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ON THE ACCUMULATION AND THE DECREASING OF SNOW IN PINE DOMINATED FOREST IN FINLAND

BY

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PREFACE

In my duties at the Hydrological Office is included the estimation of the amount of snow on drainage areas. This estimation is based on the results of measurements of snow in different types of terrain.

In dealing with the results of measurement in forest for the above mentioned purpose, I have observed that many factors remain uninvestigated even though a great deal of research work has been carried out in Finland concerning snow conditions in forest. I have, therefore, tried to clear up some of the aforementioned problems.

My investigations have mainly concerned the accumulation and decreasing of snow in pine dominated forest in Finland. As the elevation and the unevenness of terrain have their own effect on both the accumulation and the decreasing of snow, I have limited my investigation to snow cover on level ground only.

Consideration shown my investigation by Imatran Voima Oy. and Oulujoki Oy. has greatly expediated my work. To these water power companies, which have also supplied the funds for the operation of Juuka and Pyhäkoski snow stations, I express my greatest gratitude.

I also express my thanks to the Delegation of Sohlberg of the Societas Scientiarum Fennica which has given its economical support to my investigation.

I am greatly indebted to Dr. H. Simojoki, for providing me with invaluable advice and suggestions concerning this paper.

To the assistants who have handled the observation material, Miss Ruth Rask, Mrs. Berit Winquist, and Mrs. Ethel Yli-Pohja, the last who has also carried out the translation work of this paper and the proofreading, I express my best thanks.

I wish to thank Mr. Arthur M. Pearson for kindly correcting the English of my manuscript.

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Helsinki, January, 1961.

M. Seppänen

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INTRODUCTION

The main theme of this investigation is concerned with the accumulation and the decreasing of snow cover in the pine dominated forest of Finland.

When estimating the average water equivalent of the snow cover of drainage areas, the data concerning the snow cover in pine dominated forests becomes especially important as about 40 per cent of the whole area of Finland is covered with such an association.

The forest density on the measuring sites of the snow stations is, in general, not the same as the local average. At some snow stations observations have been carried out in thin forest, in others in dense forest. In such cases one has to estimate the magnitude of the water equivalent of snow in forest with a density corresponding to the local average. This estimation involves many variables and becomes both complicated and difficult. It has thus become necessary to obtain further knowledge of the dependency of the accumulation and decreasing of snow on the density of the forest.

Even in the same forest stand the accumulation and the decreasing of snow may vary. Each tree and tree group has an influence of its own in this respect. If from a particular forest stand a minimum number of observations are available, the average amount of snow of the stand calculated from these observations may be, particularly during the time of snow melting, dependent on the selection of observation site. It is therefore justified to make additional investigations in order to clarify this matter.

In this investigation the influence of uneven ground on the snow cover has not been considered. Only such cases are analysed where the ground is level.

The problem with which this investigation is mainly concerned can be briefly stated as follows:

> How does the accumulation and the decreasing
> of snow depend on the density of the forest
> and the position of the trees?

The accumulation and the decreasing of snow in the forests of Finland has been investigated earlier. SUNDELL (1898) compared the depth of snow in forest and in open areas. KORHONEN (1915, 1918, 1923, 1927, 1936) studied the accumulation and the decreasing of snow in different types of terrain including coniferous forest. KERÄNEN (1920, 1923, 1943) studied the temperature inside the snow pack and at different depths of soil, and in conjunction with this he also analysed the snow cover in forest. AALTONEN (1919) measured the depth, the density and the water equivalent of snow. He also recorded the temperature of different layers of snow in pine dominated forest in the Finnish Lapland. AIRAKSINEN (1919) made observations on the effect of trees on melting of snow. HEIKINHEIMO (1920) studied the occurrences of snow damage in forests and the dependency of the amount of snow on the elevation of the terrain. SIRÉN, A. (1936) compared the amounts of snow in forest and open areas. KAITERA (1939, 1949) studied the accumulation and the decreasing of snow in different types of terrain and in forests of different density. SIMOJOKI (1947) investigated the timing of the beginning and end of the permanent snow cover in forest and open areas. TEIVAINEN (1952) studied the distribution and the amount of snow in arctic mountain terrain and the influence of the forest density on the accumulation of snow in pine stands. SIRÉN, G. (1955) carried out snow measurements in spruce dominated forest using fixed measuring stakes. YLI-VAKKURI (1960) also used fixed measuring stakes in studies concerning snow cover in forests. His studies also refer to pine dominated forests.

The purpose of my investigation has been to obtain additional knowledge on many problems concerning the accumulation and the decreasing of snow in pine dominated forest, which have not or have been scantily investigated.

SNOW STATIONS AND METHODS OF MEASUREMENT

All data used here are from the snow measurements of the snow stations of the Hydrological Office. Only results from stations where the data included both snow measurements in pine dominated forests and the forest density on the observation plots have been used. Those kind of stations are:

a. *Snow course stations* in which a part of the measuring route includes pine dominated forest.

b. *Stake-stations* with fixed measuring stakes established in groups in pine dominated forest.

Using the data from the two methods I have, in the first case, studied the dependency of the accumulation of snow on the density of forest and, in the latter instance, the unevenness of the accumulation and decreasing of snow caused by the variability of the density of forest and the position of the trees.

Snow course stations

Snow course refers to a method of measurement where the measuring route is a straight line or a polygon with readings taken at regular intervals. The route of snow courses in Finland usually takes the form of a 1 kilometer square including as many local types of terrain as possible. In this paper such measurements are referred to as the *regular snow courses.*

Besides the regular snow course stations the Hydrological Office has stations where measurements are carried out separately in different types of terrain but otherwise in the same manner as in the regular snow courses. Measurements of this type have been called the *snow measurements in different types of terrain.*

In calculating the average water equivalent of snow cover of different types of terrain the results of the regular snow courses have to be subdivided into smaller units for each type of terrain, thus resembling, in fact, the snow measurements in different types of terrain.

The regular snow courses were first started in Finland by the Meteorological Institute in 1923 (KORHONEN 1927), and in 1936 the Hydrological Office established their own snow course stations (A. SIRÉN 1936). In connection with the water survey of the Agricultural Board snow courses have also been carried out, particularly in 1934—1937 (KAITERA 1939). The snow measurements in different types of terrain were started by the Hydrological Office in 1951, in addition to their regular snow courses. In the winter 1959—60 there were 115 snow course stations in operation for the Hydrological Office.

In the regular snow courses the points of measurement of the depth of snow were 50 meters apart and the water equivalent of snow has been determined at each tenth depth measuring point. In the snow measurements in different types of terrain the depth of snow was measured at shorter distances and were limited in numbers in order to obtain the necessary number of observations required for each type. In both methods of measurement the depth of snow was measured with a loose stake and the density of snow determined by a snow balance (KORHONEN 1923, p. 9).

Based on the results of the snow course measurements carried out in 1952—1960, I have, in my investigation, calculated the approximate influence of the forest density on the accumulation of snow in pine dominated forest.

Stake-stations

In studying the variation in the accumulation and decreasing of snow caused by the variability of the forest density and the position of the trees, continuous observations at the same observation point were needed. For this purpose a large number of stakes were fixed in the ground in the forest area subjected to the investigation. The stakes were grouped in different ways depending on the purpose of the investigation. For studying snow cover in forests groups of fixed stakes have previously been used in Finland by G. Sirén (1955, p. 169) whose investigation concerned spruce and birch stands,

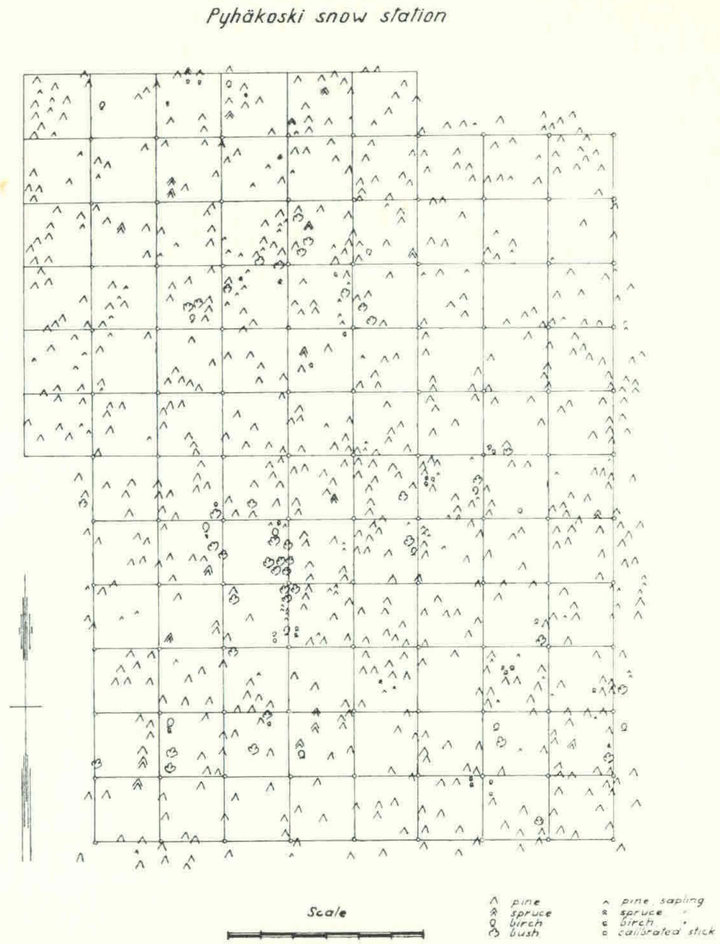

Fig. 1. Pyhäkoski stake-station in 1955—57

and YLI-VAKKURI (1960, p. 9) the investigations of whom also included pine dominated forests.

In autumn 1955 at Pyhäkoski (Fig. 2) a snow station was established where 108 stakes were fixed before the beginning of the winter into level ground in pine dominated forest. The stakes were set up in 9 rows of 12 stakes per row, each stake being 10 meters from the nearest in any directions. The size of the whole area was 80 m by 110 m or 8,800 m². All the brushwood, which might have supported the snow, was removed from around the stakes up to a radius

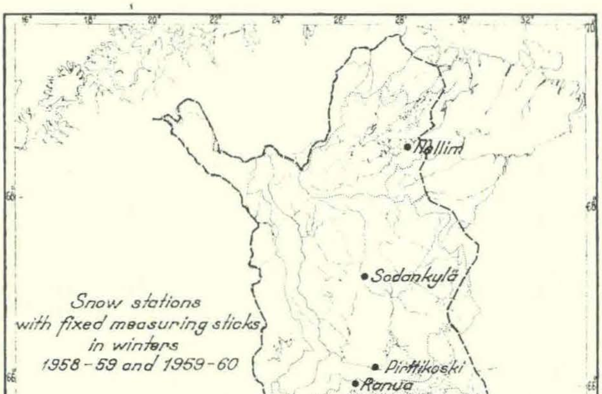

Fig. 2. Stake-stations in 1958—60 with groups of stakes both in pine dominated forest and unshaded open area

of 1.5 meters. A map was drawn of the measuring site (Fig. 1) with the position, size, and type of the trees and the points of stakes duly marked.

Measurements were carried out 6 times monthly beginning in mid-winter and continued until the snow had disappeared from around all the measuring stakes. At each observation the depth of snow was read from each of the 108 measuring stakes and the density of the snow was determined at 16 observation points.

