Studies on the Stand Structure and Light Climate (II)* Methods of Investigating the Sunfleck on the Forest Floor (1)

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林分構造と光環境に関する研究 (II)* 陽斑点の測定法 (1)

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Contents

要 旨

林内光の直射成分，すなわち陽斑点 (Sunfleck, SF) について調べた。

林内の相対照度が4.7％の日野ヒノキ林（滋賀県蒲生郡日野町綿向山）で陽斑点を調べた結果，全測定数中陽斑点は23％であるが，量的にみると総受光量の63％が陽斑点により占められていることがわかった。陽斑点の空間分布はほとんど機会分布をしており，太陽高度が低くなるにつれ機会分布から一様分布に変化する傾向がみられた。陽斑点出現率 (SFn rate) は１日のうちで太陽高度が最も高い時必ずしも高くならず，その前後にピークを示していた。全天空写真により角高度について林冠空隙率 (G, ％) を調べた結果，調査林分では G のピークは40～70度の間にあり季節変化し SFn rate のピークを示す角高度と一致した。陽斑点の大きさ (l) とその中心の相対照度 (r_0)，陽斑点の中心からの距離 (d) とその点の明るさ (r) の関係を求めることにより陽斑点の出現率と量の推定が可能となった。

l～r_0 の関係は

$$r_0=\frac{100}{1+ke^{-\lambda l}}$$

r～d 関係は

$$r=\frac{R}{1+pe^{\mu d}}$$

$k, \lambda, R, p, \mu,$ ：定数　　に近似された。

陽斑点の必要測定点数 (N) は陽斑点の時期的移動，測定所要時間を考慮するとこの調査林分では25点 (100m^2) 以上必要である。

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* This work was part of that undertaken for the degree of Doctor at Kyoto University.

Summary: This paper deals with the direct light in a stand, defined as sunfleck. Light climate in plant communities has been measured under diffuse light conditions. In surveying the relationship between production of plant communities and incident light, a direct light factor should be added to the relationship. Of special importance is its effect on the growth of understorey plants.

The results of this investigation were as follows:

1) In a *Chamaecyparis obtusa* stand, with a mean relative light intensity of 4.7 per cent, the proportion of the area occupied by sunflecks (SFn rate) was 23 per cent. However sunflecks were attributed with as much as 63 per cent of the total light intensity on the forest floor.

2) The distribution patterns of sunflecks on the floor were mostly random, but had a tendency to change from random to uniform with declining angular height of the sun.

3) The proportion of the area occupied by sunflecks was not the largest when solar angular height was at its diurnal maximum. The propotion of gaps in the canopy at an angular height (G, %), investigated by the hemispherical photographic method showed the maximum value (G_{max}) between 40 and 70 degrees by seasonal crown conditions in this stand. The angular height of G_{max} varied with species, tree density and so on. In a sapling stand of *Alnus hirsuta* var. sibirica the angular height of G_{max} showed a value close to the zenieth.

4) Total light intensity and the proportion of total sunfleck light to the total light intensity over the forest per unit area (SF rate) could be calculated by the estmation of the relationships between diameter (l) and light intensity at the center (r_o) of the sunfleck, distance from the center of the sunfleck (d) and relative light intensity at any point (r).

The relationship between r_o or r and l or d gave a close approximation as follows:

$$r_o = \frac{100}{1+kd^{-\lambda l}}$$

and

$$r = \frac{R}{1+pe^{\mu d}}$$

k, λ, R, μ, P: constants

5) The necessary number of measured sunflecks (N) was 25 (100 m^2 in area) in the stand, considering the sunflecks varied with time, and the time necessary for measuring sunflecks.

Introduction

Measurements of light climate in woodlands have been made under cloudy conditions. Under clear sky conditions, the direct sunlight has been excluded from measurements in a stand. However direct light is important to the growth of woodland floor plants, and is more favourable for photosynthesis than shade light. Light in woodland is composed of diffuse and direct light, the latter termed "sunfleck". Sunlight through gaps in the canopy gives rise to sunflecks on the woodland floor. Considering the relationship of light intensity to growth of the plants under the canopy, measruement of sunflecks must be made in both space and time. The spatial variation in the structure of the plant community will be reflected in the spatial variation of the sunflecks on the woodland floor.

