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Influence of Diffused Solar Radiation on the Solar Concentrating System of a Plant Shoot Configuration*

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Abstract
Investigation of a plant shoot configuration is used to obtain valuable information concerning the received light system. Additionally, analysis results concerning a plant shoot configuration interaction with direct solar radiation were taken from a past study. However, in order to consider a plant shoot as a received sunlight system, it is necessary to understand the received light characteristics of both direct solar radiation and diffused solar radiation. Under a clear sky, the ratio of direct solar radiation to diffused solar radiation is large. However, under a clouded sky, the amount of diffused solar radiation becomes larger. Therefore, in this paper, we investigate the received light characteristics of a plant shoot configuration under the influence of diffused solar radiation. As a result, we clarify the relationship between the amount of diffused solar radiation and the amount of received light as a function of the characteristics of the plant shoot configuration. In order to obtain diffused solar radiation, it is necessary to correspond to the radiation of the multi-directions. In the analysis, the characteristic of the difference in arrangement of the top leaf and the other leaf was obtained. Therefore, in analysis, leaves other than the top were distributed in the wide range.

Key words: Solar Concentrating System, Diffused Solar Radiation, Plant Shoot Arrangement, Genetic Algorithm, Ginkgo Biloba

1. Introduction

If a plant's received light characteristics becomes clear, the possibility of the high effectiveness and a miniaturization of received light equipment is expected. In a plant community, there is competition concerning the space available for capture of solar radiation. From this reason, the configuration and growth rate of a plant shoot (consisting of stem, branches, and leaves) influence in existence of a strong individual strongly. However, the case of an individual plant without competition for a solar radiation occurs very infrequently in nature. Therefore, it is expected that study of plant shape within a plant community gives important information for the aim of increasing the performance of a received light system.

The global solar radiation components obtained by a plant are composed mainly of direct solar radiation, diffused solar radiation, and reflected light. In a plant community, it is

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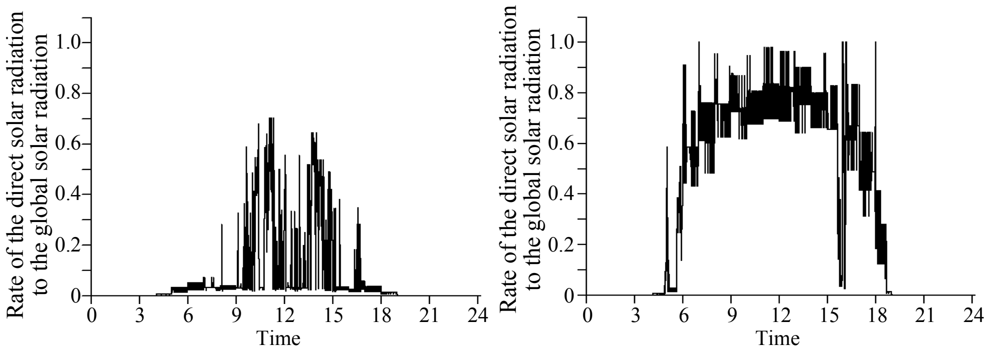
expected that the ratio of the diffused radiation component to global solar radiation is large. When an actual plant is observed, a leaf that receives only a small amount of received light will wither and fall. Arrangement of the leaves is therefore optimized for capture of sunlight, and it is thought that the quantities of production of the biomass are restricted by the arrangement of leaves. Therefore, capture of diffused solar radiation should be included in the received light strategy of the individual plant to a greater degree than that of direct solar radiation. On the other hand, study of a radiative heat transfer and global solar radiation is reported in the past [1-3].

The received light characteristics of a plant shoot are studied in fields such as morphological botany [4,5]. However, there are few examples in the literature of studies of the received light characteristics of the plant shoot configuration that use numerical analysis [6,7]. Moreover, examples of investigation concerning the relationship between the rate of the diffused solar radiation to global solar radiation and a plant shoot configuration is not found. Therefore, in this paper, we develop an analysis algorithm which considers the component of diffused solar radiation and optimization of the plant shoot configuration. The relationship among the ratio of direct solar radiation to diffused solar radiation, received light characteristics, and the shape of a plant shoot is explained using the proposed analysis program. Information on a high-performance received light system is obtained from these results.

2. Relationship Between Global Solar Radiation and Plant Shoot Configuration

2.1 Received light system and plant shoot

The received light system in a plant shoot configuration is applied to an energy conversion system using radiation and a compact photovoltaics. When introducing this system as a radiation energy conversion system, it is necessary to carefully examine the received light performance with respect to direct solar radiation. In contrast, when modelling this system with a photovoltaics, it is necessary to extend the received light characteristics further to diffused solar radiation and reflected light. Since reflected light differs with the installation environment of the system, it is not taken into consideration in this study. In this paper, the light received analysis algorithm of a plant shoot system [6] developed in past research is modified, and optimization of the received light characteristics of a plant shoot model under diffused solar radiation is investigated.



