Monitoring for potential effects of climate change on the vegetation of two alpine meadows in the White Mountains of California, USA

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Abstract

East Shield (3658 m) and Barcroft Gate (3697 m) Meadows in the White Mountains of California on the Inyo National Forest were selected for a pilot baseline monitoring study over five-year intervals to determine potential effects of future climate change on the meadows. Stated as a hypothesis: given the natural range of temporal variability of meadow vegetation, a significant portion of that variability is attributed to the effects of climatic variation. The study is associated with the Global Observation Research Initiative in Alpine Environments Project (GLORIA) hosted by the University of California White Mountain Research Station. Both meadows are sedge–rush–grass wet meadows, or fens, which are sustained by surface water in the form of streams and springs. A comprehensive plant list was compiled and the plant species of each meadow were sampled by a point intercept method along two randomly placed transects. The occurrence of all species at predetermined one-meter interval sample points along the transects were recorded, percent occurrence was calculated, and descriptive statistics were done. The monitoring objective is to detect a 20% biologically meaningful change in the vegetation over time with 90% confidence, and accept a 10% chance of a false change error (Type 1 error). Monitoring is planned to be done in conjunction with tracking change in precipitation and temperature. Three indicators of possible climate change were chosen. One indicator is increase in the abundance of those species whose upper range is at or below meadow elevations. The rationale for this indicator is based the 2007 IPCC report estimation that a doubling of atmospheric CO₂ will increase global temperature with a best estimate of +3.0°C. Assuming that the present general lapse rate of −6.32 °C per kilometer for the White Mountains will persist, a 3.0 °C increase may result in an equivalent elevation of the meadows of about +475 m. Published elevation ranges indicate that most recorded species are not likely to be affected by the estimated temperature increase. Second and third indicators are a shift in cover from wet meadow to dry meadow species, and the presence and increase of shrub species resulting from postulated reduced precipitation with drying of meadows and encroachment by surrounding shrubs (sagebrush and rabbitbrush). This monitoring study has the potential to detect long-term responses of vegetation to climate change, and reduce uncertainties and confirm or correct the expected consequences of temperature change.

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1. Introduction

The effects of global climate change on ecosystems have been of increasing concern and the subject of intense research on an international scale as investigated by the IPCC 2007 report (Christensen et al., 2007). Climatically sensitive biomes have been identified in high latitudes and high elevations, particularly on mountain peaks above timberline where increasing temperature may constrain vegetation habitats and lead to changes in plant associations including alteration in species compositions, range shifts, local extirpations, and extinctions of endemic species (Pauli et al., 2004). The latter concern induced an Austrian IGBP/GCTE research initiative, led by Prof. Grabherr of the Institute of Ecology and Conservation Biology at the University of Vienna, to develop a concept for a worldwide comparative observation network to monitor mountain ecosystems that was launched in 2000 as the Global Observation Research Initiative in Alpine Environments (GLORIA).

In 2004, the University of California White Mountain Research Station joined the GLORIA project in collaboration with the USDA...
assumed to be a factor since wildfires are infrequent and fire suppression or natural changes in the fire regime are not introduced to the area beginning in 1852 and 1865, respectively. Centuries location on meadow fringes. This has been attributed to the Kern Plateau of the Sierra Nevada from their mid-nineteenth century.

Photography and anecdotal observations indicate that sagebrush (Artemisia sp.) (an aquatic liverwort), Poaceae (grass family) and Asteraceae (sunflower family) dominated the vegetation until the middle 19th and early 20th centuries when Artemisia and Cyperaceae (sedge family) dramatically increased (Dull, 1999). As with 20th Century conifer encroachment a warming trend began at the same time as the introduction of livestock and introduced another element into the mix of effects. To come to terms with climate change, an investigation of the relationship of climate and sagebrush incursion between 1958 and 1997 in two of the Kern Plateau meadows using observations, measurements of growth rings and stem radii, and May snowpack water content suggest that the initial recruitment of sagebrush (A. rothrockii) occurred during El-Nino driven wet years after which seed production maintained recruitment independent of climate (Bauer et al., 2002). This is consistent with another study which demonstrated that sagebrush is more likely to expand into mesic areas with high water tables, particularly when the surface of the soil was disturbed to prevent competition from herbs, even though such recruitment is usually explained by increased meadow aridity (Berlow et al., 2002).

