Management of Light Climate in Multistoried Agroforestry Systems

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Abstract

The purpose of agroforestry systems is to establish forests by minimizing the friction between agricultural and silvicultural land-use. For harmonizing both and operating the system effectively, various studies must be undertaken not only from socio-economic but also from technical and scientific aspects. Multistoried system of agroforestry, where trees and agricultural crops form the upper and lower layers, respectively, can be observed very often in Southeast Asia. In this system, the upper layer controls the light climate for the lower crops. Light is an essential factor for the growth of plants. Therefore, analyses of the light climate under the forest canopy were attempted in this report. Light measurement under the shade showed the importance of differentiation between direct and diffuse fractions of sunlight. Only the diffuse fraction affected the light climate under the shade. There was a high positive correlation between the diffuse light measured under the canopy and the opening proportion in the canopy visualized by hemispherical photographs. Based on actual measurements of sunlight in the forest and hemispherical photography, the light reaching the ground was evaluated in connection with the stand structure. Furthermore, the relationship between the light conditions under the canopy and the stand structure was illustrated diagrammatically, and the possibility of light management was suggested.

Introduction

For the rehabilitaion of degraded land, agroforestry systems have been introduced in the tropical region. Generally these systems involve the combination of agriculture with forestry, to harmonize crop production with land conservation. There are many types of temporal and spatial combinations of agriculture and forestry. In any case, this system results in the production of crops at a higher cost than monoculture systems of agriculture or forestry, from the economic viewpoint. It is considered that some economic support from pubilc organaizations is essential for the implementation of agroforestry. Apart from such socio-economic aspects, technical and scientific aspects are also important for the implementation of this system.

Mixed farming systems incorporating trees and agricultural crops are very popular in Southeast Asia and a multistoried stand structure can be often seen in plantations based on this system, where trees form the upper layer. However, at the same time, field crops with inadequate growth also can be seen in the lower layer under the trees. In this case, the crops on the ground apparently require more light, since the light factor is essential for the growth of green plants. Therefore, techniques should be developed for adequate crop production both in the upper and the lower layers.

In this report, I attempted to analyze the light climate under the canopy and to discuss the possibility of light control for the crops in the lower layer.

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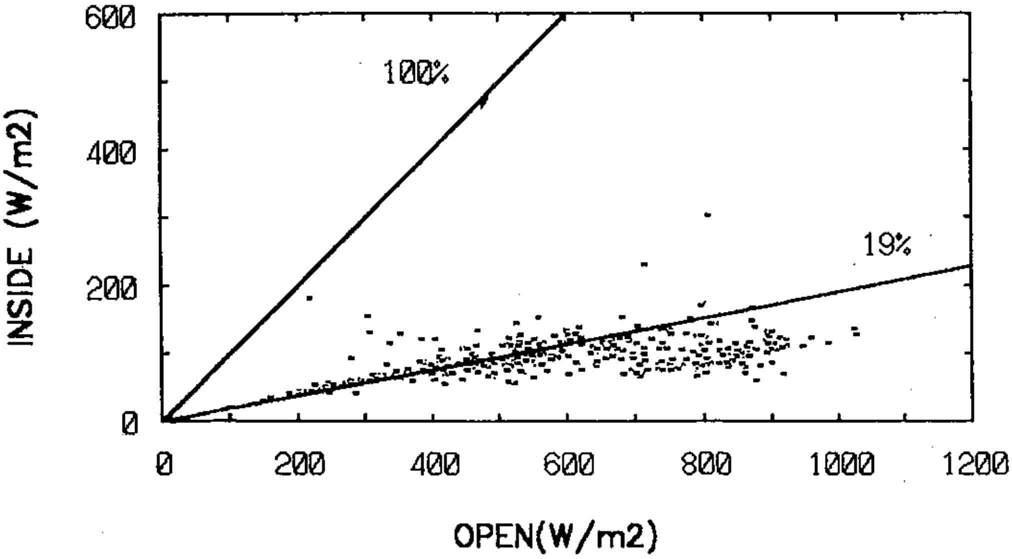

Fig. 1 Relationship between instantaneous irradiance inside the stand and that in the open.