(a) July 9, 2007 (b) July 14, 2007

Fig. 1 The direct solar radiation component of a global solar radiation

2.2 Direct solar radiation and diffused solar radiation

The ratio of the direct and diffused solar radiation components changes with weather. With a clear sky, the amount of direct solar radiation is high, while under a clouded sky, the amount of diffused solar radiation is high. Figure 1 shows the ratio of the direct solar radiation component to the global solar radiation observed in Sapporo in Japan on July 9 and July 14, 2007 [8)]. Clouded sky time was longer on July 9 (Fig. 1 (a)), and clear sky time was longer on July 14 (Fig. 1 (b)). From these figures, it can be observed that the ratio of direct solar radiation and diffused solar radiation changes significantly with weather. Therefore, it is necessary to investigate the relationship between the rates of direct and diffused solar radiation and system performance in a system using solar radiation.

3. Analysis Method

3.1 Coordinate system

The analysis coordinate system for the plant shoot model is shown in Fig. 2. The *x*-axis direction represents the north/south direction and *y*-axis direction shows the east/west. The *x*-*y* plane is a horizontal plane, and the *z*-axis is the axis perpendicular to the horizontal plane. In this paper, the *y*-axis is defined as a basis. Each leaf model can move to a free position. However, the length of each branch of a leaf is determined beforehand, and one end of the branch of a leaf is always joined with the centre of the coordinate system.

3.2 Emission model of direct and diffused solar radiation

The radiation positions of direct and diffused solar radiation are arbitrary points on the virtual radiation surface. The virtual radiation surface of direct solar radiation is a flat surface, while the virtual radiation surface of diffused solar radiation lies on a surface of a sphere with the same centre as the coordinate system. Additionally, the normal line at the central point of the virtual radiation surface of direct solar radiation always passes through the centre of the coordinate system. The distance between the centres of each virtual radiation surface and the centres of the coordinate system is given by l_{rd} in the case of direct solar radiation, and is given by l_{rf} in the case of diffused solar radiation. Here, l_{rd}

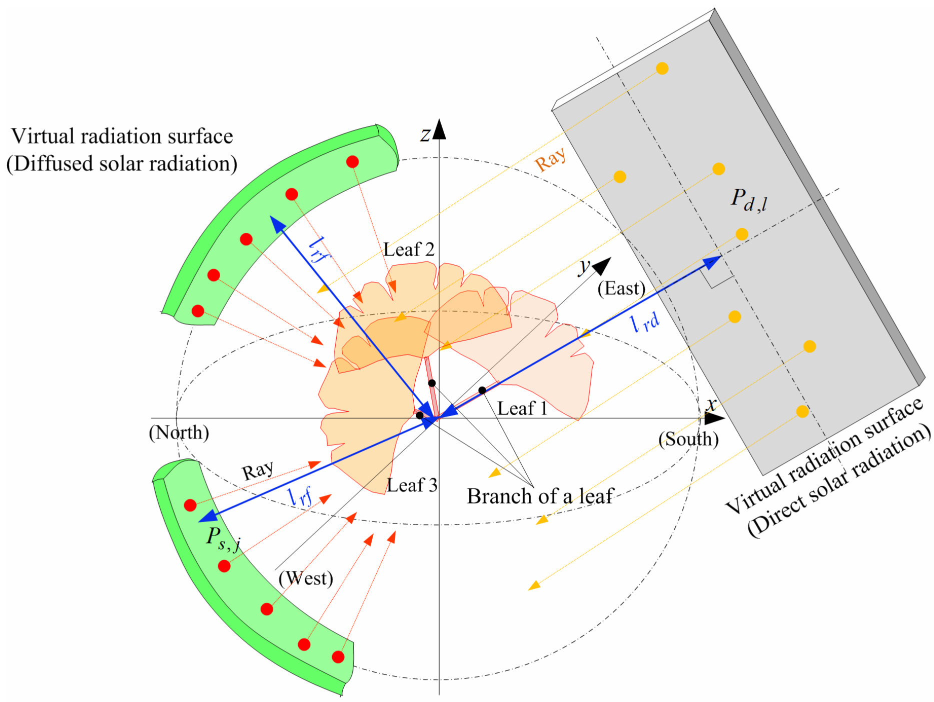
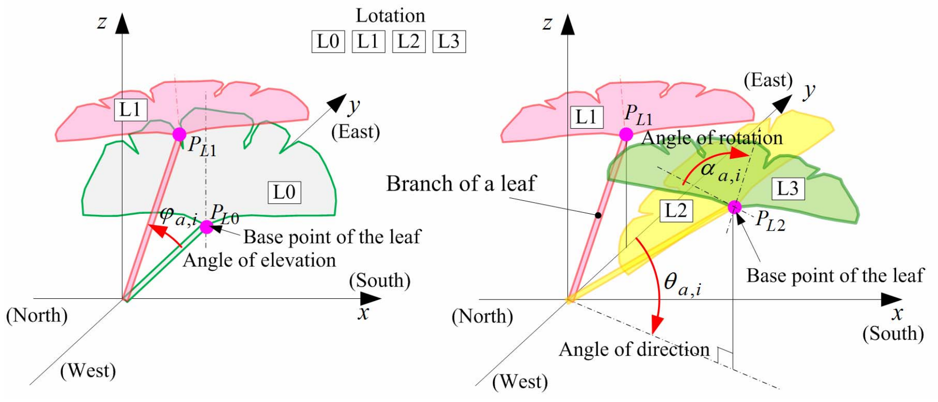
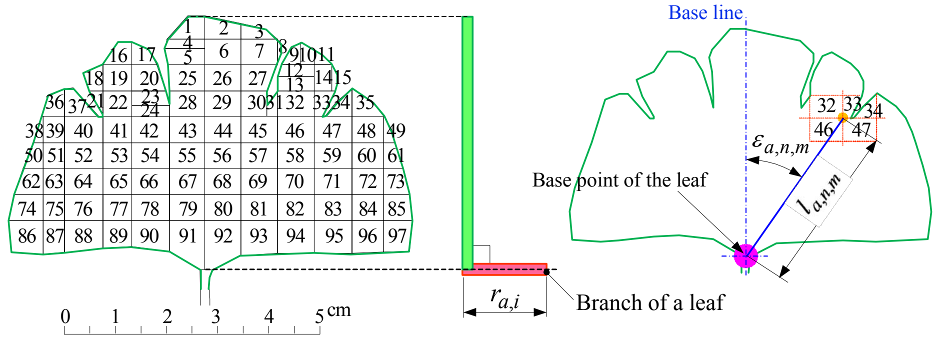