The effects of climate change on plant associations specific to meadows, their phenology, abundance, biomass, and recruitment are not known from long-term studies or historical data but have primarily been predictive or experimental (Dunne et al., 2003). Complex and sometimes ambiguous results of experimental methods of snowpack manipulation and radiant heater warming, and an analysis of variability on sites along a gradient, on small and landscape spatial scales between 1995 and 1998 for subalpine meadows (approximately 2920 m) in Colorado indicated that the date of earlier snowmelt, along with warmer soil temperatures will advance the timing and lengthen the duration of flowering, particularly early blooming forbs (Dunne et al., 2003). This corroborates other findings for subalpine, alpine, and arctic species that advanced phenology is correlated with earlier snowmelt, shallower snowpack, or lower total snowfall (cited in Dunne et al., 2003).

The vegetation of montane meadows has thus been shown to be responsive to climate change but the nature of meadow-climate dynamics varies according to the time scale, climate variables, and methods of investigation used.

2. The study

The research objective for this pilot study is to determine potential effects of future climate change on the vegetation of two alpine wet meadows as an associated research project of WMRS-GLORIA. Stated as a hypothesis: given the natural range of temporal variability of meadow vegetation, a significant portion of that variability is attributed to the effects of climatic variation. East Shield Meadow (3658 m) and Barcroft Gate Meadow (3697 m) are near the GLORIA monitoring site on Barcroft Mountain (3975 m). In this paper, we classify both meadows as sedge–rush–grass wet meadows (fens) fed by melting snowpack in the spring and runoff from surrounding persistent snowfields and springs. A protocol based on a Bureau of Land Management technical manual for plant monitoring (Elzinga et al., 1988) has been designed to provide quantitative descriptions of vegetation associations as a baseline for monitoring vegetation change over time.

2 Data will be available through the White Mountain Research Station, Bishop, CA.
3. Environmental setting

The White Mountains is the northern part of the high, arid White-Inyo Range with a northwest–southeast axis, located east of and running parallel to the Sierra Nevada in southeastern California (Fig. 1). It is an easterly tilted block with an elevation range from 1310 m at the Chalfant and Owens Valley floors to 4342 m at the summit of White Mountain Peak.

The complex rock substrate consists of metamorphosed marine sediments, volcanic deposits, intrusive granitic plutons, and recent surficial deposits resulting from tectonics, orogenies, and Quaternary glacial activity and erosion, dating from the late Proterozoic, about 700 Ma, through the Cenozoic (Nelson et al., 1991). Most of the area around the meadows is underlain by Jurassic granodiorite of the Barcroft Pluton. The geomorphology is composed of smooth, rounded, unglaciated, and stream dissected mountain ridges and gently rolling planation surfaces with residual bedrock outcrops mantled with frost-fractured rock and periglacial features (Elliot-Fisk, 1991).

Meadow soils have not been analyzed. The surrounding soils in the Mt. Barcroft area are mapped as the Pergelic Cryoborolls–Soakpak family association (Gallegos, 1994). Pergelic Cryoborolls is classified as loamy-skeletal, mixed Xeric Haplocryolls (a subgroup of Mollisols that have a cryic soil temperature regime and xeric moisture regime), and the Soakpak family is loamy-skeletal, mixed Xeric Eutrocyrepts or Xeric Dystrocyrepts (subgroups of Inceptisols that have cryic soil temperature and xeric moisture regimes). They are moderately deep to deep, very stony or cobbly well drained loam soils formed on mountainsides, remnant alluvial fans, and alluvial and colluvial flats and derived from granitic rock.

The climatic conditions of the alpine areas of White Mountains are characterized by low temperatures, aridity, high winds, thin air, high solar radiation, intense ultraviolet exposure, and summer storms, which can deposit snow. The modern mountain climate has three overlapping precipitation maxima. Winter is the season of the primary maximum, delivered by extratropical Pacific cyclones tracked by the polar jet stream supplemented by anomalous cold storms from the north and anomalous warm storms from the southwest. A secondary late spring maximum arrives from the northeast, and a secondary convective summer maximum originates from tropical moisture in the Gulf of California, the Pacific, and, to some extent, the Gulf of Mexico (Hales, 1974; Powell and Klieforth, 1991; Pyke, 1972). Precipitation is distributed more evenly throughout the year than the Mediterranean-type climate of cismontane California (Fig. 2). Vegetation reflects this climate pattern and has changed over time with variation of that climate.