Definition of sunfleck

The light component in woodland is composed of direct and diffuse light. The direct light factor is sunlight penetrating through the canopy, and composed of sunfleck and shade light. As sunfleck is superimposed on a basic shade light, sunfleck light can be deducted from the total incident light and remaining light is due to shade light. The diffuse light is composed of direct sky light pentrating through the canopy gaps, and the light reflected from and transmitted throgh individual plant parts, defined as the shade light. In this present paper, sunfleck light intensity was discovered experimentally to exceed double the shade light intensity; therefore direct light intensity was more than three times that of shade light. The method of distinguishing direct light from shade light on the forest floor is dealt with in the following section.

Stand outlines and methods of the investigation

The investigation was made in *Chamaecyparis obtusa* plantation aged 37 years on a flattish slope of Mt. Watamuki in Hino town, Shiga Prefecture. The altitude is about 440 meters above sea level. There were scarcely any woodland floor plant living. The crowns were fully closed. There were 3800 trees per hectare with a stand basal area of 50.9 square meters per hectare. The mean stem diameter at breast height and the mean tree height were 13.3 cm and 11.5 m respectively. The investigation was undertaken from 1969 to 1973. The main area studied was a 10×20 m plot situated at the center of the stand. For the purpose of the study the plot (200 m^2) was divided by white lines 50 cm apart into 800 square blocks. The intersections of lines were fixed with piles, and used for measuring sunflecks and light intensities. The investigation of the spatial distribution of sunflecks were made by the following three methods.

Direct method (*D*-Method): Measuring light intensities at the intersections with photometers.

Photographic method (*P*-Method): Recording sunflecks on the floor photographically by taking photographs with a wide-lens at 3 meters height.

Visual method (*E*-Method): Similar to *P*-Method. Judging sunflecks visually. Other methods of analyzing sunflecks are dealt with in the following section.

Analysis of sample data and discussion

Before preceeding, we have to estimate sunfleck light intensity and the total number of sunflecks from every measuring point. We consider data obtained by *D*-Method on May 9th, 1969 as an example of the methods of calculation. In determing the basic shade

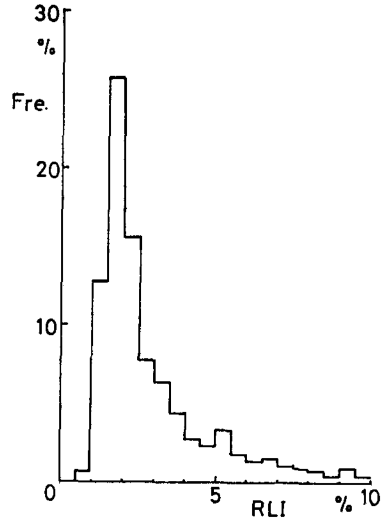

Fig. 1. An example of the frequency distribution of relative light intensity in *Chamaecyparis obtusa* stand at Hino (May 9, 1969).

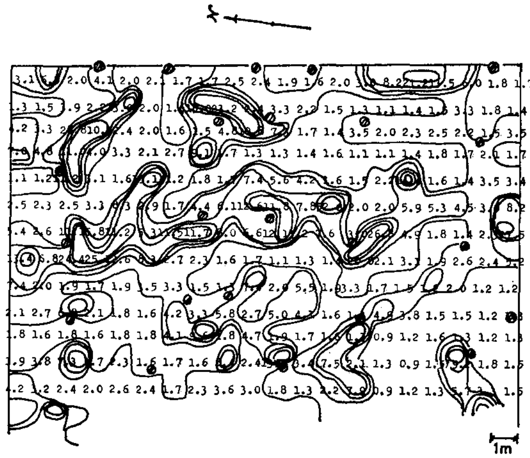

Fig. 2. Distribution map of sunflecks.
Values show relative light intensities at the points.
●: Position of tree.

