SNOWPACK-VEGETATION DYNAMICS:
MOUNTAIN HEMLOCKS IN THE LAKE TAHOE AREA

By

Janet L. Nachlinger[1] and Neil H. Berg[2]

The spatial extent of snow cover, snow depth, and snow duration are important determinants of vegetation distribution in alpine and subalpine areas. "Snowdrift" communities, for instance, occur to the lee of snowdrifts at high elevations in western mountains where water from slowly melting drifts provides moisture to an otherwise dry summer environment (Billings and Bliss, 1959). This paper analyzes the relationship between snow cover, depth, and duration and vegetation dynamics in subalpine mountain hemlock (Tsuga mertensiana [Bong.] Carr) stands in central California and Nevada.

Forests dominated by mountain hemlock occur along the North American coast from the Kenai Peninsula in southern Alaska to southwestern British Columbia. From there southward, the distribution of hemlock is restricted to higher elevations in the Cascade Range of Washington and Oregon, and the Sierra Nevada of California. Mountain hemlock also occurs in the mountains of southeastern British Columbia, western Montana, northern Idaho, southeastern Washington, northeastern Oregon, and the Olympic Peninsula (Fowells, 1965).

Mountain hemlock forests in the Sierra Nevada are thought to represent remnants of a diverse coniferous forest present throughout the western United States approximately 5-28 million years ago (Axelrod, 1977). A decrease in summer precipitation gradually restricted the occurrence of mountain hemlock to its present distribution in the northern and central Sierra Nevada, where it is associated with cool and moist northern exposures, cold air drainage, and snow (Taylor, 1976; Rundel et al., 1977). In the northern and central Sierra, mountain hemlock forests occur where the annual precipitation is estimated to be about 350-850 mm less than at the driest forest sites in the Cascades (Franklin and Dyrness, 1973; Rundel et al., 1977). This paper examines the hypothesis that mountain hemlocks in the Lake Tahoe region occur on microsites that effectively receive more moisture--through snow redistribution, horizontal movement of ground and surface water from surrounding sites, or other snow-related factors--than regional climatic information would indicate.

METHODS

The dynamics of mountain hemlock stands near Lake Tahoe were intensively studied in relation to observed variation in annual snowpack. We investigated differences between snow patterns and melt dynamics within the hemlock stands and adjacent subalpine vegetation types. We also evaluated the important environmental factors associated with hemlock stand demography and species composition to determine the relative importance of snow depth and duration.

Study Sites

During the summer and fall of 1982, 49 mountain hemlock stands in the Lake Tahoe region of California and Nevada were selected and sampled (Figure 1). This region is characterized by a dry summer/wet winter precipitation pattern with an annual total at the Central Sierra Snow Laboratory (2100 m, 1 km east of Soda Springs, California) of approximately 1340 mm (Smith, 1982). At higher elevations, where hemlock occurs in the central Sierra Nevada, annual precipitation is probably lower (Houghton, 1978; Moore, 1981).

Paper presented at the Western Snow Conference, April 19-21, 1988, Kalispell, MT.

[1] Plant Ecologist, Biological Sciences Center, Desert Research Institute, P.O. Box 60220, Reno, NV 89506-0220

[2] Supervisory Hydrologist, Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture, P.O. Box 245, Berkeley, CA 94701

Stands were selected in a stratified random sample design based on a combination of elevation, aspect, and latitude to ensure coverage of the region and the various habitats in which hemlock occur. Study sites ranged in elevation from 2300 to 2900 m, occurred on all aspects except due south, and ranged in latitude from 38°45' to 39°27' N.

Stands at Castle Peak, Incline Lake, Ward Peak, and Waterhouse Peak were chosen for further study (Figure 1). These stands were selected such that, collectively, they represented the variation in stand structure, species composition, and habitat found in the entire sample of 49 stands. Adjacent to each of these intensively studied hemlock stands, a stand of another subalpine vegetation type with similar elevation and exposure was selected for comparison of snow-vegetation dynamics (Table 1).

Table 1. Vegetation types selected for comparison with mountain hemlock stands at each intensive study site

Location	Comparative Vegetation Type	Composition
Castle Peak	Mixed shrub	*Artemisia tridentata* spp. *vaseyana* (mountain big sagebrush), *Haploppappus suffruticosus* (big-head macronema), *Symphoricarpos vaccinioides* (mountain snowberry), *Sitanion hystrix* (bottlebrush squirreltail), and *Poa epilis* (skyline bluegrass)
Incline Lake	Lodgepole pine	*Pinus contorta* spp. *murrayana* (lodgepole pine), with minor cover of *T. mertensiana* (mountain hemlock) and *P. albicaulis* (whitebark pine)
Ward Peak	Red fir	*Abies magnifica* (red fir) with minor cover of *T. mertensiana* (mountain hemlock)
Waterhouse Peak	Mixed conifer and whitebark pine	*P. albicaulis* (whitebark pine), *T. mertensiana* (mountain hemlock), *P. contorta* ssp. *murrayana* (lodgepole pine), and *P. monticola* (western white pine)

Procedures

At each of the 49 mountain hemlock stands a 0.1 ha area was sampled within a homogeneous area of vegetation. From a random starting point, ten 5 m x 20 m plots were set out along a transect at 10 m intervals. Within each plot, all conifer species were counted, and their diameter at breast height was measured (or they were recorded as "seedlings"). Within the homogeneous area at each stand, floristic data were recorded using Braun-Blanquet methods (Mueller-Dombois and Ellenberg, 1974). Cover of each species present was estimated using the Braun-Blanquet cover-abundance scale (Braun-Blanquet, 1965). Nomenclature follows Munz and Keck (1959). Environmental data collected at each site consisted of elevation, slope, aspect, topographic position, parent rock type, duff depth, surface rockiness, percent bare ground, moisture status of the top 5 cm of soil, and physical disturbance.