The nearest weather station with a long-term record is White Mountain 2 (049633, 37°35’N. 118°14’W), located on the east slope...
of Mt. Barcroft, at 3800 m. The record begins in 1956 but the collection of data in winter months stopped in 1980 (Powell and Klieforth, 1991). There are two other overlapping records for the periods 1960–1990 and 1971–2000 but snowfall and snow depth are not recorded. The average annual maximum and minimum temperatures during the period of record are 2.2 °C and −7.3 °C, respectively (Fig. 3a–c). The mean annual temperature is −2.5 °C. The average annual precipitation is 469 mm primarily falling as snow from October through May, although snowfall is recorded during the entire year. Average total snowfall is 402 cm and average snow depth for the months of October through June is 34.2 cm. Fig. 4 indicates that temperatures are above 0 °C from June to September and snow depth is zero from July to September. Therefore, degree days above 0 °C can be used as a simple proxy for temperature-driven snow melt. The relationship between snowfall and snow depth for the 1955–1980 period of record is plotted in Fig. 5. Even though all months record snowfall, snow does not accumulate from July to September when temperatures are greater than 0 °C. In June, snowfall is relatively high but the snowpack has decreased since the temperature is above freezing and spring snowmelt has commenced.

Analysis of the climate records show some trends. A comparison of all three records (1956–1980, 1960–1990, 1971–2000), which overlap by 6–10 years indicates an increase in precipitation in December and January, and a decrease in May and July (Fig. 6). Precipitation is variable in other months. During the last 29 years there was a precipitation decrease from May to August and an increase in September, October, December, and January. When minimum and maximum temperature ranges from 1955 to 1980 are compared (the other age ranges do not have annual data), there is a slight rise in maximum temperature by ~1.5 °C (Fig. 7). This is consistent with earlier findings from California (Duffy et al., 2007).

A new weather station, located at the White Mountain Research Station’s Barcroft Research Facility (37°34′59″ N, 118°14′14″ W, elevation 3783 m) began operation in November 2003 but the only period of time with complete data is from July 2007 to the present day. However, the ongoing generation of data is needed for future vegetation monitoring. Another new station, located at a lower elevation at the White Mountain Research Station’s Crooked Creek Research Facility (37°32′35″ N, 118°12′16″ W, elevation 3094 m) began operation in April 2005 and continues to the present day. Even at 689 m lower, the station’s data would have been useful for documenting the climate for the 12 months preceding the baseline sampling but the critical months of November and December are missing from the 2005 data set.

The surrounding vegetation in the Mt. Barcroft area consists of several near-treeless alpine associations, often collectively called a fell field habitat. It is relatively diverse for the harsh climate and usually has a dense plant cover. An ecological survey of the nearby McAfee Research Natural Area (RNA) has classified the vegetation into nine associations grouped into five general categories: alpine grassland steppe, shrubland, sedge meadow, scree slopes, and
aspen forest along South Fork McAfee Creek (Travers, 1993; Cheng, 2000). A few scattered individuals of limber pine (Pinus flexilis) and bristlecone pine (Pinus longaeva) are located upstream from the aspen forest. The grassland steppe, which is the largest category, is divided into five associations, listed here according to the size of area, Koeleria macrantha (junegrass), Ivesia lycopodioides (club moss ivesia), Carex sp. (sedge), Eriogonum ovalifolium (buckwheat), and Trifolium monoense (synonym for Trifolium andersonii var. beatleyae and Trifolium andersonii ssp. monoense). Artemisia arbuscula (low sagebrush) and Chrysothamnus parryi (rabbitbrush) associations comprise the shrublands, the Carex–Deschampsia association occupies wetlands such as McAfee Meadow (termed a sedge meadow), Ribes viscosissimum (sticky current) is the only association on sparsely vegetated scree slopes, and Populus tremuloides (quaking aspen) grows along perennial streams and slopes (Travers, 1993; Cheng, 2000).