Diffuse site factor as an index of light climate

The site factor defined by Anderson (1964) is the ratio of the light intensity inside the stand to that in the open. The relative illuminance (RI) is therefore a kind of site factor measured in terms of illuminance. So far, the RI expressed by a percentage has been used to assess the light conditions in the stand. The use of illuminance remains a problem, because the photometric definition of illuminance can not express the light environment for photosynthesis. However, the most important aspect is that this index based on instantaneous measurements fluctuates considerably depending on the weather conditions. Continuous record of instantaneous values, generally, results in the relationship shown in Fig. 1 (Sasaki and Mori, 1981), despite measurements on the same point. If these values form a line through the origin, the relative value calculated as a ratio of the value inside to that in the open would be stable, leading to a stable site factor. The fluctuation of site factors is usually ascribed to the confluence of two fractions of sunlight: direct light and diffuse light. The light in the open consists of both direct and diffuse light, whereas the fraction in the stand consists only of diffuse light except for sunflecks. These two fractions of light should be separated to calculate the site factor. If the direct light fraction is included in the calculation, the value of the site factor may decrease even when the value inside the stand remains constant. To avoid the confluence and to obtain the site factor as an index expressing the light climate, direct light should be excluded in the measurement. That is, light measurements for the site factor should be carried out on a cloudy day as suggested by Monsi and Saeki (1953). The site factor measured under diffuse light conditions is called diffuse site factor. The diffuse site factor also is closely related to the total sunlight including direct light, because it is generally proportional to the total area of gaps in the canopy and direct light comes through those gaps. This is why the diffuse site factor should be adopted as an index expressing the light climate.

Estimation of diffuse site factor using hemispherical photography

The use of hemispherical photographs (HSP) taken with a fisheye lens is one of the methods to estimate the diffuse site factor. This method combines the model of angular distribution of diffuse light in the sky characterized by the direct proportion of the radius in the hemispherical image to the angle from the zenith. There are two models for the simulation of diffuse light; standard overcast sky (SOC) model and uniform overcast sky (UOC) model (Moteith, 1973). Based on these models, diffuse site factors of SOC as D_1 and UOC as D_2 can be calculated as follows (Kanazawa *et al.*, 1989):

Table 1 Measured and computed diffuse site factor obtained from hemispherical photographs (HSP) under the canopy of a 3-year-old *Eucalyptus camaldulensis* stand

No.	Measured (%)	Computed (%)
1	62.4	75.6
2	75.0	75.6
3	73.2	63.1
4	55.8	61.7
5	59.5	61.5
6	57.5	57.5
7	55.4	47.2
8	54.9	59.9
9	42.9	51.3
10	46.7	45.3

$$D_1=\frac{\int_0^{\pi/2}(\cos\delta+2\cos^2\delta)\sin\delta\, k(\delta)\, d\delta}{\int_0^{\pi/2}(\cos\delta+2\cos^2\delta)\sin\delta\, d\delta} \quad \text{(SOC)}$$

$$D_2=\frac{\int_0^{\pi/2}\cos\delta\sin\delta\, k(\delta)\, d\delta}{\int_0^{\pi/2}\cos\delta\sin\delta\, d\delta} \quad \text{(UOC)},$$

where δ and $k(\delta)$ are the zenith angle and the ratio of the unshaded arc on the circumferece at δ, respectively. Next, using the proprtion of radius δ' in the HSP to δ, the following equation can be obtained:

$$D_1=\frac{\Sigma\,(\cos\delta'+2\cos^2\delta'_i)\sin\delta'_i\, k(\delta'_i)}{\Sigma\,(\cos\delta'_i+2\cos^2\delta'_i)\sin\delta'_i} \quad \text{(SOC)}$$

$$D_2=\frac{\Sigma\cos\delta'_i\sin\delta'_i\, k(\delta'_i)}{\Sigma\cos\delta'_i\sin\delta'_i} \quad \text{(UOC)},$$