Table 1. Total sunfleck light and the proportion of the sunfleck to the total light on the floor in *Chamaecyparis obtusa* stand, Hino

Date		9th May 1669 (A)	22nd June 1973 (B)
Total relative light intensity (%)	(1)	3723.90	2502.25
Total sunfleck light intensity (%)	(2)	2356.04	560.10
The proportion of total sunfleck light to the total light intensity (SF rate) (2)/(1)	(3)	0.6348	0.2238
The proportion of sunfleck to the total measuring points (SFn rate)	(4)	0.2250	0.0750
Mean value of relative light intensity (%)	(5)	4.65	3.13

light intensity, we used the histograms of relative light intensities and maps which were constructed with contour lines of light intensities on the floor (Fig. 1, 2). Under sunny conditions, the mode of light frequency distribution in closed crown woodlands was approximately the mean shade light intensity. The other estimation was made by analyzing contour maps of relative light intensities. The mean value of light intensities observing no visible sunfleck is defined as a shade light. The values for shade light measured with a photometer directly agreed with those estimated from the previous method. Having analyzed the distribution of light intensity on woodland floors, visible sunfleck light intensity proved to be more than twice that of shade light; therefore direct light intensity exceeds three times that of shade light, derived from the relationship between r and d, r being relative light intensity and d being distance from the center of sunfleck. Derived from the values on May 9th 1969, mean shade light intensity was 1.7 per cent (1401 lux), as shown in Table 1. Therefore direct light intensities were more than

5.1 per cent (1.7% × 3). As sunflecks are superimposed on a basic shade light, sunfleck light is what remains after deducting shade light from the total light. In Table 1 with total light being 3723.9 per cent, of which total shade light was 1360 per cent (1.7% × 800), total sunfleck light was 2363.9 per cent. The proportion of the total sunfleck light to the total incident light was 0.6348 ((2)/(1)). As the number of readings for observing sunflecks was 180, the proportion of the area occupied by sunflecks would be 0.225 (180/800; (4)). Investigation-*B* was the same method as *A*, but the number of meauring points of *B* was only 320, *A* being 800 points. In Table 1 the values of *B* are converted into those for 800 points. The SF rate of *B* had decreased to one-third of that of *A*. Although total light intensity of *B* had two-thirds of that of *A*, total sunfleck light was only a quarter of *A*. On the other hand the SFn rate was 33 per cent of *A*. Due to the decrease in high light intensity, the rate of decrease of SFn rate was larger than that of SF rate. This reason was proved by the histograms of relative light intensities. The proportion of high light intensities to total light decreased in 1973 compared with middle and low light intensities. Estimation of the relationship between integrated area and light intensity of the sunflecks leads to the total light climate on the floor. We could estimate the relationship between *Ar* and *RLI*, *Ar* being integrated sunfleck area and *RLI* being relative light intensity per cent (Fig. 3). The smooth curve plotted in Fig. 3 is for $RLI = 33.7 \exp(-0.117\, Ar)$. Evans (1956) was reported that *RLI* exponentialy decreased with *Ar*, and the same result was obtained in this observation. In this stand the *RLI*–*Ar* relationship was obtained from the following equation;

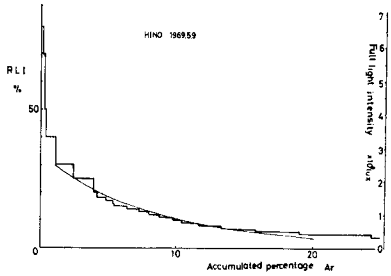

Fig. 3. Relative lighti ntensity (RLI)–accumulated percentage (Ar) relationship. The smooth curve shows the empirical relation.

$$RLI = \alpha e^{-\beta Ar} \cdots\cdots\cdots\cdots\cdots\cdots (1)$$

α: constant, β: coefficient

As the crown of a stand gradually closed, α decreased and β increased. Under the same light conditions in the open, the curve shifted with decreasing α, as leaf biomass increased. In a stand of the same leaf biomass, the maximum value of sunfleck light intensity was higher and the minimum became lower, as light intensity in the open became higher. Sunfleck light intensity decreases with distance from the center of the sunfleck. An accurate value for sunfleck light energy in a stand is reqired for estimation of area and changing sunfleck light intensity from the center to edge.

First of all, we investigated with r_o-l relationship, r being relative light intensity at the center, l being diameter of the sunfleck. Where l was calculated by following formula;

$$l = \frac{l_1 + l_2 \sin H}{2}$$

l_1, l_2: diameter at azimuth 90°, 0° from the sun respectively
H: solar angular height

l changes by solar angular height. Mitscherlich (1971) reported that the r_o-l relationship was approximately linear. But in Fig. 4–1 it was approximated by a logstic curve. Therefore

$$r_o=\frac{R_o}{1+ke^{-\lambda l}} \quad\cdots\cdots\cdots\cdots\cdots(2)$$

R_o, k, λ: constants

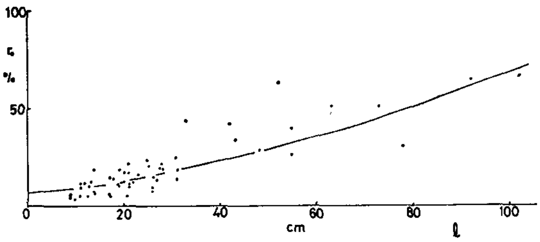

Fig. 4–1. Relationship between relative light intensity at the center (r_0) and diameter (l) of a sunfleck.