Fig. 2 Component of solar insolation



(a) Rotation concerning x-axis (b) Rotation concerning z-axis and base point of the leaf

Fig. 3 Coordinate system of a shoot



(a) Ginkgo biloba leaf model (b) Coordinate of the surface element

Fig. 4 Leaf model

and l_{rf} are sufficiently separated in the model, and the size of the virtual radiation surface of direct solar radiation ensures that emitted light (ray) covers the entire plant shoot model. In contrast, for diffused solar radiation, ray can be emitted in a 360-degree direction towards the centre of the coordinate system. With an actual plant, it is thought that there is a distribution in the incidence direction of diffused solar radiation. However, in the analysis given in this paper, diffused solar radiation is defined to enter uniformly from all directions.

3.3 Configuration of the plant shoot model

In this paper, the configuration of the plant shoot model is defined by giving the angle of elevation and angle of direction based on the y-axis, as shown in Fig. 2. Figure 3 shows the determination procedure for the plant shoot model configuration. First, as shown in Fig. 3 (a), the plant shoot model is set at the position L0. Here, movement with respect to the coordinate P_{L0} (X, Y, Z) at the base of the leaf (as shown in Fig. 3) is described as an example. Rotation about the *x*-axis of the angle of elevation $\varphi_{a,i}$ is added for P_{L0}. At this time, the position of the plant shoot model is Position L1 in Fig. 3 (a), and P_{L0} moves to P_{L1} (x', y', z') (Eq. (1)). Next, rotation about the *z*-axis of the angle of direction $\theta_{a,i}$ is added for the plant shoot model. The position in this case is position L2 in Fig. 3 (b), and P_{L1} moves to $P_{L2}(x'', y'', z'')$ (Eq. (2)). Finally, the rotation angle $\alpha_{a,i}$ is added to the radial direction of the branch of a leaf (position L3 in Fig. 3 (b)).

Rotation with respect to the *x*-axis (angle of elevation)

$$x' = X \qquad (1)$$

$$y' = Y\cos\varphi_{a,i} - Z\sin\varphi_{a,i}$$

$$z' = Y\sin\varphi_{a,i} + Z\cos\varphi_{a,i}$$

Rotation with respect to z-axis (Angle of direction)

$$x'' = x'\cos\theta_{a,i} - y'\sin\theta_{a,i}$$
$$y'' = x'\sin\theta_{a,i} + y'\cos\theta_{a,i} \qquad (2)$$
$$z'' = z'$$

3.4 Position of the virtual radiation surface

The position of the virtual radiation surface for direct and diffused solar radiation is set up using the same procedure as the plant shoot model described previously. That is, it is determined by giving an angle of elevation and an angle of direction based on the y-axis. The virtual radiation surface of direct solar radiation simulates the solar trajectory. In addition, virtual radiation surfaces of a small size are installed in all directions with a uniform spacing, and diffused solar radiation is simulated by emitted ray. In the analysis in this paper, the position of diffused solar radiation is decided by random numbers. Accordingly, a Monte Carlo [1)] simulation is introduced for the emission of diffused solar radiation.

3.5 Leaf model

The leaf model for a ginkgo biloba plant is shown in Fig. 4. The branch of a leaf of length $r_{a,i}$ (i is the number of the leaf) is fixed to the rectangular leaf model consisting of 97 surface elements. The apex coordinate of each surface element is expressed by the distance $l_{a,n,m}$ (n is the surface element number and m is the apex number) from the base point of the leaf in Fig. 4 (b), and the angle $\varepsilon_{a,n,m}$ with the base line. Therefore, all of the surface elements are defined by the sets of $l_{a,n,m}$ and $\varepsilon_{a,n,m}$ (n=97, m=1, 2, 3, 4) and Eq. (3) is the formula of a space plane. Here, a_n, b_n, c_n, and d_n are constants. The leaf model of Fig. 4 (a) is an assembly of the space planes expressed with Eq. (3). The equation of a space surface (surface element) is given by:

$$a_n \cdot x_{n,m} + b_n \cdot y_{n,m} + c_n \cdot z_{n,m} + d_n = 0 \qquad (3)$$