In the summer of 1958 stake-stations for measuring snow were established in different parts in Finland. Measurements were carried out both in pine dominated forest and on unshaded open area. At those stations stakes were fixed to the ground in squares in the same way as shown in Figure 1. Twenty-five stakes 10 meters apart were set up in pine dominated forest and 9 stakes 5 meters apart on an unshaded open area. At the last mentioned site the stakes were set up in such a way that the shadows of trees or buildings did not reach the stakes, at least not at such a time when the solar radiation could have had

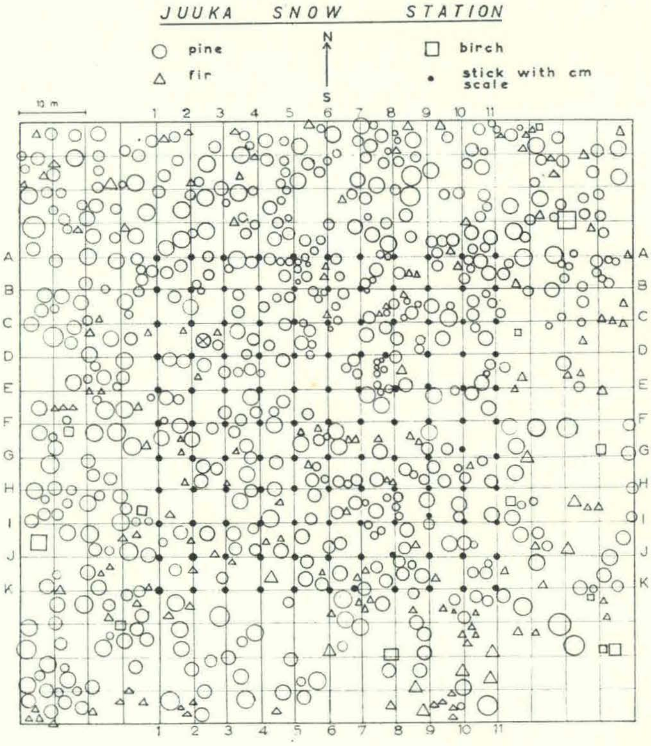

Fig. 3. Juuka stake-station

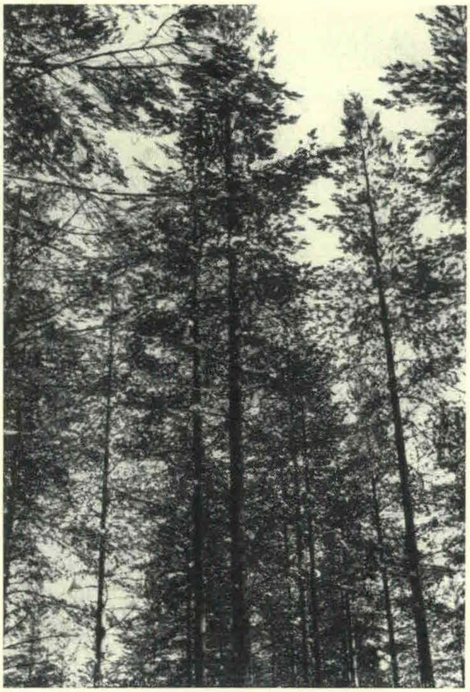

Fig. 4. Crown canopy of the pine dominated forest at Juuka stake-station
Photo by M. Seppänen, March 4, 1960

Fig. 5. Type of terrain at Juuka stake-station
Photo by M. Seppänen, March 4, 1960

any influence on the snow cover. The stake-station at Pyhäkoski was also altered similarly. All together 17 similar kind of stations were in operation in the winters 1958—59 and 1959—60.

At these stations measurements were recorded in mid-winter and early spring 6 times monthly until all snow had disappeared from around all the stakes. The snow density samples were taken at 4 points in the forest and at 2 points in the open area on each observation date.

For more accurate investigations of snow a bigger stake-station was established in Juuka in the autumn of 1959. At this new station 121 stakes were set up in a square in pine dominated forest similarly to other stake-stations but with the stakes 5 meters apart (Figures 3, 4 and 5). At this station measurements were recorded only once monthly. The density of the snow was determined at 8 points on each observation date.

Forest density at snow stations

In investigations concerning the snow cover in forest standard methods of estimating the density of forest are commonly used. The most common of them are:

1. The sum of the crown projection area expressed in decimals or as percentage of forest area under estimation.

1 (a). The amount of forest openings (the sum of the open spaces remaining outside the crown projection area) expressed as percentage of forest area under estimation.

2. The amount of tree expressed in cubicmeters, usually represented by the amount of trunks expressed in cubicmeters per hectare.

3. The number of trees, or stem density, meaning the number of trees exceeding a certain limit of size per unit area, usually per hectare.

At snow stations providing the basic results for my investigation the density of forest was determined as follows:

At snow course stations the density of forest was estimated at each observation point using the following scale: thin, rather thin, normal, rather dense and dense. The limits of the scale have not been fixed more accurately. Therefore different observers at different localities may have different opinion as to the limits. However, this error is negated when the means of the results of different snow course stations are calculated.

In December 1960, at the initiative of the Hydrological Office an investigation was made into the distribution of the observation points in different types

Table 1. Distribution of the number of observation points *(n)* falling on parts of forest with different density at the 45 snow stations. Both the regular snow courses and the snow measurements in different types of terrain were carried out in December, 1960

Forest type	Forest density	Regular snow courses		Snow measurements in different types of terrain	
		n	%	*n*	%
Pine dominated forests	Thin	187	15	83	12
	Rather thin	409	33	194	27
	Normal	517	42	350	49
	Rather dense	105	9	79	11
	Dense	7	1	7	1
	Sum	1,225	100	713	100
Spruce dominated forests	Thin	19	4	47	9
	Rather thin	134	25	79	16
	Normal	224	42	202	40
	Rather dense	112	21	118	24
	Dense	46	8	56	11
	Sum	535	100	502	100
Birch dominated forests	Thin	71	24	60	14
	Rather thin	94	33	165	37
	Normal	94	33	185	42
	Rather dense	23	8	29	6
	Dense	7	2	6	1
	Sum	289	100	445	100
Mixed forests	Thin	67	12	34	7
	Rather thin	222	39	107	22
	Normal	217	38	210	43
	Rather dense	57	10	105	22
	Dense	7	1	27	6
	Sum	570	100	483	100
All forests	Thin	344	13	224	10
	Rather thin	859	33	545	25
	Normal	1,052	40	1,017	46
	Rather dense	297	11	331	15
	Dense	67	3	95	4
	Sum	2,619	100	2,212	100

of forests with different density both in regular snow courses and in snow measurements in different types of terrain. These observations were recorded at 45 snow course stations in such a way that, at each station, both types of snow courses were carried out on consecutive days. As at each station both types of measurements were carried out by the same person, his opinion of the density of the forest thus affected both measurements in a similar way. The results are seen in Table 1.

The observation points on open areas and peatlands have been excluded from Table 1.

The observation points both in the regular snow courses and the snow measurements in different types of terrain totalled 3,600. Of this amount 34 per cent fell on pine dominated forest in the regular snow courses and only 20 per cent in snow measurements in different types of terrain. The lower latter figure was a manifestation of the fact that the number of observations in pine dominated forest in snow measurements in different types of terrain was limited in order to obtain a sufficient number of observations also from other types of terrain.

Table 1 shows that in the regular snow courses the observation points fall on the average into thinner parts of the forest than in snow measurements in different types of terrain, and, calculated in percentage, less into parts of forest of normal density. This is perhaps due to the fact that at the forest edge more measurements were taken in the regular snow courses than in the snow measurements in different types of terrain.

In accordance with the line survey for the forest valuation carried out during the years 1921—24 and 1936—38 (ILVESSALO, YRJÖ 1927, Tables 71—72, pp. 86—89 and 1943, Table 83, p. 352) half of the observation points in pine dominated forest fell on parts of forest where the density was 0.6—0.7 when using method No. 1 for estimating the density of forest presented on page 11. Forest density scale »normal» in snow course measurements will perhaps correspond on the average with this density of forest.

As a measure for forest density at the *Juuka stake-station* I have used the sum of the vertical profile area (SEPPÄNEN 1961) of pines (m^2) on a specific unit area (e.g. 100 m^2). In the map in Figure 3 the pines have been marked with circles corresponding by eye sight with the respective size of the pine. Using photos the average vertical profile area of the pine corresponding with the circles has then been estimated. In using the sum of the vertical profile area the depth and the breadth of the crown is important as the most effectual hindrance to snow fall and direct insolation and must be considered along with the length and breadth of the trunks.

At the Juuka snow station the average forest density close to the measuring stakes was 350 m² (vertical profile area) per 400 m² of forest area.

At other stake-stations I have estimated the density of forest by using the number of trees or trunks. Only trees whose height exceeded one half of the height of the dominant tree have been considered.

At the bigger stake-station at Pyhäkoski the density of the forest close to the measuring stakes was on the average 27 trees per 400 m² of forest area.

At the stake-stations with measuring stakes both in pine dominated forest and on unshaded open area the density of the forest close to the stakes was different at different stations, ranging from 10 to 36 trees per 400 m².

SNOW OBSERVATION RECORDS

Results of snow courses

In the snow courses the depth of snow is measured with a loose stake. A clearer picture of the unevenness of the snow cover is obtained if the mean deviation of the depth of snow in each type of terrain is calculated from the results of observations carried out on level ground only. At first the mean deviation of the depth of snow will be calculated separately for each snow course station using the following formula:

$$\vartheta_k = \sum_{k=1}^{n_k} \frac{|d_i|}{n_k}$$

where d_i is the deviation of the individual depth of snow from the average depth and n_k the number of depth measurements at each snow station in question. After that the weighted mean deviation for all stations will be calculated

$$\overline{\vartheta} = \frac{\sum_{k=1}^{m} n_k \cdot \vartheta_k}{\sum_{k=1}^{m} n_k}$$

where m indicates the number of snow stations.

The average depth of snow $(\overline{h})$ is calculated as a mean of all measurements.

On March 16, in years 1952—56 at the snow stations of the Hydrological Office the average depth of snow $(\bar{h})$, the average deviation $(\bar{\vartheta})$ and the number (n) of observations in different types of terrain on level ground were as follows:

Type of terrain		$\bar{h}$ cm	$\bar{\vartheta}$ %	n
Open area		57	7	3,567
Forest opening		70	5	1,118
Pine dominated forest,	thin	69	6	889
	rather thin	66	6	1,760
	normal	59	6	2,160
	rather dense	66	5	451
Spruce dominated forest,	thin	69	5	259
	rather thin	65	5	646
	normal	61	6	878
	rather dense	54	5	310
Birch dominated forest,	thin	70	5	320
	rather thin	69	4	508
	normal	70	3	388
	rather dense	79	3	145
Mixed forest,	thin	67	5	444
	rather thin	67	5	683
	normal	62	6	695
	rather dense	65	5	214

The standard deviation of the depth of snow $(\bar{\vartheta})$ expressed in percentage was greatest on open areas and least in birch dominated forest.

Owing to the method of calculation the values of depth of snow do not illustrate the correct relative magnitude considering different types of terrain and forests of different density. The chief purpose was to present the standard deviation of the results of depth measurements expressed in percentage.