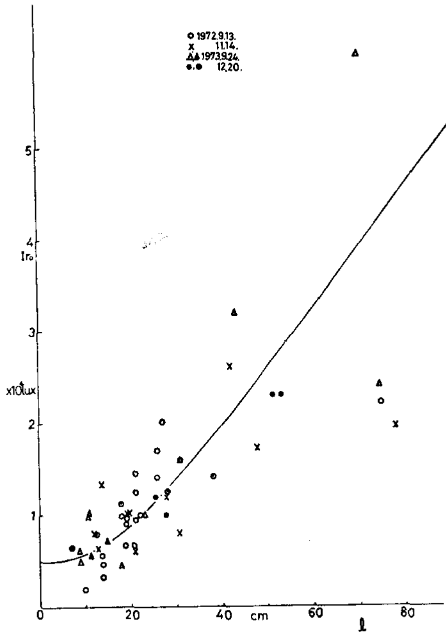

Fig. 4–2. Relationship between light intensity at the center (Ir_0) and diameter (l) of a sunfleck.
○, ×, △, ●: measured ▲, ⊙: calculated

When $r_{o)l=\infty}=R_o=100$, formula (2) is

$$r_o=\frac{100}{1+ke^{-\lambda l}} \quad\cdots\cdots\cdots\cdots(2)'$$

Calculating r_o from Fig. 4–1, $k=13.637$, $\lambda=0.0331$:

$$r_o=\frac{100}{1+13.637e^{-0.0331l}} \quad\cdots\cdots\cdots\cdots(2)''$$

When $l=0$, the light intensity in the open is a composed of diffuse light factor. Then,

$$r_{o)l=0}=\frac{100}{1+13.637e^{-0.0331\times 0}}=6.832 \quad\cdots\cdots\cdots\cdots(2)'''$$

The calculated value was twice as much as that observed. There was a large dispersion in relation between r_o and l, and formula (2)″ was obtained from regulation that fitted the highest frequency values, so that the relative error of r_o became large. From formula (2)″, diameters of sunfleck were calculated as follows;

$$l_{)ro=95.0}=168,\quad l_{)ro=99.0}=217,\quad l_{)r_o=99.9}=289$$

Under sunny conditions, the relative light intensity at the center of a sunfleck which was about 300 cm in diameter was approximately as high as that in the open. Formula (2) was applied under sunny conditions but not under cloudy ones. Under clear sky, r_o was almost 100 when l was 300 cm as the light in the open was almost wholly occupied by the direct factor. But under cloudy conditions the light in the open is occupied by the diffuse factor and the light in the forest is more occupied by lower angle incident

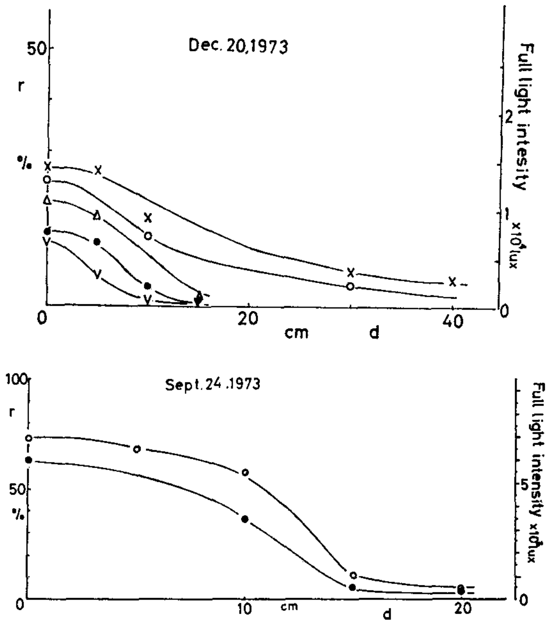

Fig. 5. Relationship between distance from the center of sunfleck (d) and relative light intensity at the point (r).

