INTERCEPTION AND REDISTRIBUTION OF SNOW IN A SUBALPINE FOREST ON A STORM-BY-STORM BASIS

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INTRODUCTION

Many studies have shown that there is an unequal distribution of snow in subalpine watersheds that have been partially clearcut. The clearcuts often accumulate 30% to 40% more snow than the surrounding forest. The effect of clearcuts on snow accumulation is well documented; however, the cause of the unequal distribution of snow is not well understood.

Two hypotheses are often used to explain the increased snow accumulation in clearings: 1) The unequal distribution is a result of decreased interception losses (interception savings). By clearcutting, snow that would have been caught by the canopy and sublimated is deposited in the clearing. 2) The unequal distribution of snow is a result of the effect of clearcutting on the aerodynamics of the forest. This allows small clearings to capture wind transported snow, either during or after the storm.

This study is designed to determine if the increase in snow accumulation can be attributed to the effects of the clearing on the aerodynamics of the forest. This hypothesis will be tested in two ways:

1) Can the captured wind transported snow during storms account for the increased snow accumulation?

2) Can redistribution of intercepted snow between storms account for the increased snow accumulation?

Answering these questions should help determine if the aerodynamic changes produced by small clearcuts are the primary cause of the increased snow accumulation.

PREVIOUS RESEARCH

Increased streamflow from partially clearcut subalpine watersheds is well documented (Bates and Henry, 1928; Hoover and Leaf, 1967; Troendle, 1982; Troendle and King, 1985). However, the processes that produce these larger streamflows are not well understood. The differential accumulation of snow on the treated watershed appears to play an important role in increasing streamflow. Small clearings average between 30% and 40% more snow water equivalences (SWE) than the surrounding forest (Wilm and Dunford, 1948; Hoover and Leaf, 1967; Gary, 1980; Swanson and Golding, 1982; Troendle and Meiman, 1984; Golding and Swanson, 1986; Troendle and Meiman, 1986).

The hypothesis that wind transported snow is being caught by the clearing is supported by two lines of evidence. First, is the finding that the total snowpack water equivalence for the entire watershed does not increase following timber harvesting (Hoover and Leaf,1967; Swanson and Golding, 1982; Troendle, 1982). Second, is the finding that there are large decreases in the SWE in the downwind forest (Anderson and Gleason, 1959; Gary, 1980). This suggests that wind transported snow is caught or "stolen" by the clearing at the expense of the downwind forest.

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An earlier study postulated that redistribution of intercepted snow was responsible for the unequal snow distribution. This was based on photographs taken at regular intervals throughout the winter showing snow being blown out of the canopy (Hoover and Leaf, 1967).

Recent studies at the Fraser Experimental Forest have suggested that the increased accumulation in clearings is not solely a result of the aerodynamic changes. At Short Creek, measurements of snow distribution showed only minor decreases in the SWE downwind from the clearing (Troendle and Meiman, 1986). Two separate studies have shown that very little intercepted snow is redistributed into the clearing between storm events (Troendle and Meiman, 1984; Troendle and Meiman, 1986).

STUDY AREA

This study was conducted at the Fraser Experimental Forest, south of Fraser, Colorado. The study site is a small clearcut, 76m wide (3.6H) by 110m long (5.2H), with the long axis perpendicular to prevailing winds. It is located in the Short Creek drainage, northeast of Byers Peak. The predominate wind direction (west to east), uniform canopy, and long undisturbed upwind fetch make this site ideal for snow transport studies. The elevation of the study plot is 2800 m (9,186 ft) and is situated on a steep (35%), north facing slope. The forest is composed of Engelmann spruce, subalpine fir, and lodgepole pine. The forest has an average canopy height of 21 m (Troendle and Meiman, 1986). Regeneration of all three conifers underneath the canopy has created a multistory stand allowing interception at all levels in the forest.

SAMPLING

This experiment measured snow accumulation in the clearcut and the surrounding forest. To measure snow accumulation, snowboards (30 cm x 60 cm) were systematically placed in the clearcut and in the upwind and downwind forest. The SWE was measured on every snowboard immediately following each snow storm and then again, if needed, after the canopy cleared. This allowed the comparison of snow accumulation on a storm-by-storm basis. The average windspeed was also calculated for each storm using an anemometer placed in the center of the opening, 21 m above the ground.