3.6 Received light check of the surface element

In emission of direct and diffused solar radiation, ray are emitted in the direction normal to a random position on the virtual radiation surface. The following procedure confirms whether light reaches a leaf model with these ray (the example of direct solar radiation is described). The arbitrary emission positions on the virtual radiation surface are expressed in $P_{d,l}(x_l, y_l, z_l)$. Here, l is a ray number for emission. Moreover, the formula of the plane of the surface element number n on the leaf model is given in Eq. (3), and a straight line of distance k_b from $P_{d,l}(x_l, y_l, z_l)$ is assumed. The coordinate of the point $Q_{p,n,r}$ on this straight line is obtained by Eq. (4). Here, $E(e_x, e_y, e_z)$ is a normal vector (unit vector) of the ray emitted from $P_{d,l}$.

$$Q = P_{d,l} + k_b \cdot E = (x_l + k_b \cdot e_x, y_l + k_b \cdot e_y, z_l + k_b \cdot e_z) \qquad (4)$$

By substituting Eq. (4) for Eq. (3), the distance k_b between planes (including the surface element n and $P_{d,l}$) can be obtained (Eq. (5)).

$$k_b = -(a_n \cdot x_l + b_n \cdot y_l + c_n \cdot z_l + d_n)/(a_n \cdot e_x + b_n \cdot e_y + c_n \cdot e_z) \tag{5}$$

Furthermore, the intersection $Q_{p,n,r}$ of the ray emitted from $P_{d,l}$ and a plane including the surface element n is obtained by substituting k_b for Eq. (4). Equation (6) is satisfied when $Q_{p,n,r}$ exists in the surface element n. Equation (6) is satisfied when the point of intersection $Q_{p,n,r}$ is located on the lefthand side of all the sides of the surface element (Fig. 5)

$$\begin{aligned} &\{(Q_{a,n,4} - Q_{a,n,1}) \times (Q_{p,n,r} - Q_{a,n,1})\} \cdot N_a \geq 0 \\ &\{(Q_{a,n,3} - Q_{a,n,4}) \times (Q_{p,n,r} - Q_{a,n,4})\} \cdot N_a \geq 0 \\ &\{(Q_{a,n,2} - Q_{a,n,3}) \times (Q_{p,n,r} - Q_{a,n,3})\} \cdot N_a \geq 0 \\ &\{(Q_{a,n,1} - Q_{a,n,2}) \times (Q_{p,n,r} - Q_{a,n,2})\} \cdot N_a \geq 0 \end{aligned} \tag{6}$$

However, $\times$ in Eq. (6) is an outer product of a vector, and N_a is a normal vector of the surface element n. For each surface element of all the leaf models, calculations are used to check whether $Q_{p,n,r}$ is included. As a result, the leaf model number and surface element number including $Q_{p,n,r}$ can be known.

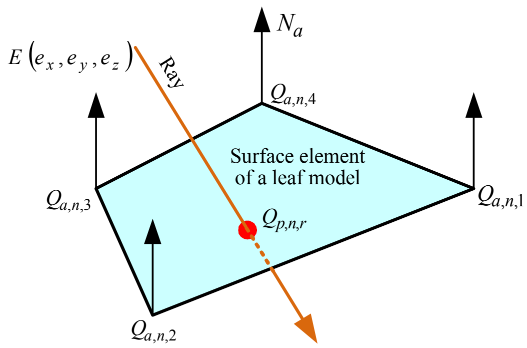


Fig. 5 Intersection coordinate

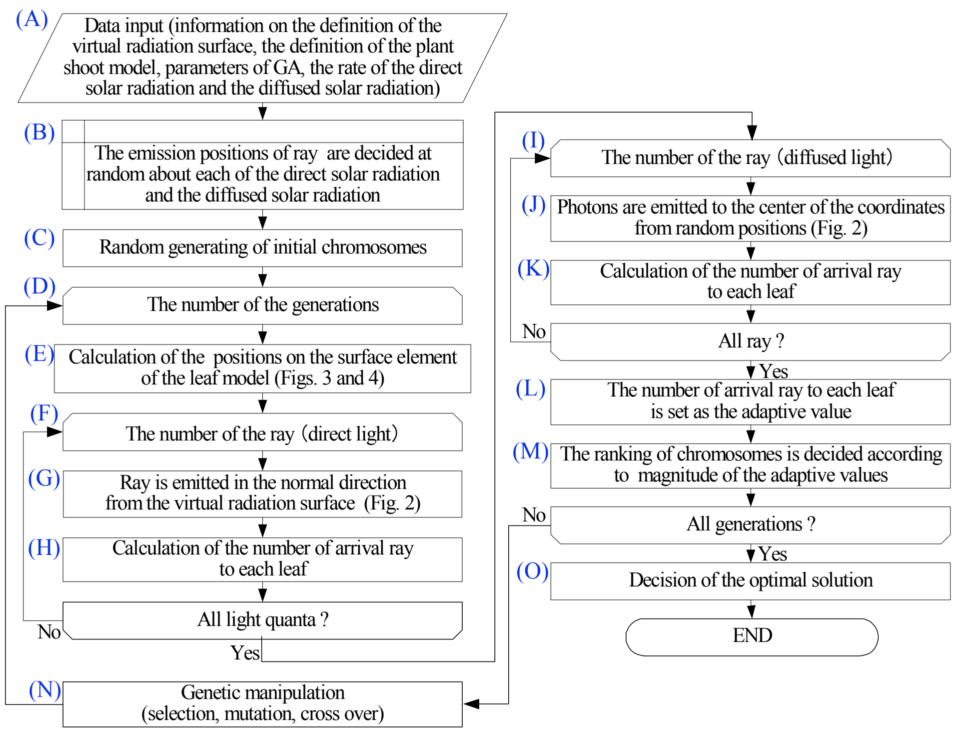


Fig. 6 Program flow

4. Analysis Flow

Figure 6 shows the flow of the analysis program. (A) to (O) of the blue characters in this figure give each analysis process.

