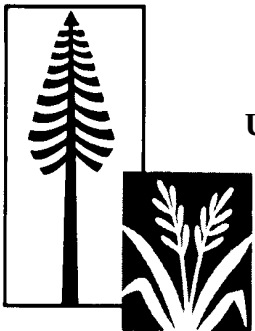


Interception Processes During Snowstorms

David H. Miller



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Foreword

The West looks to winter snowfall for much of its water, and there is a good deal of evidence from Forest Service and other research that management of mountain lands for wood, forage and recreational amenities can affect the accumulation of snow into a long-lasting pack. Studies of the physical processes that influence this accumulation, however, have lagged behind empirical studies. To help research workers interested in planning future basic studies, Dr. Miller has reviewed past research related to interception of snowfall by vegetation—the first step in a complex chain of events that affect the accumulation and melting of snow.

This paper is the first of several reporting the results of his investigation. The study was part of the cooperative snow research program of the Forest Service and the State of California Department of Water Resources. Valued aid has also come from the University of California at Berkeley, and from the U. S. Army Cold Regions Research and Engineering Laboratory.

—JOHN R. McGUIRE, *Director*

Miller, David H.

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Four processes are identified as determining the initial interception of falling snow by forest during storms: delivery of snow particles from the airstream to the forest; true throughfall of particles to the forest floor; impaction and adhesion of particles to foliage and branches; and cohesion of particles into masses of snow. Delivery and impaction processes seem amenable to aerodynamic analysis; adhesion of particles and cohesion both depend on air temperature and foliage roughness. Promising leads for laboratory and field research on aerodynamic and thermodynamic factors influencing interception are described.

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The Author

DAVID H. MILLER has been studying problems in snow hydrology and meteorology for more than 20 years—in operational work of the U. S. Army Corps of Engineers (1941-1943), and in research with the Engineers' snow studies (1946-1953) and with the U. S. Forest Service (1959-1964). He earned bachelor's (1939) and master's (1944) degrees in geography and meteorology at the University of California at Los Angeles and a doctorate (1953) at the University of California.

The vegetation of a drainage basin alters the way in which precipitation is delivered to the receiving surfaces of the basin's soil mantle. Plants that intercept precipitation change the amount, timing, and areal distribution of the water input to the basin as a hydrologic system; yet interception has been studied mostly as a by-product after all the effects of vegetation upon runoff or soil moisture are lumped. The Kerr Report (U. S. Senate 1960) speaks of the need to establish "the importance of interception in the water balance," and Hoover (1962) poses several questions about interception of snowfall in particular, which, despite its great importance to land management, cannot be answered from present knowledge. A search for answers to these questions can be considered a logical starting point for an examination of the role of forest vege-

tation in the hydrologic systems of snow-covered drainage basins, looking upon interception as the series of events that precede those other geophysical processes affecting the winter snow mantle on the ground and its dissolution in spring.

Such an examination of available evidence on snowfall interception suggests that the term encompasses a group of some 15 to 20 physical processes that can be distinguished and separated in field measurements and laboratory experiments. Four of these processes are discussed in this paper: delivery of snow to a forested slope, throughfall of particles to the forest floor, impactation and adhesion of particles to foliage and branches, and cohesion of particles into snow loads. Processes that have to do with disposition of the intercepted snow will be described in later papers.

Delivery

Many studies of the effects of exposure on the accuracy of precipitation measurement emphasize the disruption of the air flow by the gages and by obstacles near them, but the effect of roughness of the upper surface of forest canopy on falling particles has seldom been studied. There is little knowledge of the delivery of snow to the canopy surface, though it is plain that it must vary greatly from place to place, and add to the problems of sampling the snow that penetrates to the forest floor or adheres to the canopy.

Kuz'min (1963) discusses velocities of snow particles falling in the open and summarizes some observations on speeds and angles obtained from photographic observations. The average angle from the horizontal is 4 degrees, confirming the visual impression one receives of the nearly horizontal movement of snowflakes. He also discusses a motion analogous to Brownian motion of molecules, when snowflakes fall in calm air, which also enters the problem of delivery of snow to forest.

Delivery of snowflakes from the airstream to forest has been measured a few times by precipitation cans at crown level (Davis 1939, for ex-

ample), but results have not been analyzed with regard to turbulent motion of the air or roughness of the forest surface. The siting of precipitation gages is difficult, and sampling snowfall at crown level may require many gages. Where snow falls in wet storms of low wind speed, annual catch at crown level approximates that in cans in small openings (Rowe and Hendrix 1951), but the relation in single snowstorms, especially if the snow is dry and winds are high, is not known. As is well known, some doubt attaches to the interpretation of measurements in forest openings, again for reasons of complex turbulent motion.

The speed of falling snowflakes, less than a meter per second and an eighth or tenth that of rain drops, produces a basic difference in impingement on vegetation. The low speed causes the flakes in a moving air stream to approach the ground or trees at low angle, and hence to hit the sides of tree crowns nearly directly, as Harrington (1893) notes. When trees are in a forest, the low angle of approach of snowflakes has the effect of increasing the surface of an incompletely closed forest canopy.

Horton (1919) points out that the number and

sizes of openings in such a forest are reduced, so that to the approaching snowflake the forest is a continuous, though irregular, surface. Delfs (1955) also discusses increased storage of snow by forest from this cause. The effect is like the absorption of low-angle solar radiation by a forest that, viewed in a vertical aerial photograph, has low density. Perhaps for this reason, crown coverage if regarded only as a two-dimensional plane, has turned out to be a poor predictor of snowfall interception when measurements in many stands of forest are compared.

Analyses of data published by Kittredge (1953) suggest to me that selective logging influences interception less by changing crown cover than by removing dominant trees that project above the canopy—and perhaps by making forest edges more porous. Both conditions act directly upon snow delivered at low angles.

When snowflakes enter the zone of lower wind speed just above the crowns, their angle of approach becomes more vertical, but their paths also come under the influence of eddies produced by the rough upper crown surface and by openings. These eddies bring snowflakes into contact with the foliage, so that at no time, except in dead calm, is throughfall governed merely by the openings in a two-dimensional plane seen by a man below it looking at the sky. While crown closure is often the only reported variable describing forest, and has to be used in lieu of quantitative data on foliage area, branch-wood volume, and structure, it is not an accurate predictor of throughfall.

The boundary airstream through which precipitation particles pass before reaching the ground is always in turbulent motion, of particular severity when it flows over rough surface. Increased turbulence brings more precipitation particles down into the crowns, a process that has been studied for fog droplets (Hori 1953). Costin, Gay, Wimbush, and Kerr (1961) refer to the effect of the turbulence produced by the tree canopy and by small openings upon snow deposition, and its decrease as the size of openings grows larger. Turbulent eddies induced by topography also affect the delivery of snowflakes and may account for the extreme snow loads sometimes reported on trees of lee slopes.

Deposition of Snow from the Air Stream

Deposition of snow out of a flow of snow and air impinging on the porous layer of the forest can-

opy can probably be determined from formulas established by such students of snow drifting as Dyunin (1961, 1963) and Komarov (1963). Komarov, for example, concludes that deposition “depends on the difference between at least the cube of the initial and final velocities” so that a small decrease in wind speed results in large deposition of snow. Wind measurements in the air stream above and at the crown level would make possible the application of these relationships, which should be particularly useful in mosaic landscapes of tree groups and interspersed openings.