As the density of the snow in snow courses is determined in the same manner as at the stake-stations, the dispersion of the density of snow will be examined together with the examination of the results of measurements of the stake-stations.

Results of measurements at stake-stations

In spite of the fact that level ground had been chosen for the measuring sites of the stake-stations and that the brushwood supporting the snow had been removed close to the fixed measuring stakes, snow depth values deviating considerably from each other were obtained for different measuring stakes in the same stand. The unevenness of the snow cover becomes apparent from the dispersion of the depth, the density and the water equivalent of snow.

In examining the results of the measurements at the stake-stations the dispersion of the depth of snow was calculated from the following formula

$$\sigma = \sqrt{\left(\sum_{i=1}^{n} d_i^2\right) : n}$$

where d_i is the deviation of the individual results from the mean value of the measurement results and n is the number of observations. At the Pyhäkoski stake-station the dispersion of the density of snow has also been calculated. On the other hand at the Juuka stake-station the dispersion of the density could not be calculated because of the small number of density samples. In this investigation the results of density samples of the Juuka stake-station have not been considered. The results of measurements at stake-stations with stakes set up both in pine dominated forest and unshaded open area will in my investigation be presented as mean values of the results of measurements at a greater number of stations. At these stations the deviations of the individual observations have been calculated as percentages from the mean values of the station and the dispersion of the deviations have been determined for the whole group of stations.

Before beginning to calculate the dispersion of the water equivalent of snow, the probable dependency of the density of snow in any significant way on the depth of snow will be examined. Denoting $\varrho_i - \bar{\varrho} = a\,(h_i - \bar{h})$, where ϱ_i and h_i are respectively the density and the depth of snow of the individual density sample, $\bar{\varrho}$ and $\bar{h}$ are the average values of the depth and the density of snow and a is a constant. By the method of least squares an average value for $|a|$ of 0.001 g/cm³/cm was obtained. Provided small variations in the depth of snow are in question one may regard the density of snow as being independent of the depth of snow in any significant way.

Thus we may regard that during the measuring at stake-stations the water equivalent of snow (w) was a function $w = w(h, \varrho)$ of two independent variables, the depth (h) and the density (ϱ) of snow. The dispersion of the water equivalent of snow can now be calculated from the formula

$$\sigma_w = \sqrt{\left(\frac{\partial w}{\partial h} \cdot \sigma_h\right)^2 + \left(\frac{\partial w}{\partial \varrho} \cdot \sigma_\varrho\right)^2}$$

where σ_h and σ_ϱ are the dispersions of the depth and the density of snow and $\frac{\partial w}{\partial h} = \varrho$ and $\frac{\partial w}{\partial \varrho} = h$.

In the pine dominated forest at the Pyhäkoski stake-station the depth $(\bar{h})$, the density $(\bar{\varrho})$ and the water equivalent of snow $(\bar{w})$ and their dispersion (σ_h, σ_ϱ, and σ_w) were:

	Before melting phase		During melting phase	
	March 16 1956	March 15 1957	April 30 1956	April 26 1957
$\bar{h}$ (cm)	65	68	38	33
σ_h (%)	9	8	17	18
$\bar{\varrho}$ (g/cm³)	0.24	0.22	0.30	0.32
σ_ϱ (%)	3	4	7	5
$\bar{w}$ (mm)	152	150	113	107
σ_w (%)	9	9	16	18

In the pine dominated forest at the Juuka stake-station the depth of snow $(\bar{h})$ and the dispersion (σ_h) were:

	Before melting phase			During melting phase
	Jan. 15 1960	Febr. 15 1960	March 15 1960	April 16 1960
$\bar{h}$ (cm)	41	52	60	30
σ_h (%)	8	7	6	16

At stake-stations with measuring stakes both in pine dominated forest and unshaded open area the depth and the density and the water equivalent of snow and the dispersion of them expressed as percentage averaged as follows:

		In the beginning of February				When melting had begun also in forest			
		Forest		Open area		Forest		Open area	
	Year	1959	1960	1959	1960	1959	1960	1959	1960
$\bar{h}$	(cm)	52	42	53	42	34	31	30	25
σ_h	(%)	9	9	6	7	24	20	16	14
$\bar{\varrho}$	(g/cm³)	0.21	0.20	0.21	0.21	0.33	0.31	0.35	0.35
σ_ϱ	(%)	6	4	2	3	6	6	4	4
$\bar{w}$	(mm)	106	85	113	89	112	97	102	89
σ_w	(%)	11	10	6	8	25	20	16	15

The dispersion, expressed here in per cent, was greater in forest than the corresponding dispersion on open area. The dispersion of the density of snow was nearly the same in mid-winter and during the melting period. On the other hand, the dispersion of the depth and the density of snow were twice as great during the melting period than the corresponding dispersion in mid-winter.

Figure 6 shows the average course of the water equivalent, the depth, and the density of snow at the approach of the melting period and at the earlier part of the melting period in 1959 and 1960 at the stake-stations with measuring stakes both in pine dominated forest and unshaded open area. The last date of observation (τ_0) with some snow still around all the measuring stakes in forest and open area has been used as a basis in the combination of the measuring results of different stations. The marks indicate the following mean values:

$\bar{w}$ = water equivalent of snow in pine dominated forest
$\bar{w}'$ = water equivalent of snow on unshaded open area
$\bar{h}$ = depth of snow in pine dominated forest
h_{max} = maximum depth of snow in pine dominated forest
h_{min} = minimum depth of snow in pine dominated forest
σ_h = dispersion of the depth of snow
$\bar{h}'$ = depth of snow on unshaded open area
h'_{max} = maximum depth of snow on unshaded open area
h'_{min} = minimum depth of snow on unshaded open area
$\bar{\varrho}$ = density of snow in pine dominated forest
ϱ_{max} = maximum density of snow in pine dominated forest
ϱ_{min} = minimum density of snow in pine dominated forest
$\bar{\varrho}'$ = density of snow on unshaded open area

From Figure 6 it is seen that the average depth of snow in pine dominated forest at time point τ_0 — 25 days was the same as the average depth of snow on unshaded open area. However, at time point τ_0 it was approximately the same as the maximum depth of snow on unshaded open area. The amplitude of the depth of snow was twice as great in pine dominated forest than on

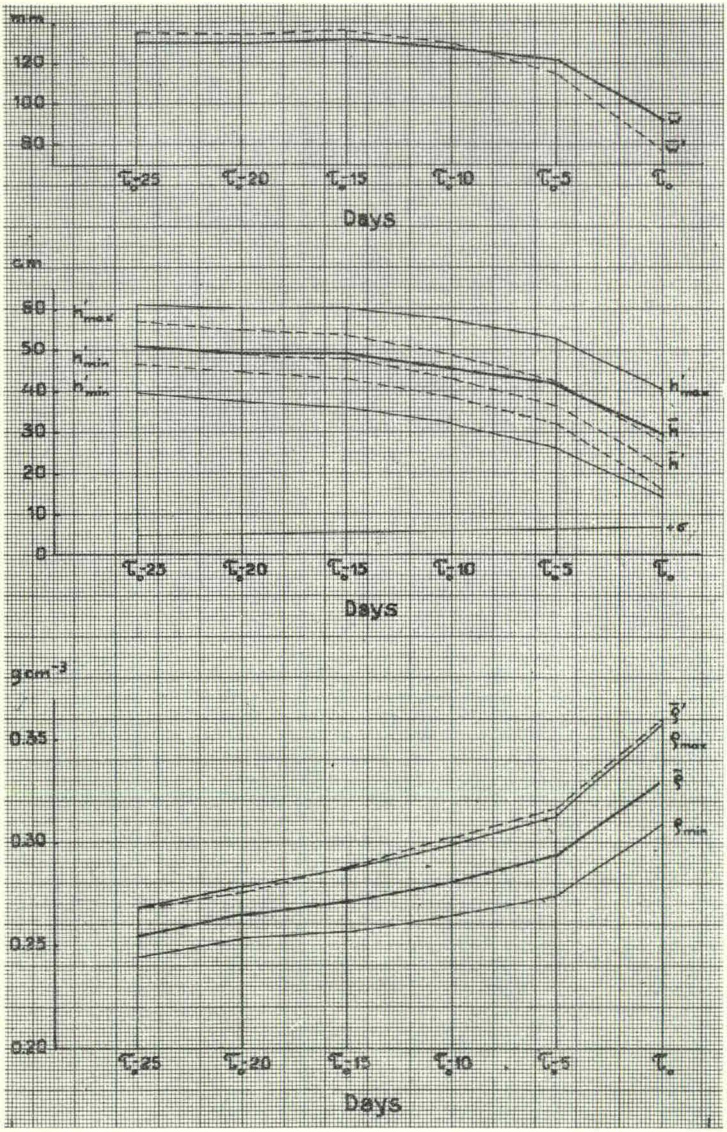

Fig. 6. The average course of the water equivalent of snow, the depth and the density of snow in pine dominated forest and on unshaded open area at the approach of and beginning of the melting period in winters 1959 and 1960

unshaded open area. The average density of snow on unshaded open area was approximately the same as the maximum density of snow in pine dominated forest. In pine dominated forest the amplitude of the density of snow was at time point τ_0 twice as large as 25 days earlier.

ON THE ACCUMULATION OF SNOW IN PINE DOMINATED FOREST

The information on the amount of snow accumulated in forests is important, for example, in estimating the average amount of snow on certain drainage areas. If this estimation were based solely on the measurements of snow on open areas the accuracy of the results will vary inversely with the variation between the amount of snow on open areas and other types of terrain.

On some locations more and on other locations less snow may accumulate in forest than on open areas. Even in the same area the relation between the water equivalent of snow cover in forest and open areas may differ with different years.

These facts become apparent from the results of different investigators. Because of the importance of this matter some additional examples on the accumulation of snow in pine dominated forest compared with the accumulation of snow on open areas are presented (p. 26, Table 2).

In estimating the amount of snow in forests attention should also be directed to the effect of the density of forest on the accumulation of snow. In general less snow accumulates in denser forest than in thinner. Although this is general knowledge additional proof in the form of examples have been presented (p. 27).

Even in the same stand trees may stand denser in one spot and thinner in another. These kind of variations in the density of forest cause unevenness in the snow cover of the stand. Also to this quite important matter referring to snow measurements further explanations have been presented (pp. 29—31).

In addition each tree in the stand has an effect of its own on the accumulation of snow close to it. An example of the effect of one pine in pine dominated forest on the accumulation of snow has been recorded (pp. 31—33).

Besides the air temperature, the amount and the type of precipitation, and other meteorological factors, the accumulation of snow in the forest is also influenced by the following factors:

Interception of snow and rain by trees.

The fact that in general the ground freezes earlier in the open areas than in the forest.

The forming of permanent snow cover occurs on the average earlier on open areas than in the forest.

The partial melting of snow during the accumulation period, when more snow melts on the open areas than in the forest.

Turbulence caused by trees and groups of trees.

Snow, chunks of ice, and drops of water falling from trees.

The accumulation of snow in pine dominated forest compared with the accumulation on open areas

Firstly, some of the causes affecting the variation in the accumulation of snow on open areas and in forest, as mentioned above, will be examined closer.