light than that under sunny conditions. $l)_{r_0=99,9}$ will be estimated as larger under cloudy conditions than that under sunny ones. We were concerned with the relation between the distance from the center of sunfleck (d) and the relative light intensity at the point (r). Fig. 5 shows the relationship between r and d. The value of r decreases with d. That is,

$$r = \frac{R}{1+pe^{\mu d}} \cdots (3)$$

R, p, μ : constants,

When $d=0$, from formula (3) $r_o = r)_{d=0}$. And between r and d, we defined that direct light intensity was more higher than r_s.

Then

$$r)_{d=0} = \frac{R}{1+p} \cdots\cdots (3)'$$

From formula (2)′ and (3)′, we found that

$$\frac{R}{1+p} = \frac{100}{1+ke^{-\lambda l}}$$

Since R and p were estimated from these formula, we could estimate relationships r, r_o, l, d. The relationship of r_o and l was experimentally calculated from r_s, and the values were fitted to the relationship in Fig. 4–2. In this investigation sunfleck was treated as relative light intensity. Under the same light intensity in the open, the area of sunflecks in high tree density stands is lager than that in low density ones. According to relative light intensity estimated by the photographic method as described previously, relative light intensity of more than 5 per cent was regarded as direct light in the forest. It is possible that the values of direct light intensity may vary with light intensity in the open. Then we investigated the relationship between the light intensity of the sunfleck at the center (Ir_o) and the diameter of the sunfleck (l). The trend in Fig. 4–2 is almost the same as that of Fig. 4–1, and the relationship between Ir_o-l and r_o-l are slightly separated by light intensity in the open. When direct light intensity on the floor was more than 5000 lux, the calculated values ageed with the experiment. The more light there was in the open, the larger Ir_o and r_o became. The relationships of Ir_o-l and r_o-l are not sparated by light intensity in the open. Sunfleck made its′ appearance when light intensity in the open was greater than 50000 lux in this stand. As we investigated sunfleck under about 90000 lux, there were no large errors when light intensity of sunfleck was estimated from either r_0-l or Ir_0-l. We investigated the sunfleck at the fixed measuring points and analyzed distribution patterns of sunflecks. Distribution patterns of sunflecks were analyzed by C_A-Index proposed by Kuno (1968) as follow;

$$C_A=\frac{\sigma^2-m}{m} \quad \cdots\cdots (4)$$

σ^2: variance, m: mean value

When the distribution pattern is a Poisson, $C_A=0$, uniform distribution gives $C_A<0$ (minimum value: -1), clumped gives $C_A<0$. Then the $\overset{*}{m}$-m analysis method proposed by Iwao (1968) is adopted.

$$\overset{*}{m}=m+\left(\frac{\sigma^2}{m}-1\right) \quad \cdots\cdots (5)$$

so that

$$\frac{\overset{*}{m}}{m}=1+C_A \quad \cdots\cdots (6)$$

Then $\overset{*}{m}/m$-C_A relationship can be estimated from formula (6). C_A-Index of the distribution of sunflecks in this stand is shown in Table 2. In Table 2 the distribution

Table 2. Spatial distribution of sunflecks and the necessary number of quadrats for measuring sunflecks

Date	Time	C_A	SFn rate	N $t=1$ $\varepsilon=0.1$	$t=1$ $\varepsilon=0.2$	$t=2$ $\varepsilon=0.1$	Method
1969.	5. 9. 1200	−0.0098	0.1038	68	17	271	D
1972.	4.13. 1020	0.2665	0.0525				E*
	1100	−0.0461	0.1051				P*
	1200	−0.0616	0.0550				E*
	1300	−0.1890	0.0625				E*
	5.17. 1140	−0.0097	0.1325	40	10	159	E
	1240	−0.0149	0.1375	34	9	135	P
	1300	−0.0187	0.1130	67	17	268	E
	1350	−0.0107	0.1425	49	13	195	E
	1430	−0.2030	0.0825	91	23	361	P
	6.21. 1055	−0.0389	0.0975	64	16	256	P
	8.19. 1200	0.0157	0.1275	33	9	130	P
	1300	−0.0290	0.1325	51	13	205	P
	9.13. 1100	0.0145	0.1825	46	12	182	P
	1300	0.0070	0.1725	47	12	188	P
	10.18. 1135	−0.219	0.1413	51	13	201	P
1973.	9.24. 915	−0.0217	0.1100	67	17	267	P
	1000	−0.0081	0.1400	42	11	168	P
	1100	−0.0149	0.1663	29	8	105	P
	1155	−0.1050	0.1475	38	10	152	P
	1255	−0.0153	0.1900	22	6	87	P