Some idea of deposition of snow from an air stream can be gained by studying Japanese measurements of snow load on models and on a tree (Japan 1952). The snow load on models was measured with reference to that received on a flat, elevated board, and I have computed loads at zero and 1 meter per second wind speed for comparison. Compared to the deposit of snow at zero wind, that at 1 m/sec. is as follows:

1. On flat, exposed board (Japan 1952, p. 126) — (Load 650 g. at zero wind, 420 g. at 1 m/sec.)
35 percent decrease;
2. In stack of shelves of same size, 15 cm. apart (equation 8, p. 124) — (excluding top shelf) 140 percent increase;
3. In pyramidal stack of shelves, 15 cm. apart (equation 14, p. 131) —
55 percent increase;
4. On solid pyramid (equation 9, p. 127) —
40 percent decrease;
5. On crown of cryptomeria tree (fig. 8, p. 145) —
maximum deposits (from enveloping line)
30 percent decrease;
mean deposits (from mean line)
25 percent decrease.

The decrease of snow on the tree at a wind speed of 1 m/sec. is like that on the solid pyramid, where all snow accumulates on the outer surface. The snow load on a solid hexagonal pyramid of base 585 sq. cm. and height 25 cm., in percent of accumulation on the flat board, was equal to $91 - 36v$, in which v is wind speed in m/sec.; on a steeper pyramid the wind coefficient is about the same. Stacks of boards separated by various spaces and supported above the ground to simulate a tree crown displayed an increase in relative accumulation as wind speed increased to 1.2 m/sec.; moderate air movement transports snow into the

interior of the stacks. The increase is largest on boards separated the most. Hexagonal pyramids showed similar results, the wind coefficient being modified by vertical spacing of shelves. Snow loads in these experiments ranged to about 15 mm. mass on a flat exposed board and 25 mm. in the vertical stack, on the basis of its horizontal projected area.

When the snow load on a cryptomeria tree, as a percentage of snowfall reaching the ground, is plotted against wind speed in the range 0.5 to 2.5 m/sec. (Japan 1952; fig. 8, p. 145), a line that envelopes 34 of the 37 storms indicates that at wind speeds above 2 m/sec. interception is usually, but not always, small. At speeds around 1 m/sec., it varies from 40 to 130 percent of snowfall. Photographs of the tree under loads of 10 and 40 kg. show how snow loads force the crown into a pyramidal shape. More rigid branches would open access to the interior of the crown, and an increase in wind, up to some critical value, would deposit more snow, as it does in the stack of shelves. I estimate from published graphs (Japan 1952; pp. 142, 143) that storage of snow at temperatures higher than -3°C . may have reached 15 mm. water equivalent.

That transport of snow into the interior of crowns and extension inward of the wetted or supporting surface may have increased storage in Kittredge's (1953) study is suggested by Court's (1957) finding that near Donner Summit in the Sierra Nevada in California less than 2 percent of the precipitation in three winter months (which totaled 33 inches) occurred during calm. On the other hand, extremely high winds are not common during snowfall in many forested areas. Deposition on trees in high winds becomes a function of adhesion, greatest not in snow but in supercooled rain. Many studies discuss the formation of rime, which represents a situation in which the forest augments the amount of atmospheric water received by the earth's surface, but their results have little direct value for determining delivery of snow to a forested slope.

Klintsov (1958) describes gales of wet snow in Sakhalin, in which heavy snow accumulated on the windward and upper halves of crowns of conifers about 7 m. tall, to nearly 100 kg. Near the freezing point, snow may be mixed with undercooled droplets of liquid water and form rime on solid objects. Heikinheimo (1920) describes storms of northern Finland in which rime and snow are plastered on trees by strong winds. Al-

though the admixture of liquid droplets is not large, since he reports that density of the deposit averages 0.15 and seldom exceeds 0.3, it helps the snow adhere to the trees in layers 30 cm. thick. This admixture is common enough to have a Finnish word—*tykky*. At high wind speed, the angle of approach of the snow is nearly horizontal, and the deposits have a sharp lower limit, about 300 meters above sea level, that is visible on mountain sides from great distances. This limit is also noted by Hustich (1940), who measured accretion on sticks of 7 cm. diameter; those mounted on birch trees at elevations of 360 meters and 470 meters (treeline) accumulated six to seven times as much snow and rime as those at 300 meters. Deposits on bare poles were as thick as 13 cm.

Grunow (1955) points out that water in the solid state intercepted from a horizontal airstream makes up 15 percent of the total received by the forest floor in the interior of the stand, and 45 percent at the edge; corresponding figures for liquid horizontal precipitation are 20 and 57 percent. Although less snow is screened out of the air or deposited by turbulence on vegetation than liquid water, the amounts are significant and indicate the role of high wind speeds; in Salamin's (1959) words, "trees 'sift' snow out of the moving air." The relative heights of the level of condensation and the level of freezing often are such that in cloudy weather the zone of heavy fog drip is near ridges. However, in snow storms, the snow is often dry near the crests and wet at lower elevations (Baumgartner 1957), where the wind is weaker and horizontal interception is minor (Baumgartner 1958).

Ratzel (1889) reports excess interception of snow by trees on edges of forest or valley, or on exposed slopes, to the point of frequent snow break. Eidmann (1954) shows that spruce intercepts more on slopes, perhaps because crowns are more densely closed. Costin and Wimbush (1961) weighed the deposits of rime and ice formed on eucalyptus foliage in sub-freezing weather, finding rates greater than 25 mm. per day, considerably greater than in warmer air, when little condensation of vapor occurs to add to the intercepted load of raindrops.

Research Approaches

Understanding delivery of precipitation requires looking at the forest cover from above, as a mantle

on the earth's surface. This comes more naturally to biologists used to microscopes than to the man on the ground. Harrington (1893) takes this point of view, and Horton (1919) visualizes the scene as a snowflake descending toward the forest top. Micrometeorologists also generally have this point of view toward a grass cover underlying a turbulent air stream.

As micrometeorological research produces expressions of turbulent exchange, shear stress or drag, level of displacement, and other boundary-layer concepts, these expressions should be immediately seized on to elucidate the complex deposition of snow particles from a turbulent air stream onto and into a rough porous layer over which the stream flows, into which it penetrates, and which it deforms.

Micrometeorological work over forest cover faces a problem of reproducibility. The upper surface of the crown canopy, even in a simple forest type of unbroken closure, has not been described adequately. Without means of quantifying the boundary surface, students of turbulence will be reluctant to choose trial-and-error field measurement over more concrete problems confronting them elsewhere. Mosaic forests of tree groups and interspersed openings present an experimental situation of greater complexity, which perhaps can be studied by profile measurements of wind speed and fluctuation, not to 10 meters above the canopy, but to the next larger order of magnitude, through a boundary layer some hundreds of meters deep. Studies of storms on a synoptic scale are also needed, to determine eddy turbulence in the deposition of snowflakes.

The vibration of trees in wind, and their changes of shape and relative position as gusts pass over, are perhaps too complex to formulate other than as a recurrent quasi-elastic perturbation in roughness of the boundary and a recurrent fluctuation in drag. The coupling of perturbations in wind flow and boundary roughness that might come into phase with each other where wind fetch is long enough is a problem to which current work on the interaction between wind and waves can perhaps be applied.

Penetration of moving air into crowns may be measurable by micrometeorological instruments. It is indirectly made visible in terms of transport of snowflakes into crown interiors, and this should be measurable, as these paths are now studied photographically in the open (Kuz'min 1963). Determination of the wind speed at which trans-

port and deposition is largest has begun with models, and should continue on trees with rigid branches in wind tunnels. Work can then be extended to trees that deform or close up under wind stress.

Wind-tunnel studies must simulate snowflakes of proper size, density, roughness, shape, falling speed, and wetness. It is doubtful that ice shavings fill this need. Materials lighter than ice have been used in some reduced-scale studies (Gerdel and Strom 1960) and may be useful in studies of forest action. Eventually, full-scale wind-tunnel studies should be done, at first with tree branches, and then including such phenomena as bending and deforming of trees. Deposition of snow in calm air onto branches and trees of various shapes would be studied first, then deposition from a moving air stream. The concentration of snowflakes in the air stream can probably be sampled by the drift meters used in Antarctic studies. Hydraulic model experiments on bed load and suspended load in streams may furnish parallels to the delivery of snow to a forest; their analogies to snow drifting have been noted by Kuz'min (1963) and others.