All the wetlands, however, apparently do not fall in the Carex–Deschampsia category. East Shield Meadow, located just south of the McAfee Meadow RNA boundary, within the RNA ecological study area, is dominated by Juncus balticus (Baltic rush), Muhlenbergia richardsonis ssp. beatleyae (mat muhly) and Trisetum spicatum. Although Carex sp. is present the sedges are not very abundant. East Shield Meadow could properly be termed a rush meadow. On the other hand, Eleocharis quinqueflora (four-angled spikerush), Muhlenbergia richardsonis and T. spicatum are the dominant sedge and grass species in Barcroft Gate Meadow and so could properly be categorized as a spikerush meadow (Hickman, 1993). According to the McAfee Meadow RNA ecological survey and establishment report (Travers, 1993; Cheng, 2000), wetland associations have the highest percentage plant cover and the lowest species diversity. They are also the wettest of all the associations in the alpine zone, being associated for the most part with pooling or flowing surface water from seeps.

The alpine zone of the White Mountains is considered a marginal environment even though resources are relatively abundant. Surface water in the form of streams and springs sustain the meadows, which provide habitat for rodents – particularly yellow-bellied marmots (Marmota flaviventris) – desert bighorn sheep (Ovis canadensis), and mule deer (Odocoileus hemionus). Most of the food of marmots consists of grasses, sedges, and forbs (Armitage, 1991), while that of bighorn sheep and deer include grasses, sedges, forbs, and shrubs such as sagebrush, mountain mahogany, and creambush (Wehausen, 1983). The marginality rests more on harsh climatic conditions such as aridity, high winds, low temperatures, thin air, high solar radiation, intense ultraviolet exposure, and sudden summer storms.

4. Research design and field application

In this study, the vegetation of East Shield Meadow and Barcroft Gate Meadow is quantitatively and qualitatively described to establish a baseline for monitoring over five-year intervals. The rationale for choosing the two meadows is their proximity to the Mt. Barcroft GLORIA site, accessibility and similarity of human impacts. Change in vegetation is planned to be monitored in conjunction with change in several climate variables given below.

A plant list was compiled for the meadows in order to estimate the population of species present at the time and account for those species that may be missed in the sample, and a point intercept sampling method was used to describe the cover of each species (Elzinga et al., 1988). The point intercept method was chosen because cost, equipment and time constraints dictated a method with a relatively low bias that can objectively characterize an attribute (cover) of the vegetation population that can significantly
detect change within the limitations of the method (Elzinga et al., 1988). The most consequential limitation is a bias against sampling species with low cover values.

Basic descriptive statistics were done for each meadow and data were analyzed in order to characterize the patterns, especially whether the data approximate a normal distribution. Histograms, normal probability plots and the Shapiro–Wilk test were used. Also, the percentage of each monitored plant species was calculated by dividing the number of species at all transects by the total number of plants. Standard significance tests, such as the t test, analysis of variance and Chi square will be used for comparing data from re-sampling.

The following protocols for monitoring meadow vegetation in the field were used:

Step 1: Describe the meadow and its environment: For the purpose of this protocol, a wet meadow is defined as a predominant grass–sedge–rush association. The physical setting and general characteristics of the meadow (landform, slope and aspect, anthropogenic disturbance, surrounding vegetation, and surrounding soil type) was described.

Step 2: Establish the middle point: The edges of the wet meadows were indicated by the first change in vegetation, i.e., absence of sedges and rushes. A measuring tape was extended across the north to south and east to west coordinates of the meadow and the halfway points along each transect by the total number of plants. Standard significance tests, such as the t test, analysis of variance and Chi square will be used for comparing data from re-sampling.

The cross point is the middle point.

Step 3: Install transects: From the middle point, bearings were randomly selected with a die according to the four cardinal directions, and transects were extended along those four cardinals. The ends of the transects were established at the edges of the wet meadow. The beginning and end of each transect was permanently marked by a length of rebar sunk in the ground. The coordinates were assigned as follows, N = 1, S = 2, E = 3, W = 4. Sampling points were established at every meter along the tape. Transects were terminated at the edge of the meadows.

Step 4: Sampling procedure: A list of all observed plant species in each meadow was initially compiled by randomly walking in a zig-zag pattern through the meadow. Transects were established as described above and all species that were intersected at each sample point along the transects by a vertically held pointer was recorded. The ground surface class (bare ground, litter, rock, down wood, moss, live plant base) where the pointer intersects the ground was documented. Transects were photographed from each direction; a record of the photographs giving the transect name, date, exposure, and bearing was recorded. Unknown species were either collected or photographed and described for later identification.3

East Shield Meadow was plotted and sampled on July 25, 2006, and Barcroft Gate Meadow was plotted on July 25, 2006 and sampled on July 26, 2006.

