

ALPINE PLANTS AS INDICATORS OF CLIMATE CHANGE
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As an ecosystem at a climate extreme—one that is very temperature dependent—the alpine zone is a sensitive indicator of climate changes. And it is an ideal habitat to observe globally for biological change.

UNDERSTANDING THE ALPINE ZONE

Understanding the environmental stresses on alpine plants, and their adaptations, is the foundation for viewing their climate responses. The alpine zone is defined as that region above the upper treeline—a remarkably consistent average elevation in a given climate zone, with the trees dropping out over elevation increases of just meters. There are deviations from that elevation due to microclimate and site history, but the overall picture is consistent. The absence of trees (treeforms over 3m height) creates the alpine zone. Why should trees have such a limit to their growth? To address this question consider two points: how temperature limits plant cell growth, and how air temperature controls tree “operating temperature”.

Plant cell metabolism is very sensitive to low temperatures, with cell growth slowing dramatically as the environmental temperature declines down into the range of about 8 to 5 °C. By 5 °C plant cell growth essentially stops, and that is true for both tree root and shoot elongation. The limiting processes are those of cell construction and maturation—photosynthesis is not sufficiently diminished in that temperature range to account for the reduced cell growth (and actually continues down to and even below 0 °C). A very plausible place for low cell temperature to have such an effect on cell development is on the “molecular motors” (dynein, kinesin, myosin) that convey materials throughout the cell on the cytoskeletal framework, because they are critically dependent on thermal energy for their motion.

Tree growth

Some definitions:

- *Tree* is at least 3m in height (and the term *treeform* here means a tree at least that tall).
- *Treeline* is the line that connects the uppermost (or northernmost in the arctic) extent of tree patches.
- *Air temperature* is measured in a shelter at 1.5 meter height. The soil temperature at 10cm depth at treeline elevations is a good proxy for air temperature.
- *Mean air temperature* is the average for the day (average of maximum and minimum, or a more detailed weighted average, but they will be very similar).
- *Growing season* is that period when there is meristematic activity and ongoing tissue maturation. It is well measured for trees by the total number of days on which mean air temperature exceeds 0.9 °C. A very similar measure is that period beginning when the weekly mean air temperature rises above 0 °C and ending when it drops below 0 °C.

Tree foliage is effectively cooled by the air flow, and even sun-warmed foliage averages only a degree or two above air temperature. Tree root zones are shaded by the crowns, and root zones remain close to average air temperature during the growing season. Effectively a tree experiences a cold-temperature limit dictated by average air temperature. Average temperature in the lower atmosphere declines about 0.6 °C per 100m elevation gain (with local and short-term deviations from that average). Therefore, above treeline elevation, the growing season is simply too cool overall to sustain tree growth

The effect of temperature limits on cell growth, and of air temperature on tree temperature, sets the following requirements to permit the presence of trees (and therefore sets their upper limit):

- The growing season must be at least 94 days (90 days by the second criteria above).
- The daily mean air temperature averaged over the growing season must be at least 6.4 °C (6½ °C used in this paper).
- Additionally, annual precipitation must be at least 200mm.

That 6½ °C growing-season isotherm occurs globally, consistent over different taxonomic families, elevations, growing season lengths, latitudes, and precipitation regimes (though there are small deviations in response to regional or microclimate variations, or to site history). Though that climatic isotherm is a good guide to treeline, there are many downward deflections of the actual tree cover below that line due to such things as cold air drainage, rockfalls, avalanches, snowbeds, and logging.

Alpine plant growth

But alpine plants persist in the alpine zone, in spite of cooler air temperatures there—even though they have same temperature-limited basic metabolism as trees. How do plants that live above the treeline survive? The secret lies in their ground-hugging form and stature, allowing them to be warmer overall than air temperature would indicate

The low stature and compact form of alpine plants place them in the lowermost atmospheric boundary layer, where airflow is much reduced, and near the sun-warmed ground where air temperatures are slightly higher, therefore allowing them to be warmer overall than ambient air temperature. Reduced air-flow cooling of foliage allows absorption of sunlight to warm above-ground plant parts. Foliage of alpine plants can be sun-warmed above air temperature by some 20°C (the temperature of an alpine plant might be well over 30°C on a 10°C day). The typically sparse distribution of alpine plants exposes much ground (usually over 50%, often 80% or 90%) to solar heating, and their low forms transmit more heat into the ground than do raised crowns (compact low plants lose less of their solar heat to the airflow, and conduct it much shorter distances into the uppermost soil). Consequently their root system temperature is above the average of that for shaded sites. Even though alpine plants grow at a higher elevation than trees, they experience a warmer microclimate.