Many studies in controlled environments may be needed before going to field installations, except perhaps that driftmeter measurements could start in a few places.

Our estimates of the amount of snow delivered to the upper surface of a forest—whether based on measurements in cans in small glades or in large open areas, or in sites subjectively appearing sheltered but not too much so—must be recognized as no more than estimates that we have no way to check. Traditional means of measuring precipitation in the canopy zone have unknown accuracy, and exploration might begin by positioning precipitation cans, drift meters, and anemometers in the humps and hollows of a forest top, to help identify sampling problems.

The old question, whether precipitation is greater on forest than on open land, was in doubt when Harrington in 1893 suggested it was necessary to measure precipitation over a forest. By 1913 Pearson indicated that the question was dead. It was not to revive until the 1950's. While active in the latter 1800's, it occasioned great interest in forest problems generally, and indirectly benefited interception research. If the question again becomes scientifically attractive, it may bring interest in determining rate of delivery of snow to forest.

'True' Throughfall

Defining as "true" throughfall the snow that penetrates forest canopy without alighting for any length of time on branches or foliage, as mentioned by Colman (1953), we find a problem analogous to that of solar radiation penetrating directly to the forest floor. However, sunflecks can usually be measured separately, while directly penetrating snowflakes are not easily distinguished from those falling from snow masses on branches, except in dead calm. Laboratory and wind-tunnel experiments should give the amount of true throughfall and its relation to snow delivered to the forest top. At times when no snow is blowing through the trunk space or falling from overloaded branches, true throughfall can be measured accurately. If foliage is very open, some precipitation particles are bound to fall through, no mat-

ter how light the intensity (Costin and Wimbush 1961; Ney 1894). If stands are dense, such as those described by Fenton (1959), with a "nearly impermeable" meshwork of branches, true throughfall in a wet snowstorm is very small.

In laboratory and field, short-exposure photographs may prove useful in determining the density of snow per unit volume of air above and beneath the canopy. Some method of measuring attenuation of radiation over a fixed course, as is used in determining concentrations of vapor or carbon dioxide, might also be employed. Another approach is indicated by studies on oil sprays released above forest (Maksymiuk 1963), in which the true throughfall of particulates is measured by oil-sensitive cards on the ground.

Impaction and Adhesion of Snow on Foliage

Recent aerodynamic research on impaction of airborne particulates on solid objects of different sizes has relevance to collection of snowflakes by foliage and branches of forest,¹ but the necessary bridging work has not yet been done. Present discussion of this process can only be empirical, by summarizing what is known of the effects of characteristics of (a) the impacted particles—the snowflakes, as related to temperature-dependent wetness; (b) the relative motion of particles and obstacles—wind speed through the forest crowns; and (c) the obstacles.

Temperature Effects

Adhesion of snow to foliage presumably increases as temperature rises toward the freezing point. The Japanese study reports snow loads to be small at low temperatures, moderate to large at temperatures just below freezing; the trend can be expressed as an increase in interception of approximately 30 percent of snowfall for each Celsius degree of warming. Much of this increase can be ascribed to increased adhesion, which has been shown in laboratory

studies (Kuriowa 1962) and field experiments (Minsk 1961) to be temperature-dependent, perhaps because of the role of a thin liquid-water film.

In frontal weather, snow falling through quiet air near the earth's surface approaches the ground vertically; references to wet snow "clinging" to trees are common (Chittenden 1909; Delfs 1958; Kittredge 1948; Tikhomirov 1934). Baldwin's (1957) comment that high-density snow is more intercepted than low-density presumably refers to wet snow. Rosenfeld (1944) speaks of wet snow overbalancing the crowns so that trees lean, and intercept more snow until they break; trees on sheltered lee slopes intercept the most snow, and are most subject to damage; he says that in the catastrophic break of 1888 in Silesia, when wind was from the northwest, trees on north and west slopes sustained a third of the damage, while trees on south and east slopes, in wind shadow or calm, sustained two-thirds. Hirata and Hotta (1951) describe heavy damage on steep lee slopes and on the concave slopes between spurs.

¹Personal correspondence with G. M. Corcos, University of California, 1961.

Wind Effects

Wind-transported particles impact upon obstacles because they come out of the air stream where its acceleration is largest, which occurs at sharp changes in direction. Minsk (1961) reports that winds of 8 to 10 knots increased the frequency of adhesion of snow to mesh panels, though the amount of snow accumulating was less than at lower speeds.

Dry snow in strong winds is generally intercepted less than wet snow. (We are not discussing drifting snow here.) Five storms in which a cryptomeria tree (Japan 1952) intercepted snow amounting to less than 20 percent of that on the ground were cold—temperature lower than -3°C .—and presumably the snow was dry; wind speed was moderate in two storms and low in three. Wellington (1950), discussing snow interception in a cold region (Sault Ste. Marie, Ontario), says that the small retention of dry snow in deciduous trees is caused by greater vibration rather than lack of impaction. Rusanov (1938) notes that snow storms have stronger winds in the deserts of central Asia than in the bordering semi-arid regions, and intercepted snow does not build up on desert plants enough to break them.

Jaenicke and Foerster (1915) compared snow-storm deposits on a large open “park” in Arizona with those in an adjacent area of intermingled tree groups and small openings where wind speed during storms was less than half that in the park. The reported net difference in snow reaching the ground in four winters was small and variable. Their description of snow being deposited like silt settling out of a stream of water suggests horizontal transport of snow, such that catching of falling snow by crowns of tree groups would not necessarily be evident on the ground immediately beneath. From their figures of wind speed in storms of two winters, I could detect no relation to differences in the deposit in park and forest.

Wind that transports snow into the interior of tree crowns influences the shape in which it accumulates there. Salamin (1959) says that in fir the snow lies loosely, but in pine crowns it forms cushions or balls, a difference that may reflect relative penetration of the crowns by snow-bearing and snow-packing winds. His photographs suggest that snow masses may be classified by shape. Micro-structure of the wind field within forest canopy presumably differs from species to species.

The difference in storage of snow and rain is much commented on, but seldom measured. The equations of Rowe and Hendrix (1951) for interception in snowstorms and rainstorms of comparable size indicate greater storage of rain (3 mm.) than of snow (2 mm.). But while the authors say that the smaller value for snow indicates that less water is “retained in wetting the vegetation than when precipitation occurred as rain,” they also state that differences between the equations are not of significance. (Their measurements include few if any storms of cold, dry snow, so that “wetting” means adherence of snow.) Costin and Wimbush (1961) report much greater interception at temperatures below freezing—one to two liters water equivalent per pound of foliage an hour, rather than a quarter of a liter. An approximate value of crown wetting coefficient was determined in *Pinus silvestris* as 1 millimeter for rain; 0.7 millimeter for snow (Krečmer and Fojt 1960).

Okhliabin (1911) reports 22 percent interception on rainy days in the cold season of the year, 16 percent on snowy days. Differences in interception of rain and snow, however, depend on adhesion of water or snow to foliage. Without better information on surface roughness, it is hard to make a decision between the two conflicting ideas, or even to formulate a hypothesis that would account for the observations.

Vegetation warmer than freezing melts the first snow to touch it, but if cold snow continues to fall the meltwater refreezes into a firm bond, according to Heikinheimo (1920). The opposite situation—when trees are cold and snow warm and wet, perhaps more common—leads to adhesion of great quantities of snow; Tikhomirov (1934) regards weather favoring this sequence of events as the most important factor in formation of heavy deposits of crown snow. Sometimes snow falling after glaze adds to tree loading (Ben-nett 1959, p. 154).