where the radius of the whole image is 90° or $\pi/2$. Based on these equations, computing systems for the determination of the diffuse site factor have been developed by several authors (Chan *et al*., 1986; Smith and Somers, 1991). Examples of computation using our system (unpublished) are shown in Table 1. In this system, the ratio of the unshaded arc was calculated for every 5° or $\pi/36$. One of the shortcomings of this system is that the tone of the positive print affects the computaion results. Based on the fact that measurements at different times often give different RI values even on the same point, the HSP is considered to be a useful measurement for the estimation of the diffuse site factor.

Relationship between stand structure and diffuse site factor

Based on the analysis of the HSP in the preceding section, the diffuse site factor can be determined by the position and size of gaps in the canopy. The formation of gaps is closely related to the stand structure. When there is a high density of tall trees around the measurement point, the size and number of gaps must be small. On the other hand, the number may increase in a sparse and/or low height stand. Thus, the light climate in the stand can be determined based on the conditions of the trees around the measurement point. In other words, the altitude of the trees as obstruction around the point affects the light climate at that point. The term "altitude" is used here for angular elevation. Based on the UOC model, an equation simulating the diffuse site factor can be derived as follows:

$$Du=1-\int_0^{\theta'}2\sin\theta\cos\theta\, k'(\theta)\, d\theta$$

where Du, θ, θ' and $k'(\theta)$ refer to the diffuse site factor, angle above the horizon, altitude of obstruction and the ratio of the shaded arc on the circumference at θ. The relationship between δ and θ is expressed as $\delta+\theta=\pi/2$ and $k'(\theta)=1-k(\pi/2-\delta)$. This concept is illustrated diagrammatically in Fig. 2.

Assuming that $k'(\theta)=K$,

$$Du=1-K\sin^2\theta'$$

Here, the fitness of this equation was examined by linear regression, using the data collected in *Eucalyptus camaldulensis* and *Acacia auriculiformis* stands in Thailand. In this calculation, the RI was used as Du and the average altitude of trees ranging from 1 to 10 around the measurement point as θ'. The trees used for the calculation of θ' were selected in decreasing order from the tree with the highest altitude. However, the results of the linear regression were represented by the equation:

$$Du=A-K\sin^2\theta' \qquad A>1, \quad K>1.$$

Coefficients of determination of the linear regression are shown in Fig. 3 for each number. These results show that the coefficient of determination in *E. camaldulensis* exceeded 0.8 for 5 trees and in *A.*

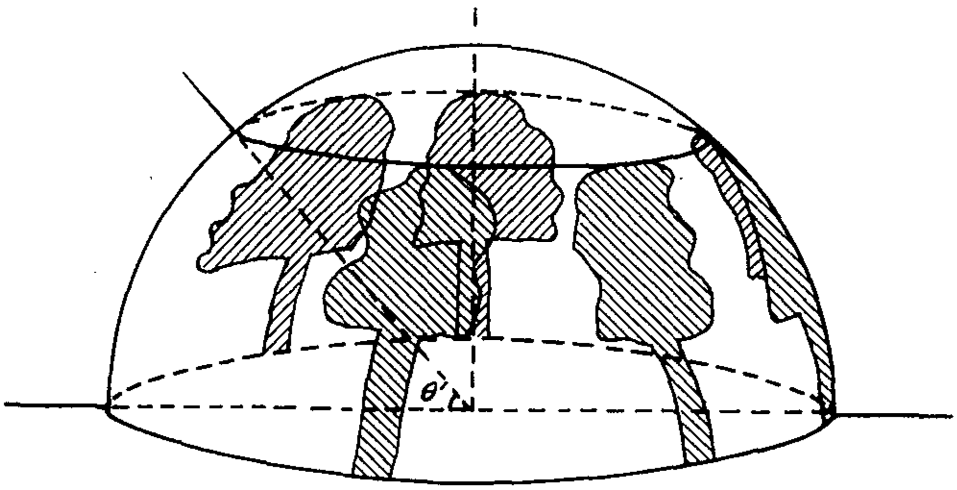

Fig. 2 Obstruction treatment for computation of diffuse site factor.