Beautifully adapted though they are, alpine plants still live at the edge of adequate warmth, and they benefit from the lack of competition from the cold-limited trees (in one survey showing a 3X reduction in areal cover of low-stature plants in sub-alpine woodland). So they are very vulnerable to overall temperature changes. Alpine ecosystems are also very dependent on snow distribution. Snow cover provides shelter from extremes of winter cold and desiccation. Late-season snowfields retard growth until they melt, and upon melting release a flush of nutrients and water. Alpine vegetation patterns are strongly controlled by the distribution of snowfields. Wind desiccation is yet another alpine-habitat challenge.

It is expected that at least two variables related to climate change could significantly affect alpine ecosystems—1. warmer temperatures, and 2. the amounts and patterns of precipitation and snowmelt. Warmer temperatures can raise the treeline/shrubline, and will also raise the elevations at which a greater variety of alpine and subalpine plants can be more competitive. Less snow or more snow, and changes in patterns of snow deposition and melt schedule can also alter alpine plant distributions.

IMPETUS FOR A UNIVERSAL PROTOCOL

During the past century, scientists have observed changes in alpine flora and in treeline elevation. In Scandinavia, for example, treelines have risen by 160 meters. Furthermore, in many areas upper tree zones are filling in with new trees, even if treeline elevation has not risen notably. Where conditions become less harsh, a greater number of species can compete. Species richness of many alpine peaks has increased, and on one summit in the European Alps increased from 1 to 10 species in 100 years. That would be expected if the cold alpine elevations are warming. But until 2001 there had not been a standard, universal, and replicable process deployed for assessing such changes.

In response to the need for better scientific data, replicability, and more valid comparisons, the Global Observation Research Initiative in Alpine Environments (GLORIA, <http://www.gloria.ac.at/>) was conceived at the University of Vienna and operationally established at field sites in Europe in 2001. GLORIA defines a protocol that can be applied to alpine summits anywhere in the world. The alpine zone is ideal for detecting biological effects of global climate changes. It spans nearly all latitudes and elevations, it samples the major climate zones of the world—maritime and continental; tropical, mid-latitude, and polar—and human disturbance there is often minimal.

GLORIA IN CALIFORNIA

GLORIA began in California in 2004 (due to the tireless efforts of Connie Millar of the Pacific Southwest Research Station, USFS) and was the location of the first project completed in the Western Hemisphere. Surveys will be remeasured every five years to monitor change in the alpine flora. The information that is gathered will be shared globally, as it is at sites in other countries around the world.

Each GLORIA project is organized around a target region (TR), comprising a group of 3 or 4 summits, spaced in elevation from the highest peaks down to near treeline. California/Nevada GLORIA summits now number 29, in 8 TRs, from Langley Peak in the Southern Sierras to the Carson Range near Lake Tahoe, throughout the White Mountains, and in the Great Basin (*Figure 1*). The studies of the alpine ecosystem and its changes are conducted by a team of volunteers, students, and some agency employees and university staff.



Figure 1. Showing the 8 Target Regions (TRs) in California and Nevada. The years in which the TR was established and, if applicable, resurveyed are shown.

THE GLORIA SURVEY PROTOCOL

The main objective of the GLORIA protocol is to record all plant species that grow on the summit, to note where they are distributed around the peak, and to estimate how much area each species covers. That requires looking at both large-scale and small-scale plots, and on the differently-oriented slopes.

The summit-centered GLORIA protocol outlines a set of nested survey plots that occupy the slopes of the four main compass directions (N, E, S, and W), or “aspects”, on each peak (*Figure 2*). An upper elevation band takes in the 5 meters just below the peak, and a lower band lies between 5 and 10 meters in elevation below the peak.

Information collected includes: each plant species present (including voucher specimens); its degree of cover (as a measure of each species’ abundance and its influence on available space, light, air, and water); and the cover of other elements such as rock or soil. The relative amount of rock and soil indicates the potential for expansion/loss of plant cover, and plant cover may change as climate changes.

In each summit area section (SAS)—the area on one aspect and within one elevation band, 8 total per summit—the plant cover is visually estimated on a relative scale (early efforts attempted to be more quantitative, but were not successful...as noted below). In the 1mX1m quadrats (outlined with a frame containing 100 cells), cover is estimated by noting the occurrence of each species in each of the cells and the cover at each of 100 sample points. Each group of four quadrats is centered on a main aspect at the 5m perimeter

Over 60 photographs are taken on each summit, from broader photos of the SASs, to the square meter of each quadrat. The photos document the plants and to some extent their coverage, as well as the survey system reference points for placing resurveys. Resurveys can usually be placed within a few centimeters of the original reference points, though the boundaries of the larger plots can vary more than that—in any case the change in the sampled area between surveys is no more than a few % of the area, usually less.