5. Results

East Shield Meadow (Figs. 8 and 9) is located on an extensive plateau on the eastern slope of Mt. Barcroft and about 772 m southeast of the White Mountain Research Station’s Barcroft Research Facility at an elevation of 3658 m (T.4S., R.34E., NW ¼, SE

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3 Species vouchers are archived at White Mountain Research Center, Bishop, CA. Photographs are in possession of the primary author.
The plateau is between South Fork McAfee Creek on the north and Cottonwood Creek on the south. The meadow is on the west side of a rocky outcrop, which apparently dams groundwater and surface flow to create seeps and ponding. It is within the treeless alpine zone approximately 2600 km above the upper tree-line of the bristlecone-limber pine subalpine forest, which is at an elevation of about 3536 m. East Shield Meadow is a small, irregularly shaped and slightly hummocky wetland with a long axis of approximately 68 m by 45 m wide (2403 m²). It has a slope ranging from about 0% to 5% and an easterly aspect. It is dominated by Antennaria rosea ssp. Rosea (pussy-toes) and J. balticus, along with Draba oligosperma var. oligosperma, Potentilla pensylvanica, Carex douglasii, Muhlenbergia richardsonis, T. spicatum, and Festuca brachyphylla (fescue) among other species, surrounded by grassland steppe (K. macrantha and T. andersonii var. beatleyae) (Fig. 10). A stand of R. viscosissimum inhabits the outcrop. All of the recorded species are perennial except for Androsace septentrionalis ssp. subumbellata, which is annual or weak perennial (Hickman, 1993). A Basque shepherder shelter and oven built of stone is on the south edge of the meadow.

The result of the Shapiro–Wilk test (W: 0.8434, p: 0.06296), indicates that the sample comes from a normally distributed population or the data is normally distributed. Also the data points are closely arrayed along the expected probably line of a probability plot. The histogram shows a slight positive skewness of the data, reflecting the skewness value, because there are more low numbers of sampled species. Even with a normal distribution the sample size is too low to adequately characterize the vegetation. Although the departure from normality isn’t severe, the sample size should be increased (i.e., more transects) for re-monitoring.

Barcroft Gate Meadow (Figs. 11 and 12) is located in the upper drainage basin of Cottonwood Creek at the headwaters of one of its forks at an elevation of 3597 m (T.4S., R.34E., W ½ of SW ¼ of NW ¼ of Sec. 33, Mt. Barcroft, CA quadrangle; 37°33′33″N, 118°14′06″W). It is just below a saddle at the White Mountain crest on the west slope of Cottonwood Basin and enclosed on the northwest, west and south by rocky ridges. The Barcroft Road and gate is approximately 180 m upslope to the southwest. The slope of the meadow ranges from about 0% to 15%, and its aspect is generally east. The
The meadow consists of a mosaic of wetlands, alpine grassland steppe, and sagebrush shrub distributed according to substrate and abundance of water. The long axis is northwest–southeast, approximately 234 m by 110 m wide (20,216 m²). The wet meadow that was sampled is on the southern portion of the meadow complex, on both sides of Cottonwood Creek, and measures approximately 27 m north–south and 90 m east–west and approximate the meadow dimensions. Twenty seven species were recorded and sixteen species (59%) were sampled for a total of 247 “hits”, and their percentages calculated (Table 2). The descriptive statistics are:

<table>
<thead>
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<th>N:</th>
<th>16</th>
</tr>
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<tbody>
<tr>
<td>Min:</td>
<td>1</td>
</tr>
<tr>
<td>Max:</td>
<td>49</td>
</tr>
<tr>
<td>Sum:</td>
<td>247</td>
</tr>
<tr>
<td>Mean:</td>
<td>15.4375</td>
</tr>
<tr>
<td>Std. error:</td>
<td>3.99997</td>
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<tr>
<td>Std. error:</td>
<td>0.8253, p: 0.00603</td>
</tr>
<tr>
<td>Std. error:</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The similarity of the mean and standard deviation, the positive skewness value and results of the Shapiro–Wilks test (W: 0.8253, p: 0.00603), indicate that the sample may not come from a normally distributed population or the data may not be normally distributed, although the problem is minor. On a probability plot, the data points are arrayed diagonally but in an S-shaped curve they cluster around the expected probably line. The histogram indicates that many lower numbers of species were sampled. As with East Shield Meadow, more transects are needed to increase the number of species sampled.