Each of the four intensively studied mountain hemlock stands and its paired vegetation stand was visited monthly to measure snow depths from April 1 until snow-free in 1983 and 1986, and one to three times during the melt season in 1984. To measure snow depth within each stand, three or four depth transects were placed across the slope to span the entire stand. Two-to-four probes per transect were made for a total of 9-12 measurements per hemlock stand and 6-16 measurements per stand of adjacent vegetation. A vertical measurement with no correction for slope was taken. When a significant amount of ground became visible, visual estimates of snow cover and snowfree dates were made. Snow depths were statistically analyzed with a t-test (Ryan *et al.*, 1985:185). To follow hemlock seedling establishment and survival, seedlings in several randomly-placed, 1 m^2 plots were tagged and counted monthly during the growing season.

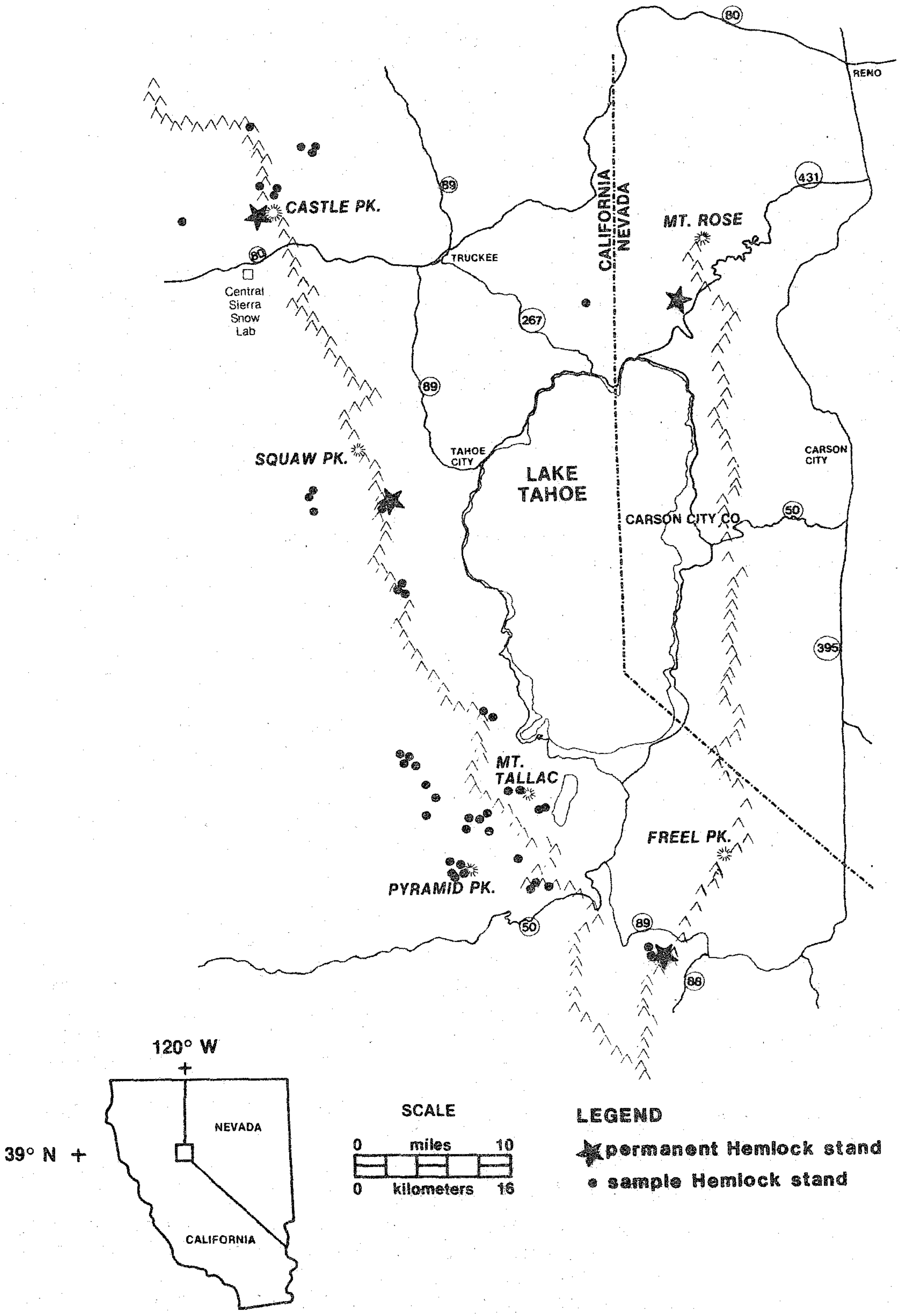

Figure 1. Map of Lake Tahoe region showing all 49 mountain hemlock (Tsuga mertensiana) stands sampled (dots), and the four intensively studied sites (stars).