The snowboards were placed at regularly spaced intervals on a grid system which consisted of five east-west traverses. These traverses started in the downwind forest and continued through the opening and into the upwind forest (Figure 1). The distance between snowboards depended on the number of samples taken in each plot. The downwind snowboards were moved into the clearing and upwind plots when no decrease in snow accumulation was found in the downwind forest.

Since snow accumulation in the forest may be partially dependent on the overlying canopy, the snowboards in the forest were moved 66 cm upwind after each measurement. This ensured that the treewells, doghair stands of lodgepole pine, and the more open areas under the canopy were all sampled adequately. If a tree trunk was located where the sample should have been taken, the sample was given a value of 0.0 g cm^{-2}.

In the clearing there is no overlying canopy to affect snow accumulation. Therefore, snowboards in the clearing were measured and replaced on the same spot. The surrounding snow surface was then smoothed to decrease surface roughness and approximate the undisturbed snow surface.

SNOW MEASUREMENTS

The SWE was measured on each snowboard using a cylindrical carton with a known mass and cross-sectional area. The carton was inverted and pushed onto the board like a cookie cutter. Flipping the board permitted the snow to fall back into the carton. After collecting all of the samples, the cartons were weighed using an electronic balance. The balance was calibrated to 0.1 g and optically interpolated to 0.01 g.

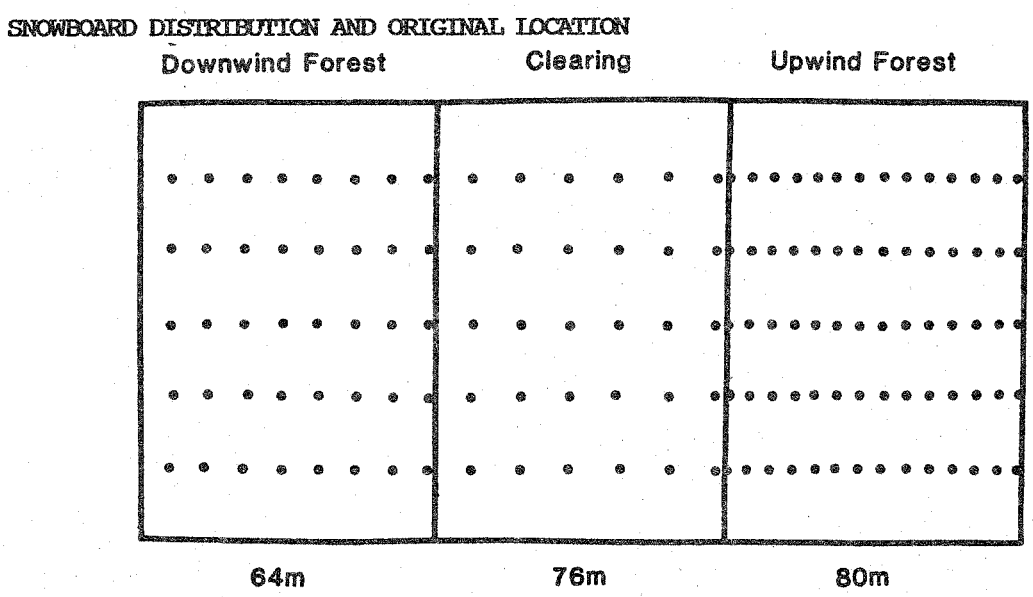

Figure 1 The sampling grid, dots indicate the original distribution of the snowboards. The snowboards in the forest were moved 66 cm upwind (west) after each storm.

METHODS

Snow Accumulation During Storm Events

The first experiment was designed to determine if the clearing captured wind transported snow during storms. Two tests were used to investigate this hypothesis.

The first test compared the mean SWE in the upwind and downwind forest during seven separate storm events. The mean SWE was compared for each storm using Analysis of Variance (ANOVA). If wind transported snow is captured by the clearing, there should be a decrease in snow accumulation in the downwind forest when compared to the upwind forest. Decreased SWE in the downwind forest could explain part, if not all, of the increased SWE in the clearing.

The second test compared the percent difference between the SWE in the clearing and the upwind forest ($\text{MEAN SWE}_{clearing} - \text{MEAN SWE}_{upwind} / \text{MEAN SWE}_{upwind}$) with the average windspeed for each storm. As windspeeds increase so does the wind's ability to transport snow. If the clearing is capturing wind transported snow, then intuitively one would expect the percent difference to increase with increasing wind velocities, because of the greater amount of snow available for capture.