Plot size; 10×20 m (800 points), *; 10×10 m (400 points) of sunflecks in the stand may be seen as random when C_A–Indices are almost zero. When analyzing the distribution pattern with the I_δ method proposed by Morisita (1959), the distribution did not depart from expectation at the 5 per cent level of significance. The spatial distribution of sunflecks varied diurnally and seasonally with the regular change of light intensity in the open. Under the same light intensity in the open the distribution of sunflecks reflects that of gaps at a certain angle in the forest crown. In Table 2 the previous tendency is not clearly shown. But the values of C_A–Indices on 17th May 1972 and 24th September 1973 show that the distribution pattern changed from random to uniform as the solar angular height became lower. The stand was uniformly planted and at this time the spatial distribution of trees was uniform (Kitamoto et al. 1972). Analyzed by hemispherical photographs (refer to Tamai et al. 1972b), the gaps near the zenith were composed of those in individual crown and of inter-tree spaces, but those in the middle to low angular height were almost composed of those of inter-tree spaces. When solar angular height was high, direct sunlight penetrated directly into the crowns of plants and inter-crown gaps of trees, and the distribution of sunflecks was nearly uniform parrern. The proportion of the area occupied by sunflecks varied with light intensity in the open and became higher as the daylight intensity became higher. But in this investigation sunflecks were measured under the conditions of 90000 lux in the open, and there was scarecely any variation in the proportion with difference of day light intensity. The proportion of the area occupied by sunflecks (SFn rate) in 1972 and 1973 was nearly 10 per cent. Now we analyze SFn rate diurnally. If the spatial distribution of leaves in the forest canopy was random, the length of penetration of day light through the leaf layer is the shortest when solar angular height is at its highest in a day between May and October in this stand. Therefore the time when SFn rate is highest in a day must be nearly 1155 hours. As SFn rate differs with measuring methods, we investigated it by the same method. Then we considered data obtained on April 13th, 1972 measured by the E–Method and on September 24th, 1973 measured by the P–Method. Though the time of the highest solar angular height in the former day was 1155 hours and that in the latter day was 1147 hours, the time that SFn rate was the highest in a day did not agreed with either of them. In Table 2 SFn rate at 1300 hours on April 13th, 1972 exceeded that at 1200 hours close to 1155 hours and the value on September 24th, 1973 showed the same tendency. Now we consider the conditions of sunfleck appearance. SFn rate will be the highest in a day when solar angular height agrees with that of the maxmum proportion of gaps in canopy under the same light intensity in the open. It has been considered that SFn rate becomes greater as angle of light through the canopy becomes greater. Then we investigated the gaps by using hemispherical photographs in the stand. Fig. 6 shows the propotion of gaps (G, %) of an angular height in canopy (Ah). Maximum value of G (G_{max}) was obtained between 35 and 70 degrees, and so was not at the zenith (Ah=90). Looking at the maximum values of G from monthly variation, angular height of G_{max} in April was the highest in a year and was equivalent to 60 degrees. The angular heights of G_{max} in June and October were 50 and 40 degrees respectively. Considering the probability of sunflecks through the gaps under the same conditions in the stand, the probability is the highest in a day when solar angular height agrees with

