USING WIND-DEFORMED CONIFERS TO MEASURE WIND PATTERNS IN ALPINE TRANSITION AT GLEES

Robert C. Musselman
Gene L. Wooldridge
Douglas G. Fox
Bernadette H. Connell

ABSTRACT

The Glacier Lakes Ecosystem Experiments Site (GLEES) is a high-elevation ecosystem in the Snowy Range west of Laramie, WY, that is perceived to be highly sensitive to changes in chemical and physical climate. Deposition of atmospheric chemicals to this ecosystem is, in part, governed by the wind pattern. The GLEES has numerous wind-swept areas where the coniferous vegetation growth pattern is characteristically wind deformed or krummholz. Studies conducted in 1988 determined direction and degree of wind deformation of Engelmann spruce (Picea engelmannii) and subalpine fir (Abies lasiocarpa) trees. Where both species occurred together, their wind deformation was similar. Limber pine (Pinus flexilis) occurred as scattered, isolated individuals on exposed ridges with extensive deformation, but because of its sparse occurrence was not useful in determining windspeed and direction in the GLEES. Engelmann spruce and subalpine fir tree deformation patterns were used to determine wind fields, which were compared with measured meteorological data at GLEES.

INTRODUCTION

In recent years, forest managers have been faced with questions concerning the impact on sensitive ecosystems of atmospheric deposition of air pollutants from new or proposed point sources. Air quality legislation, written to prevent significant deterioration of present air quality in Class I or wilderness areas, requires forest managers to determine potential impact of pollutant sources on the ecosystems they manage. Alpine and subalpine wilderness ecosystems are thought to be particularly sensitive to increased atmospheric deposition. The existence of these high-elevation ecosystems is already fragile; any additional stress might have a large negative impact on their growth and survival. Few data are available to determine the potential effects of increased atmospheric deposition on such sensitive ecosystems.

A study area has been established in southeastern Wyoming to examine the effects of atmospheric deposition on alpine and subalpine ecosystems. The Glacier Lakes Ecosystem Experiments Site (GLEES) is a 200-ha alpine and subalpine watershed on the Medicine Bow National Forest, about 70 km west of Laramie, WY. The following site characteristics make it ideal for studying the effects of atmospheric deposition on wilderness ecosystems.

1. High elevation (3,400 m) typical of many western U.S. wilderness ecosystems
2. Management to preserve its natural state, but not a statutory wilderness area restricting research use
3. Exposed, slowly weathering bedrock, with shallow immature soils having low base saturation
4. Habitats similar to western wilderness ecosystems, with alpine and subalpine types dominated by spruce-fir; wind deformed spruce, fir, and willow; extensive meadow; and cushion plants
5. Low pollution impact at present, yet ecosystem is sensitive to any additional stress such as atmospheric pollutants
6. Lakes with low acid neutralizing capacity
7. Short growing seasons with cool temperatures and summer frosts
8. Deep snowpack that accumulates atmospheric pollutants
9. Complex terrain with rapid changes in topography
10. Persistent, high winds

Windspeed and wind direction are climatological components that exert major influence on alpine and subalpine ecosystems. Winds interact with terrain, producing local changes in wind direction, turbulent zones, and windspeeds over and through the surface vegetation. They determine precipitation patterns, snow distribution, snow pack accumulation, and resultant vegetation type and growth form. Atmospheric deposition will likely be greatest in areas where windspeeds are low, and turbulence is enhanced. Low windspeed allows particulates to settle. With greater turbulence, gaseous pollutants have greater potential for absorption or plant uptake, due to increased vertical mixing.

Meteorological data on wind direction and speed are expensive and difficult to obtain at remote, high-elevation sites. A surrogate for wind instrumentation has been the use of asymmetric tree deformation to indicate direction and speed of prevailing wind. Direction of wind is indicated by compass direction of the deformation. Speed is calculated from empirical equations derived from actual windspeed data and amount of tree deformation in areas where both weather monitoring and tree deformation data are available.

The relationship between windspeed and deformation varies with tree species. Some species are more susceptible to deformation than others. Deformation is caused by ice crystal abrasion and desiccation of leaf bud and foliage tissue on the windward side of the tree (Holtmeier 1980). This tissue is killed, causing a slow development of surviving buds and branches on the lee side of the tree. Such selective upwind mortality leads to growth and development of branches and foliage primarily on the protected, lee side of the tree. As branch development and growth become dominant on the lee side of the tree, the tree becomes asymmetric. The degree of asymmetry or deformation is related to the speed of the wind. Season of high wind is also important, since plant tissue differs in sensitivity to wind abrasion with stage of development. Data from GLEES indicate that wind direction varies little with season. Although windspeeds are highest during the winter and spring months, winds are still strong during sensitive stages of plant growth. Measurement of amount of tree deformation also will give a long-term integrated estimate of snow depth at individual tree locations, as indicated by snow cover effects on tree growth and development.