(1) Process A

First, the definition of the virtual radiation surface with respect to direct and diffused solar radiation (size, distances l_{rf} and l_{rd}), data concerning the plant shoot model (Fig. 4), each parameter of genetic algorithm (GA) (a number of individuals, the probability of mutation and crossover, a generation number, the ranking to select), and the rate of direct and diffused solar radiation (each number of ray to emit) are input into the analysis program.

(2) Process B

The emission position on the virtual radiation surface of direct and diffused solar radiation is decided at random (Fig. 2).

(3) Process C

The chromosome models of the initial generation are generated. This chromosome model expresses the configuration ($\varphi_{a,i}$, $\theta_{a,i}$, $\alpha_{a,i}$ in Fig. 3) of the plant shoot model. $\varphi_{a,i}$, $\theta_{a,i}$, $\alpha_{a,i}$ in a chromosome model consisting of 10 bits, each of 1 or 0.

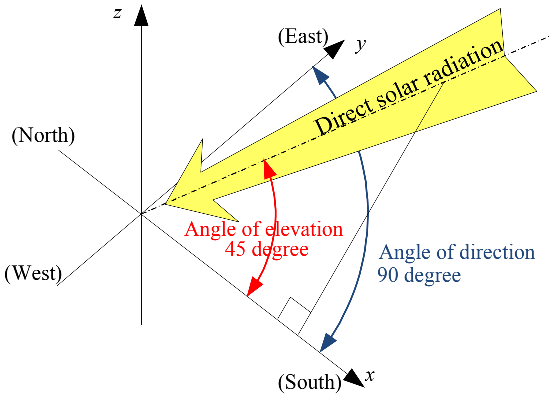
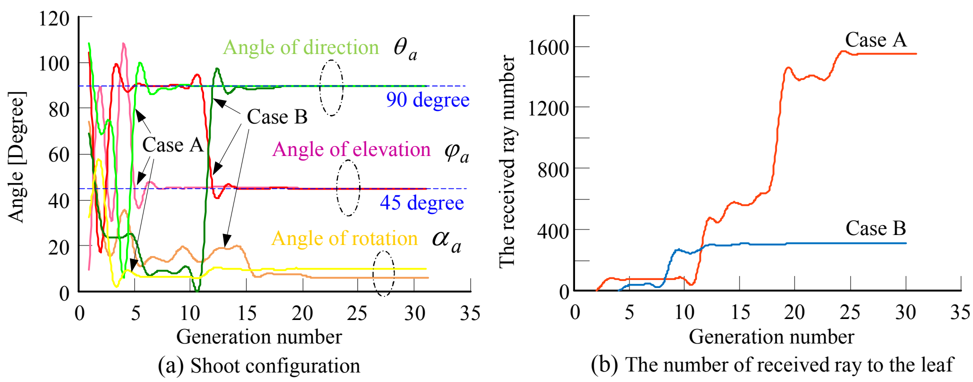


Fig. 7 The coordinate system used in the case analysis



Analysis condition

Leaf model : Ginkgo biloba (Fig. 4 (a))
The number of leaves : 1
Length of the branch of the leaf : 10mm
Size of the virtual radiation surface :
Width and height 500mm
The number of the ray (direct light only) :
Case A 5000, Case B 1000
Direction of the virtual radiation surface : Angle direction 90 degree, elevation 45 degree

Distance between the virtual radiation surface and the coordinate system center (Fig. 2): 500mm
GA parameters
Selection : Top 15 chromosomes
Probability of the mutation : 0.2
The number of chromosome models : 500
Last generation number : 30

Fig. 8 Convergence characteristics of the analysis program

(4) Processes D to K

The process first performs calculations using the method described in Sections 3.3 and 3.5 for the space position (Fig. 3) of the surface element on the leaf model (Fig. 4). Furthermore, the received light for these leaf models is counted using the method described in Section 3.6. Processes F to H involve calculation of direct solar radiation, and the processes I to K perform calculations concerning diffused solar radiation.

(5) Processes L and M

The adaptive value of all chromosome models is calculated. Adaptive value can be as high as the plant shoot configuration with the most light received. Furthermore, all of the chromosome models are sorted according to the large order of adaptive value.

(6) Process N

The chromosome model with lowest adaptive value is moved into a model newly decided at random. Moreover, for the chromosome model with high adaptive value, in order to maintain diversity, the genetic manipulation of mutation and crossover is added using the probability selected previously.

(7) Process O

Calculation of processes D to M is repeated based on the generation number given beforehand. The chromosome model with the highest adaptive value in the last generation chromosome model is selected. The information for $\varphi_{a,i}$, $\theta_{a,i}$ and $\alpha_{a,i}$ in this chromosome is decoded, and the optimal configuration of the plant shoot is selected.