RESULTS AND DISCUSSION

To put the study years into perspective, 1 April snowpacks in the Tahoe- Truckee basin were estimated at 139, 207, 100, 90, and 135% of average for water years 1982-1986, respectively (Soil Conservation Service, 1982-1986). Thus, during the years of this study, the snowpack ranged from slightly below average to much above average. However, the 20-yr record indicates a highly variable annual snowpack for this region, ranging from 33% of average in 1977 to 207% of average in 1983 (Klieforth et al., 1983).

Snow Patterns in the Subalpine Zone

Snow was always deeper in the mountain hemlock stands than in adjacent shrub stands at Castle Peak (Table 2). In lodgepole pine and red fir stands adjacent to hemlock stands at Incline Lake and Ward Peak, mean snow depths in the hemlock stands were slightly greater than those in the adjacent vegetation stands, but within-stand variation was relatively large and statistical differences in snow depth between stands was identifiable only at the last measurement in 1986. At Waterhouse Peak, results were not as straightforward. During 1983 mean snow depth differences between hemlock and mixed conifer stands were statistically significant on two of the four dates surveyed. In 1983 also, mean snow depth differences between hemlock and whitebark pine stands were statistically significant at all survey dates. Differences were not significantly different during any surveys in 1984 or 1986 (Table 2).

Although the reasons for the differences in snow depths between the hemlocks and shrubs at Castle Peak are incompletely known, they may be due to vegetation height differences. Wind redistribution at these high-elevation sites may result in greater snow accumulation in the taller vegetation; once snow depths reached the top of the shrubs, snow transport by wind could redistribute snow away from the shrub areas. Low wind velocity zones within the hemlock stands could function as sinks for redistributed snow. Alternatively, greater snow depths within the hemlock stands may be the result of the combined effects of slope, inclination, stand density, and structure of individual tree crowns. Large snow cornices were observed on the slopes immediately above the hemlock stands, whereas smaller or no cornices were observed above the paired vegetation stands. The large cornices lying upslope from the hemlocks are a probable source of additional moisture late in the growing season. Reasons for year-to-year differences in depth differences at Waterhouse Peak are also incompletely understood. Record or near-record precipitation at many sites in the Sierra Nevada in 1983 may make results from this year more representative of extreme conditions than the norm.

On the average, snow cover lasted 5-30 days longer in the mountain hemlock stands than in the paired subalpine vegetation stands (Table 3). In early July of 1986, for instance, snow covered 15-97% of the ground in the hemlock stands, whereas three of the adjacent paired vegetation stands were snow-free while the fourth had 70% cover (compared to 97% in the hemlocks). During the three years of observation, the order of subalpine vegetation types from longest to shortest snow duration was mountain hemlock, lodgepole pine, red fir, mixed conifer, and mixed shrub. Rates of snow melt were comparable in all subalpine cover types, and after 1 May averaged approximately 6.5 cm of snow depth per day. Thus, the persistence of snow within the hemlock stands is likely due to greater snow depths rather than the result of differential snow melt rates.

Hemlock Stand Structure and Related Environmental Factors

Histograms of size class were constructed for each of the 49 sampled hemlock stands. These histograms were grouped by visual inspection into four similar patterns--unimodal, reverse-J, even, and bimodal (Benedict and Fites, 1984; Figure 2, Table 4)--based on similar analyses of giant sequoia (Sequoiadendron giganteum) (Rundel, 1971), white fir (Abies concolor), whitebark pine (Pinus albicaulis), and western white pine (Pinus monticola) (Rundel et al., 1977), and limber pine (Pinus flexilis) (Lepper, 1974) stands in California.

The relationship between the four histogram groups and the various measured environmental factors was examined using discriminant analysis (Nie et al., 1975). A stepwise multiple selection procedure was used to select those factors most effective in discriminating between the four histogram groups. Non-pooled covariance matrices were used. Four variables were found to be good predictors of membership in the four histogram

Table 2. Snow depths (cm) in 1983, 1984, and 1986 in mountain hemlock and adjacent subalpine vegetation types