The objectives of this study were to determine wind direction, windspeed, and snow depth in the GLEES watershed from tree deformation indices. The resulting information will be used to estimate areas of greatest impact from atmospheric deposition. Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) are the dominant coniferous species in the watershed. Scattered individuals of limber pine (*Pinus flexilis*) also occur. Limber pine rarely fruits in the watershed, and young trees are rare. For Engelmann spruce and subalpine fir, seedling trees are evident in the lower, subalpine portions of the watershed; but most reproduction near alpine appears to be vegetative by layering.

EXPERIMENTAL METHODS

Tree deformation indices have been developed to estimate windspeed. The Griggs-Putman technique (Robertson 1987) rates degree of deformation on a scale of 1 to 8, with 1 indicating no deformation and 8 indicating deformation such that tree growth is flattened against the ground in what is often referred to as "krummholz" form. This method uses regression techniques with constants from empirical data to calculate windspeed. The

Wade-Hewson deformation ratio (Wade and Hewson 1979) measures the asymmetry of the crown and the down-wind bending of the trunk. The tree is photographed perpendicular to the maximum deformation, and analyzed using a grid overlay on the photo to measure deformation angles. Tree ring analysis can also be used to estimate windspeed (Robertson 1986). Tree sections are measured for ring width on the lee and windward side of the trunk, with ring width wider on the lee or branched side. This technique is less sensitive as an indicator of wind deformation than the others, and requires destructive sampling.

In many mountainous areas, maximum snow depth occurs early in the snow season, often as early as January (Schild and Gliott 1981), with additional snowfall settling and compacting the snowpack. Therefore, the portion of the tree exposed to wind desiccation and snow or ice crystal abrasion remains somewhat constant throughout the coldest part of the winter. This maximum depth of snowpack on trees can be measured by observed differences between snow-covered and snow-free portions of the crown resulting from the long period of exposure to their snowy or snow-free environment.

Snow depth is estimated on trees by two contrasting methods, depending on the density of the canopy. In dense canopies with deep snow, brown felt blight (*Herpotrichia juniperi*) develops on snow-covered foliage resulting in death of the needles. This is indicated by areas of dead, fungus-covered needles, or defoliated branches near the base of larger trees. The top of the dead area generally marks the maximum snow depth. The other method relates directly to wind deformation, caused by ice abrasion at the top of the snow pack (Hadley and Smith 1986; Holtmeier 1985). Beneath the snowpack, asymmetric deformation does not occur. Above the snowpack, often delineated by a sharp line of a few centimeters, tree deformation becomes evident. This indicator of snow depth is much more distinct than the snow mold technique, but is not useful in dense canopies where wind abrasion and deformation may occur only in the tops of the tree crowns. Some evidence of the depth of the snowpack is also indicated by the bending of branches downward from the weight and settling of the snowpack; but subalpine conifers are remarkably resilient in resisting this type of damage.

For this study, the GLEES was divided into 100-meter grid mapping units, with a tree sampled for deformation near each grid intersection. Individual trees near each grid point, considered typical of that area in amount of deformation, were selected as sample points. This scale of sampling was considered adequate to identify areas of different atmospheric deposition potential within the watershed. Individual trees sampled were identified on aerial photos for precise location of windspeed and direction data within the watershed. Wind direction was determined by measuring compass direction of the primary orientation of asymmetry or bending. Windspeed was

calculated using both the Griggs-Putman and Wade-Hewson index methods described above. Snow depth was estimated from tree deformation markers at the lower portion of the tree trunk.

RESULTS AND DISCUSSION

Results of the study indicated that tree deformation indices for Engelmann spruce and subalpine fir were useful for estimating wind direction, windspeed, and snow depth at the GLEES. Wind direction was consistent, generally from a westerly direction at all sites within the watershed. The wind direction indices reflected local patterns of topography, with wind generally following parallel to a steep ridge bordering the watershed, but with some minor channeling around smaller ridges and knolls. Some convergence was evident in a small valley, and slight divergence of flow was evident where it passed over a ridge line as it exited the watershed.