5. Case Analysis

5.1 Analysis conditions

Analysis conditions are described below.

(1) Direct solar radiation

As shown in Fig. 7, the emission position of direct solar radiation is 90-degrees in direction and 45-degrees in elevation. Accordingly, direct solar radiation is emitted to the plant shoot model at angle of 45-degree from the south.

(2) Diffused solar radiation

Diffused solar radiation can be emitted in a 360-degree direction towards the centre of the coordinate system. However, the diffused solar radiation in this case is restricted to the upper hemisphere, as shown in Fig. 2. Diffused solar radiation is emitted towards the centre of the coordinate system from a random position in the upper hemisphere and is then emitted to the plant shoot by uniform distribution from the arbitrary position on the upper hemisphere.

(3) Received light

The ray of direct and diffused solar radiation reaches the back of the leaf model depending on the direction of the plant shoot. In this analysis, the received light is counted when the ray arrives at the surface of the leaf model. Moreover, it does not take into consideration the transmission light and reflection light seen by the leaf. Distributed solar cell module is assumed in this paper. In a solar cell module, the light changed into the electrical energy is only one side (front side). Therefore, the reflected light to the back of other leaves does not contribute to power generation. Furthermore, when the geometric conditions (Fig. 9 right) of a branch of a leaf and leaf size are taken into consideration, it will be expected that there is little contribution to power generation by the reflected light.

(4) Restricted conditions of the plant shoot

Restricted conditions are not prepared in each moving range of $\varphi_{a,i}$, $\theta_{a,i}$, and $\alpha_{a,i}$ of the plant shoot model shown in Figs. 2 and 3. The length of each branch of a leaf $r_{a,i}$ (i =1, 2, 3, 4) is fixed to each value. All of the leaf models used for the analysis are introduced in

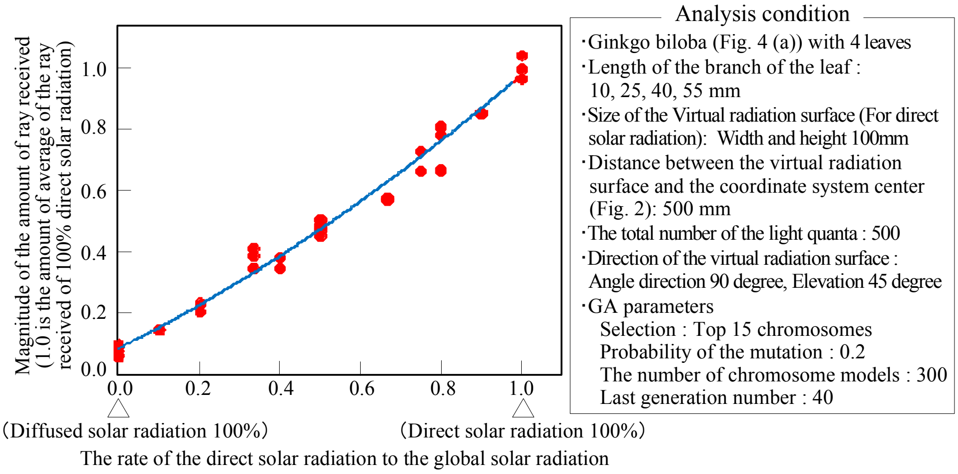


Fig. 9 Analysis result of a the amount of ray received

Fig. 4 (a).

5.2 Preliminary survey

First, the analysis accuracy and the convergence characteristics of the proposed analysis program (Fig. 6) are investigated. Here, only direct solar radiation is given to one plant shoot, and analysis accuracy and the convergence characteristics are measured. The emission position of direct solar radiation is the same as in Fig. 7, and 5000 (Case A) and 1000 (Case B) rays are emitted from the virtual radiation surface. Detailed analysis conditions are shown in Fig. 8.

Figure 8 (a) shows the analysis results for the relationship between GA generation number, and the convergence characteristics of $\varphi_{a,i}$, $\theta_{a,i}$, and $\alpha_{a,i}$. The optimal solutions of this analysis are $\theta_{a,i}$ = 90-degrees and $\varphi_{a,i}$ = 45-degrees, as shown in the figure. Figure 8 (b) shows analysis results for the generation number and the received light number of these plant shoot models. As shown in Figs. 8 (a) and (b), the analysis accuracy and the convergence characteristic for direct solar radiation given to one plant shoot are good. However, the difference as the result of $\alpha_{a,i}$ of Case A and Case B is 25%.The reason of $\alpha_{a,i}$'s difference is a set number of the ray. If the parameters of the GA increase, it is expected that variation will occur in the convergence value for every analysis. Therefore, in the following analyses, the same condition calculation is repeated two or more times, and the optimal solution is obtained. In this case, all the initial conditions of these analyses in this case are the same.

6. Analysis Results

6.1 Result for received light

Figure 9 shows analysis results for the ratio of direct solar radiation to global solar radiation, and the received light from the global solar radiation when four plant shoots are introduced. Here, the received light of the global solar radiation sets the value of average received light by direct solar radiation to 1.0. The result of Fig. 9 shows that the received light in the entire plant shoot decreases when the rate of diffused solar radiation increases. This reason is considered together with the analysis results of the plant shoot configuration described below.