Characteristics of the Obstacles

Roughness of surfaces of leaves, twigs, branches, and tree trunks affects adhesion of snow; for example, Salamin (1959) points out that snow forms in bands on deciduous trees if bark is smooth, in heaps if it is rough. Horton (1919) refers to roughness as a factor in the wetting caused by rain and hence in interception storage; and it would play a similar role in wetting by meltwater. In discussing stemflow, Delfs (1955) notes

that the wetting value is less on smooth surfaces.

Flexibility of foliage determines its value for support of adhering snow. Time-lapse photography shows that white pine needles accumulate snow only at the base of the fascicles before the needles are bent into a platform (Lull and Rushmore 1961). Balsam fir, with many stiff branchlets and with needles persisting along the branches, was the best collector of snow; hemlock, of the four species studied, was the poorest since its needles are "feathery and flexible." Maule (1934) comments on the difference between stiff needles of Norway spruce, which intercepted the most snow, and the long, soft needles of red and white pine, which intercepted the least. The brush-like arrangement of needles on a variety of spruce is important in holding snow (Delfs 1955). Alpine ash eucalyptus (*Eucalyptus delegatensis*) intercepts little snow because foliage is open and twigs flexible (Gay 1958), whereas snowgum eucalyptus (*E. pauciflora*) has heavy leaves and stiff twigs and petioles which mat down, as snow piles on them, into a platform that can bear a heavy load. This load has been estimated as great as 100 cu. ft. of snow per tree, or 25 mm. of water on an areal basis (Costin, *et al.* 1961).

Surface area or volume of foliage plays a role in interception but its exact importance is not well defined. Insect-killed lodgepole pine and Engelmann spruce that had lost needles and finer branches intercepted less snow than live trees (Love 1955), but remaining branches still intercepted some snowfall.

Kittredge (1948) reports leaf area of pines at 5,000 ft. elevation in the same part of the Sierra Nevada as his snow research; 28-year-old ponderosa pines had 4.2 sq. cm. of leaf surface (both sides) for each sq. cm. of crown projectional area. If the leaf-surface ratio of the stand is estimated as 3, and interception storage of snow over the stand as 1 mm. (or 0.1 cu. cm./sq. cm. of ground surface), then 0.1 cu. cm. of water is held on 3 sq. cm. of leaf surface, of which half would be upper surfaces; the water equivalent on the average upper surface of needles is 0.6 mm. Strong adhesion of rime particles intercepted at an air temperature below freezing results in a loading of approximately 2 mm., as calculated from data of Costin and Wimbush (1961). For comparison with liquid-water films, it may be noted that Grah and Wilson (1944), in a sprinkling experiment on a small Monterey pine, found approximately 0.1 mm. of liquid water remaining, after shaking, per unit

area of upper surfaces of needles.

Foliage weight, from Kittredge (1948), may be taken as of the order of 0.1 g/sq. cm. of ground surface. Weight of a 2 mm. snow load is 0.2 g/sq. cm., but some of it is borne by the branches directly. A load ratio of 2:1 is much smaller than ratios reported in severe ice storms, which have reached 10:1 or 20:1 (Bennett 1959), but mainly on the bare branches of deciduous trees. It is comparable to the ratio of 3:1 from the data by Costin and Wimbush (1961) on rime interception.

Winter bareness of hardwoods may deceptively lead one to the assumption that they intercept no snow, when this is not true. Wellington (1950) says that they hold less only because they vibrate more in the wind than conifers, not because surface area is less. He points out that deciduous trees that are overtopped and out of the wind hold on branches and forks snow as deep as the snow on conifers (20 cm.). The role of foliage is difficult to separate from that of branches, but the difference may not be as important as it seems. Wood (1937) feels that rainfall was about equally intercepted summer and winter in an oak-pine forest, and that loss of oak foliage in winter made little difference. Bühler (1884, 1886, 1892) reports appreciable interception by beech and larch; Burger (1933) by beech. On the other hand, zero or negative interception by hardwoods sheltered from wind, in comparison to snowfall in open fields, is reported by many investigators (Eitingen 1938; Garstka 1944; Kienholz 1940; Maule 1934; Ratzel 1889).

Snowfall while leaves remain on a hardwood stand, while rare, throws additional light on the effect of foliage volume on interception. Roth (1941) reports that an early snowfall at Fernow Experimental Forest in 1935 damaged 27 percent of a stand of poplars by breakage that led to stem decay. *Climatological Data* does not show a large snowstorm at any station near this West Virginia forest; I conclude that this storm probably did not bring more than 6 or 8 inches of snow, or more than an inch water equivalent. The heavy damage which Roth (1941) ascribes to the fact that leaves were still on the poplars presumably represents heavy interception. Australian investigators could help clarify this effect by more measurements of interception by eucalyptus.

Differences between beech and spruce interception are reported in most of the Central European studies of forest weather since Fankhauser (1882), but it is not always clear how much of

the change measured in throughfall between summer and winter is caused by change in foliage and how much by the change in phase of precipitation.

Horton (1919) speaks of water storage with moist snow on trunks and branches of deciduous trees as being larger than with rain. Salamin (1959) illustrates accumulation of snow in deciduous trees in a variety of forms: cushions and balls on branches and on dry leaves remaining on the trees, and "walls" along tops of horizontal branches. Generally such snow is more compacted than the loose snow in conifer crowns.

Flexibility of branches affects snow load. Baldwin (1957) shows that when heavily loaded, the branches of fir, spruce, and hemlock droop and let the snow slide off, while the stiffer branches of pine continue to hold it. The flexibility of pine needles may be countered, in large storms, by stiffness of pine branches. Klintsov (1958) ascribes the difference in snow load, 8 mm. on a pine and 6 mm. on a spruce, to rigidity of the pine and flexibility of the spruce; however, the spruce was 10 percent smaller than the pine in d. b. h., height, and crown area.

A comparison of accumulation of dry and wet sawdust on a cryptomeria branch and on a slat model (Japan 1952) showed that beyond a certain load the branch accumulated no more, while accumulation continued on the model. This difference can be interpreted as due to the bending of the branch. Reports of less snow being caught in large storms (Horton 1919; Kienholz 1940; Morey 1942) suggest the vulnerability of large masses to being blown off, or sliding off, if they force branches to bend.

The effect of branch width is indicated in the Japanese model study (Japan 1952, p. 118), in which snow depth was about six times the board width taken to a fractional exponent of 0.7 to 0.9; that is, $D = 6W^{0.7}$

Bühler's (1886) statement that critical damage in a snowstorm near Zürich was reached at 26 mm. in hardwoods, and at 46 mm. in needle-leaf trees, may reflect the more vulnerable branching habit of hardwoods. Hardwoods are shown much more vulnerable to damage by ice loading (Bennett 1959, p. 159) than conifers with their resilient branches, small upper crowns, and mechanically strong branching habit. Gay² notes that the erect habit of branching of alpine-ash eucalyptus does not favor interception on the limbs. Delfs (1955) compared interception in spruce varieties

with different crown shapes; it was least in Kammfichte (comb-spruce) and greatest in Burstenfichte (brush-spruce) that had side branches that rise sharply upward. A photographic report (Anon. 1953) shows natural selection among races of spruce, particularly the contrasting Kammfichte and Plattenfichte (flat spruce). The Plattenfichte has spreading horizontal branches and is more vulnerable to snow break, but is strong in ice and rime loading.

Wide separation of branch whorls in Scotch pine is described by Bühler (1886) as reducing the surface storage for snow, in spite of its long needles. Models of separated stacked boards (Japan 1952, page 124) show greater relative catch per board when they are separated, but the separations were not large, and this result may reflect transport of snow into the interior of the stack. At a given wind speed, there is probably an optimum separation of whorls for interception.