Snow Accumulation Between Storm Events

The second experiment was designed to measure the amount of intercepted snow blown out of the canopy and redistributed into the clearing between storms. Earlier work had postulated that the redistribution of the intercepted snow could account for the increased accumulation in the clearing.

Interception is defined as the precipitation that is caught in the vegetation. Interception loss is the amount intercepted that is evaporated, sublimated, or otherwise lost. This study assumed the net difference between the initial snow accumulation in the clearing and the upwind forest was "intercepted snow", and attempted to determine the final disposition of that snow. Was it redistributed into the clearing or under the canopy (throughfall), or was it sublimated and an actual loss to the hydrologic system.

Redistribution of intercepted snow can occur anytime during a storm period. The storm periods were the entire duration that the canopy contained snow. Some storm periods contained inter-storm breaks between individual storms. These were periods during which snow was not falling, but intercepted snow was in the canopy and available for redistribution.

To determine the amount of snow that was redistributed, the SWE was measured on each snowboard immediately after every storm and the board was cleared. If snow accumulated on the snowboards during the inter-storm breaks, the boards were remeasured before the next storm started. Likewise, if any snow was redistributed after the storm ended the boards were remeasured when the canopy cleared. Because redistribution of intercepted snow may be partially dependent on windspeed, the average windspeed was calculated for the inter-storm break or the first 24 hours following each storm.

RESULTS

Snow Accumulation During Storm Events

The average windspeed and mean SWE for the seven storms in which measurements were taken in the downwind forest are shown in Table 1. The seven storms represent a wide range of wind velocities from 0.8 m s^{-1} to 11.8 m s^{-1}.

Analysis of Variance was used to compare the mean SWE in the upwind and downwind forests. The null hypothesis in each test was that there is no difference in the means (H_o: $X_1 = X_2$). The alternative hypothesis was that the means are different (H_a: $X_1 \neq X_2$). The null hypothesis was not rejected, there was no significant difference ($p = 0.05$) in the mean SWE between the upwind and downwind forest for the seven storms.

Table 1
The average SWE for the upwind and downwind forest and average wind velocity for seven storms.

STORM	UPWIND SWE MEAN (g cm^{-2})	UPWIND SWE S.E. (g cm^{-2})	DOWNWIND SWE MEAN (g cm^{-2})	DOWNWIND SWE S.E. (g cm^{-2})	DIFFERENCE FROM UPWIND (g cm^{-2})	AVERAGE VELOCITY (m s^{-1})	
3B	0.20	0.008	0.19	0.009	0.01	0.8	
3F	0.04	0.001	0.04	0.002	0.00	1.7	**
2A	0.58	0.022	0.65	0.042	-0.07	2.2	*
3A	0.09	0.004	0.10	0.005	-0.01	2.9	
1A	0.21	0.006	0.20	0.035	0.01	4.5	*
3G	0.46	0.012	0.48	0.028	-0.02	8.9	
3H	1.23	0.297	1.12	0.032	0.11	11.8	

* estimate
** averaged from a single maximum and minimum value

The second test attempted to correlate the average wind velocity with the percent difference between the upwind forest and the clearing. Table 2 shows the mean SWE found in the upwind forest and the clearing, and the average wind velocity for each storm. The regression of all storms with greater than 0.10 g cm^{-2} SWE in the upwind forest (Figure 2) has a correlation coefficient (r) of -0.74 ($p = 0.002$). The small storms were eliminated from this data set because of the relative magnitude of measurement error when compared to the total SWE (see Discussion). This data set includes storm 7A, during which the average windspeed was underestimated due to heavy snow accumulation on the anemometer cups.

Snow Accumulation Between Storm Events

Table 3 shows the original distribution of snow. Redistribution or throughfall of intercepted snow could have occurred after any one of the 21 storms. Yet, redistribution occurred only once, after storm 4A; this storm had the highest average and peak windspeeds for the inter-storm period (Table 4).

Table 2
The average SWE and windspeeds for each storm.