East Shield Meadow and Barcroft Gate Meadow are environmentally comparable. Both are in an alpine zone near the crest of the White Mountains with an eastern aspect, about 8400 km apart, within 61 m elevation of each other, and subject to similar climatic conditions. Species richness for the meadows is also comparable: East Shield Meadow has 24 species and Barcroft Gate Meadow has 27 species although only 16 species are common to both (10 shrubs and herbs, three sedges and rushes, and three grass species). Based on the composition of species, however, the similarity index (Sorenson’s Quotient of Similarity) (Looman and Cambpell, 1960) is a moderate 63% (1).
Sim = \frac{z \sum nc}{\sum n1 + \sum n2} \tag{1}

Where

nc = common species between the meadows.
n1 = species of East Shield Meadow.
n2 = species of Barcroft Gate Meadow.

Furthermore, Barcroft Gate Meadow has a greater abundance of species with 247 samples of 15 species recorded relative to 36 samples of 10 species recorded at East Shield Meadow (Tables 1 and 2). Another difference is that the Barcroft Gate Meadow area includes A. arbuscula and East Shield Meadow lacks that shrub.

6. Long-term monitoring and direction of change

The quantitative sampling objective is to detect a 20% biologically meaningful change in the vegetation over time with 90% confidence, and accept a 10% chance of a false change error (Type 1 error) (Elzinga et al., 1988). The five-year sampling interval was selected as the most likely period of time for sampling to detect change in relatively short-lived forbs and graminoids. Sampling is planned to be done at the same time of the year in order to observe a consistent phenology. Temporal change in phenology, recruitment, establishment and mortality of species may occur from such external factors as human disturbance and climate variability, and internal biotic factors such as succession.

Detected change will be correlated with several climate variables taken from the Barcroft Research Facility weather station to ascertain if climate has had a significant effect. Variables to be used are the average annual maximum and minimum temperature, mean annual temperature, number and dates of degree days above 0 °C, average annual precipitation, percentage of precipitation falling as snow, average total snowfall and average snow depth.

Trends in precipitation, temperature and minimum and maximum temperature will be plotted during each five-year monitoring period and compared with the earlier trends from White Mountain 2, accounting for the time gap.

In order to support the hypothesis that, given the natural range of temporal variability of meadow vegetation, a significant portion of that variability is attributed to the effects of climatic variation, indicators of vegetation response to climate change should be specified. The context for future climate change has been established in Christensen et al. (2007). According to the ensemble mean of the Multi-Model Data Set (MMD), using the medium emissions scenario (A1B) with a doubling of atmospheric CO2 concentrations by A.D. 2100, the projected mean annual surface air temperatures of southeastern California is likely to be greater than 3.5 °C. For the
winter months (December, January, February) it is likely to be 3 °C and for the summer months (June, July, August), 4 °C. A decrease in mean annual precipitation is likely to be –5% to –10% from north to south in southeastern California. Warming temperatures are likely to shift the westerties northward and intensify the Aleutian low, which may have no effect on winter precipitation or a result in decrease of –5% in winter. On the other hand, a summer decrease of –5% may be caused by the amplification of the subtropical high pressure anticyclone off the coast of California with attendant subsiding drier air. The coarse spatial resolution of the MMD cannot for southeastern California cited above. Assuming that the present general lapse rate of –6.32 °C per kilometer for the White Mountains will persist, a 3.0 °C increase may result in an equivalent elevation of the meadows of about +475 m. The plots in Fig. 14a and b indicate that it is likely that the projected temperature increase will minimally affect the present distribution of the meadow plants.

Elevation ranges of the species were taken from The Jepson Manual (Hickman, 1993). They are not always accurate since four species that were recorded in the meadows are above the specified upper limits of their range, and so must be considered tentative in this discussion. Two other species recorded in the meadows are also above their given elevations although no range is specified and are not included in the diagrams. According to The Jepson Manual, J. balticus grows below 2200 m and Koehlaria macrantha grows below 3500 m. These diagrams indicate that, if the upper range limits of selected plant species in East Shield and Barcroft Gate meadows resulting from a temperature increase were made instead. The estimations are based on the “most likely value” of a global increase of about 3.0 °C from the doubling of atmospheric CO2 given in the 2007 IPCC report (Meehl et al., 2007). This is a more moderate value than the projected mean annual increase of 3.5 °C for southeastern California cited above. Assuming that the present general lapse rate of –6.32 °C per kilometer for the White Mountains will persist, a 3.0 °C increase may result in an equivalent elevation of the meadows of about +475 m. The plots in Fig. 14a and b indicate that it is likely that the projected temperature increase will minimally affect the present distribution of the meadow plants.