Bühler (1886) was the first to note that snow lies in the interior and lower parts of crowns of bare trees, whereas it lies on the upper whorls and ends of branches of evergreens, which are thus more subject to top break. Many later authors note this tendency for the load to be exterior; this pattern also occurs with glaze loads, which total less in conifers than in hardwoods because they coat the outside of the crowns (Bennett 1959, p. 163).

Ratio of branchwood to stem size is important. Rosenfeld (1944) says that spruce stands damaged worst in a severe storm in 1916 were in an age class in which dense stocking produced slender, high-crowned trees; and Pfeffer (1955) analyzes the mechanics of break in terms of concentration of snow load in a crown at the end of a long lever arm. Even brittle-wooded trees survive heavy loads if they have coarse branching (Bennett 1959, p. 169).

Location of snow load in the crowns is especially important if crowns are unsymmetrical, and many foresters report the hazard of unsymmetrical development. Snowthrow, defined as the bending or uprooting of trees, is ascribed by Spaeth (1941) to unsymmetrical snow loads in crowns; snow-break he ascribes to top damage from wind action on frozen wet snow. Leaning trees intercept more

²Gay, L. W. The influence of vegetation upon the accumulation and persistence of snow in the Australian Alps. 1958. (Unpublished thesis on file at Australia Forestry School, Canberra.)

snow and the unbalanced trees bend and take on more load until they break (Rosenfeld 1944). Unsymmetrical crowns on trees growing on mountain slopes may make them more vulnerable. Eidmann (1954) and Delis (1955) report higher interception by trees on slopes, apparently due to a larger catching surface. The increase in spruce is half again as much on 31- to 40-degree slopes as on 11- to 20-degree slopes; the change in beech is less marked. The sides of crowns of individual trees on steep slopes are more exposed to snow falling at a low angle than those on flat sites.

Trappe and Harris (1958) report that young, thin-stemmed lodgepole pine in Oregon are often damaged by snowbreak: "...once a small patch of snowbreak starts, it grows larger every year. Trees along the edge of the patch, having lost support, bend into the opening under snow weight." Residual trees left on a clear-cut area were similarly subject to damage (Trappe 1959). Curtis (1936) makes a similar statement about plantations in Massachusetts, in which trees bordering openings develop one-sided crowns that make them vulnerable to snow-bending.

Crown depth, volume, and density, more undefined characteristics than crown coverage or closure, recognize the three-dimensional nature of forest canopy. These characteristics can be used as indexes to interception of precipitation or radiation (Miller 1959), which bear certain analogies to each other. If flakes are wet and stick to foliage, there is an analogy to solar radiation absorbed each time it touches a leaf surface, if allowance is made for the effect of gravity on snowflakes. If flakes do not easily adhere to foliage on contact, they penetrate deeply about twice as much snow as solar radiation penetrates a forest of the same stem density (Miller 1955, fig. 7).

Morey (1942) compares crown depth and closure, and concludes that a stand with more trees per acre and thinner canopy intercepts less snow than one with fewer trees and deeper canopy.

Research Approaches

Catching of the first snow by foliage and branch-wood represents adhesion between the rough surface of a dry snowflake, or the wet surface of a warm sticky one, and the rough or smooth foliage surface. Friction coefficients and roughness generally have not been measured. Those of the

snowflake seem to be temperature-dependent, and also bear the marks of the flake's history of growth, evaporation, and melting as it fell, and of its abrasion against other flakes. The angle of leaf surface at which friction is equal to the gravity component parallel to the slope has gone unmeasured, either initially or as it changes under snow loading. Under load, evergreens with flexible branches become more like solid objects, and snow is held by adhesion on pendant outer surfaces as well as supported on top of branch whorls. In some evergreens, branches are rigid and needles flexible, and adhesion of snow is important if a load is to accumulate. The variety of kinds of snow damage to trees—top break, throw, crushing—suggest the variety of load distributions. Snow damage differs from ice damage, suggesting differences in adhesion as well as weight.

The freezing of a wet flake to cold foliage has been observed during storms, when the problem of interception passes over into that of accumulation of glaze and rime. Refreezing of snow to foliage when weather suddenly gets colder is frequently reported, but only qualitatively.

The methodology of investigating the adhesion of snow to foliage has been non-instrumental, and also sporadic. Analogy between adhesion of snow and rain can be misleading, although in wet snow the concept of wetting coefficient is useful.

Adhesion of snow has been determined in laboratory work, mostly with old snow on plastic or metal surfaces. New snow on foliage should be measured by the same methods. Friction coefficients of several kinds of snow and foliage should be measured by standard methods at different temperatures, to develop experimental relationships. In wind tunnels it would then be possible to test adhesion of snow deposited under various wind impacts on modelled or real foliage.

The freezing of wet snow to cold foliage could be simulated in cold chambers. The heat balances of refreezing situations could be reconstructed, and the strength of the bonds measured.

Extension of laboratory work to the field requires consideration of the slopes of needle surfaces, which might be quantitatively described by methods developed to obtain slope distributions of ocean waves. This information would make it possible to distinguish adhesion of snow to the pendant outer branches of a fir tree from the supporting action of a branch directly beneath the load.

Analogies to adhesion of snow may be found

in wetting of foliage by rain, and in adhesion of rime or glaze icing. Current investigations in these areas should be examined for methods and

results, as soon as enough laboratory work on snow has been done to give a basis for comparisons.

Cohesion of Snow

After the first layer of snow particles has adhered to the foliage, further accumulation is a function of cohesion among particles. Cohesion may represent the toothed interlocking of young dendritic flakes or the sintering that later develops with translocation of vapor or liquid water to form new solid bonds, in response to temperature gradients or wind pumping.

In light winds, vertical piling up of snow requires enough cohesive strength to counter the force of gravity at the angle of repose, and experiments with snow accumulations on boards indicate a steep angle. Dry snow particles cohere by friction, as Kuz'min (1963) notes, especially, according to Wellington (1950), if they are of the crystal, plate, or graupel forms rather than powder. Wellington (1950) and Pruitt (1958) report considerable depths of snow piled up in crowns or Arctic forests, and Pruitt's comments suggest that although crown snow between storms may seldom be deeper than 3 to 5 cm., during storms the depths of low-density snow on spruce in sheltered valleys must be much greater to produce the snowbreak reported.

Maximum depths of fresh snow upon cut branches supported in similar positions above the ground was measured by Lull and Rushmore (1961) as between 10 and 12 cm. on balsam fir, red spruce, and hemlock, and 16 cm. on white pine. Goodell (1959) reports weights of snow caught by a severed tree (a 4.5-m. Engelmann spruce) after one storm that brought 19 cm. of dry cold snow with a water equivalent of about 10 mm., as 16 kg., which adhered so tenaciously "that violent shaking to simulate a strong wind dislodged but one-third of the initial accumulation." Assuming a crown projectional area of 3 sq. m., the load is equivalent to 5 mm. water. I have weighed snow beaten off a young lodgepole pine at the Central Sierra Snow Laboratory as equivalent to 6 mm. water.

Atmospheric Conditions

Shidei (1954) says that "the snow crown of the tree grows large and heavy at night, when the air temperature falls to about 0°C. and the air is calm, with no radiation," and points out that the depth of snow crowns depends on the width of the supporting objects. Each leaf and branch catches a small amount of snow, but the closing of adjacent snow caps increases the base width and allows the depth to become much greater, so that as "the snowfall continues, the crowns of trees become covered with one large and deep snow crown at last." In another Japanese study, the depths of snow crowns on boards in various arrangements were recorded in 47 storms (Japan 1952) when wind speeds were relatively light, averaging 0.6 m/sec. in all the storms. The influence of temperature on cohesion of snow can be examined from the Japanese model and tree experiments. Depth of snow on boards 1, 2, and 4 cm. wide, relative to that on a 16-cm. board, was greater at higher temperatures: at -1°C. it was double that at -3°C. Similarly the catch of wet sawdust, to simulate warm snow, by a tree branch and a board model was twice that of dry sawdust (Japan 1952, p. 151).

