintains alpine-like open areas on some low-elevation rocky ridges (Sperduto and Kimball 2011). Most alpine summits in the region also have hiking trails, and trampling by hikers can impact plant communities (Ketchledge et al. 1985). However, since the 1970s, management techniques such as treadpath definition with low rock scree walls has limited damage mostly to a 1–2 m-wide area, and natural re-vegetation can occur within decades or less (Doucette and Kimball 1990).

Numerous theories have been advanced to explain the northeastern North American treeline (reviewed in Richardson and Friedland 2009). The northern latitude treeline corresponds with the 6.7 ºC isotherm for mean growing-season temperature or a mean temperature of 10 ºC for the warmest month (Jones and Willey 2012a, Nagy and Grabherr 2009, Richardson and Friedland 2009). Problematic aspects of the hypothesis that temperature is the dominant factor explaining treeline in the region are that the mean growing-season and July temperatures for the summit of Mount Washington are 8.3 ºC (Seidel et al. 2009) and 9.5 ºC (Mount Washington Observatory 2013), respectively, and *Abies balsamea* L. (Balsam Fir) grows in protected areas near the summit at 1846 m (D. Weihrauch, Appalachian Mountain Club, Pinkahm Notch, NH, unpubl, data). The alpine treeline ecotone boundary occurs at ≈1480 m in the Adirondack Mountains, ≈1490 m in the White Mountains, ≈1280 m on Mount Katahdin and ≈1160 m on the Chic-Choc Mountains of the Gaspé peninsula, declining 83 m for each 1 degree increase in latitude (Cogbill and White 1991), and there is considerable variation in the treeline on each of these massifs, i.e., ranging by 573 m and 661 m in the Presidential range and on Katahdin, respectively (Kimball and Weihrauch 2000), and by 293 m on the Chic-Chocs. Northeastern North American mountains are some of the cloudiest in the world due to orographic effects and their proximity to oceanic moisture. They experience frequent air mass changes that give rise to winds that accelerate as they pass over the mountains, and these factors cause winter cloud-ice accretion to increase exponentially above 800 m asl (Ryerson 1990). Exposure and conditions for ice accretion from clouds and mechanical damage are greatest on ridges and least in protected gulfs, corresponding with treeline variability in the Presidential and Katahdin ranges (Kimball and Weihrauch 2000). These factors provide possible explanations for both the region's relatively low elevation alpine ecosystems and survival of alpine ecosystems during the warmer Hypsithermal period. How changes in temperature and precipitation may impact the magnitude, elevation, and frequency of mountain icing events is not understood.

Alpine areas in northeastern North America attracted botanists and entomologists during the 19th and early 20th centuries (Alexander 1940, Bailey 1837, Bliss 1963, Bowditch 1896, Fernald 1901, Scudder 1863, Thoreau 1864), and bird species that nest or forage in the alpine zone have received some attention from conservation agencies in recent years (Goulet and Fuller 2005, Verbeek and Hendricks 1994). However, few studies or inventories have been done on other organisms. A number of students have conducted research in alpine areas, but these efforts have been largely ad hoc, and most of their results remain unpublished. A number of organizations (Appalachian Mountain Club, the Adirondack chapter of The Nature Conservancy, the Adirondack Mountain Club, the Green Mountain Club, Beyond Ktaadn) and governmental agencies (the US Forest Service, Parcs Québec, and state environmental protection offices) have an interest in alpine conservation and research, but no organization exists to plan or coordinate the necessary research, and no vehicle exists for discussion of what research questions need to be addressed most urgently for conservation action. Even among relatively well-studied taxa, basic survey work provides evidence that much remains to be learned. For instance, a survey of alpine lichens in the Gaspé Peninsula of Québec (Sirois et al. 1988) yielded 11 species never before recorded in North America, and a more recent survey on Katahdin (Miller 2009) added 13 lichen species new to North America, and at least three that were new to science.