To learn how the actual temperatures and snow cover are changing, a temperature recorder is buried 10 centimeters deep on each aspect. Temperature is recorded approximately hourly until the next resurvey. The recorder is then dug up, the dataloggers reset, and the records are recovered. The soil-temperature curve has a narrower daily temperature range than the surface-temperature curve, but has a similar average. Changes in average air temperature will be reflected in soil temperature. But when snow covers the ground, the soil temperature remains essentially constant at 0°C, and in that way reveals precisely the periods of snow cover.

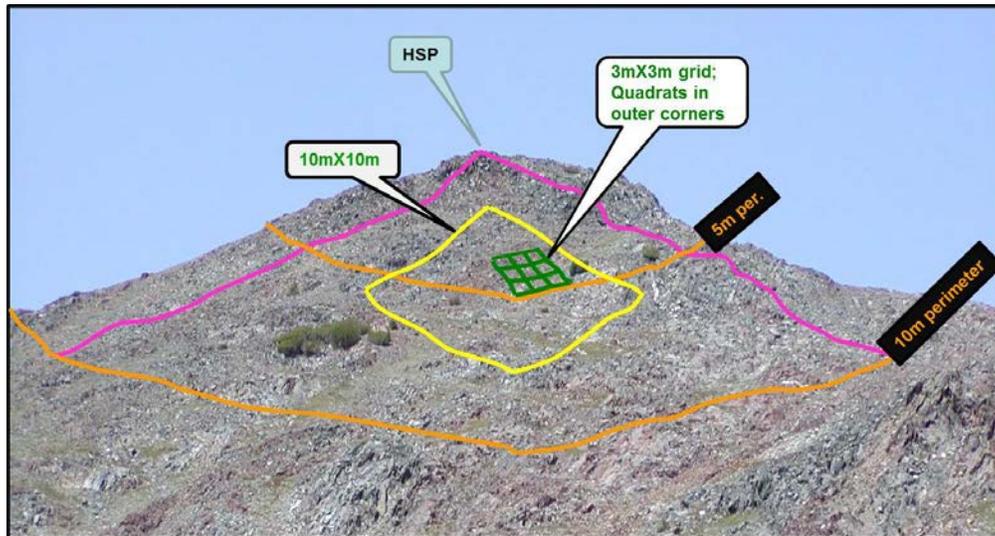


Figure 2. The south aspect of a central Sierra peak, with the major GLORIA survey plots outlined, much as they might actually lay on real terrain. Each of the other 3 aspects would have similar plots. HSP is the “high summit point”, the origin point of the survey system.

AN ADDITIONAL PROTOCOL: THE CALIFORNIA METHOD

Early on it was evident that coverage estimates in the SASs were not sufficiently accurate or reliable. Time constraints, large areas (of order hundreds of square meters), and many very-low-cover species (fractions of 1% cover) made useful numerical cover estimates difficult. The 1mX1m quadrats provided good quantitative data but for very small and not sufficiently representative areas. So we developed a method for getting good quantitative data for areas large enough to represent the range of plant/substrate cover...the “California method.” It has now been adopted as an enhancement into the international protocol.

A 10mX10m “diamond” is centered in each aspect on the 5-meter perimeter (Figure 2). Within the plot, 400 sample points set on a ½-meter grid produce very useful quantitative data on plant and substrate cover at the mid-scale (surveys prior to 2009 used 100 points). All species present are listed within each 1-meter-wide strip across the plot, 10 strips per plot, the number of strips per plot in which a given species occurs being its “frequency” (for example: occurrence in 6 strips being a frequency of “6”).

The 10mX10m 400-point data is statistically very robust for measuring the major substrate types, such as rock, soil, plants, etc. It does an adequate job of measuring the most abundant individual species, which have cover values of a few areal percent. For species having cover values less than 1% (most species) the 400 sample point “cover” does not adequately represent them. The indication of their abundance/presence is captured in the number of strips in which they occur, the frequency (or possibly in an “index” that combines cover and frequency).

LOOKING DOWN THE SLOPES

A major addition to the summit surveys are the “downslope surveys,” observations that cover the alpine zone below the GLORIA summits and provide a more comprehensive view of the alpine ecosystem throughout its entire elevation span. The elevational resolution of the downslope surveys is much higher than that of the peaks within a TR, of order 10X higher. To date, such surveys have been conducted on five major slopes in

the White Mountains, collectively spanning the elevation from White Mountain Peak at over 4300 meters down into the bristlecone-limber-pine woodland at 3300 meters.

Meter-wide belt transects along the elevation contour are spaced every 25 meters in elevation (*Figure 3*). Each transect is 100 meters long (100 square meters total area), divided into ten 10-meter segments end-to-end. All species present in each 10-meter segment are recorded (giving the “frequency” for each species). At sample points spaced every half meter (400 for the entire transect) the plant species or other substrate type is identified (giving the “cover” for each kind of area). The downslope transects duplicate, in area and sampling density, the 10mX10m California-method plots on the summits.