The windspeed calculations for both the Griggs-Putnam and Wade-Hewson index methods provided similar windspeed values for individual trees. Because of their similarity, an average of the two methods was used as the estimate of windspeed at each data point in the watershed. The windspeed data, derived from individual trees based on their deformation indices, varied from 3 to 11 m/sec at different sites throughout the watershed, with an average watershed windspeed of 7.4 m/sec. The data derived from tree deformation indices are consistent with limited (1-year) data from a meteorological tower located within the watershed. The meteorological tower data indicate an average windspeed of 9.4 m/sec at that particular site. Tree deformation at a grid point located 20 m southeast of the tower indicated an identical windspeed of 9.4 m/sec. This degree of accuracy is perhaps coincidental, but demonstrates the usefulness of tree deformation as a surrogate for meteorological instrumentation.

The snow depth estimations from height of fungal injury and initiation of tree deformation indicated that snow depth varied from less than 0.5 m to over 4.5 m within the watershed. The average snow depth within the watershed estimated from tree indices in this study was 1.9 m. Precipitation data recorded from a raingauge located within the watershed from 1979 to 1988 have indicated an average maximum seasonal snowfall of about 2.1 m. This estimate is based on a 20-percent adjustment for observed collection inefficiency of raingauges located in windy sites (Sommerfeld and others in preparation). This correction may be low, particularly for snowfall at high wind sites (Sturges 1986). It also does not account for snowpack settling. On the other hand, the tree deformation index of snow depth is also likely low, since trees would be deformed to the lowest point on the trunk during low snowfall years. The techniques used for identifying snow depth on trees in this study would indicate this minimum height of snow accumulation on the tree trunk.

Engelmann spruce and subalpine fir tree species were useful to estimate wind direction, windspeed, and snow depth. These species occurred at sufficient frequency to allow adequate coverage of all areas of the watershed except the highest elevation alpine meadows, talus slopes, and snowfields. These treeless areas, on the lee side of the large ridge bordering the watershed, accumulate large amounts of snow and appear to experience high windspeeds. Tree deformation indices indicated increases in windspeed moving upslope toward these areas.

Engelmann spruce occurred most frequently in the lower subalpine portions of the watershed. However, the species did occasionally occur as krummholz at the higher elevations. Subalpine fir was most abundant in the upper portions of the watershed near alpine, where it was extensively wind deformed as krummholz. Individuals of subalpine fir also occasionally occurred at the lower elevations. Where both species occurred together, no difference was noted in the degree of wind deformation. At higher elevations, both species formed ribbons and hedges (Holtmeier 1978, 1980, 1982), wave patterns typical of high-wind areas in the Rocky Mountains. Engelmann spruce and subalpine fir krummholz forms were indistinguishable at a distance.

Limber pine deformation was not useful for determining wind and snow depth parameters in the watershed. Limber pine did not occur in lower elevation or protected areas where subalpine fir and Engelmann spruce were more abundant and less wind deformed. Limber pine was found primarily as widely scattered, isolated individual mature trees on ridgetop sites. Occasionally, it occurred as isolated, scattered individuals in the higher elevation areas of the extensive krummholz mats of Engelmann spruce or subalpine fir. Although almost always wind deformed at the exposed sites where it occurred, its scattered distribution prevented observations sufficient to determine wind direction and speed throughout the watershed. Since no rooting of the species was evident, extensive mat or wave patterns typical of Engelmann spruce and subalpine fir did not occur with limber pine. The inability of limber pine to reproduce vegetatively by layering likely contributed to its limited distribution in the watershed.

On the exposed sites where limber pine did occur, it was often extensively wind deformed; windspeed, direction, and snow depth could be determined from those individual trees. In areas where it might occur in denser, more widespread stands, it may be useful to estimate windspeed and direction. However, since it did not occur in more protected areas of the GLEES, sensitivity of the species to deformation at lower windspeeds could not be determined. At a few exposed sites at the GLEES, limber pine, Engelmann spruce, and subalpine fir occurred together. At these high-wind sites, limber pine appeared to indicate wind deformation patterns similar to those of the spruce and fir.

Limber pine and whitebark pine (*Pinus albicaulis*) are closely related species that occur in similar habitats. It is expected that whitebark pine would respond similarly to limber pine in susceptibility to wind deformation. Whitebark pine has been documented to occur in krummholz form (Arno and Hoff 1989; Tomback 1986). Although

rooting of krummholz whitebark pine by layering can occasionally occur (Arno and Hoff 1989), vegetative reproduction of the species in krummholz is rare. Reproduction of the species is predominately from seed transported to timberline sites by birds (Tomback 1986). Local seed production in krummholz stands is low, and seeds produced have lower germination capacity than nonkrummholz stands (Tomback 1986). Scavenging of seed cones by birds and mammals is high in these sites (Tomback 1986). Thus the distribution of whitebark pine in sites subject to wind deformation is limited compared to distribution of Engelmann spruce and subalpine fir, which readily spread in krummholz stands by layering.