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the plants are controlled by lower temperatures, then a 3 °C warming would permit them to grow at higher elevations. None would be extirpated from the meadows. There may be an increase in the abundance of those species whose upper range is at or below meadow elevations, according to the Jepson Manual. Presence and increase of these species in the sample – *Androsace septentrionalis* and *Juncus baltica* in East Shield and Barcroft Gate meadows, *Muhlenbergia richardsonis* and *T. spicatum* in East Shield Meadow and *Juncus montanus*, *K. macrantha* and *P. primuloides* in Barcroft Gate Meadow – can be considered indicators for potential effects from temperature increase.

Based on the studies cited above, another expected effect of warming is reduced precipitation with earlier drying of meadows in late summer, general drying of meadows from decreased water availability from surrounding runoff and spring discharge and encroachment by surrounding shrubs (sagebrush and rabbitbrush). A second indicator, therefore, is shift in cover from wet meadow to dry meadow species, and the third indicator is the presence and increase of the shrubs *A. arbuscula* and *C. parryi*.

7. Discussion and conclusion

Given the complexities of ecosystems and their response to climate change the present monitoring study is very simple for detecting change, not only in vegetation cover, but in the three inferred climatically sensitive indicators. Consequently, there are several uncertainties about the predictive hypothesis. Species composition may shift to an unknown degree due to the possible increase in the abundance of those plants now at their upper elevation range limits, the up slope migration of plants whose upper ranges are now at lower elevations, and local extirpation of species. Monitoring may detect this behavior and hypotheses adjusted accordingly. Other uncertainties include the unknown behavior of meadow plants in addition to the above, adequate sampling of their present species ranges, non-linear (non-directional) changes in vegetation due to complex interactions between plants and climate, and non-linear changes in climate variables, and their rates and direction of change, including the future distribution of precipitation. These uncertainties may result in no-analog conditions (Williams et al., 2007).

A further uncertainty is the effect on the meadows from human activities. East Shield Meadow is downslope and east of the Barcroft Laboratory and may have been affected by construction of the station facilities and road, and research projects. The meadow area was used in the historic period by Basque shepherders as is apparent by the presence of a rock shelter and oven. Barcroft Gate Meadow is within the influence zone of Barcroft road, gate and parking area, which affect the drainage patterns from the slopes on the south and west. The motorized trail may also have affected the vegetation. In addition, rock shelters built by Basque shepherders on the upper west slopes above the meadow show that sheep have been grazed in the meadow, and an obsidian lithic scatter on the lower slopes indicates use of the area by prehistoric hunter-gatherers. Prehistoric human land use for at least the past 2000 years (Bettinger, 1977) may have had a minimal effect but historic sheep grazing may have altered the vegetation composition. Recovery has been taking place since grazing was proscribed on 1988. A complication is that, although the meadow may be recovering from grazing pressure, there may be a reversal of effects that could be attributed to climate.

Further studies have the potential to address these uncertainties. Paleoecological data have shown that montane meadows have been affected by climate change, which probably also had an impact on the meadows in the White Mountains. In order to establish historic reference conditions and past responses of meadow vegetation to climate variability, it would be necessary to compile pollen sequences from sediment cores retrieved from the meadows. Since no such research has been done baseline data is restricted to the recent surveys in this study for monitoring future changes. Any future pollen studies, however, have the benefit of reconstructed precipitation and temperature chronologies based on the analysis of growth rings from bristlecone pine for correlation purposes (e.g., LaMarche, 1974; Hughes and Graumlich, 1996; Ababneh, 2006). These dendroclimatic studies have established significant climate variation for the past 2000 years, including several episodes of severe drought.

In conclusion, this study establishes the baseline for future monitoring that may detect changes in the vegetation of two wet alpine meadows in the White Mountains in relation to annual and decadal changes in temperature and precipitation. Monitoring has the potential to reduce the uncertainties and confirm or correct expected consequences of climate change.

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