Because of concerns about the effects that changes in environmental conditions could have on alpine communities in northeastern North America, we organized a workshop in 2011 to discuss these issues and improve communication among researchers studying these effects. The principal goals of the workshop were to 1) improve understanding of the threats facing the region's limited alpine habitat, 2) exchange information on recent and ongoing research, and 3) identify neglected alpine research questions. More than 50 scientists, including lichenologists, botanists, herpetologists, ornithologists, ecosystem scientists, climatologists, conservation biologists, land managers and others, were invited to participate. All had conducted alpine research or been involved in managing alpine habitat in the region within the previous decade.

The workshop produced a preliminary list of research needs, which, following further communication among participants, was refined to produce a consensus document that captured the views of researchers regarding the most important alpine research questions that need to be addressed in the region. Those research priorities are presented here. This list provides guidance both to researchers already working in alpine areas and to others interested in expanding into alpine habitat from related work in the arctic or in montane forests. Finally, the methods used to solicit, compile, and evaluate the views of researchers working across several disciplines and geographic locations may be useful to others considering similar exercises.

Methods

In the fall of 2010, researchers were invited to participate in a workshop on alpine research in northeastern North America. Researchers were identified by online literature searches (using the Web of Science and Biosis Previews databases, searching for "alpine" in the title and each of the states/provinces in all disciplines of interest), by networking with scientists known to have worked in the region's alpine areas, by searching university and state agency websites for information on alpine research, and by contacting state and federal permitting agencies for information on anyone who had done recent studies in alpine areas (e.g., the US Forest Service, which handles applications for work in the White Mountains of New Hampshire).

A total of 48 alpine researchers were invited to participate in the workshop. Four alpine researchers with extensive experience outside the region (both national and international) were invited to offer advice on how the region might establish a more robust research plan like those with which they had long been associated.

The workshop was conducted in April 1–3, 2011, and was attended by 39 researchers. Lists of potential research projects were produced through small-group discussions. These lists were consolidated, organizing projects into categories, and then emailed to 45 alpine researchers, including all workshop participants as well as other alpine researchers who had been unable to attend but were interested in the research priorities. The conference organizers revised the project descriptions through email correspondence, and a final list of 24 research projects emerged. A brief description of each project was written, and a web-based survey was designed using SurveyMonkey (www.surveymonkey.com) to assess the level of support for each project among the 45 participating researchers. Email messages asked researchers to indicate how important and urgent they considered the various projects, assigning one of three ranks to each project: critically important and urgent = 1, somewhat important and urgent = 2, less important or not urgent = 3. A weighted mean score was calculated by summing and then dividing by the number of total votes on each question. Low scores indicated stronger overall support for a project.

Results

Twenty-five researchers responded to the survey. Six projects were deemed critically important and urgent by a majority of the respondents (Table 1). Six other projects were judged important but somewhat less urgent (Table 2), and 12 projects were considered worthwhile but either less important or less urgent (See Supplemental File 2, available online at http://www.eaglehill.us/NENAonline/suppl-files/n20-4-N1158-Capers-s2, and, for BioOne subscribers, at http://dx.doi.org/10.1656/N1158.s2). Workshop participants also recommended two major initiatives to support identified research projects. These initiatives are listed as separate recommendations below.

Table 1. Research projects given the strongest support by scientists working in the alpine ecosystems of northeastern North America. These six projects were considered critically important and urgent by a majority of respondents to a survey. Lower scores indicate stronger support.

Project	Score (mean [± SE])
Project 1	1.20 ± 0.082
Description: Identifying the location, community composition, duration of snow cover and timing of snow melt in snowbed communities, which occur in alpine locations with accumulations of late-melting snow.	
Justification: These species-rich communities support organisms that occur nowhere else in the alpine zone and are thought to be among the most vulnerable to changing climatic conditions (Gottfried et al. 2012, Sætersdal and Birks 1997). Declines in snowbed plants have been reported elsewhere (Klanderud and Birks 2003). The sensitivity of snowbed communities makes them potentially good indicators of climate change.	

Table 1, continued.