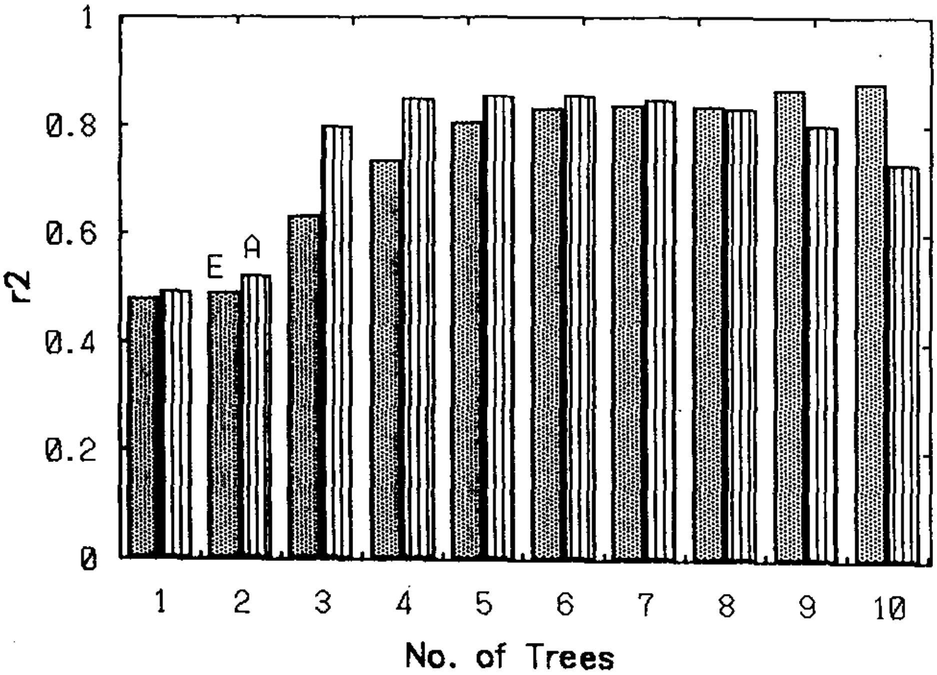

Fig. 3 Changes of coefficients of determination in the linear regression with the increase of the number of trees for the calculation of an average altitude. E and A refer to the *E. camaldulensis* and *A. auriculiformis* stands, respectively.

Table 2 Table for estimating diffuse site factor from an average of the 5 highest altitudes of the trees around the given point

E. camaldulensis		*A. auriculiformis*	
ALTITUDE (°)	%	ATITUDE (°)	%
60	72.3	50	72.3
62	68.6	52	66.5
64	65.0	54	60.9
66	61.6	56	55.4
68	58.4	58	50.0
70	55.4	60	44.8
72	52.7	62	39.9
74	50.2	64	35.1
76	48.0	66	30.6
78	46.1	68	26.4
80	44.4	70	22.5

auriculiformis for 4 trees. A simple table for the estimation of the diffuse site factor can be constructed using this relationship. For this purpose, the parameters A and K were estimated from θ' of an average altitude of 5 trees. The results are shown in Table 2. The equations were as follows:

$Du = 1.6754 - 1.2696\sin^2\theta'$: $r^2 = 0.8072$ (*E. camaldulensis*)

$Du = 1.7096 - 1.6817\sin^2\theta'$: $r^2 = 0.8572$ (*A. auriculiformis*).

From an average of the 5 highest altitudes around the given point, a rough diffuse site factor at that point can be estimated based on these tables. However, the collection of a larger number of data is required for further accuracy.