The data gathered from the slopes reveals flora that could potentially be moving up toward the summits in response to warming. It indicates how species cover and richness varies above vs. below treeline, and how substrate type varies with elevation. It also shows the distribution of each species by elevation. That information helps with defining the habitats and distributions of “functional groups”—groups of plants that are similar in anatomy, habitat needs, and ecophysiology that would be expected to have similar responses to climate change. Furthermore, the detailed elevation distribution of a given species taken at one time can also be compared with its distribution at a later time (for example 10 years later). That comparison can produce a very useful quantitative measure (a cross-correlation function) of just how much the elevation distribution of that species has shifted over time, very possibly rising as the world warms.

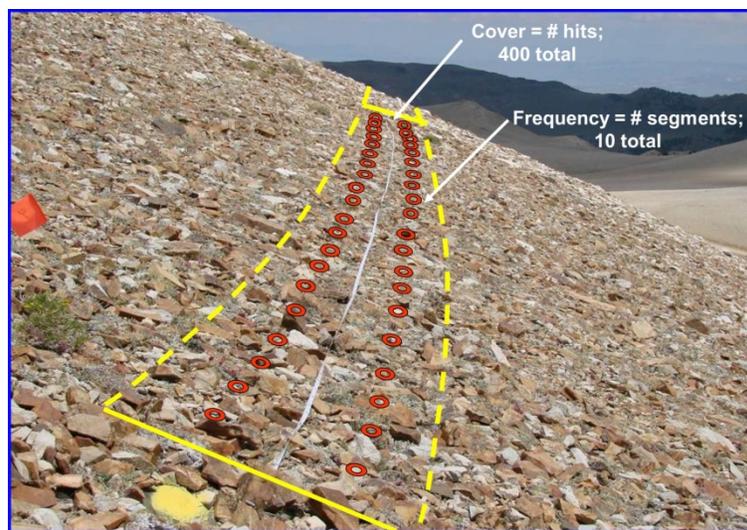


Figure 3. One segment of a downslope survey transect, a meter-wide belt transect along the contour.

EARLY RESULTS

The results so far fall into two groups, and show some interesting trends:

1. The initial baseline surveys have provided useful and detailed information on the species that are present, their relative abundance, and their detailed distributions on summits and slopes of the alpine zone in California and Nevada. Downslope surveys have also shown how substrate is distributed with elevation, and with position on the slope.
2. Resurveys of GLORIA summits presently span 10 years in Europe, and 5 years in California (2 TRs to be resurveyed at 10 years summer 2014). Some hints of change are evident in even those comparisons, though they are not indicative of climate change (for which at least about 20 years are needed). In addition, there are comparisons possible with earlier non-GLORIA surveys. Some of them show clear evidence of upward advance of some sub-alpine plant species.

In California, 4 of 7 target regions have been resurveyed, and 4 of the downslope surveys in the White Mountains have been repeated. The summit resurveys tended to closely duplicate the species richness found earlier, a welcome confirmation that the method is capturing the whole species set each time. The recent downslope resurveys showed an increase in the number of annual species (perennial habit is best suited to the demands of the alpine environment, and alpine annuals are uncommon)—however, that may be due, in part, to a wetter-than-normal year. There were improvements to the methodology of the 2nd surveys, both summit and downslope, so future inter-comparisons will be more meaningful than current ones.

Findings over the 10-year resurveys from the European Alps have shown reductions in cover of the highest elevation species (those in the zone of permanent snow, or the “nival” zone), with lesser reductions and some

increases within the alpine subzones below that. These changes suggest that the highest plants are losing ground to plants from lower elevations, at least over a recent decade.

Even if the changes observed in the GLORIA resurveys are significant, it is not possible to attribute change over 5 years or even 10 years to long-term climate trends. Inter-seasonal variation can easily affect the flora represented in a given year. The value of the current comparisons is that they demonstrate the potential of the protocols to reveal change. However, only changes in a direction consistent with a warming world, sustained over two or more decades, will indeed be compelling evidence.

Current GLORIA and downslope data is also being compared to earlier botanical data from the White Mountains. For example, the uppermost occurrence on granitic substrates of dwarf sagebrush (*Artemesia arbuscula*, or maybe *A. rothrockii*) as reported in 1961 has been compared to the recent upper shrubline surveys and downslope surveys. Based on those observations, which span a 50-year interval, this species' upper limit has risen 150 meters, and several common alpine plants have been reduced in cover wherever the *Artemesia* has encroached. Aerial photo comparisons from the late 1940s into the 2000s show bristlecone pine woodland filling in along its upper margins, and young trees spreading upslope.

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Jim Bishop, with his botanist wife Catie Bishop, has conducted GLORIA field work since the project began in California in 2004. He also helped to develop the strategy and methods for the project's downslope surveys.

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