	UPWIND SWE g cm^{-2}	CLEARING SWE g cm^{-2}	PERCENT DIFFERENCE	AVERAGE WINDSPEED (m s^{-1})
STORM 1A	0.21	0.36	71%	4 *
STORM 2A	0.58	1.09	88%	2 *
STORM 3A	0.09	0.21	133%	2.9
STORM 3B	0.20	0.34	70%	0.8
STORM 3C	0.06	0.10	66%	1.8**
STORM 3D	0.17	0.32	88%	0.9**
STORM 3E	0.09	0.16	78%	3.1**
STORM 3F	0.04	0.08	100%	1.8**
STORM 3G	0.46	0.53	15%	8.9
STORM 3H	1.23	1.54	25%	11.8
STORM 3I	1.67	2.10	26%	11.1
STORM 4A	2.87	4.01	40%	5.8
STORM 5A	0.15	0.21	40%	12.4
STORM 6A	0.22	0.40	82%	1.7
STORM 6B	0.23	0.37	61%	3.8
STORM 6C	0.22	0.34	55%	5.9
STORM 6D	0.22	0.35	59%	4.3
STORM 6E	0.07	0.12	71%	1.7
STORM 6F	0.09	0.16	78%	8.9
STORM 6G	0.61	1.10	80%	7.4
STORM 7A	3.25	4.69	44%	1.7***

* estimate
** averaged from a single maximum and minimum value
*** possible error

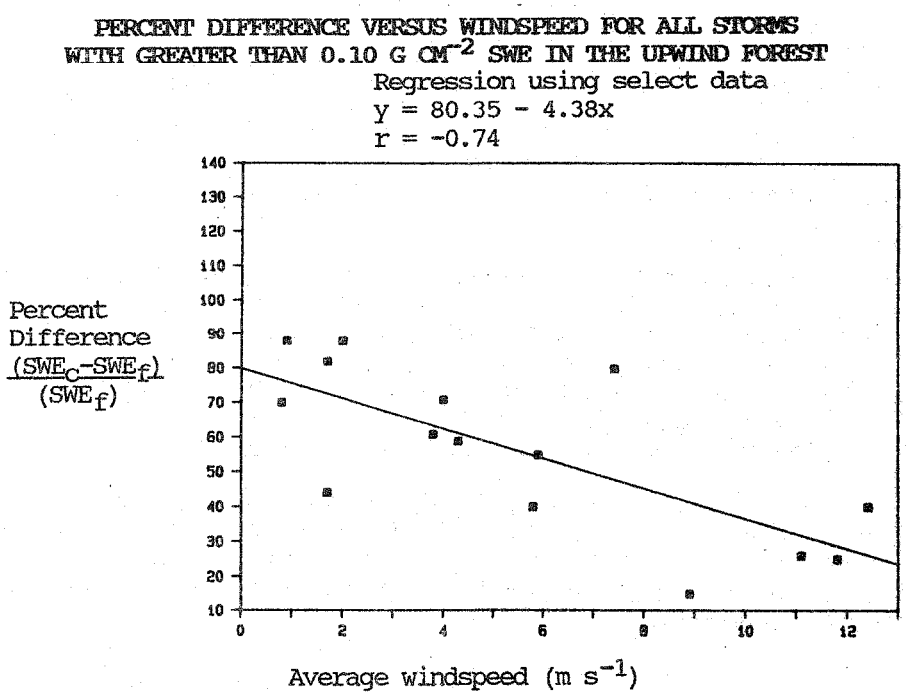

Figure 2 The regression of percent difference versus average windspeed using only storms with SWE greater than 0.10 g cm^{-2} in the upwind forest.

Redistribution accounted for 2% of the snow accumulation in the clearing, and throughfall accounted for 3% of the snow accumulation in the forest. There was a 31% net difference between the snow accumulation in the upwind forest and the clearing. Throughfall and redistribution accounted for 7% of the net difference; the remainder was missing and apparently sublimated.

Table 3
The average SWE and the net difference between the upwind forest and the clearing.

	SWE IN UPWIND $g\ cm^{-2}$		SWE IN CLEARING $g\ cm^{-2}$		NET DIFFERENCE $g\ cm^{-2}$	
STORM	MEAN	S.E.	MEAN	S.E.	MEAN	S.E.
1A	0.21	0.006	0.36	0.031	0.15	0.015
2A	0.58	0.022	1.09	0.033	0.51	0.028
3A	0.09	0.004	0.21	0.004	0.12	0.004
3B	0.20	0.008	0.34	0.002	0.14	0.008
3C	0.06	0.003	0.10	0.000	0.04	0.003
3D	0.17	0.009	0.32	0.002	0.15	0.009
3E	0.09	0.004	0.16	0.004	0.07	0.004
3F	0.04	0.001	0.08	0.002	0.04	0.002
3G	0.46	0.012	0.53	0.018	0.07	0.015
3H	1.23	0.039	1.54	0.037	0.31	0.043
3I	1.67	0.033	2.10	0.044	0.43	0.039
4A	2.87	0.083	4.01	0.066	1.14	0.089
5A	0.15	0.005	0.21	0.019	0.06	0.010
6A	0.22	0.009	0.40	0.002	0.18	0.009
6B	0.23	0.010	0.37	0.003	0.14	0.010
6C	0.22	0.009	0.34	0.002	0.12	0.009
6D	0.22	0.007	0.35	0.003	0.13	0.007
6E	0.07	0.002	0.12	0.002	0.05	0.002
6F	0.09	0.003	0.16	0.002	0.07	0.003
6G	0.61	0.017	1.10	0.014	0.49	0.018
7A	3.25	0.111	4.69	0.019	1.44	0.111