Stand Location	Date	Hemlock Type			Paired Vegetation Type			Significance Level
		Mean	SD[1]	N[2]	Mean	SD[1]	N[2]	
Castle	4-08-83	646	108	10	357	105	10	0.01
Peak	5-02-83	642	181	10	441	162	10	0.01
	6-07-83	471	119	10	254	116	10	0.01
(shrub)	7-09-83	211	177	10	41	71	10	0.01
	8-09-83	24	60	10	0	0	10	
	6-16-84	160	113	10	38	62	10	0.01
	7-13-84	21	52	10	0	0	10	
	3-31-86	452	106	10	296	98	10	0.01
	4-29-86	408	108	10	207	58	10	0.01
	6-09-86	215	88	10	0	0	10	0.01
Incline	4-09-83	596	45	12	559	30	8	
Lake	5-03-83	599	67	12	596	37	16	
	6-03-83	435	63	12	436	29	16	
(lodge-	7-01-83	224	74	12	209	28	16	
pole	8-09-83	54	60	12	5	14	16	
pine)								
	5-24-84	217	59	12	195	28	8	
	6-13-84	159	53	12	137	34	8	
	7-11-84	9	21	12	0	0	8	
	4-03-86	460	42	12	434	34	6	
	5-01-86	420	33	12	388	34	6	
	6-12-86	245	28	12	207	39	6	
	7-07-86	76	37	12	12	29	6	0.01
Ward	4-13-83	719	47	10	702	97	6	
Peak	5-09-83	723	38	10	701	84	6	
	6-06-83	542	77	10	502	122	6	
(red	7-08-83	262	61	10	223	117	6	
fir)	8-10-83	15	31	10	4	10	6	
	6-16-84	244	67	10	327	91	7	
	7-14-84	57	59	10	32	43	7	
	4-01-86	461	46	10	438	87	7	
	4-30-86	415	37	10	360	80	7	
	6-11-86	206	49	10	120	74	7	0.05
Water-	4-15-83	472	68	10	400	76	9^3	0.05
house	4-15-83	549	56	9	286	42	7^4	0.01
Peak	5-11-83	447	65	10	451	59	9^3	
	5-11-83	562	63	9	324	33	6^4	0.05
(mixed	6-02-83	265	59	10	324	48	9^3	0.01
conifer	6-02-83	434	59	9	187	24	6^4	0.05
and	7-11-83	67	83	10	126	67	9^3	
white-	7-11-83	177	52	9	0	0	7^4	0.05
bark								
pine)	6-14-84	59	44	10	87	18	9^3	
	4-04-86	309	44	10	297	34	9^3	
	5-02-86	264	35	10	247	63	9^3	
	6-13-86	60	40	10	93	28	9^3	

[1] Standard deviation.
[2] Sample size.
[3] Paired vegetation type is mixed conifer.
[4] Paired vegetation type is whitebark pine (Pinus albicaulis).

types. They were: elevation, largest size class of *T. mertensiana*, *Abies magnifica* density, and slope. The first two discriminant functions accounted for 95.8% of the variance between the four histogram types. The first function, accounting for 71% of the variance, was primarily an elevation gradient while the second discriminant function was primarily a slope gradient (Benedict and Fites, 1984).

In the speculations below, caution is needed in extrapolating to cause-and- effect relationships because within-group variation for all variables was relatively great compared to differences between means (Table 4).

The unimodal (normal) and bimodal size structure patterns could be a result of periodic waves of establishment due to either intermittent seed production or seedling establishment. Intermittent seedling establishment would result if (1) climatic conditions

Table 3. Estimated snowfree date in 1983, 1984, and 1986 for mountain hemlock and adjacent subalpine vegetation types

Stand Location (Paired vegetation type)	Year	Snowfree date: Hemlock Type	Snowfree date: Paired Vegetation Type
Castle Peak (shrub)	1983	12 Aug	14 Jul
	1984	17 Jul	22 Jun
	1986	15 Jul	18 Jun
Incline Lake (lodgepole pine)	1983	8 Aug	11 Aug
	1984	12 Jul	1 Jul
	1986	16 Jul	8 Jul
Ward Peak (red fir)	1983	12 Aug	10 Aug
	1984	30 Jul	16 Jul
	1986	12 Jul	26 Jun
Waterhouse Peak (mixed conifer)	1983	4 Aug	28 Jul
	1984	5 Jul	22 Jun
	1986	5 Jul	22 Jun