Example of light control in *A. auriculiformis* stand

The above regression can be applied to the total radiation reaching a given point during a certain period. Based on irradiance data measured in an *A. auriculiformis* stand in the Philippines, the same regression analysis as that listed previously was applied. Irradiance was measured during a 27 day period. Before the analysis, the irradiance data in the stand were transformed into relative values to that in the open. Although the values of the coefficients of determination were lower than those of the diffuse site factor in the *E. camaldulensis* and *A. auriculiformis* stands cited perviously, they increased with the increase of the number of trees. As in the former case, an average altitude of 5 trees was adopted to estimate the parameters A and K ($r^2 = 0.7250$) of 1.4538 and 1.2864, respectively. Based on the values of these parameters, a table for the estimation of relative irradiance was constructed (Table 3).

Based on this equation, the changes in the relative irradiance with the increase of the tree height could be simulated. As shown in Fig. 4, let four points *a*, *b*, *c*, and *d* be arranged between rows of the trees planted at a spacing of 2 × 2m and 2 × 4m. From this map, the distance from each point to nearby trees can be determined easily. When the height increment of the trees around the points is assumed to be equal, the altitude of the trees from each point can be calculated from the ratio of the distance between the tree and the point to the tree height. Then, the 5 highest altitudes can be averaged. Thus, Fig.5 can be drawn by linking the relative irradiance at each tree height.

Based on this diagram, silvicultural practices can be adopted to obtain an objective relative irradiance or to maintain a stable value for reaching the ground. For example, suppose that the value of the relative irradiance is maintained at 40% for the growth of vegetables at point *a*, according to the diagram, the value decreases from 40% when the tree height exceeds 3.5m. If, however, a thinning practice is applied to the stand, the average altitude decreases even though the tree height around the point *a* is still the same as before thinning because the distance between the remaining tree and the point *a* increases. As a result, the value of 40% can be maintained. This kind of diagram may be useful for controlling the

Table 3 Table for estimating relative irradiance in *A. auriculiformis* stand from an average of the 5 highest altitudes around the given point

A. auriculiformis

ALTITUDE (°)	%
40	92.2
42	87.8
44	83.3
46	78.8
48	74.3
50	69.9
52	65.5
54	61.2
56	57.0
58	52.9
60	48.9
62	45.1
64	41.5
66	38.0
68	34.8
70	31.8
72	29.0
74	26.5
76	24.3
78	22.3
80	20.6