Weights of snow on a cryptomeria tree, in percentage of snowfall in the open, at air temperatures ranging from -5°C. to +1°C., were always small at low temperatures, but moderate or heavy at high temperatures. The envelope of points on a graph of air temperature against snow load as a percentage of snowfall is expressed by: $Y = 156.8 + 27.5x$, in which Y is snow load in percentage of snowfall, and x is air temperature, which was below freezing. No storms plot above this enveloping line, and most seem to follow a trend of similar slope expressed as: $Y = 130 + 30x$. While cohesion in some types of snow grows even at low temperatures, it generally increases most

rapidly at temperatures approaching the freezing point. The opposing actions of different metamorphic processes, one destroying the mechanical linking of irregular flakes, the other increasing the sintering or bonding by vapor translocation, are oppositely temperature-dependent, but the latter seems dominant.

Continuous weighing of a snow-laden tree provides case histories of interception in individual storms. In one, for example (Japan 1952, p. 143, fig. 6), when air temperature remained between -3°C . and -4°C . during the whole period, the snow load closely followed the curve of accumulated storm precipitation. In another storm, in which the air temperature, initially slightly above freezing, fell to -1°C ., snow load accumulated rapidly and uniformly. In proportion to snowfall on the ground, it outweighed loads in other storms, reaching 22 kg. in 10 hours. The rate of increase of load, 1 mm. water equivalent per hour, was a large fraction of the rate of snowfall. Most of this increase occurred at night.

Snowfall at night added more to the load on the tree than that by day, as is indicated by a plotting of weights during seven storms on a common time scale (Japan 1952, p. 142, fig. 4). The most rapid accumulation of crown snow occurred after 2000, with peak loads being reached near sunrise. From these graphs, I calculate the average load at 1800 to be 2 kg., and by 2-hour intervals thereafter to be 5, 7, 11 (midnight), 12, 14, 14, 10, 6 (noon), 3, and 1 kg. (1600). The most rapid accumulation was between 2200 and midnight.

Wind accelerates metamorphosis of snow that is suspended in small masses in the airstream, and may cause cohesion to increase, although this effect is difficult to separate from its effect in transporting snow into the crowns and plastering it onto the foliage by impact. Current laboratory and field research on the metamorphosis of snow on the ground, as being done by the U. S. Army Cold Regions Research and Engineering Laboratory, is developing much knowledge about such thermal and mechanical phenomena as bonding of grains, viscous flow, permeability to air, density, and grain-size distribution, that bear on the problem of cohesion and accumulation of snow in large masses and thick coatings on foliage. Results of this research may be directly transferable to future studies of intercepted snow, or, at least transferrable after experiments are made in wind tunnels or other controlled environments

on snow masses of various ages and histories of exposure.

The accumulations of snow measured by Klintsov (1958) after warm gales in Sakhalin were mostly on the windward sides of the small conifers (spruce and pine 7 m. tall), and totaled 6 and 8 mm. water equivalent, respectively, over the crown projectional area. The peak load was greater, since he reports that some snow had slid off before he could knock off the load and weigh it. These values indicate the amount of snow that can be plastered onto a tree under conditions of wind and good cohesion.

Rime droplets mixed with snow particles increase cohesion, since the freezing of the supercooled droplets cements the snow load together more rapidly than cohesive forces develop among solid particles. On the fields of north Finland, these coatings reach great thicknesses, reported by Heikinheimo (1920) in terms from which I calculate a load of as much as 30 mm. water equivalent.

Contradictory reports of heavy interception on windward slopes and on lee wind-shadow slopes suggest that adhesion and cohesion may be large in either high or light winds, presumably depending on wetness and temperature. If snow is sticky, high winds plaster it over a large intercepting surface on the crowns, especially in an open forest or one on a windward slope. If snow does not adhere strongly to the foliage but has appreciable cohesion, light winds and lee slopes allow deposition to reach a great thickness on a small intercepting area.

In general, adhesion and cohesion depend on temperature, with maximum effect just below zero degrees. Layering of the atmosphere, so that cold snow falls into warmer air or wet snow into colder air, produces different kinds of adhesion. Wind beyond some critical speed that depends on snow cohesion extends the intercepting and storing surfaces of tree crowns. The critical wind speed at which deposition is largest depends on meteorological factors other than air movement, and joint action is evident in snowstorms with high winds. If the snow has considerable adhesive strength, as when it is mixed with supercooled droplets of liquid water, or has acquired water films aloft that are supercooled in colder air near the ground, interception loads are increased by stronger winds.

Some of the interrelationships between the effects of temperature and movement of the air

may be summarized in the following statements:

1. In calm, the relation of snow load to temperature is asymmetrically curvilinear, with a maximum at or just above the freezing point.

2. In cold storms, the relation of snow load to wind speed is curvilinear, with a flat maximum at 1 to 2 meters per second. Load decreases rapidly at higher wind speeds.

3. In storms with temperatures just below the freezing point, snow load increases with wind speed up to a fairly high value, particularly on trees that close their crowns under wind pressure or load.

An unsealed pattern developed from these three statements (fig. 1) shows maximum load occurring at low wind speeds and temperatures near freezing, in a distribution that with increasing wind speed slopes toward lower temperature. Away from this zone of maximum load, the gradient is most steep upward with increase in temperature above freezing, and diagonally downward toward cold, windy weather. This pattern represents only the two macroatmospheric parameters of air movement and temperature. It takes no account of micrometeorologic factors within the tree crowns, which are evidenced in the shaping of snow masses illustrated by Salamin (1959), nor of radiative energy exchange. Nor does it consider such biological factors as crown geometry, which affects micrometeorologic forces, or vibration of branches and deformation of trees in the wind.

Crown Conditions

Biological factors that may affect cohesion of snow particles and the snow loads in tree crowns should be mentioned, though few numerical data on their effects are available. Some trees hold snow on sprays of foliage, others on their branches, but the long rivalry between beech and spruce in Central European forestry yielded few data on the question whether foliage or branchwood is more important in intercepting snow. Since the difference between leafless beech and evergreen spruce is confounded with the difference between summer rain and winter snow, careful observations of snow catch over many winters are insufficient to permit us to determine the relative roles of foliage and branches. Every statement in the literature that deciduous trees intercept no snow can be matched by a statement that they intercept considerable amounts.

Flexible leaves hold less snow than rigid ones, but this condition may be confounded with branch flexibility. A pine that has soft needles on stubby branches may hold as much snow as a fir that has stiff needles on drooping branches. Without data on the mechanical properties of each member of the load-bearing structure, we cannot evaluate the relative roles of leaves and branches in interception studies by Buhler (1884) as an implausible idea that less snow is intercepted in big storms, when overloaded branches shed their loads, than in small storms.

Age of trees, which looks like a useful parameter because it is a number, was brought into interception, and cannot prove or disprove the provement on the oversimplified dichotomy forest-versus-open. However, its relevance to interception hinges upon an association with crown coverage that is not consistent. It does not seem to be a good predictor of interception unless combined with such physical dimensions as stem numbers or basal area.

"Species" is a catchall that lumps the roughness, area, and pattern and flexibility of foliage with the size, strength, and structure of branchwood, giving a single term impervious to analytical attack. Differences that are measured between throughfall of snow in stands of different species cannot be definitely ascribed to any single characteristic, because species usually differ with respect to several characteristics rather than one only. Moreover, differences between species are not always found; some pure stands of different species differ less from one another in throughfall than they do from mixed stands made up of the same species. Buhler (1886) identified closure, foliage, and branchwood as factors, but these characteristics have not yet been measured adequately for the analysis of snow loading.