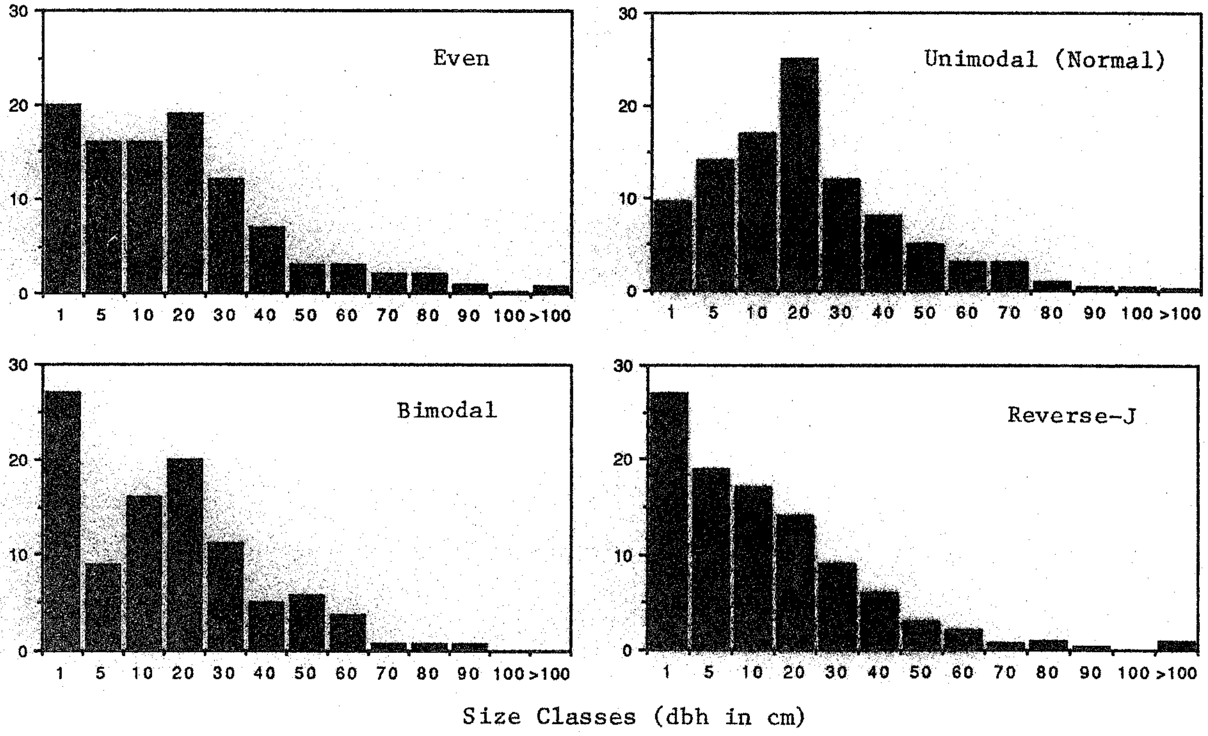

Figure 2. Size class (mean dbh in cm) histograms for each of the four general patterns of stand size structure in mountain hemlock (Tsuga mertensiana) stands in the Lake Tahoe area.

favorable for seedling establishment were intermittent, (2) inter- or intraspecific competition between seedlings varied, or (3) a physical disturbance periodically created abundant microsites favorable for seedling establishment. Depending upon the time of the most recent wave of establishment, a unimodal or bimodal size distribution would result (Benedict and Fites, 1984).

Stands sampled in the Lake Tahoe basin having unimodal and bimodal size distributions were generally north-facing and had intermediate to low slope inclinations (Table 4). The lower slope results in a greater amount of effective incident solar radiation, potentially creating a more xeric soil moisture regime during the growing season. Seedling establishment on these sites would be favored during years with more snow or cooler temperatures, and would therefore be intermittent.

Table 4. Mean and standard deviations of selected variables for each histogram type and for all types combined for *Tsuga mertensiana* in the Lake Tahoe basin (Benedict and Fites, 1984).

Histogram Type	Number of Stands	*Tsuga mertensiana* density[1]	*Abies magnifica* density[2]	*Pinus monticola* density	*Pinus albicaulis* density	Average Elevation[2] (m)	Slope[2] (°)	Mean of largest size class *Tsuga mertensiana*[2] (cm)
Unimodal	21	21.3 (±14.6)	1.8 (±3.4)	9.5 (±12.7)	5.3 (±15.8)	2587 (±75)	17.7 (±8.1)	67.6 (±24.5)
Reverse-J	7	12.4 (±5.5)	3.4 (±8.6)	5.7 (±9.1)	20.6 (±27.9)	2716 (±143)	22.0 (±6.6)	85.7 (±16.2)
Even	10	18.1 (±11.5)	7.1 (±14.9)	11.1 (±16.2)	0.9 (±2.9)	2516 (±139)	24.7 (±6.7)	85.0 (±15.8)
Bimodal	7	19.3 (±11.7)	8.4 (±16.6)	6.0 (±4.6)	6.9 (±18.1)	2524 (±64)	15.9 (±10.7)	65.7 (±20.7)
Total	45	18.9 (±12.5)	4.2 (±10.3)	8.7 (±12.0)	7.0 (±17.5)	2581 (±115)	19.7 (±8.4)	74.0 (±22.3)

[1] Densities are number of individuals/100 m^2.
[2] Variables used in discriminant function.

Of the 49 stands sampled, 12 had evidence of recent avalanche activity. Of these 12, 11 had either unimodal or bimodal size distributions. And the 11 comprised 35% of the stands with unimodal or bimodal size distributions. Site disturbance from avalanche activity could periodically create microsites favorable for seedling establishment.

The reverse-J size distribution could result from (1) increasing mortality with size, (2) low competition among smaller trees in combination with increasing mortality with size, and/or (3) slow recruitment into the larger size classes. The harsh environment of the reverse-J stands may increase mortality of larger specimens. The harshness of the environment is indicated by the high average elevation (on the average 129 m higher than the next highest stand type) and the high average _Pinus albicaulis_ density in the reverse-J stands (Table 4). The growing season generally decreases with increasing elevation, and a decrease in the length of the growing season may be important in determining the survival of conifer needles at high elevations (Tranquillini, 1979). The reverse-J stands also have the lowest _Tsuga_ density which might lessen intraspecific competition and possibly allow for greater seedling establishment. On the other hand, the low _Tsuga_ density may indicate a low number of suitable safe sites for _Tsuga_ growth. A low number of suitable safe sites, combined with a slow growth rate due to a harsh environment, could result in slow recruitment into the larger size classes (Benedict and Fites, 1984).

An even size distribution could result from continuous and equal seedling establishment rates combined with equal mortality rates for all size classes. Continuous seedling establishment would depend on continuous conditions favorable for seedling establishment. The 10 mountain hemlock stands with even size distributions were at marginally lower elevations (suggesting warmer temperatures, longer growing seasons, and less snowpack) and had steeper average slope (indicating lower effective incident solar radiation) than other stand types (Table 4). In combination, these two factors probably result in a mesic soil water regime, low evaporative stress, and a longer growing season. The moderate environments present at these sites are also indicated by the high average densities of _Pinus monticola_ and _Abies magnifica_ (Benedict and Fites, 1984; Table 4).