Interception of snow and rain by trees. In the beginning of the winter rains occur often. In the forest the rain intercepted by the trees partly drips down from the crowns and partly flows down the trunks, the rest is retained on the trees as moisture. On the open areas the total amount of the rain reaches the snow, thus increasing the water equivalent of the snow cover by the number of millimeters of rain. The exception is when sufficient rain occurs to filtrate through the snow cover. Rain in forest stands has been frequently measured. In Finland LUKKALA (1942, p. 7) carried out rain measurements in a rather dense pine stand where the branches were so crowded that trees with normal crowns could not have been inserted between them. The height of the trees varied from 10 to 15 meters. The measurements indicated that 48 per cent of rain, totalling 2 millimeters, was retained in the crowns, 29 per cent of rain of 5 millimeters, 20 per cent of rain of 10 millimeters, and 15 per cent of rain of 20 millimeters was retained in the crowns. The moisture retained on the trees is removed by evaporation. SIRÉN, G. (1955, p. 168) has measured rain in spruce stands. Commencing in 1959 the Hydrological Office has also recorded rain-water measurements in pine dominated forest.

The snow intercepted by trees partly falls to the ground or, in the case of thawing weather, drips from the crowns or flows as water along the trunks. A small part of the snow is retained in the forks formed by the needles. In the case of thawing weather much of the water is retained in the trees and exposed to evaporation.

The accumulation of ice and snow on trees may be so heavy that the weaker branches and even trees may break. In Finland such cases may occur on the higher hills and mountain terrain. Heikinheimo (1920, p. 53) stated that in the winter of 1918—1919 in Rovaniemi parish, avout 300 meters above the sea level in the hilltop forest in Iso-Suuas, some 680,000 kilograms of snow per hectare had lodged on trees. The forest had been spruce dominated.

Great damage caused by snow piling on trees occurred in South-Finland during 1958—59. By its weight the snow caused particularly the young unthinned pines to break. Figure 7 presents the weather condition on January 3rd and Figure 8 the dispersion of both the air temperature and the dew point in Jokioinen and Tallinn, on the same date, one of the dates of the snow damage.

The weather condition mentioned above was very advantageous for the formation of supercooled rain. On January 3rd, 1959, the author happened to be on his way to Hyvinkää about 50 kilometers north of Helsinki. Freezing rain made the roads so slippery that it was necessary to have chains on the tires. There was no noticeable wind in the forest but a constant cracking and booming could be heard and branches and tree tops were seen breaking, even whole trees collapsing. These forests were pine dominated.

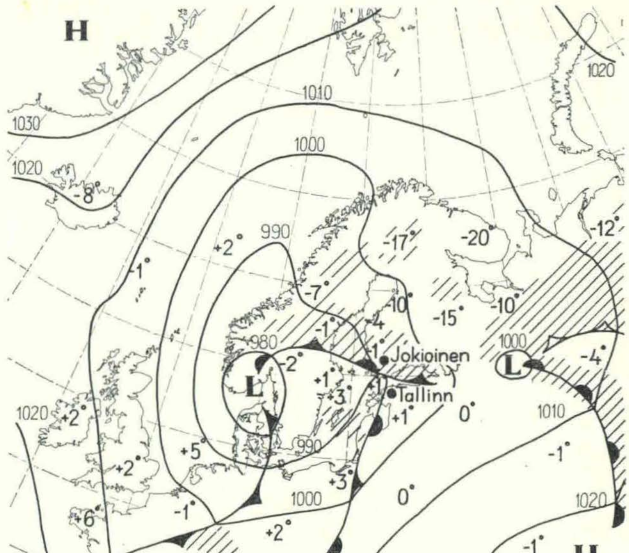

Fig. 7. Weather condition at 0200 January 3rd, 1959

The freezing of the soil usually begins earlier in the open areas than in the forest. This is mainly caused by the fact that in the forest the trees and brushwood absorb the outcoming long-wave radiation from the soil and return a part of it back to the ground. According to KAITERA and HELENELUND (1947,

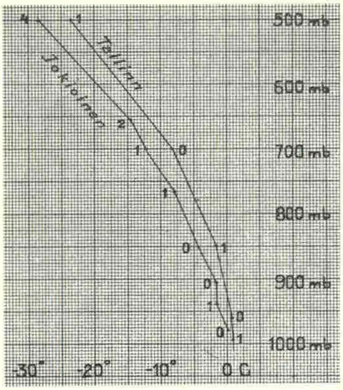

Fig. 8. The dispersion of both air temperature and dew point at 0200 in Jokioinen and Tallinn, January 3rd, 1959

p. 395) in dense forest the depth of the frozen soil had averaged 60 per cent of the depth of the frozen soil measured on an adjoining meadow. RONGE (1928, p. 328) has observed that the layer of the frozen soil remained thinner in thinned forest where the snow forms a deeper protecting layer than in dense unthinned forest. In the case of forming of permanent snow cover on unfrozen soil it often happens that the soil remains unfrozen throughout the whole winter (KERÄNEN, 1923, p. 24). Also such cases occur where the soil freezes on the open areas but not in the forest.

The freezing of the soil earlier on open areas than in forest has also been observed at the stations of the Hydrological Office. Observations were made upon the first appearance of frozen soil and in 173 cases frozen soil was observed both on open areas and forest, in 126 cases only on open areas and in 2 cases in forest only.

If the soil remains unfrozen in the forest longer than on the open area, the current of heat upward in the ground to the soil-surface may cause the under layer of the snow cover to melt more in the forest than in the open.

The formation of permanent snow cover usually occurs earlier in the open than in the forest owing partly to the fact mentioned above and partly to the interception of snow by the trees. In individual cases it may occur the other way round, for example, in such a case when warm weather occurs in the beginning of the winter and causes the snow to melt on open areas but does not reach the forest in time to melt the snow before the next snow fall.

The effect of the partial melting of snow. Particularly in the beginning of the winter a partial melting of snow often occurs as a result of the effect of the flow of warm air into the local environment. As the cold air is retained longer in the forest than in the open (Rakhmanov 1957, p. 210) and as the cold air retards the melting of snow and decreases the evaporation from the snow surface, the melting of snow begins earlier in the open than in the forest causing the water equivalent of snow to decrease more in the open. As an example it may be mentioned that during the period December 16, 1956 and January 16, 1957 the decrease of the water equivalent of snow at snow course stations south of Oulujoki river water system averaged 5 millimeters (9 per cent) in the open areas and 3 millimeters (6 per cent) in pine dominated forest.

The relation between the water equivalent of snow cover on open areas and forests during the accumulation phase may be different in different localities.

At the Experimental Forest Station in Idaho in U.S.A. (Connaughton 1935, pp. 564—569), before the beginning of the melting period in the years 1931—33, the average water equivalent of snow cover in virgin conifer forest with dense undergrowth was 69 per cent and in virgin conifer forest without undergrowth 75 per cent of the water equivalent of snow on open areas. Also in investigations carried out in the hilly parts of Hungary in the years 1954—59 (Salamin 1959, p. 76) results indicated that in more extensive forests, particularly in pine forests, the water equivalent of snow was less in the forest than on open areas before the beginning of the melting period.

In U.S.S.R. (Rakhmanov 1957, p. 212) it has been reported that during the time of maximum water equivalent of snow in the years 1947—54, the water equivalent of snow in forest averaged 112 per cent in the mid-part of the European part of U.S.S.R. and 108 per cent in Western Sibirian of the water equivalent of snow cover on open areas. Rakhmanov concluded that the ratio between the amount of snow on open areas and forest during maximum water equivalent of snow does not depend only on the type of the forest, but also on weather conditions prevailing in the winter. When the weather conditions in winter have been more cyclonic in character with frequent changes in the weather, it has increased the ratio between the water equivalent of snow in forest and open areas. If, instead, the changes of weather have been slow and of anticyclonic character, the ratio between the water equivalent of snow has been smaller.

Larger water equivalents of snow cover in forest than on open areas have also been measured in Finland during the time of maximum water equivalent of snow. KORHONEN (1936, pp. 4—5) obtained for the average equivalent of snow cover on open areas and in forest in the middle of March in years 1919—34 the following values:

Area	Water equivalent of snow	
	open areas (mm)	forest (mm)
Uusimaa	83	89
Kymijoki river drainage area	103	112
Oulujoki river drainage area	135	153
Kemijoki river drainage area	132	150

In forests consisting of both pine stands and mixed forests, the equivalent of snow cover expressed in percentage of the water equivalent of snow on open areas was in Uusimaa 107 per cent and on the respective drainage systems of Kymijoki river 109 per cent, Oulujoki river 113 per cent and Kemijoki river 114 per cent. The percentage increased with the higher latitudes.

The results of measurements carried out in the middle of March or at the time of maximum water equivalent of snow do not give a clear picture of the accumulation of snow in forest and on open areas. At that time the higher intensity of the insolation already contributes more heat to the evaporation and melting on open areas than in the forests.

The great difference between the results of Connaughton and Rakhmanov mentioned above may be partly due to the differences in the amount of snow intercepted by trees. According to calculations by Connaughton in Idaho, when compared to the amount of snow on open areas, 24.5 per cent of snow was retained on trees in a virgin timber forest without second growth and 29.8 per cent in virgin timber forest with strong growth. Connaughton considered it possible that these values were somewhat exaggerated as the melt-water of the snow which had possibly run down the trunk had not been measured.

In North-Finland the ratio between the water equivalent of snow cover in forest and on open areas is greater than in South-Finland. I have calculated the average water equivalent of snow in pine dominated forest and on open areas on January 16 in years 1952—60 on zones between 60°—62° N lat, 62°—64° N lat and between 64°—70° N lat. The density of the forest has not been considered in the calculations. The average water equivalent of snow in pine dominated forest has also been expressed as a percentage of the average water equivalent of snow on open areas and the standard deviation of these percentages ($\bar{\vartheta}$) has been calculated.

Table 2. The average water equivalent of snow on open areas and pine dominated forest on January 16 on snow course stations according to zones, 1952—60

Zone	Water equivalent of snow				$\bar{\vartheta}$ %
	Open areas		Pine dominated forest		
	mm	%	mm	%	
60°—62° N lat	61	100	53	85	6
62°—64° N lat	76	100	72	94	3
64°—70° N lat	81	100	80	99	2

The amount of snow in pine dominated forest in relation to that on the open areas was least in the most southern zone (60°—62° N lat) and increased towards the north so that in zone 64°—70° N lat about the same amount of snow was in pine dominated forest and on open areas. The standard deviation ($\bar{\vartheta}$) of the yearly percentages was greatest in South-Finland.

Effect of the density of forest on the accumulation of snow in pine dominated forest

In the same general environment in similar stands differing only in tree density, the equivalent of snow generally differs in magnitude. The interception of snow and rain by trees, the freezing of the soil, and the forming of permanent snow cover earlier in thinner forest than in denser are some of the causes for greater snow accumulation in thinner stands than in denser. But if, at the time of accumulation of snow, a partial melting should occur, more snow will melt in thinner forest as cold air is detained longer in denser stands. Due to this, less snow may be found during the accumulation of snow in thinner stands than in denser. Those factors are general knowledge qualitatively speaking. The effect of the density of forest has also been studied quantitatively.