Studies of the ecology of marginal areas, like the Arctic or alpine forest, suggest that interception of snow is an agent of natural selection that favors one tree form, species, or forest pattern over others. On the equatorial margin of the zone of frequent snowfalls, Griffith (1945) reports heavy damage in the New Forest estate at Debra Dun in India to exotic 20-year old trees that had never experienced snow, from a storm with 24-hour precipitation of 0.98-inch water equivalent. Local species were hardly affected. While these ideas suggest that certain mechanisms of interception may be active, the interactions among the mechanisms make it difficult to ascribe a de-

finite role in interception to any one biological characteristic.

Breaking or other damage of trees by snow loads is commonly reported, but often the atmospheric data are too few to permit one to estimate how large the loads were and what their relation was to storm precipitation, wind, and temperature. Spaeth (1941) describes snow break, snow throw, and snow crushing, which differ in origin as a result of different sequences of weather after a snow load is established. Stoeckeler³ says that "the problem of resistance to breakage and uprooting of various tree species is of transcendent importance in practical forest management. It is complex. Involved are type and strength of central stem, rooting habits, crown depth, branch angle, branch length, number of branches per whorl, needle type and quantity. The snow-or-glaze retention capacity is certainly correlated to some extent with crown geometry."

It appears that some of the properties of trees relevant to snowfall interception can be expressed in geometrical terms (roughness, exposed area of branchwood, slope of branches), and others in mechanical terms (flexibility of needles, Rigidity and breaking strength of branches). However, data on these properties are few, and interpretation of snowbreak information to give information about interception is correspondingly difficult. Moreover, break often affects groups of trees, and interpretation requires data on stand density and mutual support among trees.

A snowstorm in Michigan with about 30 mm. water equivalent caused extensive damage, mostly by stem breakage but also by stem bending and uprooting, among 24-year-old recently thinned jack pine plantations (Godman and Olmstead 1962). Unthinned stands were little damaged.

Roe and Stoeckeler (1950), studying effects of a storm in 1947, found least damage in 10-year-old jack pine stands thinned 5 years before, heavy damage in unthinned stands, and worst damage in stands thinned the preceding year and having over-large, misshapen crowns. Reference to *Climatological Data* suggests that this result was brought about by snowfall of less than an inch of water equivalent, and presumably less snow load. Damage was not evenly distributed but

produced patches as large as a quarter acre: "Mortality resulting from snow damage, because of its haphazard nature, cannot be relied upon to correct serious overstocking...On the contrary, it leads to an undesirable stand of patch-wise character" (Roe and Stoeckeler 1950).

A similar mosaic of tree-groups and openings is caused by snowbreak of spruce around edges of small openings in interior Alaska (Pruitt 1958), the openings enlarging to the size at which snow loads are restrained by entry of wind and sun. Fenton (1959) also reports hundreds of 6- to 15-year-old pine saplings going down in patches of a quarter-acre size.

Results of a snowfall of 35 to 45 cm. depth on tended and untended stands in a municipal forest in Switzerland (Grünig 1963) provide a comparison of some 19 species in four age classes, from which Grünig draws silvicultural recommendations, such as the avoidance of vertical edges in the stands. It appears that the thermodynamic role of forest in a snow-covered landscape might in some situations be difficult to reconcile with its survival in snowstorms.

Some species are able to withstand heavy snowloads, perhaps having been improved by selection. Eisen (1892) describes the elimination from snow country of evergreens that do not have sloping branches and upright stems and hence pyramidal form, and Butters (1932) ascribes the spire shape of spruce and fir of the Selkirk Mountains to heavy snowfall, which tends to make the branches short and pendant.

The development of a race of spruce (*Kammfichte*) in lower mountainous regions of Germany (Anon. 1953) is described as natural selection in an area of heavy wet snow. On higher slopes, presumably within storm clouds, where rime and icing are common, the native race (*Plattenfichte*) has sturdy horizontal branches less likely to be torn out by a load that in this climate does not as easily slide off as does wet snow. Hess (1933) describes differences in resistance to damage among races of pines.

Rusanov (1938) says that snow loads on tamarix of central Asia are large enough to reduce the trees to bush form, and cites a saksaul (*Haloxylon*) of 5 m. height broken to less than a meter. Iashina (1960) says that damage in particularly snowy winters is a major factor in forest ecology. This role of snow load in marginal sites may be confounded with the effects of deep spring snow cover on reproduction, but *Heikinheimo*

³Personal correspondence with J. H. Stoeckler, Lake States Forest Experiment Station, U. S. Forest Service, St. Paul, Minn., 1963.

(1920) says that in the zone most subject to damage from accumulation of snow and rime, near the Arctic tree line, 60 percent of the forest is pure spruce or spruce mixed with birch, pine being relatively uncommon; the more frequent the damage from snow loading, the higher the percentage of spruce-birch.

One may wonder whether paleontological distributions have been influenced by snow interception; the rapid northwest movement of spruce after the Pleistocene glaciation may be related to its behavior under snow loads. Much snow-break damage in the wet mountains of Germany

followed replacement of deciduous trees by spruce, often in overstocked monoculture, often by races less resistant to snow loads than to ice.

It should not be hard to determine the mechanical strength of stems and branches under snow loading, and to devise models for testing the loads that can be borne by trees and stands of different ages, species, densities, and crown sizes. The experiences cited suggest that less than an inch of water equivalent may be critical in some circumstances. This figure provides a crude approximation to limiting interception amounts but must vary widely in different sites and climates.

Recent Research on Snow Interception

Two recent papers on snow interception in Japan confirm and amplify some of the conclusions tentatively stated in this report. The long-awaited sequel to the preliminary study on weight of intercepted snow (Japan 1952), from which many basic data were drawn for this report, has recently been published (Watanabe and Ôzeki 1964) and was brought to my attention by G. C. Wilken, Geography Department, University of California, Berkeley. It reported weighing experiments in six winters. In three of the winters extensive measurements were made of snow load (kg.), depth of load (kg./m.²), taking into account the decrease in crown projectional area under load and corresponding to mm. water equivalent, wind speed, air temperature, and dimensions of the crowns—area and depth, and the number, angle, and length of branches. Several trees, supported on scales, stood in a row in the open, exposed to falling snow that generally was warm (temperatures seldom lower than -2°C.) and of moderate density (0.10 on the average, not lower in any storm than 0.06) and in storms of moderate size (median water equivalent of precipitation about 20 mm.) The amounts of snow intercepted were, perhaps, larger than would be observed in a forest stand or in less favorable atmospheric conditions.

Trials compared two varieties of *Cryptomeria japonica* D. Don that have become differentiated in the Toyama Prefecture and the snowier Niigata Prefecture, an area exposed to frequent snowfalls in polar air streaming across the warm Sea of

Japan. The trials also included trees of five ages, and trees subjected to silvicultural treatment in which crowns were shortened or thinned of intermediate branches. Weights of snow loads were associated with these biological and silvicultural differences but, more important, Watanabe and Ôzeki reported dimensions of the tree crowns that were directly and physically related to snow load. For example, the medians of maximum loads per unit crown area in 12 storms were 8, 10, 10.5, 9.5, and 10 mm. in crowns of the *kumasugi* variety of *Cryptomeria* of ages 10, 24, 32, 43, and 57 years, respectively; the largest load was held by the 32-year-old tree at culmination of growth. Moreover, measurements of total length of branches made possible a more direct association. These lengths were 52, 56, 86, 48, and 54 meters, respectively (all crowns had the same depth, 4.8 m.), and can replace age as a parameter in snowfall interception to form a more relevant relation.