Of the four intensively studied hemlock stands, the Castle Peak and Ward Peak stands each had a unimodal stand size pattern while the Incline Lake and Waterhouse Peak stands had a reverse-J size pattern (Figure 3). A unimodal pattern suggests less successful seedling establishment and survival, and greater adult survivorship and/or recruitment into medium size classes than a reverse-J pattern. Therefore, stands having a unimodal pattern should correspond with physical characteristics that are more favorable for survival of mid-sized adults and less favorable for seedling establishment. The tendency for greater snow depths in these stands may cover and protect mid-sized trees from damage by avalanches. Also, the Castle Peak and Ward Peak stands tended to have lower seedling densities and survival rates in 1983 and 1986 (years following bumper cone productions) than the other two hemlock stands (Table 5). The Castle Peak and Ward Peak stands, located at lower elevations on volcanically-derived soils (Table 6), may experience mid-summer soil moisture deficits unfavorable for seedlings. It is questionable, though, that these stands, which show heavy avalanche activity, provide an environment favorable to the survival of large adults. The reverse-J stand structure pattern at Incline Lake and Waterhouse Peak may be the result of favorable seedling establishment at high elevations, northerly exposures, and granitically-derived soils with adequate soil moisture. We found that the Incline Lake stand had the highest seedling densities and survival rates; whereas seedling survival rates at the Waterhouse Peak stand were lower than expected (Table 5).

Table 5. Mountain hemlock survival rates (percent) within the first season of establishment after two extremely heavy cone production events in 1982 and 1985, and mean mountain hemlock seedling densities in 1983 and 1986

Stand Location	Plots Sampled		Survival Rates		Number of seedlings per m^2	
	1983	1986	1983	1986	1983	1986
Castle Peak	5	2	73	53	20.7	4.2
Incline Lake	8	6	79	57	41.7	167.2
Ward Peak	4	4	12	0	0.9	8.6
Waterhouse Peak	4	2	65	34	27.6	7.7

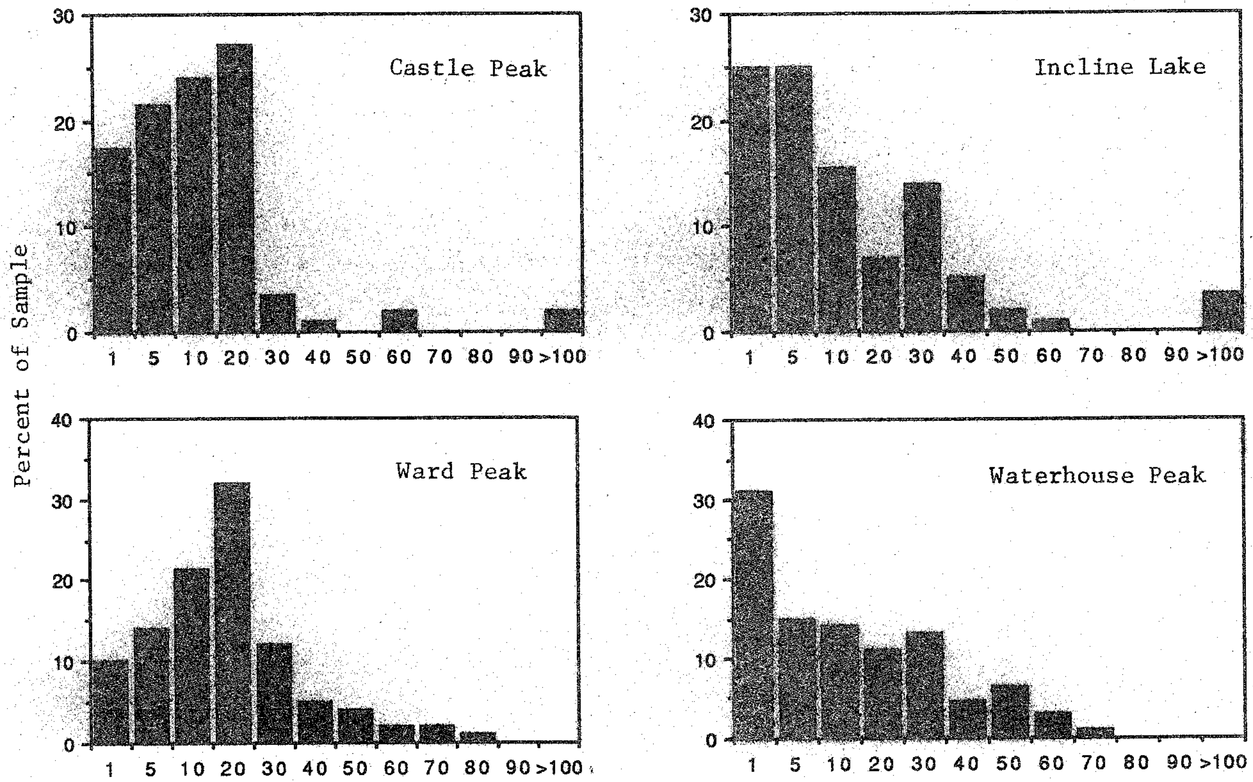

Figure 3. Size class (dbh in cm) histograms for each of the four intensively studied mountain hemlock (*Tsuga mertensiana*) stands in the Lake Tahoe area.

Species Composition

Based on the Braun-Blanquet floristic association system, four associations and twelve subassociations were described in the 49 hemlock stands sampled in the Lake Tahoe region (Benedict and Nachlinger, 1983). The four associations are briefly characterized below.