Project	Score (mean [± SE])
Project 2	1.28 ± 0.108
Description: Monitoring treeline to establish how it changes and over what time scales, and to determine the mechanisms that establish treeline in the region.	
Justification: Evidence that the treeline is advancing upslope into alpine ecosystems has been found in many areas globally (Danby and Hik 2007, Hughes 2000, Kullman 2002). This research would identify factors associated with variation in rates of change (e.g., aspect, elevation, nitrogen deposition, exposure and edaphic factors), and assess the implications for long-term persistence of the region's alpine communities. Numerous methodological approaches may be appropriate, including resurveys of historical transects and plots, dendrochronological studies, analysis of historical photographs, and studies of how physical stresses limit tree growth.	
Project 3	1.40 ± 0.129
Description: Analyzing the extent and rate of change in woody species occurrence and abundance, particularly in species exhibiting significant vertical growth.	
Justification: Shrubs are becoming more important in alpine communities globally (Klanderud and Birks 2003, Wilson and Nillson 2009), and are an important component of northeastern alpine ecosystems (Kimball and Weihrauch 2000). There is evidence that woody species are increasing in the Northeast as well (Capers and Stone 2011), which could threaten the persistence of alpine herbs and cause fundamental changes in the structure and function of alpine communities.	
Project 4	1.52 ± 0.117
Description: Conducting plant surveys on mountains where surveys were previously completed to determine if species richness has changed and to establish improved quantitative baseline study plots for future comparisons with greater resolution than just presence and absence.	
Justification: Increases in plant species richness have been detected in alpine areas of mountains worldwide as lower montane species and/or invasive species colonize areas where they did not previously occur (Erschbamer et al. 2009, Grabherr et al. 2001, Klanderud and Birks 2003, Kullman 2007, Pauli et al. 2012, Walther et al. 2005).	
Project 5	1.52 ± 0.131
Description: Characterizing variation in weather, including mean, minimum, and maximum temperatures; amount and timing of precipitation; wind speed; cloud immersion; ice accretion; and radiation budget.	
Justification: Abiotic factors typically are more important than biotic interactions in environments with high physical stresses. The effects of variation in these conditions on plant and animal communities can be manifest at multiple scales (within communities, among communities and across mountain ranges in the region), and the conditions (and likely their effects) may be changing. The causes of change in biotic communities can be understood in terms of abiotic variation only if those abiotic conditions are measured.	
Project 6	1.52 ± 0.143
Description: Investigating changes in phenology and their consequences.	
Justification: Shifts in the timing of both spring and autumn events have been observed in alpine plants in other regions (Forrest et al. 2010, Ibàñez et al. 2010) although there is much variation both among and within species. Such changes in phenology could have profound effects on other species (Berenbaum et al. 2007, Inouye 2008, Root et al. 2003) and on ecosystem function (Miller-Rushing et al. 2010). This research should include the identification of pollinators and measurement of rates of pollination, fruit production, seed germination, seedling establishment, and seedling survival in relation to environmental variables.	

Table 2. These six research projects were supported less strongly than those in Table 1. At least 40% of respondents considered these projects critically important and urgent, and at least 80% of respondents considered them at least somewhat critical and urgent.