As an example the investigations carried out at the Fraser Experimental Forest in Colorado, U.S.A. (Goodell 1959, p. 54) may be mentioned. In a mature, evenaged stand of lodge-pole pine, the original stand of which averaged 168 cubic meters per hectare in trees averaging 22 meters in height, plots of 3.2 hectare in size were established. Partial cuttings were carried out leaving 168, 84, 56, 28 and zero cubic meters of trees per hectare. Results showed a nearly linear and inverse relationship between the density of the stand and the snow reaching the ground. Thus in denser forest less snow was on the ground than in thinner forest. On the plots where no saw-timber remained 29 per cent more snow was deposited than where the original stand of 168 cubic meters per hectare was left untouched. No melting occurred during the accumulation of snow.

In Finland, according to the calculations of KAITERA (1939, p. 58), the water equivalent of snow cover in forests with 50 per cent open spaces between the tree crowns was almost the same as on the open fields in 1934—37 during the time of maximum water equivalent of snow. With 36 per cent open spaces in the forest area the water equivalent of snow cover in coniferous forest was 93 per cent of that on open fields. But with 75 per cent open spaces in the forest area the water equivalent of snow in coniferous forest was 118 per cent of that on open fields. The coniferous forests consisted of both pine and spruce dominated forests.

TEIVAINEN (1952, p. 81) concluded that in pine stands with a density of 0.6 about 95 per cent of snow fall reaches the ground and that in pine stands with a closed canopy the ground receives about 85 per cent as much snow as where the trees are thinner in the same stand.

According to my calculations the depth $(\bar{h})$, the density $(\bar{\varrho})$, and the water equivalent of snow $(\bar{w})$ averaged on open areas, forest openings, and pine dominated forest of different density at snow course stations on February 16 in 1952—60 as follows:

	$\bar{h}$		$\bar{\varrho}$		$\bar{w}$	
	cm	%	g/cm^3	%	mm	%
Open areas	53	100	0.206	100	110	100
Forest openings	58	109	0.205	99	118	108
Pine dominated forest						
thin	55	103	0.203	98	111	101
rather thin	54	101	0.202	98	108	99
normal	52	98	0.201	97	104	95
rather dense	50	94	0.202	98	100	92
dense	46	86	0.212	101	95	86

When computing those values only results of snow course stations where measurings have been done both on open area and in pine dominated forest of normal density have been considered. At first the average value of the depth, the density, and the water equivalent of snow for each type of terrain and for each different group of forest density have been calculated separately for each snow station. Further, the means of the computed values thus obtained for all stations have been determined separately for each year and finally the means for the period 1952—60.

In 1952—60 on February 16, the depth and the water equivalent of snow varied inversely with the density of the forest. The water equivalent of the snow cover averaged 5 per cent less in pine dominated forest of normal density than on open area and 8 per cent more in forest openings than on the open area.

The percentages I have calculated are slightly lower than the results of Kaitera mentioned above. One cause perhaps may be that the water equivalent of snow cover calculated by Kaitera was from the time of maximum water equivalent of snow cover and thus from a later date than the present calculations. In the beginning of March, 1935, the decrease of the water equivalent of snow cover caused by melting in South-Finland averaged about 20 per cent and, due to the new snow falls, the spring maximum was reached at the beginning of April.

Also in the same stand the density of the forest varies and this variability causes unevenness in the accumulation of snow. Reasons are the same as those which cause the water equivalent of snow cover to differ in amount in different stands in the same locality (p. 26). In addition, in sites of different density in the same stand the whirls of the wind and the snow dripping from trees may cause added unevenness in the accumulation of snow.

One may assume that the course of the air current above the forest canopy has a more extensive space over the thinner part of the forest and the velocity of the current thus decreases. Hence it would follow that air pressure above the ground in thinner forest would be greater than in the denser part of the forest. Now turbulence would occur, and near the ground the air would flow from the thinner part sidewards and from above donwwards into the thinner part of the forest. Consequently more snow would fall into the thinner part than into the denser part of the forest. Pfeiffer (1938, p. 289) has shown with experiments using smoke that in narrow forest openings there really occurs a turbulence of that kind.

When the interception of snow by the branches of pines occurs during a light wind, a deficiency of snow is formed beneath the pine. It will be formed elsewhere than beneath the tree if the interception occurs during prevailing strong winds. The snow, the ice, or the melt-water of both, or the dropping from the crowns fills the deficiency under the crown in the first case, but in the latter case the water equivalent of snow under the pine crown may increase over what it would have been had no snow been intercepted by the trees.

At such places in the stands where trees stand most dense, more snow drips from the crowns to the ground per unit area than in thinner parts of the stand.

The effect of the density of forest on accumulation of snow in pine dominated forest has also been investigated in the forest zone of the western slopes of the Sierra Nevada in U.S.A. Observations were made in pine dominated forest of different density in 10 different types at 100 stations in years 1934—38 and 1940—41 (KITTREDGE 1953, p. 3). At these stations 13—27 per cent of the snow fall of the periods was intercepted by the trees. KITTREDGE (1953, pp. 37—39) has calculated the dependency of the maximum water equivalent of snow on the density of the forest in forests of different type for different years. To mention some of his results, he obtained for the maximum water equivalent of snow in old ponderosa-sugarpine stands for 1935—36 the following formula:

$$d = 7.2 - 0.10 \cdot c$$

where d indicates the maximum water equivalent of snow in inches and c the per cent of the area covered by crown canopy in relation to the whole area.

In Finland the effect of the variability of the density of the forest on the accumulation of snow in pine dominated forest is clearly observed in the results of measurements at stake-stations. Of this an example is given.

The density of the forest close to the individual stake is recorded as the number of trees (n) on an area the size of A in the environment of the stake. Assume that the average density of the forest is $\bar{n}$ on an area the size of A close to the stake. The deviation of the density of the forest at an individual stake is $\Delta n = n - \bar{n}$.

Denoting $\Delta h = h - \bar{h}$, h and Δh indicate the depth of snow and the deviation of it at an individual stake and $\bar{h}$ is the average depth of snow close to the stakes.

Assuming that if $|\Delta h|$ is small, $\Delta h = a \cdot \Delta n$, where a is a constant. We make $\frac{dh}{dn} = a$ thus obtaining

$$h = an + b$$

where a and b are constants.

For constants a and b such values are determined that the formula $h = an + b$ best fits the value of the pairs (h, n) at different stakes. The results depend on the size of the area A used in determining the density of forest.

As in the snow measurements different values of area A will be used for determining the forest density, the calculations mentioned above will be carried out separately for each different value of area A.

This method of calculation has been applied to the results of measurements at Pyhäkoski stake-station (Fig. 1) carried out on March 16, 1956 and March 15, 1957. Calculations have been carried out separately in each case where the area A used in determination of the density of forest was 400 m², 100 m², and 25 m² respectively. The average deviation of the snow depth calculated from the formula from the measured snow depths has also been determined.

1. If the density of the forest *(n)* is determined as the number of trees on 400 m² we will obtain:

March 16, 1956	$h = -0.3\,n + 73 \pm 6$ cm
March 15, 1957	$h = -0.2\,n + 75 \pm 5$ cm
Mean	$h = -0.2\,n + 74 \pm 6$ cm

2. If the density of the forest *(n)* is determined as the number of trees on 100 m² we will obtain:

March 16, 1956	$h = -1.3\,n + 75 \pm 5$ cm
March 15, 1957	$h = -1.1\,n + 76 \pm 5$ cm
Mean	$h = -1.2\,n + 75 \pm 5$ cm

3. If the density of the forest *(n)* is determined as the number of trees on 25 m² we will obtain:

March 16, 1956	$h = -1.8\,n + 68 \pm 6$ cm
March 15, 1957	$h = -1.3\,n + 70 \pm 5$ cm
Mean	$h = -1.6\,n + 69 \pm 6$ cm

The average density of snow on March 16, 1956 at Pyhäkoski stake-station was 0.235 g/cm³ and on March 15, 1957 the density was 0.220 g/cm³. Where the area used for the determination of the density of forest was 400 m², 100 m², and 25 m² respectively, we obtain approximate expressions for the average water equivalent of snow on March 16, 1956 and March 15, 1957

If A = 400 m²	$w = -0.6\,n + 167$
If A = 100 m²	$w = -2.8\,n + 171$
If A = 25 m²	$w = -3.5\,n + 157$

The greater the number of trees *(n)* in the environment of the measuring stakes, the smaller was the water equivalent of snow *(w)* close to the stake. If, for instance, on an area the size of 100 m² there was 1 tree less than the average, it would effect the results so that the water equivalent of snow would be 3 millimeters above average.

Therefore it is important that the measurements in the forest terrain should not be carried out where the route is easier or in thinner parts of the forest stand. One should, rather, take a straight course and take measurements at regular, predetermined distances. Also at stake-stations the stakes should be set up in straight rows with constant distances between them.

Influence of an individual tree in the forest on the accumulation of snow

Each individual tree in the forest has its own influence on the accumulation of snow on the ground close to the tree. The snow may be intercepted by tree crowns for a short or a long time, or the contact of the snow with crowns may change the course of the falling snow. The tree causes turbulence, the quality of which also depends on the position of other trees and on the direction and the velocity of the wind.

The influence of an individual pine on the accumulation of snow at Juuka stake-station (Fig. 3) in the winter of 1959—60 until January 15, 1960 has been examined. Figure 9 shows the amount of snow fall during winds of different direction at the Juuka observation station between the date of formation of permanent snow cover and January 15, 1960.

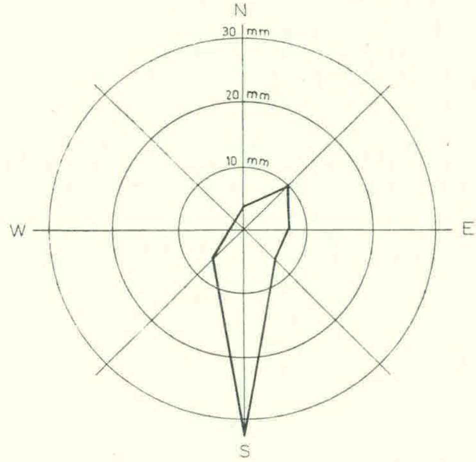

Fig. 9. Distribution of the precipitation at different wind directions at the Juuka observation station from early winter to January 15, 1959—60

It can be seen that most of the precipitation falls during prevailing south winds. This gave cause for investigations into how a pine might influence the accumulation of snow in the direction north-south during the time period mentioned above.

Close to each measuring stake 9 square areas of 25 m^2 each were separated in a north-south direction in such a way that the stake remained in the middle of the mid-square. Assume that the vertical profile area of an individual pine is B (m^2). The totals of the vertical profile areas ΣB_1, ΣB_2, . . . ΣB_9 of the pines on each square area will be calculated separately.

We assume that the deviation of the depth of snow at the measuring stake is $\Delta h = h - \bar{h}$, where h is the depth of snow read from the measuring stake and $\bar{h}$ is the mean value of all readings of depth of snow from the measuring stakes. Δh is assumed to be the linear function of ΣB_i

$$\Delta h = \sum_{i=1}^{9} (a_i \, \Sigma B_i) \text{ cm},$$

and the values of the constants a_i will be determined by the method of least squares.

The values of a_i indicate the ratio of the change of depth of snow close to the stake which are represented by the value ΣB_i per square meter in the equation. Thus we derive the magnitude of the effect of the vertical profile area on the accumulation of snow in north-south direction and at different distances. In Figure 10 the ordinates of the crosses (x) and dots (·) are the values of a_i multiplied by 25.