6.2 Results of the shoot configuration

Figure 10 shows analysis results for the optimal configuration of the plant shoot model. However, the results of the shoot configuration may differ when calculations are repeated using the same analysis conditions. In this case, the result of the shoot configuration with an abundance of received ray is shown. According to Figs. 10 (a) to (d), the rate of diffused solar radiation becomes high. The directivity of a leaf becomes low with an increase in the rate of diffused solar radiation, and the plant configuration takes on a round shape as seen from the *z*-axis. In contrast, when the rate of direct solar radiation is large, the top part of the leaf shows a much larger value of received light than the other leaves. Moreover, leaves with very little received ray also appear.

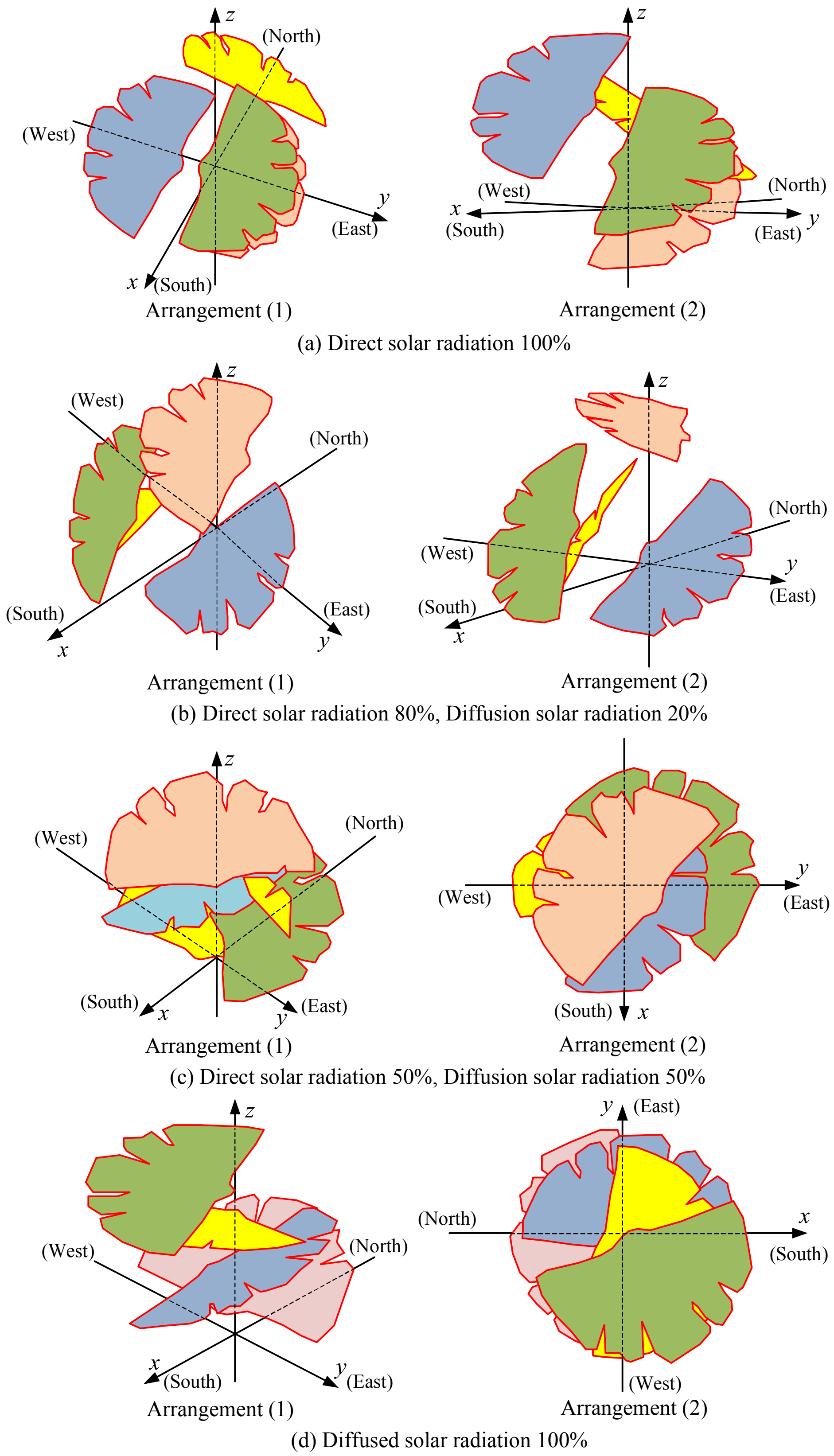


Fig. 10 Arrangement results of the Ginkgo biloba leaf model

6.3 Consideration of the plant shoot configuration

In the optimal solution obtained in the analysis, much of the direct and diffused solar radiation is received by a top leaf, and diffused solar radiation is received in leaves other than those located at the top. Therefore, except for the top areas of a real plant shoot configuration, it is thought that the arrangement of each shoot is suited for the incidence of diffused solar radiation. For a plant with a lobed leaf structure, like ginkgo biloba, the direct solar radiation component reaches the lower part of the leaf. Therefore, it is thought that the characteristics of a lobed leaf (the depth of the lobed leaf, the number of divisions, size of the leaf, shape of the leaf, etc.) have a large influence on the shoot configuration below the top. Accordingly, the shape of a leaf determines the received light characteristic of the whole plant.