Mountain hemlock-mountain red heather (Tsuga mertensiana-Phyllodoce breweri): This is a species-rich association occurring primarily on granitic rocks. Diagnostic species include dwarf bilberry (*Vaccinium nivictum*), waterleaf phacelia (*Phacelia hydrophylloides*), pine-woods lousewort (*Pedicularis semibarbata*), and pride-of-the-mountain (*Penstemon newberryi*). Stands catagorized in this association have the highest potential insolation values (Frank and Lee, 1966), yet they are relatively mesic because of the occurrence of streams within the stands. Avalanche damage is common and deep snowpacks are probable. Twenty-five of the 49 stands (51%) were floristically classified in this plant association.

Mountain hemlock-bottlebrush squirreltail (Tsuga mertensiana-Sitanion hystrix): This association is a graminoid-rich group occurring on all rock types. Diagnostic species include Presl's sedge (*Carex preslii*), forked woodrush (*Luzula divaricata*), and bottlebrush squirreltail. Stands placed in this association occur on very steep, north-trending slopes at high elevations. They have the lowest potential insolation values, but because they are wind-swept they potentially accumulate the least amount of snow and are relatively xeric. Six of the 49 stands (12%), including the one at Incline Lake, were floristically classified in this plant association.

Mountain hemlock-Davis' knotweed (Tsuga mertensiana-Polygonum davisiae): This is a species-rich association occurring only on volcanic rock types. Diagnostic species include low polemonium (*Polemonium californicum*), spurred lupine (*Lupinus arbustus* ssp. *silvicola*), and California valerian (*Valeriana capitata* ssp. *californica*). Stands placed in this association have north-trending exposures and occur at relatively lower elevations on mesic sites. They potentially accumulate deep snow packs. Twelve of the 49 stands (25%), including the Castle Peak and Ward Peak stands, were floristically classified in this plant association.

Mountain hemlock (Tsuga mertensiana): This association is species-depauperate and primarily occurs on volcanics. The understory includes little more than Parry's rush (*Juncus parryi*) and the broad-seeded rock-cress (*Arabis platysperma* ssp. *platysperma*).

Stands placed in this association occur on moderate, north-trending slopes at the middle- to upper-slope topographic positions, and at high elevations. These characteristics, along with their low potential insolation values, provide a setting for cornices, snow-drifts, or late-lying snowbanks. The resulting shortened growing season could account for the lack of understory. Six of the 49 stands (12%), including the Waterhouse Peak stand, were florisitically classified in this plant association.

Table 6. Characteristics of the four intensively-studied mountain hemlock stands.

	Castle Peak	Incline Lake	Ward Peak	Waterhouse Peak
Physical Characteristics				
Exposure	W	NE	NE	NNW
Slope (°)	23	23	17	18
Elevation (m)	2652	2856	2438	2871
Rock type	Volcanic	Granitic & Volcanic	Volcanic	Granitic
Evidence of avalanche activity	Yes	No	Yes	No
Mean April 1 snow depth (cm)	554	528	589	391
Mean snow free date[3]	25 July	26 July	28 July	15 July
Stand Characteristics				
Tsuga mertensiana density[1]	9.6	11.4	27.7	8.7
Abies magnifica density[1]	0.4	0	0.5	0
Pinus albicaulis density[1]	0	7.4	0	3.6
Tsuga size class distribution type	Unimodal	Reverse-J	Unimodal	Reverse-J
Most common *Tsuga* dbh[2] class (cm)	10-20	<1	10-20	<1
Presence of trees >100 cm dbh	Yes	Yes	No	No
Species richness (# species per stand)	33	29	24	11

[1] Number of trees per 100 m^2.

[2] Diameter at breast height.

[3] 1983, 1984, and 1986.

SUMMARY AND CONCLUSIONS

Snow accumulation and duration are important in determining subalpine vegetation at the sites in the Lake Tahoe basin evaluated in this study. Snow and snow-related parameters were found to affect stand characteristics within mountain hemlock stands.

Analysis of snow patterns and melt dynamics within the subalpine zone showed that snow tended to accumulate more and last longer in hemlock stands than in adjacent shrub stands, but not in adjacent stands of red fir or lodgepole pine. The presence of large, late-lying snow cornices above hemlock stands and not above other adjacent subalpine vegetation stands probably provides additional moisture late in the growing season. These findings support the hypothesis that hemlock stands can occur in the central Sierra Nevada despite an apparent precipitation deficit because they occur on microsites which receive more snow and greater moisture during the growing season.

Snow-related parameters (e.g., avalanche activity, elevation, slope inclination, and site moisture) are important in determining stand structure patterns in the mountain hemlock stands studied. Stands with deeper snowpacks and greater avalanche activity tended to have unimodal and bimodal stand size structure patterns and the lowest species richness, probably due to the impact of snow on the length of the growing season. Snow, site moisture, and parent rock material were found to be important factors in determining species composition within hemlock forests. Hemlock stands with relatively moderate snow accumulation potential had the highest species richness.

Should snowfall increase, either as a result of cloud seeding or climatic change, as a first approximation of long-term ecological changes, the following may occur:

1. mountain hemlock stands may increase in extent at the expense of other subalpine vegetation types;
2. mountain hemlock stands may increasingly develop unimodal and bimodal size structure patterns; and,
3. mountain hemlock stand species composition may become increasingly uniform as depauperate stands become more species rich and species rich stands become more species poor.