DISCUSSION AND INTERPRETATION

An important assumption of the aerodynamic theories is that wind transported snow is captured by the clearing at the expense of the surrounding (downwind) forest. If this is true, then a difference in snow accumulation between the upwind and downwind plots should be evident.

Snow accumulation was measured in the upwind and downwind forest during seven storms (Table 1). Storm 3H had the highest average windspeed. This storm also had the largest difference (decrease) in the mean SWE in the downwind forest (0.11 $g\ cm^{-2}$), although it was not significantly different ($p = 0.05$) from the upwind forest. None of the storms showed a significant decrease in the mean SWE in the downwind forest. These results agree with an earlier study done on the same plot (Troendle and Meiman, 1986), which showed the accumulation in the downwind plot had not changed relative to the upwind plot.

The results of the second test show a strong negative correlation between the percent difference and windspeed (Figure 2). An earlier study which tried to correlate windspeed and the resulting accumulation at the Fraser Experimental Forest found no apparent correlation (Troendle and Meiman, 1984), but in that study windspeed was measured at a site 4 km away and 300 m higher in elevation.

Table 4
Summary of the snow available for redistribution and the actual amounts redistributed.

	NET DIFFERENCE $g\ cm^{-2}$	SWE REDIST. $g\ cm^{-2}$	SWE THRUFALL $g\ cm^{-2}$	POST-MEASUREMENT WINDSPEED ($m\ s^{-1}$) AVE	MAX
STORM 1A	0.15	----	----	NA	NA
STORM 2A	0.51	----	----	NA	NA
STORM 3A	0.12	----	----	0.6	3.6
STORM 3B	0.26	----	----	NA	NA
STORM 3C	0.30	----	----	NA	NA
STORM 3D	0.45	----	----	NA	NA
STORM 3E	0.52	----	----	NA	NA
STORM 3F	0.56	----	----	NA	NA
STORM 3G	0.52	----	----	5.1	15.6
STORM 3H	0.73	----	----	9.7	22.8
STORM 3I	1.09	----	----	NA	NA
STORM 4A	1.14	0.34	0.41	10.5	37.5
STORM 5A	0.06	----	----	6.4	17.9
STORM 6A	0.18	----	----	7.9	19.2
STORM 6B	0.28	----	----	5.6	12.1
STORM 6C	0.40	----	----	3.4	20.6
STORM 6D	0.33	----	----	4.1	13.0
STORM 6E	0.38	----	----	8.1	20.1
STORM 6F	0.45	----	----	7.3	16.5
STORM 6G	0.76	----	----	4.0	25.9
STORM 7A	1.44	----	----	5.0	21.9

Eliminating the small storms in the regression of percent difference versus windspeed increased the correlation coefficient from -0.63 to -0.74. In this study the measurement error from the optical interpolation of the electronic balance was of the same magnitude as the SWE of the small storms. Measurement errors in the small storms could result in large changes in the percent difference. Therefore, eliminating small storms in the regression of percent difference versus windspeed was reasonable.

The negative correlation in Figure 2 implies that, as the wind velocities rise, the snow accumulation in the forest increases relative to the snow accumulation in the clearing. This may result from the wind mechanically shaking the canopy. This could decrease interception while not supplying enough energy to transport the snow out of the forest and into the clearing. The result would be a greater accumulation under the canopy with increasing windspeeds.

The conclusions that can be drawn about the effects of windspeed on snow accumulation during storms are important but not conclusive. It is possible that snow is captured only at low windspeeds, and as wind increases, the processes that capture snow are less effective. However, without a decrease in snow accumulation in the downwind forest it seems unlikely that the capture of wind transported snow during storms is the primary cause of the increased accumulation in clearings.