Project	Score (mean [± SE])
Project 1	1.60 ± 0.129
Description: Investigating changes in composition and abundance of lichen and bryophyte communities.	
Justification: Experiments in alpine communities in Norway and elsewhere indicate that warming and nitrogen deposition are associated with increases in the abundance of vascular plants at the expense of bryophytes and lichens (Arft et al. 1999, Cornelissen et al. 2001, Fremstad et al. 2005, Klanderud 2008, Walker et al. 2006). Evidence from the Adirondacks indicates that bryophytes and lichens may be declining in richness in the Northeast as well (Robinson et al. 2010). Northeastern mountains are also exposed to relatively high levels of ozone, acidic pollutants, and nitrogen, which could influence these species.	
Project 2	1.64 ± 0.128
Description: Assessing whether Mount Washington's meteorological and climatic trends are typical or anomalous, considering that the magnitude of climate change appears to decline with elevation (Seidel et al. 2009).	
Justification: The average regional planetary boundary layer, cloud ceiling, and alpine treeline ecotone boundary elevations are proximate and these abiotic factors may be related causal factors for the latter. The magnitude of climatic warming also declines with elevation on Mount Washington because of the stratification and uncoupling of air masses at the lower troposphere's planetary boundary layer and high cloud immersion frequency. Mount Washington's summit is higher and nearer oceanic moisture than other alpine mountains in the region; its proxy value for other mountains' cloud exposure, wind, degree of icing, planetary boundary layer, and climatic trends relative to their alpine ecosystems should be verified.	
Project 3	1.71 ± 0.153
Description: Monitoring vertebrate taxa that occur as isolated, disjunct southern populations on the high mountains of the Northeast.	
Justification: Small, isolated populations are vulnerable to demographic and genetic stochasticity, and monitoring can establish if populations are declining. Such species in the region include the *Synaptomys borealis* (Richardson) (Northern Bog Lemming; known from Katahdin, Bigelow, and the White Mountains), and *Anthus rubescens* (Tunstall) (American Pipit; breeding populations occur in the Northeast only on Katahdin, Mount Washington and the mountains of the Gaspésie). Environmental conditions (precipitation, mean and extreme temperatures, timing of snow accumulation and melt) should be measured so demographic changes can be associated with changing environmental conditions. Information also is needed on the degree of population connectivity for isolated alpine fauna.	
Project 4	1.72 ± 0.147
Description: Investigating the historic importance of anthropogenic influences on alpine peaks, including fire.	
Justification: Paleoecological research indicates that many alpine areas throughout the Northeast have been relatively stable for several thousand years (Spear 1989). However, historical evidence suggests that, within the past few hundred years, trees covered the summits of some lower mountains that now support alpine or subalpine communities. Numerous lines of inquiry may be appropriate, including analyses of historical records, paleoecology, dendrochronology, and chemical and isotopic analyses of organic material. Such analyses would provide insight into which alpine species are able to best disperse and colonize newly available habitat.	

Long-term monitoring network

Workshop participants strongly supported establishment of a regional network of alpine monitoring sites where long-term, standardized information on both environmental conditions and biological communities could be collected. The purpose of the network would be to investigate the nature of relationships among organisms and between organisms and the environment, and to record any directional changes in either environmental conditions or biological communities. A standard protocol based on the one used by the international Global Observation Research Initiative in Alpine Environments (GLORIA) network (Grabherr et al. 2010), and supplemented with additional climatic measurements would facilitate systematic inter-site comparisons as well as comparisons with other mountains in the world. The monitoring-site network should include the larger alpine complexes from New York to Maine and in the Chic-Chocs of Québec. For maximum benefit, the environmental variables to be monitored would include air temperature, soil temperature and moisture, wind speed and direction, cloud exposure and icing, solar radiation (shortwaves), terrestrial and atmospheric radiation (longwaves), atmospheric humidity, and soil pH, particle size, and nutrient content. The baseline data from these long-term monitoring sites would help address many of the questions that researchers believe are most important and urgent (Tables 1, 2), improve basic ecological understanding, and document how conditions vary at large and small spatial and temporal scales.

Alpine research consortium

Researchers strongly supported the creation of an organization to facilitate the exchange of information among US and Canadian alpine researchers and land managers. The organization would foster communication with those in other regions, sponsor future meetings, support projects of regional importance, encourage collaboration (especially collaboration between Canadian and US researchers), and

Table 2, continued.