Assume that the vertical profile area of one pine is $B = 25$ m^2. Figure 10 shows the influence it has on the depth of snow in a north-south direction from the beginning of the winter until January 15, 1960. The crosses (x) mark the results calculated according to the division of the areas.

For checking the results another similar kind of experiment has been carried out by forming 8 square areas of the size of 25 m^2 close to the measuring stakes in such a way that the measuring stake remains in the middle on the border of the two middle areas. The dots (·) show the results of the checking.

The mean depth of snow at Juuka stake-station averaged 41 cm on January 15, 1960.

About 5 meters north of the pine the deviation of the depth of snow $\Delta h = -6$ cm (according to the levelling curve) was -15 per cent of the average depth of snow on the measuring site.

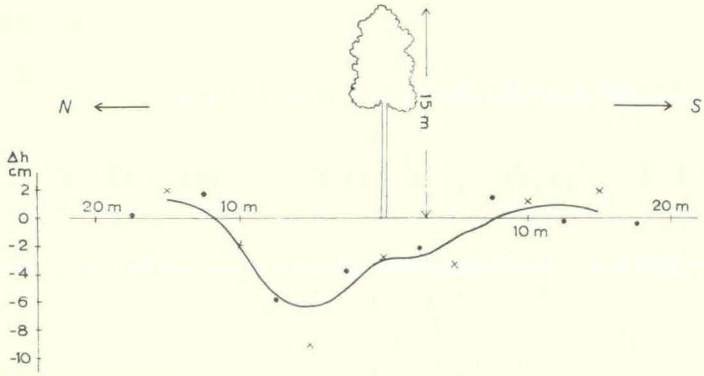

Fig. 10. Average difference (Δh) of the depth of snow caused by a pine in north-south direction in the forest at Juuka stake-station on January 15, 1960

THE DECREASING OF SNOW IN SPRING IN PINE DOMINATED FOREST

Factors causing the decrease of snow in forest

It is general knowledge that the decreasing of snow in spring occurs more slowly in the forest than on the open areas. In order to follow the average decreasing of snow on larger areas records of snow data from different types of terrain are needed. If the rate of decrease of snow at a certain time on different types of terrain is known as compared to the rate of decrease on open areas, it is possible to estimate the approximate decrease of snow on different types of terrain by only measuring the rate of decrease on open areas. By totalling those figures some indication of the total decrease on an entire heterogeneous area can be obtained. As this method has often been applied, an example of the decreasing of snow in pine dominated forest compared with the decreasing on open areas has been presented (pp. 37—38).

It is also known that the snow decreases more slowly in denser forest than in thin. An example of this is also included (pp. 37—38).

Even in the same stand the density of forest varies. The following formulas have been derived to describe this effect on the decreasing of snow (pp. 39—40).

The distribution of the last snow patches according to the density of forest has also been studied (pp. 40—41).

In conjunction with this a study has also been made of the position of the trees in the environment of the last snow patches (pp. 41—42).

It seems that the trees with the greatest delaying effect on the decreasing of snow cover stand S.S.W. of the area in question and the trees with the greatest accelerating effect stand N.N.E. of the spot. Therefore a study has been made as to how the trees in the directions mentioned above and at different distances affect the decreasing of snow (pp. 42—44).

Finally the effects of the shading of the trees and the heat radiation emitted by the trees on the decreasing of snow have been analysed (pp. 45—46).

The water equivalent of snow may decrease by evaporation, sublimation of snow or melting, if the melt water penetrates the snow cover. The melting, evaporation, and sublimation consume heat, which the snow cover may obtain from above or from underneath.

The heat flow from the interior of the soil to the surface diminishes with the advent of spring. During the melting period heat from this source is rather small in relation to the amount of heat energy reaching the snow cover from above. If the soil is frozen, the melting of snow from below is rather negligable (Keränen 1923, p. 23).

The most important factor in the melting of snow in the spring is the radiation energy reaching the snow cover. A second factor is the advection of the warm air mass reaching the environment. From this warm air the snow cover receives heat energy by exchange. If the air is humid and the dew point is above 0° C water will condensate on the snow surface whence the released heat melts the snow. Warm rain may also melt a small amount of snow.

Sublimation of snow may be different on different places of the snow surface. Goodell (1959, p. 53) notes as an example that, if the temperature of the snow cover exposed to solar radiation is —1° C and that in the shade is —7° C and the dew point of the air is —15° C, the rate of sublimation from the warmer surface will be more than twice as great as from the colder one, provided the wind speed is the same. Although the temperature of the evaporation surface may be the same, the evaporation of the melt water may vary on different places of the surface of the snow cover, if the wind speed, the exchange or the saturation loss is different at the surfaces.

The majority of the snow melting occurs in April. According to Keränen (1942, p. 135) the ground in South-Finland in April obtains short-wave radiation as direct insolation 4.3 kcal/cm^2 and as dispersed radiation of the hemisphere 4.3 kcal/cm^2, the same amount. Of this 2.4 kcal/cm^2 is reflected back so the net gain of short-wave radiation on the ground is 6.2 kcal/cm^2. The ground surface radiates out long-wave radiation, of which a part returns as atmospheric re-radiation so that the heat energy loss by long-wave radiation from the ground amounts to 3.6 kcal/cm^2. Thus the radiation balance of the ground surface in South-Finland is 2.6 $kcal/cm^2$ in April. This amount of energy would be able to melt snow of about 1 meter thick with a density of 0.3 g/cm^3.

According to LUNELUND (1940, p. 7) the 24 hour totals of radiation striking level, horizontal ground surface on a clear, cloudless day of March 15 are as follows:

Latitude	60°	70°
Direct insolation	365 $gcal/cm^2$	284 $gcal/cm^2$
Diffusive radiation	64 $gcal/cm^2$	60 $gcal/cm^2$

In the forest a part of the incoming short-wave radiation is reflected back to the atmosphere and part is absorbed by the branches, leaves, and needles. The final portion passes through the interference to contact the ground surface.

Summarized from the results by LAUSCHER and SCHWALBE (1934) and SAUBERER (1937) of the luminousity measurements in pine forests, GEIGER (1950, p. 306) showed that 22—40 per cent of all the short-wave radiation passes through the crown foliage in old pine forest. MILLER (1955, p. 108) stated that only 8 per cent of the insolation on crown foliage is transmitted. Of the short-wave radiation reaching the snow surface the greatest part is reflected back. The albedo of the new snow related to the short-wave radiation is 75—90 per cent. However, the albedo of old and wet snow may be as small as 43 per cent (GEIGER 1950, p. 165). Of the reflected radiation the greatest part is absorbed by the trees.

The energy absorbed by the trees is utilized by them for convection of air, for transpiration, for long-wave radiation upwards, for long-wave radiation towards the snow, and for photosynthesis in the trees.

The snow cover absorbs 99.5 per cent of the in-coming long-wave radiation and reflects long-wave radiation as a black-body (FRANSSILA 1949, p. 133). Of the long-wave radiation reflected by the snow cover the trees intercept the greatest part and, in turn, reflect some of it back to the snow surface.

The following figures illustrate the distribution of the insolation energy in pine dominated forest according to MILLER (1955, p. 109). They represent the thermal balance of a forest stand in the Sierra Crest Region at midday during weathering periods in winter and spring from 1946—47 to 1950—51 in $cal/cm^2/hour$

	Winter	Spring
Insolation	50	90
Disposal of insolation		
Reflection from trees	2	4
Reflection from snow	11	12
Absorbed by snow	6	23
Absorbed by trees	31	51

	Winter	Spring
Loss of heat absorbed in trees		
To the air by convection	17	24
As latent heat through transpiration	5	13
By long-wave radiation to the sky	5	7
By long-wave radiation to the snow	3	4
In photosynthesis	1	2
By storage overnight in branches	0	1

The short-wave radiation is able to penetrate the snow cover rather deep. In case of new snow 50 per cent of the radiation penetrating the snow reaches a depth of 10 cm and 10 per cent reaches 30 cm. Radiation penetrates old snow to a lesser degree.

If the radiation penetrating the snow meets a stone, a twig, brushwood or other obstacle inside the snow, the temperature of those may exceed 0° C in which case coniformed cavities are formed due to the increased melting rate. The same reason also causes the snow cover to disappear more quickly around the tree trunks than from the forest in general.

The decreasing of snow in forest compared with the decrease on open areas

It is general knowledge that snow disappears earlier from the open areas than from the forests. In many western states in U.S.A. for example, in Idaho (CONNAUGHTON 1935), in Colorado (WILM and E. G. DUNFORD 1948), and in California (KITTREDGE 1953) the rate of the melting of snow in pine dominated forests has been investigated and in general it has been established that the rate of snow melt under forest canopy is about 70—80 per cent of the melting rate in forest openings (GOODELL 1959, p. 52). In Idaho it has been established that thick branches have a positive effect in decreasing the rate of snow melt. The melting of the snow in mature timber forest lasted 8 days longer than on open areas (CONNAUGHTON 1935, pp. 564—569). In Finland KAITERA (1939, p. 70) has observed that in 1934—37 the snow disappeared from the transects 4—6 days earlier in the open than in the forest. KORHONEN (1918, p. 6) suggested that the snow disappears from the open fields on an average two weeks earlier than from the forest. The great difference between the estimates of Kaitera and Korhonen may be due to the character of the winter or to the different determination of the time point of disappearance of snow (KAITERA 1939, p. 71). SIMOJOKI (1947, p. 21) has calculated that on an average between 1892—1941 the snow disappeared from the unshaded open areas 13—14 days earlier than from the forests.

In U.S.S.R. it has been established that, depending on the weather during the melting period, the difference of the time of melting in forest and open area may vary from one or two days to many weeks. In the forest the snow remains longer during prevailing clear anticyclonic weather when the air warms slowly (RAKHMANOV 1957, p. 210).

Patches of snow may be found in dark shaded spots long after the snow has disappeared from the greater part of the forest. It is difficult to estimate the disappearance of the last patch of snow if the forest is not thoroughly investigated continuously.

The rate of the decreasing of snow in pine dominated forests and on the open areas is easier to compare if the investigation is limited to the end of the time of permanent snow cover. The decreasing of snow cover has herein been investigated in this way at the stake-stations where stakes are found both in forest and in the open. The stations have been divided into two groups according to the density of the forest. In both groups the average water equivalent of snow cover on open areas and in forest has been calculated at time point τ_0 — 20 days, τ_0 — 15 days, τ_0 — 10 days, τ_0 — 5 days, and at τ_0, the last mentioned indicating the end of the observation days when some snow could be found around all measuring stakes. For simplification and clarity the water equivalents of the snow have been reduced to the mean value of the water equivalent of snow calculated for the open fields for all the stations. In Figure

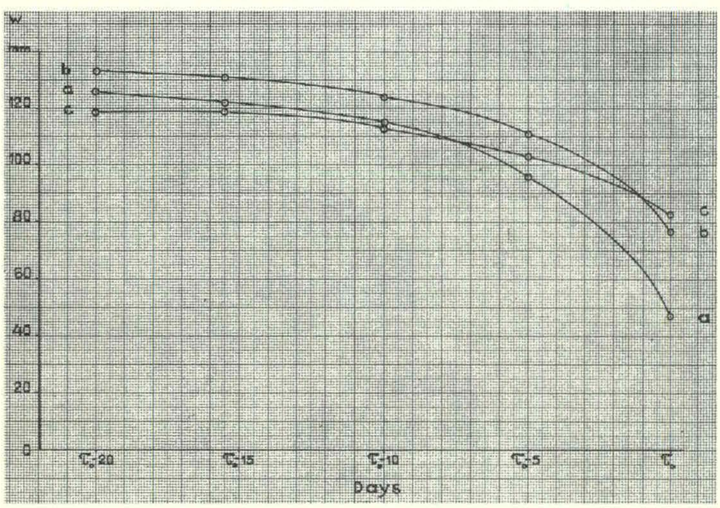

Fig. 11. Water equivalent of snow cover at the time of permanent snow cover in 1959—60 on open areas (a), in thin pine dominated forest (b), and in dense pine dominated forest (c)

11 curve (a) shows the average course of the water equivalent of snow on open areas of all stake-stations, curves (b) and (c) the reduced means of the water equivalent of snow for groups of stations of thin and dense forest. At the stations with thin forest the density of the forest averaged 13 pines per 400 m^2 while the dense averaged 28 pines per 400 m^2.