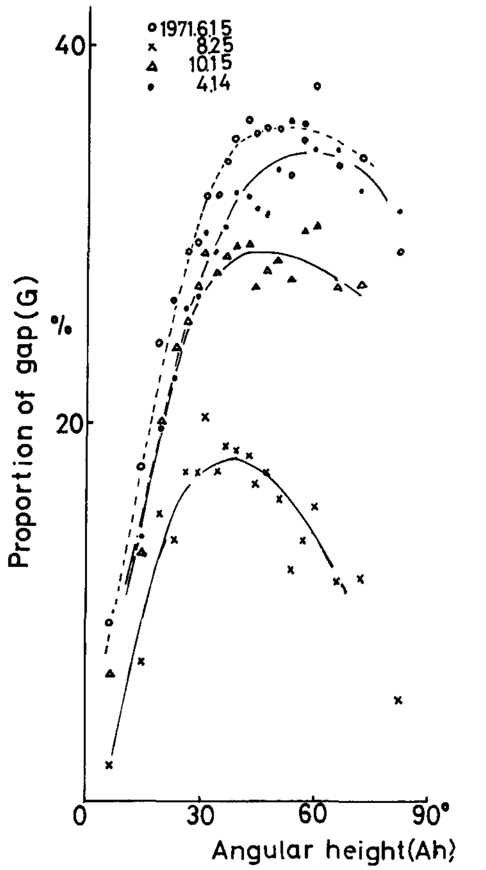

Fig. 6. Proportion of gap in forest canopy (G) at an angular height (Ah) of incident light in the Hinoki stand.

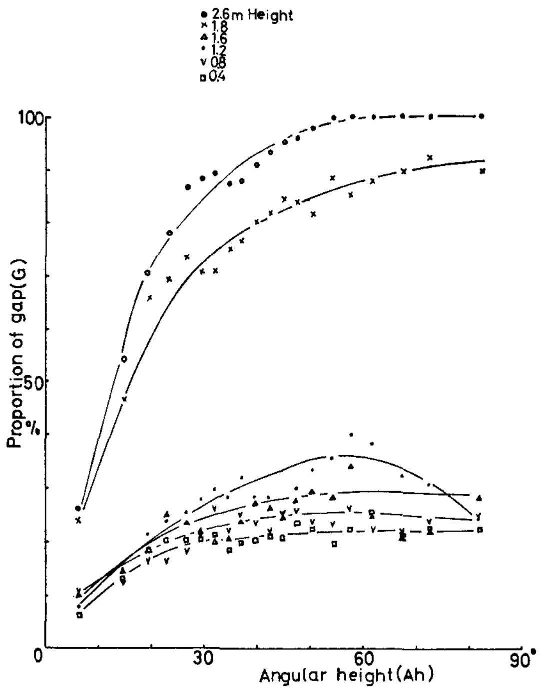

Fig. 7. Proportion of gap in the canopy (G) at an angular height of incident light (Ah) in a sapling stand of *Alnus hirsuta* var. sibirica.

the angle of G_{max}. Estimating G_{max} from Fig. 6, Ah of G_{max} in April and September were 60, 50 degrees respectively. Estimating the times of solar angular height with which angle of G_{max} agreed on April 13th and September 24th, they were 1014 and 1338, 1026 and 1308 hours respectively. SFn rate at the nearest time to them shows the highest proportion in the two or three hours around that time. The results measured on September 24th 1973 show this tendency clearly, and the values at 1026 and 1308 hours are maximum in a day. The other results showed the same. SFn rate is the highest in a day when angle of G_{max} agreed with solar angular height. But the probability of sunflecks should not dealt with G–Ah relationship alone. The probability varied with day light intensity. G–Ah relationship in the stand was in agreement with the result which Warren Wilson (1965) surveyed in herbaceous communiteis measured by point-quadrat method. As G_{max} in the relationship of G and Ah is varied by tree density, tree age, species and so on, relationship of G and Ah should be newly estimated in the different stand. The results investigated in the sapling stand of *Alnus hirsuta* var. sibirica (Fig. 7) differed from those in the Hinoki stand, Hino (Fig. 6), and Ah of G_{max} was near to the zenith (Ah $=90$). Finally we estimate the necessary number of measuring points to obtain an accurate estimate of sunflecks and relative light intensity under clear sky conditions. The necessary number of quadrats for measuring sunflecks (N) is shown in Table 2. $N=1$ means 16 measuring points, that is a qudrats of 2×2 m. N is calculated by using Student's t-distribution (t). When t equals 1, 2, the confidence coefficients are approximately 75, 95 per cent respectively. When t and relative error (ε) is 2, 0.1 respectively, N is nearly equal to 200 (800 square meters). 5 minutes is reqired for measuring 800 m^2, but by E or D-Method it required between 30 minutes and an hour. As the distribution of sunflecks varies from time to time, it is adequate that N equals nearly 13 (52 m^2, $t=1$, $\varepsilon=0.1$), therefore 100 square meters (N=25) are sufficient for analyzing sunflecks.

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