Project	Score (mean [± SE])
Project 5	1.72 ± 0.136
Description: Establishing the environmental factors that prevent or limit tree growth and survival in alpine environments, such as the frequency and magnitude of ice-loading and abrasion from blowing snow across environmental gradients (aspect, elevation, and topographic position).	
Justification: Atmospheric conditions including wind, the planetary boundary layer, cloud exposure, and ice accretion rates may not remain stable as the region's climate continues to change. Quantifying the environmental stress factors that limit treeline is necessary to predict the future of plant communities with changing environmental conditions.	
Project 6	1.76 ± 0.145
Description: Conducting observational and experimental studies to identify the response of individual species to warming, nitrogen enrichment and the combined effects of both. Justification: Both increasing temperature and atmospheric nitrogen deposition have been linked with changes in plant community composition, structure, and function. Compositional changes are often related to the characteristics and strategies of constituent species, and the responses of individual species need to be characterized so changes at the community level can be understood.	

provide a central repository for data involving alpine communities in northeastern North America.

Discussion

The changing environmental conditions observed in recent decades inspired urgency and focus during the workshop and subsequent discussions on ecological change in alpine communities. Thus, it is not surprising that creation of a network of long-term monitoring sites received overwhelming support. Detecting change in environmental variables or in biological communities requires information on conditions from at least two time periods, often over a period of decades. Unfortunately, few surveys (Capers and Stone 2011, Ketchledge and Leonard 1984, Robinson et al. 2010) have been conducted with standardized, repeatable methods in the alpine communities of northeastern North America, and even these lack long-term measurements of most abiotic parameters, which makes assessing the causes of change difficult if not impossible. Data from a network of long-term monitoring sites could be used to analyze within-region variation as well as change in communities over a large geographical area. If data on environmental conditions were paired with occurrence and abundance of plant and animal species, then pertinent hypotheses could be generated and tested. These data are precisely what are needed to execute many of the widely supported, focused research questions identified by workshop participants.

Although its importance has been appreciated in recent years, long-term monitoring was undervalued in the past (Callaghan et al. 2004a, Gosz 1999, Tilman 1989). The need to expand or initiate such monitoring in alpine systems, in particular, has been identified previously (Becker and Bugmann 2001, Carlson et al. 2011, Grabherr et al. 2001, Ketchledge and Leonard 1984, Woodin 1959). The absence of basic data on alpine environmental conditions and natural community composition limits researchers' ability to determine if alpine communities have changed, by how much, and why the changes have taken place—information essential for their long-term conservation. Thoughtful science-based management may prevent or delay changes in particular species or communities, but planning such management requires an understanding of population dynamics and ecological processes and functions, as exemplified by the successful recovery of the once-listed, endangered alpine plant *Potentilla robbinsiana* (Lehm.) Oakes ex Rydb. (Robbins' Cinquefoil; USFWS 2002). Only consistent long-term monitoring can establish the baseline data needed to determine whether data collected describe the range of natural variation, or if these data represent evidence for directional change in abiotic conditions, populations or communities, particularly by the long-lived plant species found in alpine areas. Long-term data are also essential to capture extreme events and non-linear responses, and to separate transient community responses from equilibrium responses in alpine systems, similar to what has been described in the arctic (Callaghan et al. 2004b, Post et al. 2009).

The region has an enviable record of long-term weather data from Mount Washington's summit, where conditions have been monitored since the 1870s (continuously since 1932), and from Mount Mansfield in the Green Mountains, where a somewhat consistent record dates back to 1957. Evidence of warming conditions on Mount Washington decline with elevation, possibly because of the mountain's periodic diurnal exposure to free atmosphere conditions above the planetary boundary layer in the troposphere and frequent exposure to clouds (Seidel et al. 2009). Comparative icing data (Ryerson 1988, 1990), preliminary comparisons with Mount Mansfield climate data (G. Murray, AMC Appalachian Mountain Club, Pinkahm Notch, NH, unpubl. data), long-distance air pollutant (ozone) studies from other mountain summits, and similar relationships of alpine plant communities with topography compared to Mount Katahdin (Kimball and Weihrauch 2000) suggest that Mount Washington may be a reasonable proxy for regional climate and air pollution trends, but robustness of this assumption needs further testing. Micro-topographic features can decouple the conditions to which alpine organisms are exposed from climatic conditions measured at regional monitoring stations (Scherrer and Körner 2010).