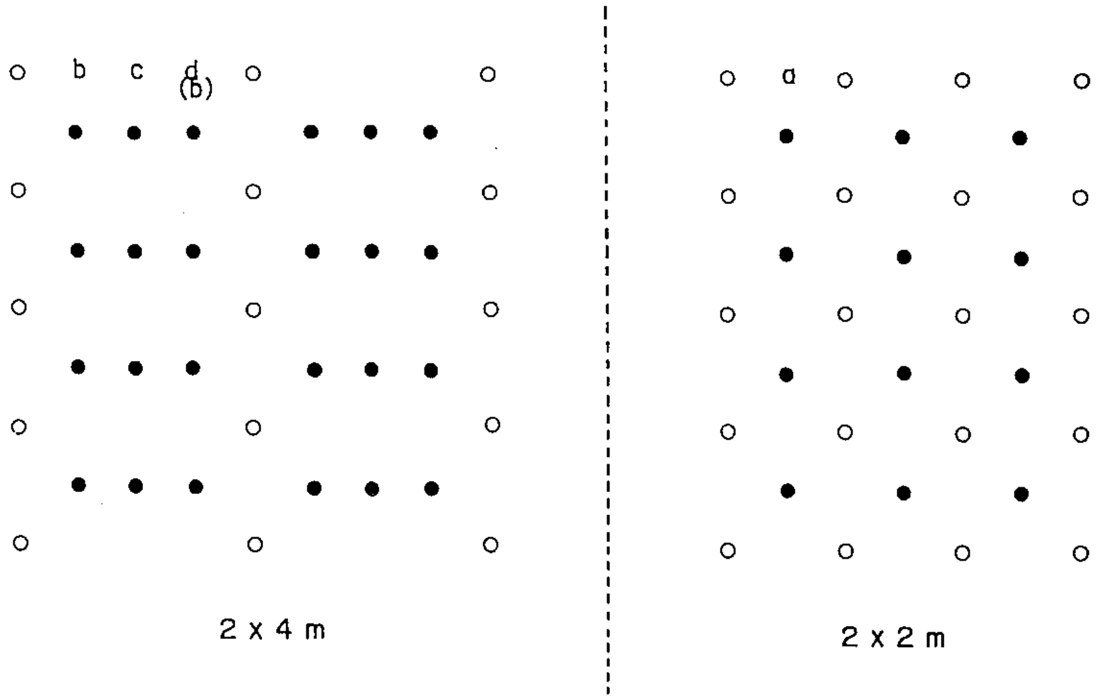

Fig. 4 Hypothetical arrangement of trees (open circles) with spacing of 2 × 4m and 2 × 2m, and points *a*, *b*, *c* and *d* (soild circles) between trees. Vertical and horizontal rows of trees and points are set at an interval of 1m.

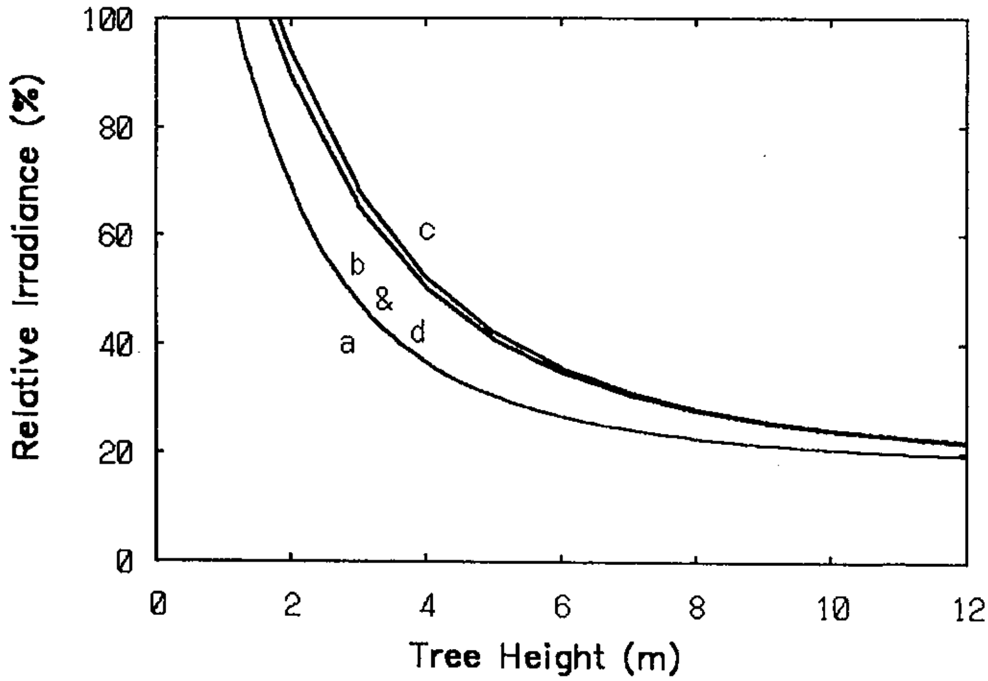

Fig. 5 Changes of relative irradiance at points *a*, *b*/*d* and *c* with the increase of tree height. *a*, *b*/*d* and *c* refer to the points shown diagrammatically in Fig. 4.

light conditions for field crops or seedlings. As the data used for this diagram were limited only to one season and one species, collection of further data is required for improvement.

The light factor is essential for plant growth. In many cases in multistoried systems, crops in the lower layer receive an insufficient amount of sunlight for growth due to the shadow of the trees in the upper layer. However, some plants require shade for growth. Therefore, light control is important in this system. However, only silvicultural practices such as thinning and pruning are available for light control. Methods for combining these practices with the light conditions should be developed. The tables and diagram for light control shown in this report are only attempts to attain this objective. Further studies will be needed for more rational management of multistoried agroforestry systems.

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