From Figure 11 it can be ascertained that at time point $\tau_0 - 20$ days most snow was found in the thin forests and least in the dense ones, whereas at time point τ_0 most snow was found in the dense forests and least on the open areas.

Some significance may be attached to the fact that at time point $\tau_0 - 1$ day the average amount of snow was the same in dense and in thin forest (Fig. 11).

The decreasing of snow in places of different density in the forest stand

In general it has been observed that the rate of snow melt is different in different places in a stand and that in general the snow melts earliest close to the trunks of the trees and is retained longest on open spaces between the trees. One of the most apparent reasons for this is that close to the trunk the excess heat radiated by the trees melts the snow and is disapated quickly. Direct insolation also penetrates the snow and may increase the temperature of the part of the trunk below the snow, again causing the snow to melt close to the trunk inside the snow pack. Of the long-wave radiation reflected by the snow surface less becomes intercepted by the crowns in spaces between the trees than close to the trees. The surface of snow in spaces between the trees also obtains less direct insolation than the snow surface under the crowns. Before the beginning of the melting of snow more snow is found in the spaces between the tree crowns than under the trees. Finally, more needles and other debris fall to the snow surface under trees, all of which absorb heat and melt the snow.

Trees do not stand at regular distances from each other in a stand. Denser foliage transmits less short-wave radiation. The rate of snow melt is inversely proportional to the amount or duration of shade. The rate of snow melt depends in addition on the threshold of the energy supply: a high input of energy will cause melt while a lower one will not, no matter how long continued (Goodell 1959, p. 53). Short-wave radiation transmitted by the thinner crown foliage may increase the amount of energy on the snow surface to a point that exceeds the threshold while the snow surface in another place in the stand may be shaded to such a degree that no melt occurs or if it does it is much slower. The sublimation of the snow is also slower in a place in dense shadow.

It has been mentioned before that less direct insolation reaches the snow surface in the spaces between trees than the snow surface directly under the crown canopy. It seems to be evident that denser and thinner parts in a stand occur alternately in such a way that close to a dense part there is a thin part. Insolation transmitted through thin foliage reaches the snow surface under the foliage of the dense part of the stand and heats the trunks in the dense part. The shadow from the dense part of the stand usually falls on the snow surface in the thin part of the stand and thus delays the decreasing of the snow there.

Many investigators in U.S.A. have reached the conclusion that in forest openings approximating 1 to 2 tree heights in diameter the snow is retained longer than in smaller or larger ones (GOODELL 1959, p. 52). As the melt season progresses the most snow is found continuously in smaller and smaller forest openings, with the last snow remaining in forest openings about one half a tree height in diameter (ANDERSON *and others* 1958, p. 48).

The dependency of the decrease of the snow on the number of neighbouring trees at Pyhäkoski stake-station for the time interval April 21—May 5, 1956 and April 15—April 30, 1957 has been studied. At the beginning and end of this time interval the average depth $(\bar{h})$, density $(\bar{\varrho})$ and water equivalent of snow $(\bar{w})$ were as follows:

Date	$\bar{h}$ cm	$\bar{\varrho}$ g/cm^3	$\bar{w}$ mm
April 21, 1956	53.1	0.274	146
May 5, 1956	18.4	0.310	56
April 15, 1957	47.7	0.307	146
April 30, 1957	21.2	0.296	63

During the first time interval the water equivalent of snow had diminished by 90 millimeters and in the latter case by 83 millimeters.

We are now able to examine the average effect of the number of trees on an area of 25 m^2 on the decreasing of snow in the middle of this area.

We denote

$$\Delta h = an + n \text{ cm}$$

where Δh is the decreasing of snow at the individual measuring stakes, n the number of trees on the 25 m^2 area close to the stake and a and b are constants. For the constants a and b the following values were obtained by the method of least squares:

Time interval	a	b
April 21—May 5, 1956	1.2	32.3
April 15—April 30, 1957	1.0	24.3

The calculated decrease of the depth of snow varied from the measured decrease in the first time interval by $\pm$ 3.6 centimeters and in the latter time interval $\pm$ 3.2 centimeters.

The computed average decrease of the water equivalent of snow (Δw) was in time intervals

April 21—May 5, 1956	$\Delta w = 3.0\, n + 84$
April 15—April 30, 1957	$\Delta w = 3.2\, n + 76$

According to these results the rate of the decreasing of snow at the Pyhäkoski stake-station, during the time interval mentioned above, was greater in denser parts of the stand than in thinner parts so that if there was one tree more on an area of 25 m² the rate of the decreasing of snow was increased on an average by about per cent.

If the average density of one stand is greater than that of another the decreasing of snow is delayed in the denser one. But when denser and thinner parts of the same stand are considered, meaning the density or the thinness caused by the uneven distances between the trees in the same stand, then according to the results at the Pyhäkoski stake-station the decreasing of the snow in the denser part of the stand would be faster than in the thinner part if the denser and thinner parts are of the size of 25 m².

We have further examined the final phase of the decreasing of snow at the Pyhäkoski stake-station. As has been mentioned before there were altogether 108 stakes fixed in the ground in pine dominated forest at this station. On May 7, 1957 the snow cover had disappeared close to 30 stakes. At other stakes some snow remained and at 52 measuring stakes the depth of snow was $\geq$ 10 centimeters.

The density of the forest was determined in number (n) of trees close to the stakes on an area of 25 m² having the measuring stake in the center of it.

The measuring stakes were grouped according to the density of the forest. The figure f indicates the number of measuring stakes in each class.

The figure f_1 in each class indicates the number of measuring stakes with no snow close to them.

The figure f_2 indicates in each class the number of measuring stakes with the depth of snow close to them > 0 but < 10 centimeters.

The figure f_3 indicates in each class the number of measuring stakes with the depth of snow close to them $\geqq$ 10 centimeters.

The following table of distribution is obtained:

n	0	1	2	3	4	5	6	7	8
f_1	2	5	5	12	5	3	—	—	1
f_2	3	4	8	4	2	2	—	—	0
f_3	14	20	9	7	2	0	—	—	0
f	19	29	22	23	9	5	0	0	1

If in each class the frequencies f_1, f_2, and f_3 are expressed in percentage of the corresponding frequency f, the table will get the following form:

n	0	1	2	3	4	5	6	7	8
f_1	11	17	23	52	56	60	—	—	100
f_2	15	14	36	20	22	40	—	—	0
f_3	74	69	41	30	22	0	—	—	0
f	100	100	100	100	100	100	—	—	100

It can be seen that the per cent of the number of cases with no snow (f_1) increased with an increasing number of trees n, and that the per cent of the number of cases f_3 with most snow ($h \geqq 10$ cm) decreased with an increasing of number of trees. In other words: Spots without snow were in general found in the denser part of the forest and most snow was in general found in spots in the thinner part of the forest.

The influence of the position of trees on the decreasing of snow

The rate of the decreasing of snow varies directly with the total energy supply at the snow surface. This total generally reaches the maximum when the sun is in a south or south-west position. For instance at the Juuka stake-station in the spring of 1960 the rate of the decreasing of snow was on an average fastest 2 hours after the sun had reached its highest position. This can be seen in Figure 12, which shows the average distribution of the density of forest close to stakes (M) where snow was still found on April 24, 1960. The density of the forest was determined as the sum of the vertical profile area of the trees (ΣB m^2) on 100 m^2. The number of cases was 26.

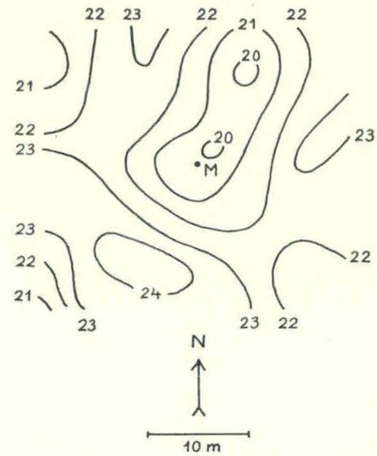

Fig. 12. The average distribution of the density of forest (ΣB m² per 100 m²) at Juuka stake-station close to stakes with some remaining snow on April 24, 1960

The density of the forest was on an average greatest at about 12 meters distance in south-west direction from the stake. Evidently such shading trees had delayed the decreasing of snow. Further it is to be noticed that the density of forest was usually relatively small in a north-east direction from the measuring stakes, which would indicate that in this direction the trees would radiate heat most effectively to the spot M.

In the following the influence of trees in a south-west and a north-east position on the decreasing of snow at Pyhäkoski stake-station during the time intervals April 21—May 5, 1956 and April 15—April 30, 1957 have been examined.

The density of the forest was recorded as the number of trees on an area the size of 25 m². In Figure 13 point M indicates the measuring stake while points A_1, A_2 . . . A_5 and B_1, B_2 . . . B_5 are points of the stand at regular distances on the same line.

Assume that in the drawing in Figure 13 are n_1 trees in the square of 25 m² with A_1 in the middle, n_2 trees in the square with A_2 in the middle of it, etc. In addition it will be assumed that all trees in the square with A_1 in the middle have reciprocally a similar kind of influence on the decreasing of snow close to the measuring stake M, that all trees in the square with A_2 in the middle have reciprocally a similar kind of effect, etc. We denote the decreasing of the snow depth Δh close to the measuring stake M

$$\Delta h = \overline{\Delta h} + \sum_{i=1}^{5} (k_i\, n_i) \text{ cm},$$

where $\overline{\Delta h}$ is the average decreasing of snow, n_i the number of trees in square A_1 and k_i a constant belonging to the figure n_i. By the method of least squares values have been determined for the constants k_i. These calculations have been done separately for the time intervals April 21—May 5, 1956 and April 15—April 30, 1957.

Further the same calculations have been carried out with B_1, $B_2 \ldots B_5$ as the center points of the squares.

Figure 14 presents the values obtained for constants k_i. Values concerning the time interval April 21—May 5, 1956 are represented by dots (·) and values concerning the time interval April 15—April 30, 1957 with crosses (x). Curves (a) and (b), drawn according to the weighted points show the adjusted values of the constant k_i on line B_1 A_5, the curve (a) in time interval April 21—May 5, 1956 and the curve (b) in time interval April 15—April 30, 1957.