Redistribution of intercepted snow has been used to explain the increased accumulation in small clearings. In this study, redistribution occurred only once (Table 4) and accounted for 2% of the accumulation. The redistribution event occurred during the post-storm period with the highest average and highest maximum windspeed. High wind velocities (average or peak) may be an important factor in the redistribution of intercepted snow. However, other factors may also influence redistribution. These include the density and volume of the intercepted snow, the energy received by the snow, and the length of time the snow has been in the canopy.

Visual observations suggest that strong winds can readily transport fresh snow out of the canopy. However, snow that remained in the trees for 24 to 36 hours formed large platforms or blocks. These platforms were very stable and not easily dislodged. This stability may result from metamorphic changes that increase the cohesive strength of the snow.

Large blocks of intercepted snow were occasionally dislodged from the canopy by strong winds. These large blocks immediately broke into many small pieces. Small impact marks on the snow surface showed that some of the small particles were deposited in the underlying forest between storms. There was no measurable accumulation from these small particles except after storm 4A.

During the redistribution event, 50% of the canopy had cleared within 24 hours of storm 4A. The average windspeed during this time was 10.5 m s^{-1} with gusts over 37 m s^{-1}. Two small squalls moved through the area before the redistributed snow was measured. They deposited a small but undetermined amount of water, probably less than 0.10 g cm^{-2}. These two squalls were notseparated from the redistribution event, leading to some unmeasured error in the amount of snow that was redistributed.

Intercepted snow was visible in the canopy after every storm. Even after the storms with the highest average windspeeds (3H, 3I, and 5A) the canopy contained substantial amounts of snow. This helps validate the assumption that the difference between the snow accumulation in the forest and the clearing is intercepted by the canopy. This assumption should be valid for storms with very low wind velocities, but may lead to some error in the amount of snow assumed to be intercepted for storms with higher wind velocities.

This study found a 31% difference between the snow accumulation in the upwind forest and the clearing. This was assumed to be intercepted. Redistribution of the intercepted snow had little effect on the total snowpack accumulation accounting for only 2% of the accumulation in the clearing.

A study in northern Idaho that measured interception on a storm-by-storm basis found one third of the falling snow was intercepted, and approximately 80% of the intercepted snow ultimately reached the ground as throughfall (Satterlund and Haupt, 1970). In the present study, only 7% of the intercepted snow reached the ground as throughfall. This sharp contrast may be due to the differences in climate between the two study sites. A large portion of the throughfall in the Idaho study resulted from rain washing the snow out of the canopy.

The almost total lack of redistribution and throughfall of intercepted snow suggests that intercepted snow was sublimated and, therefore, unavailable for streamflow. This study suggests that reducing interception would allow more snow to be deposited in the opening. Whether this increase is real or if it is offset by increased evaporation in the opening needs further study.

SUMMARY AND CONCLUSIONS

Two hypotheses have been postulated to explain the increased accumulation of snow in clearings:

1) Aerodynamic changes from clearcutting results in the unequal distribution of snow either during or between storms (aerodynamic effect).

2) Reduced interception results in more snow being deposited in clearings (interception savings).

Many studies of the snow accumulation in small openings have measured the snow at specified intervals or at peak accumulation. This experiment measured the difference in accumulation on a storm-by-storm basis. The measurement of snow distribution and windspeed on a storm-by-storm basis helped define the processes leading to increased accumulation in small clearings.

The capture of wind transported snow was not the primary process responsible for the increased snow accumulation in the clearing. The evidence that supports this conclusion is:

1) There was no significant difference ($p = 0.05$) between the mean SWE in the upwind and downwind forest.

2) The accumulation of snow in the clearing decreased relative to the accumulation in the upwind forest as wind velocity increased.

3) Measurable redistribution of intercepted snow occurred once, the remainder was presumably sublimated.

4) Redistribution of intercepted snow accounted for only 2% of the snowpack in the clearing.

These observations suggest that the effects of wind on the original distribution of snow needs further evaluation. Furthermore, redistribution of intercepted snow between storms was not an important process in increasing the accumulation in the clearing.

It should be noted that this study was conducted in a narrow and fairly well defined climatic setting. The processes could change with different exposure, forest types, and meteorological conditions. The results may well be site specific. At other sites the aerodynamic changes caused by the opening could have more of an influence on snow accumulation in the clearing.

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