6.4 Consideration of the plant-shoot-light-received system with diffused solar radiation

When the rate of diffused solar radiation becomes high, the arrangement of leaves on a plant shoot must be suitable for a wide range received light. It is necessary to capture the low density diffused solar radiation in all directions using a limited resource (biomass). Because of this, small leaves are distributed in many directions. Therefore, the plant shoot in an environment with little direct solar radiation has distributed leaves, and thus increases the received light from diffused solar radiation. In order to obtain as much diffused solar radiation as possible, it is most effective for the size of the leaf to be small and the distribution to be greater. However, if the leaves are increased extensively, a strength problem will occur. It is expected that the leaf size is a balance with maximization of the received light of the whole plant under restrictions concerning distribution of the biomass.

6.5 Future subjects concerning the distribution of biomass

A plant produces biomass by photosynthesis. Therefore, it is expected that an optimal relationship exists between the plant shoot configuration and the distribution of resources (the space density of a leaf, the length of a branch of a leaf, arrangement of a branch, etc.) of the biomass. The compact sunlight received by the system may be understood by investigating this relationship. These topics are important subjects for future research.

7. Conclusions

For differing rates of direct and diffused solar radiation of global solar radiation, the received light characteristics of the plant shoot configuration were investigated by numerical analysis. As a result, the following conclusions were obtained.

(1) At the top of the plant shoot, leaves are arranged so as to maximize the direct solar radiation component received. Additionally, in the shoots below, the arrangement becomes more suited to the incidence of diffused solar radiation from all directions.

(2) It is expected that the shape of a leaf is a major factor influencing the received light characteristics of the plant as a whole.

(3) When diffused solar radiation is taken into consideration, the plant shoot must adapt to low energy density radiation density from many directions. When the rate of diffused solar radiation becomes high, the plant shoot will adopt a configuration suitable for a wide range of incidence. In an actual plant, diffused solar radiation is condensed by distributing small leaves in all directions. The condensing strategy of diffused solar radiation by distribution of many small leaves also agrees with the analysis result in this study.

Nomenclature

E	:	Unit vector
a, b, c, d	:	Constant numbers

k_b	:	Distance (Eq. (5)) [mm]
l_a	:	Distance between the base point of the leaf model and the surface element apex (Fig. 4 (b)) [mm]
l_{rd}	:	Distance between the centre of a coordinate system and the virtual radiation surface concerning direct solar radiation (Fig. 2) [mm]
l_{rf}	:	Distance between the centre of a coordinate system and the virtual radiation surface concerning diffused solar radiation (Fig. 2) [mm]
N_a	:	Normal to the leaf model apex
P_d	:	Emission position on the virtual radiation surface concerning direct solar radiation
P_s	:	Emission position on the virtual radiation surface concerning diffused solar radiation
Q_a	:	Apex of the leaf model
Q_p	:	Position on the leaf model of a ray
r_a	:	Length of the branch of a leaf

Roman character

a_a	:	Angle of rotation of the leaf model [degree]
ε_a	:	Angle indicating the surface element apex on the leaf model (Fig. 4 (b)) [degree]
φ_a	:	Angle of elevation of the leaf model [degree]
θ_a	:	Angle of direction of the leaf model [degree]

Subscript

i	:	The number of the leaf model
j	:	Ray number of diffused solar radiation
k	:	Arrival ray number to the leaf model
l	:	Ray number of direct solar radiation
m	:	Apex number of the surface element of the leaf model
n	:	Surface element number of the leaf model
r	:	The ray number which reached a surface element on the leaf

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References

(1) Hiroshi Taniguchi, Kazuhiko Kudo, Akeno Mochida, Wen Jei Yang and Akiyoshi Kuroda, *The radiative heat transfer analysis by the Monte Carlo method of personal computer utilization*, Corona Publishing Co., Ltd., Tokyo. (1993), (in Japanese)

(2) Shigenao Maruyama, *Optical Energy Engineering*, Yokendo Co., Ltd., Tokyo. (2004), (in Japanese)

(3) Kimio Kanayama and Hiroshi Baba, *Solar Energy Application Technology*, Morikita Publishing Co., Ltd., Tokyo. (2004), (in Japanese)

(4) The Society for the Study of Species Biology, *Figures of Light, Water, and a Plant-Guide to Plant Physiological Ecology*, Bun-ichi Sogo Shyuppan, Tokyo. (2003)

(5) Hirose. T., Werger, M. J. A., Pons, T. L. and Rheenen, J. W. A., Canopy Structure and Leaf Nitrogen Distribution in a Stand of Lysimachia Vulgaris L. as Influenced by Stand Density, *Oecologia*, 77, 147-150. (1988).

(6) Shin'ya OBARA and Itaru TANNO, Arrangement Analysis of Leaves Optimized on Photon Flux Density or Photosynthetic Rate, *Journal of Computational Science and Technology*, 2(1), 118-129, (2008).

(7) Shin'ya OBARA, Itaru TANNO, Taichiro SHIRATORI, Study on Low Directivity Condensing Equipment for Solar Power Collection based on a Single Leaf Shoot Shape, *Journal of Thermal Science and Technology*, 3(3), 499-510, (2008).

(8) Homepage of Japan Meteorological Agency, http://www.data.jma.go.jp/obd/stats/etrn/index.php, (2009), (in Japanese)