These results are only approximations as other causes than trees in the squares mentioned above also have an effect on the decreasing of snow close to the measuring stakes. The purpose has been to give a rough picture of the influence of the trees on line B_1 A_5 on the decreasing of snow close to the measuring stake M.

The curve (c) shows the average adjusted values of the constant k_i at both time intervals. From the curve it is seen that in the square with point B_3 in the middle the value of the constant k_i is 1.2 cm. This is close to the average value 1.1 cm for the constant a, mentioned on page 40.

The constant k_i indicates the influence of one tree on the decreasing of snow close to the measuring stake M. According to the curve (c) a tree at 5 meters distance from the point B_3 in a south-west direction does not affect the snow melt close to the measuring stake ($k_i \backsim 0$). This could be explained by the fact that the shade of the tree mentioned nullifies the effect of the heat

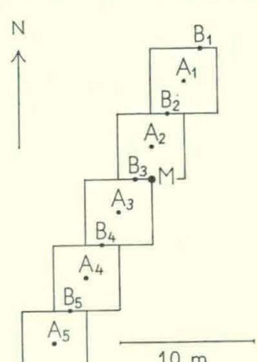

Fig. 13

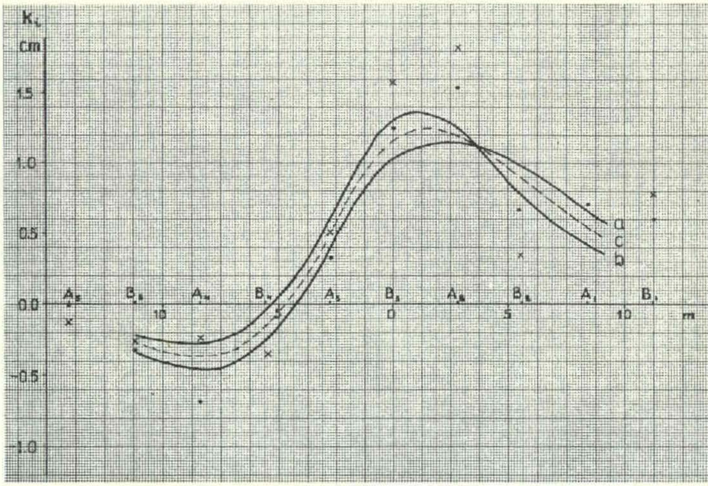

Fig. 14. Values of constant k_i in the formula $\Delta h = \overline{\Delta h} + \sum_{i=1}^{5} (k_i n_i)$ calculated according to the results of the Pyhäkoski stake-station.

radiation provided by the tree. The effect of the shade of the trees 5 to 15 meters south-westwards from point B_3 is greater than the heat radiation of the trees thus meaning that those trees delay the decreasing of snow close to the measuring stake M. According to the curve (c) the tree standing between points B_3 and A_2 would have the greatest promoting effect on the decreasing of snow.

The amount of heat radiated by pines depends chiefly on the temperature of the needles. In clear weather during the daytime the temperature of the needles is higher than the air temperature. This difference of temperature depends on the velocity of the wind. MILLER (1955, p. 99) presented a formula

$$D = 6.0 - 1.8 \, ln \, V,$$

where D is the temperature difference of needles and air (C°) and $ln \, V$ is the natural logarithm of wind speed miles per hour.

The velocity of the wind at 1400 in Oulu averaged 3.2 m/sec for the time interval April 21—May 5, 1956 and 2.2 m/sec for the time interval April 15—April 30, 1957. In the first case the velocity of the wind was, during the time of the fastest decreasing of snow, on average 1 m/sec greater than in the latter case. As the Pyhäkoski stake-station is situated only 40 kilometers south-east-east of Oulu, it may be assumed that at the Pyhäkoski stake-station at 1400 the velocity of the wind also averaged 1 m/sec greater during the first time interval than at the latter.

The influence of the shading of the trees and the heat radiated by trees on the decreasing of snow at Pyhäkoski stake-station in time intervals April 21—May 5, 1956 and April 15—30, 1957 has been roughly compared.

In Figure 15 M indicates an individual measuring stake and both A and B areas of the size of 75 m^2 each. On the whole measuring site there was an average of 5 trees per 75 m^2. Assume that there are n_1 trees on area A and n_2 trees on area B.

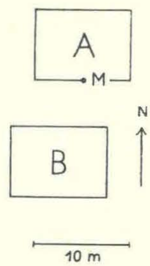

Fig. 15

Assume that the decrease of snow is Δh close to the measuring stake. We denote

$$\Delta h = an_1 + bn_2 + c,$$

there a, b, and c are constants. The values of the constants were calculated by the method of least squares separately for the time intervals April 21—May 5, 1956 and April 15—April 30, 1957. The average deviations ϑ of the calculated values of Δh from the measured ones were similarly calculated. We obtain the following expressions:

Time interval	Δh (cm)	ϑ (cm)
April 21—May 5, 1956	$0.2\, n_1 - 0.5\, n_2 + 36$	± 3
April 15—April 30, 1957	$0.3\, n_1 - 0.3\, n_2 + 26$	± 3

Assuming the average decrease of the water equivalent of snow (Δw) during those time intervals to have been proportional with the decrease of depht of snow, the following computed expressions will be obtained for the average decrease of the water equivalent of snow:

Time interval	Δw (mm)
April 21—May 5, 1956	$0.4\, n_1 - 1.2\, n_2 + 93$
April 15—April 30, 1957	$0.9\, n_1 - 1.0\, n_2 + 81$

It can be seen that the effect of the trees on area A on the decrease of snow close to the measuring stake M was, according to the expressions, less in the former time interval than in the latter one. This might indicate that in the former time interval the trees on area A radiated less heat, which could be explained as due to the stronger wind prevailing in the former time interval. However, the effect of the trees on area B on the decrease of snow close to the measuring stake M was, according to the expressions, greater at the first time interval than at the latter. This would indicate that the role of the direct insolation on the decrease of snow was greater in the former time interval.

The positive and negative signs of the coefficients a and b are evidently correct. One might also say that the ratios of the absolute values of the coefficients are not unreasonable in a quantitative sense.

The decrease of snow close to the measuring stake M is also influenced by factors other than the trees on the areas A and B. But as there were a total of 108 measuring stakes at Pyhäkoski stake-station, and, as the determination of the values of the coefficients a and b was thus based on 108 equations, the effect of those factors should have been partly negated or smoothed out.

The results show, at least, that the radiation conditions of the forest might well be studied effectively solely by snow measurements if a sufficiently large number of observations is recorded in mapped out forest stands.

SUMMARY

The main purpose of this investigation has been to further investigate the problem of how the forest density and the position of the trees affect the accumulation and decreasing of snow in pine dominated forest in Finland. The results of the investigation are necessarily of the approximative nature. However, it is to be hoped that the desired effect will be to stimulate more detailed, exact investigations into the problems which have been shown to offer the best possibilities.

The results of the investigation are herewith summarized:

1. With the regular snow courses and snow measurements in different types of terrain the number of observation points was on the average distributed more in forests thinner than normal than in denser than normal (p. 12).

2. This favouring of thinner forests was on the average greater in the regular snow courses than in the snow measurements in different types of terrain (p. 12).

3. According to snow courses on January 16, 1952—60 in Finland the water equivalent of the snow in pine dominated forest averaged 85 per cent, 94 per cent and 99 per cent of the water equivalent of snow on open areas in zones 60°—62° N lat, 62°—64° N lat, and 64°—70° N lat respectively (p. 26).

4. On February 16, 1952—60 the water equivalent of the snow on snow course stations averaged in thin pine dominated forest 101 per cent, in rather thin 99 per cent, in forest of normal density 95 per cent, in rather dense forest 92 per cent, and in dense forest 86 per cent of the water equivalent of snow on open areas (p. 27).

5. The variations in the density of forest affected the water equivalent of the snow at Pyhäkoski stake-station in the middle of March in years 1956 and 1957 as follows:
   a. If there was one tree more than the average on an area of 400 m^2 the water equivalent of snow in the middle of this area averaged 0.6 mm or 0.4 per cent less than the average water equivalent of snow on the whole measuring site (p. 30).
   b. If there was one tree more than the average on an area of 100 m_2 the water equivalent of the snow in the middle of this area averaged 2.8 mm or 1.9 per cent less than the average on the whole measuring site (p. 30).
   c. If there was one tree more than the average on an area of 25 m^2 the water equivalent of the snow in the middle of this area averaged 3.5 mm or 2.3 per cent less than the average on the whole measuring site (p. 30).

6. In winter 1959—60 at Juuka stake-station the greatest part of the precipitation which had fallen before January 15, had occurred during prevailing southerly winds. Hence, at a distance of 5 meters from a tree with a vertical profile area of 25 m^2 the depth of snow averaged 6 cm or 15 per cent less than the average depth of snow on the whole measuring site (pp. 32—33).

7. At Pyhäkoski stake-station the water equivalent of snow in the middle of an area of 25 m^2 containing one tree more than on average 25 m^2 plot, during the time intervals April 21—May 5, 1956 and April 15—April 30, 1957, had decreased on an average about 3 mm or 4 per cent more than the average on the whole measuring site (p. 40).

8. If the density of the forest is determined as number of trees on an area of 25 m^2 then

   a. the first bare spots appeared in general in such places in the forest where the density of the forest was great, and

   b. most of the snow was retained in general in such places where the density of the forest was least (p. 41).

9. If the density of the forest was determined as the sum of the vertical profile area of the trees, then the last patches of snow occurred about 12 meters north-east of the most densely forested area and 2—10 meters south-east of the least dense areas (p. 42).

10. The surface of the snow seemed to obtain the greatest amount of heat radiation from trees 1—3 meters north-east of it (p. 44).

11. The influence of the heat radiation from trees seemed to be less with stronger wind than with prevailing lighter wind (p. 46).

12. The influence of the heat radiation of north-side trees on the decreasing of snow seemed to be of the same magnitude as the influence of the trees shading in the south-east side with reference to the absolute value (p. 46).

ERRATA

Page	7,	Line 20,	Change	Institute	to	Office
»	15,	Line 24,	»	standard	»	mean
»	17,	Line 6,	»	the depth	»	the means of the depth
»	18,	Line 14,	»	density	»	water equivalent
»	19,	Fig. 6,	»	left hand lower h'_{min}	»	h_{min}
»	19,	Fig. 6,	»	right hand h'_{max}	»	h_{max}
»	32,	Line 8,	»	$\Sigma B_1, \Sigma B_2, \ldots \Sigma B_9$	»	$(\Sigma B)_1, (\Sigma B)_2, \ldots (\Sigma B)_9$
»	32,	Line 13,	»	ΣB_i	»	$(\Sigma B)_i$
»	32,	Eq.,	»	$\Delta h = \sum_{i=1}^{9} (a_i \Sigma B_i)$ cm,	»	$\Delta h = \sum_{i=1}^{9} a_i (\Sigma B)_i$ cm,
»	32,	Line 18,	»	ΣB_i	»	$(\Sigma B)_i$
»	34,	Line 2,	»	S.S.W.	»	SSW.
»	34,	Line 3,	»	N.N.E.	»	NNE.
»	39,	Eq.,	»	$\Delta h = an + n$ cm	»	$\Delta h = an + b$ cm
»	48,	Line 12,	»	north-east	»	north-west
»	50,	Line 34,	»	*50*, p. 7.	»	*50*, No. 23, p. 7.

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