Interactions with other environmental factors are nevertheless inevitable and complicate the prediction of vegetation changes. Vegetation responses to decreases in the amplitude of annual snowpack variations cannot be assessed at this time.

These conclusions are based on data from a relatively small number of sites and a short time span of observation. Additional data are needed to confirm the preliminary results reported here.

ACKNOWLEDGEMENTS

The Division of Atmospheric Resources Research, U.S. Bureau of Reclamation, funded this study. Nathan Benedict initiated the study, and he along with Linda Bjork, Josephine Fites, and Gayle Marrs-Smith helped with field measurements.

REFERENCES

Axelrod, D.I., 1977. Outline history of California vegetation. p. 139-194 In: Barbour, M.G. and J. Major (eds.), Terrestrial Vegetation of California. Wiley and Sons, New York, NY. 1002 p.

Benedict, N.B., and J.A. Fites, 1984. Stand structure and related environmental characteristics of *Tsuga mertensiana* forests in the Lake Tahoe basin, California. Unpublished report, Biology Department, University of Nevada, Reno, NV. 28 p.

Benedict, N.B., and J.L. Nachlinger, 1983. Description of tentative plant associations and species groups in *Tsuga mertensiana* forests in the Lake Tahoe region. Unpublished report, Biology Department, University of Nevada, Reno, NV. 13 p.

Billings, W.D., and L.C. Bliss, 1959. An alpine snowbank environment and its effect on vegetation, plant development, and productivity. Ecology 40:388-397.

Braun-Blanquet, J., 1965. Plant Sociology: the Study of Plant Communities. [Translated, reviewed, and edited by C.D. Fuller and H.S. Conrad] Hafner, London. 439 p.

Fowells, H.A., 1965. Silvics of forest trees of the United States. Agricultural Handbook 271. USDA, Forest Service. 762 p.

Frank, E.C., and R. Lee, 1966. Potential solar beam irradiation on slopes. Research Paper RM-18. USDA, Forest Service, Research Paper. 116 p.

Franklin, J.F., and C.T. Dyrness, 1973. Natural vegetation of Oregon and Washington. General Technical Report PNW-8. USDA, Forest Service. 417 p.

Houghton, J.G., 1978. Orographic effects on Great Basin precipitation. Preprints, Conference on Sierra Nevada Meeteorology. American Meteorological Society, Boston, MA. 109-110.

Klieforth, H., W. Albright, and J. Ashby, 1983. Measurement, tabulation and analysis of rain and snowfall in the Truckee River basin. Unpublished final report, Atmospheric Sciences Center, Desert Research Institute, Reno, NV. 29 p.

Lepper, M.J., 1974. Pinus flexilis James and its environmental relationships. Unpublished Ph.D. dissertation, Botany Department, University of California, Davis, CA.

Major, J., 1977. California climate in relation to vegetation. p. 11-74 In: Barbour, M.G. and J. Major (eds.), Terrestrial Vegetation of California. Wiley and Sons, New York, NY. 1002 p.

Moore, J.A., 1981. Some characteristics of a single Sierra Nevada precipitation echo type: the major band. Proceedings, Second Conference on Mountain Meteorology. American Meteorological Society, Boston, MA. 360-366.

Mueller-Dombois, D., and H. Ellenberg, 1974. Aims and Methods of Vegetation Ecology. John Wiley and Sons, New York, NY. 547 p.

Munz, P.A., and D.D. Keck, 1959. A California Flora. University of California Press, Berkeley, CA. 1681 p.

Nie, N.H., C.H. Hull, J.G. Jenkins, K. Steinbrenner, and D.H. Bent, 1975. SPSS Statistical Package for the Social Sciences. McGraw-Hill Book Company, New York, NY. Second edition. 675 p.

Rundel, P.W., 1971. Community structure and stability in the giant sequoia groves of the Sierra Nevada, California. American Midland Naturalist 85:478-492.

Rundel, P.W., D.J. Parsons, and D.T. Gordon, 1977. Montane and subalpine vegetation of the Sierra Nevada and Cascade Ranges. p. 559-601 In: Barbour, M.G. and J. Major (eds.), Terrestrial Vegetation of California. John Wiley and Sons, New York, NY. 1002 p.

Ryan, B.F., B.L. Joiner, and T.A. Ryan, Jr., 1985. MINITAB Handbook. Duxbury Press, Boston, MA. Second edition. 379 p.

Smith, J.L., 1982. The historical climatic regime and the projected impact of weather modification upon precipitation and temperature at Central Sierra Snow Laboratory. The Sierra Ecology Project, Volume Three. USDI Bureau of Reclamation, Office of Atmospheric Resources Research, Denver, CO. 43 p.

Soil Conservation Service, 1982, 1983, 1984. Water Supply Outlook for Nevada. April 1 Bulletins. USDA Soil Conservation Service.

Soil Conservation Service, 1985, 1986. Nevada Water Supply Outlook. April 1 Bulletins. USDA Soil Conservation Service.

Taylor, D.W., 1976. Ecology of the timberline vegetation at Carson Pass, Alpine County, California. Unpublished Ph.D. dissertation, University of California, Davis, CA.

Tranquillini, W., 1979. Physiological ecology of the alpine timberline. Springer-Verlag, New York, NY.