As with limber pine, only where whitebark pine occurs at least as densely as that required here (100-m or smaller grid) would it be useful as a surrogate to determine windspeed and wind direction data in a watershed. Another closely related species, European stone pine (*Pinus cembra*), grows in similar habitats and is commonly wind deformed. This species has been used to relate deformation to windspeed and direction in mountainous terrain (Holtmeier 1985).

The 100-m grid was sufficient to delineate wind direction, which changed little throughout the watershed, and proved adequate for windspeed. Refinement of windspeed would have been possible with survey at a closer grid pattern. The snow depth determinations appeared to be the least precise. Snow depth varied on a very small micro-relief scale, and changed with the particular tree chosen for sampling. Amount of tree deformation and direction changed little at a given site. This suggests that more precise snow depth delineation might have been possible from sampling at a finer scale of resolution. We were, however, able to refine the precision of the snow depth measurements for the watershed using a series of aerial photos of snow fields during melt to determine where areas of adjacent, similar snow depth might occur. In such cases, care was taken not to compromise the integrity of the snow depth data from tree deformation indices. For example, aerial photographs suggested that isopleths of particular snow depths may have closed in certain areas where they might have been drawn parallel.

The snow depth estimates from tree indicators provided data that generally corresponded with topographic features, such as lower snow depth on windswept ridges, and greater depth in the lee of ridges, where upslope conditions prevailed, and on the windward side of large open areas such as lake surfaces. However, a regression of windspeed on snow depth/tree as indicated by tree deformation indices was not significant. This was likely due to the lack of precision by tree indicators of snow depth, and the sensitivity of snow depth to small changes in topography. Maps showing wind direction, windspeed, and snow depth within the watershed are being published elsewhere (Wooldridge and others in preparation).

This study has demonstrated the usefulness of tree deformation indices to estimate wind direction, windspeed, and snow depth in situations where meteorological instrumentation is not available or too costly to obtain

such data. Engelmann spruce and subalpine fir were useful tree species to indicate these parameters at the GLEES, a small alpine, subalpine ecosystem in southeastern Wyoming sensitive to atmospheric deposition. The data obtained in this experiment will be useful for determining areas of maximum atmospheric deposition in the watershed, and will be useful in modeling water and chemical transport through the different subcatchments of this ecosystem.

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Speakers answered questions from the audience following their presentations. Following are the questions and answers on this topic:

Q. (from Richard Baker and Earle F. Layser)—Your preconference paper title and abstract mentioned white-bark pine, while your paper and talk referred to limber pine. Isn't the Snowy Range outside the range of white-bark pine?

A.—The species that occurs at our study site in the Snowy Range has few individuals; these rarely produce cones. No seedlings appear to be present at the site. No cone fragments were visible under the trees. We were able to locate three cones that closely resembled those of whitebark pine. When the preconference abstract was written, we had tentatively identified the species as *Pinus albicaulis* based upon these cone characteristics. However, further examination of the specimens, and considering the small number of cone samples and the location of the trees outside the range of *Pinus albicaulis* and within the range of *Pinus flexilis*, we identified the species in the paper and in the presentation as *Pinus flexilis*.

Q. (from Friedrich-Karl Holtmeier)—Did your different tree species respond in the same way to different wind-speeds; do they really display the same growth form at a similar windspeed?

A.—Engelmann spruce and subalpine fir response to wind deformation at specific locations was remarkably similar. Where both tree species occurred at the same site, tree deformation indices were the same. We could not distinguish between the two species based upon tree deformation. Limber pine appeared to respond similarly to the other two species at the few sites where it occurred with Engelmann spruce and/or subalpine fir. However, these sites were located on ridgetops where windspeeds and subsequent deformation were always higher (6-8 on the Griggs-Putnam scale). Response of limber pine at the lower windspeeds is not known. Because of the sparse occurrence of limber pine, it was not used to determine wind direction, windspeed, or snow depth in this study.

Q. (from Wendel Hann)—How do the wind/ice abraided stems of whitebark grow to the size they get before they are wind damaged? For example, why doesn't the wind take the buds off and keep them low in height?

A.—Evidence suggests that the most wind desiccation and ice abrasion damage to conifer foliage occurs in a very small zone above the snow surface. If the tops of trees are able to survive a few seasons to reach beyond this level, then the probability of survival increases. Survival during this period of time is determined by a season or two of (1) mild winters where ice abrasion and desiccation are less severe; or (2) abnormally deep snowpack where the tops are protected by snowcover. The tree top may survive once it grows beyond the few centimeters at the surface of the snowpack where conditions are most severe. However, deformation still occurs, primarily from desiccation on the windward side of the stem.