The research projects receiving the strongest support indicate that researchers want most urgently to establish which climatic changes known to be occurring on alpine mountains outside the region are also occurring in northeastern North America. Rising treeline, increasing species richness at the lowest elevations in the alpine, changes in plant and animal phenology, and increasing abundance of shrubs all have been reported, primarily on European mountains, where alpine research has a long history (Kullman 2002, Pauli et al. 2012). Some of these changes have also been observed in northeastern North America (Beale 2009, Capers and Stone 2011, Robinson et al. 2010) although too little historical information and on-site meteorological data is available to establish how widespread the changes are, or to identify the casual agents. The related highest priority project would characterize weather conditions and their effects on species' distributions and abundance.

The research projects receiving moderate support include demographic studies of vulnerable plants and animals as well as investigations to improve understanding of how abiotic conditions affect biotic communities. Admittedly, the cutoff between projects receiving "moderate support" and "less support" is arbitrary, and reasonable arguments exist for including more (or fewer) projects in either category. In fact, all research needs were widely thought to be worthwhile among participants in the workshop and during subsequent discussions, and the survey exercise was designed only to assess which were thought to be most critically important and urgent.

The recommendations presented here are similar to those made to improve the understanding of the arctic ecosystem's responses to climate change (Callaghan et al. 2004b). Such concordance is not surprising because the region's alpine habitat is of arctic origin and many of the changes predicted to occur, or which are already occurring in northeastern North America could be the same, including displacement of herbaceous plants by trees and shrubs, colonization by species previously occurring only in more benign environments, shifting distribution and phenology of plant and animal species, and declines of mosses and lichens. The research projects proposed here reflect the interests of the scientists participating in this exercise. The majority of participants in the workshop were ecologists, and discussions focused on ecological questions. Although a differently composed group might have identified other research needs, the value of a multi-disciplinary approach was strongly supported. Observed changes in environmental conditions suggest that the proposed research is urgent and were the justification for this priority-setting exercise; it is possible that because of this focus we overlooked important avenues for study unrelated to climate change and pollutant exposure.

Since the workshop was held, one long-term monitoring site has been established in the Chic-Choc Mountains of the Gaspé Peninsula of Québec, and initial vegetation surveys have been conducted. That site is part of the international GLORIA network, which will facilitate global comparisons among conditions and community-level changes. Planning for creation of additional GLORIA sites in the region has begun. In addition, region-wide collaboration among alpine researchers has increased, and at least one of the high-priority research projects, snowbed community surveys, has begun. Furthermore, a bibliography of alpine ecology in the region is being updated and expanded, the possibility of providing online access to the bibliography is being explored, and a website has been established (www.northeastalpine.org) to facilitate communication among alpine researchers in the region.

Alpine communities are vulnerable worldwide, but the most vulnerable may be those that occur as isolated biogeographic islands (Walker et al. 2001), as do most of the alpine occurrences in northeastern North America, or in temperate regions where alpine habitat is found at lower elevations (Krajick 2004). Less abundant and more specialized species are likely to be lost first as conditions change, resulting in regional homogenization of alpine communities. Homogenization of plant communities has already been reported in Adirondack alpine communities (Robinson et al. 2010). Increasing abundance and frequency of woody plants on an alpine summit in Maine also have been reported (Capers and Stone 2011). A more thorough, systematic research program in the region is needed to determine whether these changes are related to climate change and air pollutants, particularly nitrogen deposition. The research needs suggested here provide guidance in designing such an effort.

Acknowledgments

We are grateful to the National Science Foundation for providing financial support for the alpine research workshop. The Appalachian Mountain Club provided additional support. We thank Sophie Schiavone for preparing the map of alpine areas in the region. We are grateful to Charlie Cogbill for making available his extensive data on alpine areas throughout northeastern North America. We also want to thank all of the participants in the workshop as well as other scientists who contributed ideas to the subsequent discussions about the research priorities and preparation of this paper. Finally, we extend our thanks to two reviewers, whose suggestions made the paper more complete and the conclusions more clear.

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