Similarly, the two varieties of *Cryptomeria* differed in their mechanical properties in ways that could not only be seen but also quantitatively expressed as crown deformation under load. *Bokasugi*, the variety from the less snowy region, Toyama Prefecture, carried its branches, unloaded, at an angle of 53° from the vertical; when loaded, they bent only slightly, to 77° at 7 mm. load and 96° at 14 mm. This difference increased the crown projectional area and hence the total weight of snow supported. In 90 measurements the median load on *bokasugi*, 8 mm.

over the crown area, averaged 3 mm. larger than the median load on *kumasugi*, the variety native to snowy Niigata Prefecture. *Kumasugi* branches, unloaded, formed an angle of 76° from the vertical. When loaded by more than 3 mm. of snow water, they bent below the horizontal; at a load of 11 mm., their angle was 110 ° to 120°. The crown projectional area was decreased by as much as a third.

Snow load on these two varieties of *Cryptomaria japonica* measured as the maxima in each of 11 storms one winter, were much larger on the stiff, spreading branches of the *bokasugi* (median = 16 mm.) than on the drooping branches of the *kumasugi* (median = 10 mm.); measurements other than when the maxima were reached displayed differences of 3 to 4 mm., and much of this can be ascribed to differences in branch angle.

Four silvicultural treatments of crowns of 30-year-old *kumasugi* trees were applied to investigate means of reducing snowbreak damage. Crowns were shortened by pruning their lower branches, or were thinned out by removing branches all through them. Both treatments were carried out so as to reduce crown depth (4.8 m. in the control tree) or number of branches (100 in the control tree, totalling 84 m. in length), by one third and by one half. The treatments also reduced crown projectional area (5.7 sq. m. in the control tree) by removing the longer branches, and therefore reduced crown volume. The total weight of intercepted snow on individual crowns, expressed as the median of peak values in 11 storms, was reduced from 55 kg: on the control tree to 20 kg. on the 1/3-shortened crown and 14 kg. on the 1/2-shortened crown, to 35 kg. on the 1/3-thinned-out crown and 25 kg. on the 1/2-thinned-out crown. Snow load was reduced proportionately to the decreased volume of the shortened crowns (my estimates), but was reduced still more in the crowns that had been thinned

out. This reduction suggested that the absence of branches within the crown curtailed the opportunity to hold snow. Watanabe and Ozeki also found that the weight of intercepted snow was reduced in proportion to the decreased branch length in the thinned-out crowns, but more than proportionately in the shortened crowns. Branches of the shortened crowns, which were perhaps smaller in diameter because they were in the upper part of the crowns, supported thinner deposits of snow than did the average branch in the control tree.

Hydrologically significant is the effect of treatment on the mean water equivalent of intercepted snow over the projected area of the crowns. On the control tree, the water equivalent of the intercepted snow, as the median of peak values in 11 storms, was 10 mm. This value was reduced about 30 percent by shortening the crowns, and about 20 percent by thinning branches out of them; the medians of peak water equivalents of snow in the treated crowns varied between 6 and 8 mm.

A silvicultural study of snow damage (Sugiyama and Saeki 1963) in the Hokuriku District in a storm of 100-mm. precipitation showed little damage at elevations above 300 m. (where temperature would have been lower than -3°C.) and little on windward slopes. Damage in conifer plantations was severe on lee slopes, and in the analogous situation of openings in forest. Windward edges of forest, like windward slopes, incurred little damage. Damage to different species depended on "the crown form and its inner constitution"—characteristics that, so stated, do not have much practical value. But if crown characteristics are identified and measured, as Watanabe and Ôzeki did in recording crown depth and area, branch length and angle, and weights of intercepted snow, then characteristics of tree crowns can be directly related to the processes of interception.

Promising Leads for Studies

From diverse sources we can glean some information on delivery of snow to forests, its impact on foliage, and adhesion and cohesion during snowstorms—the processes that form snow loads of hydrologic and silvicultural significance. This

information shows many gaps in our knowledge of these processes. The techniques needed to bridge these gaps in knowledge can, however, be drawn from many disciplines.

Research is required on the environmental

framework in which these physical processes take place. The forest part of the environment is in need of systematic description, so that numerical expression of its attributes can be used by the laboratory experimenter to build a model that realistically simulates natural phenomena. These expressions would include such measurements as biomass in cubic centimeters or grams per square centimeters of crown projectional area, surface area of foliage, crown depth and volume, and branchwood networks of various diameters. They are more necessary in a geophysical problem than the conventional indexes of closure, or stocking, developed for other purposes and deficient in physical interpretation. Branch pattern and crown structure are attributes that need expression; methods of characterizing dendritic stream patterns in erosional terrain may, perhaps, be useful.

Mechanical strength and flexibility of foliage, twigs, and branches should be determinable by standard analysis. Besides aiding interpretation of snow loading data, such information will be useful in studying vibration or deformation of crowns under wind stress. Reduction in crown size by compression under wind pressure should be measured. Some attributes usually associated with species may be subject to measurement under standard conditions in a wind tunnel, and to standard mechanical tests of strength in compression, bending, and torsion.

The crown space of a forest or tree group can be regarded as a porous medium through which air, radiation, vapor, and snow particles flow. By analogy to general experiments with flow in porous media, such a system of pores can be characterized by certain coefficients of dispersion. Interstices and other openings, natural or cultural, among tree stands form a complex mosaic landscape, whose structures and edges influence the distribution of the moving airstream and its contained particles. Interception processes studied in crowns of single trees and tree groups can be extended to whole drainage basins if there is some means of quantifying this forest-and-openings mosaic. Research in quantitative ecology and geography may also provide techniques in which the concept of edge as a distinctive situation is taken into account.

The atmospheric part of the environmental framework in which interception processes occur is characterized by complex turbulent motion. Eddies of many sizes transport snow particles

and determine their rate of delivery, motion, and impaction on the forest elements.

Research on aerosol diffusion should be applicable to research on suspended snow particles. Large-scale air movement sets in operation a complex pattern of micrometeorological flows within the crown space, and it will be necessary to see how well current turbulence theory applies to this situation. Exploratory work with many small sensors in and above crowns of forest of reproducible dimensions should be carried out to define fundamental aerodynamic characteristics of the wind field that affect delivery and impaction of snow particles. The heterogeneity of the crown zone requires intensive spatial sampling of the field of motion, but means are now at hand for mass sampling and analyzing of data. Photographic observations, as reported by Kuz'min (1963), may be helpful in exploratory phases of the work.

Relatively short runs in controlled environments may be sufficient to outline major aerodynamic factors in the interception processes, and a few selected periods in the field, under typical synoptic conditions, may be sufficient for analysis. The more that can be done in controlled environments, the shorter need be the outdoor experiment. Adhesion and cohesion of snow particles to foliage and previously deposited snow should not be difficult to determine in the laboratory, to delimit the relative significance of such factors as air temperature, wind speed, and snowflake type.

Controlled conditions will permit comparison of foliage roughness and flexibility, and branch flexibility and strength in providing a base for adhering snow and supporting snow loads. Extreme snow loads can be applied in the laboratory, to determine breaking points and load distribution.

Field measurements of weight of trees bearing snow loads should follow the example of the thorough Japanese research, though with an improved site and more measurements of environmental conditions and of such characteristics of the snowload as area of adherence, thickness, and location. Exterior and interior locations can be compared; pendent branches versus horizontal support; load in the upper crown versus that in the lower branches; density and wetness of the snow itself.

The field sample can be expanded by shaking or melting snow off a number of trees onto plastic films for weighing, at the time of maximum load during a storm. This technique does not give the

progression of load size during a storm in response to meteorologic conditions that is obtainable by continuous weighing, but it would extend information on biological factors. Some field work as a kind of unstructured exploration of the problem and a means of getting crude data can be done while laboratory and other controlled-environment experiments are going on, as a means of assuring the eventual transferability of labor-

atory data to field sites.

The transfer of the principal investigation from the laboratory to the tree *in situ* depends on adequate information on micrometeorological conditions in both laboratory and open. Such information will also make possible the effective application of current research findings from aerodynamics and from other areas of micrometeorology to the interception problem.

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