Calculation of the irradiance of solar radiation in a greenhouse with a complex structure using a diagram for sky view factor

Shuh MATSUDA a, b, 1, Hisashi YOSHIKOSHI a, Tomoyo SUZUKI c, Yuuki OHTA d, Ayaka CHIBA e, Hiroshi ARIMA f, Hideaki KUMAGAI g, Daisuke YASUTAKE b and Masaharu KITANO b

a Western Region Agricultural Research Center, National Agriculture and Food Research Organization, 2575 Ikano, Zentsuji, Kagawa 765-0053, Japan
b Graduate School of Bioresource and Bioenvironmental Sciences, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Fukuoka 819-0395, Japan
c Southern Region Horticultural Research Section, Iwate Agricultural Research Center, 238-4 Kawasaki, Yonesaki, Rikuzentakata, Iwate 029-2206, Japan
d Riastarfarm Co., Ltd., 220-1 Kawasaki, Yonesaki, Rikuzentakata, Iwate 029-2206, Japan
e Iwate Prefecture, 10-1 Uchimaru, Morioka, Iwate 020-8570, Japan
f Iwate Agricultural Junior College, 14 Kanikozawa, Rokuhara, Kanegasaki, Isawa, Iwate 029-4501, Japan
g Kiraku Souken Co., Ltd., 42-9 Suwamae, Akasaki, Ofunato, Iwate 022-0007, Japan
h Faculty of Agriculture, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, Fukuoka 819-0395, Japan

Abstract

The irradiance of solar radiation in a greenhouse with a complex structure was calculated using a diagram for sky view factor (DSVF) and compared with observed values. Structural materials (such as side pillars and rafters) and non-structural materials (such as lock channels, door frames, and ventilation fans) were treated as sunshine obstacles, including lower rafters and equal leg angles in the inner spaces of the greenhouse. Radiation directions simulated using a DSVF were used for calculating the irradiance of diffuse solar radiation. With respect to the irradiance of total solar radiation on a sunny day, the calculated values were found to be higher than the observed values early in the morning. However, the overall fluctuation due to diurnal change of the solar elevation and in the sharp drops due to the sunshine obstacles were reproduced. Furthermore, the diurnal changes of the irradiance of non-direct solar radiation on a sunny day and the irradiance of total and non-direct solar radiations on a cloudy day could also be reproduced. The relative error of the calculated irradiance of daytime (from 04:00 to 20:00) total and non-direct solar radiations to the measured value was 4.3% for the total radiation on the sunny day, 5.5% for the non-direct radiation on the sunny day, −1.1% for the total radiation on the cloudy day, and 0.3% for the non-direct radiation on the cloudy day. The results of this study indicated that the DSVF can be useful for calculating diffuse solar radiation.

Key words: Diffuse solar radiation, Direct solar radiation, Fisheye image, Radiation direction, Single-span greenhouse

1. Introduction

Greenhouses must have structures that can capture a lot of sunshine while satisfying conditions for resistance to wind and snow. Sunshine is important in greenhouses for the photosynthesis of plants and as a source of heat. The thickness and installation span of the structural material and the installation position of the reinforcing material affect the spatial and temporal distribution of solar radiation in the greenhouse. Thus, it is important for greenhouse designers to understand the spatial and temporal distribution of solar radiation in greenhouses.

There are two methods used to assess the dynamics of the irradiance of solar radiation in greenhouses as follows: measurement and numerical calculation methods. In the measurement method, pyranometers are installed in greenhouses to observe the irradiance of solar radiation, which enables us to obtain data only for the limited position and period in which the pyranometers are installed. In contrast, with the calculation method, the irradiance of solar radiation during the requested period at any point in a greenhouse can be computed using the irradiance of outside global solar radiation. Many studies have been conducted using the calculation method (e.g., Nisen, 1962; Manbeek and Aldrich, 1967; Bowman, 1970; Takakura et al., 1971; Kozai and Sugi, 1972; Critten, 1983; Kurata, 1990; Soriano et al., 2004; Cabrera et al., 2009; Cossu et al., 2017). However, most research calculated the irradiance of solar radiation in greenhouses with a simple structure ignoring sunshine obstacles not in contact with film surface. Kozai and Sugi (1972) regarded the transmittance corresponding to the mean incident angle of the diffused light of a glass pane as the transmittance of diffuse solar radiation in the pane in a glass greenhouse. However, this method is not always applicable if there is an obstacle to sunshine in the inner space of greenhouses. This is because part of solar radiation does not reach due to the sunshine obstacles. Furthermore, there were few studies on the irradiance of solar radiation in greenhouses
comparing calculated values with observed values.

In the field of architecture, the diagram for sky view factor (DSVF) method is used to calculate sky view factors (e.g., Architectural Institute of Japan, 1977). Sky view factors are shape factors, geometric relationships between planes, of the sky, and DSVFs are diagrams divided into annular sectors or concentrically arranged dots to be equal sky view factors. The calculation methods of the sky view factors are as follows: photograph the sky with a fisheye lens from a certain point, overlay a DSVF, the diagram is the same diameter and projection method with the sky photo, on the photo, and counting the number of divided segments or dots within the sky area. Here, we propose applying a DSVF to calculate the irradiance of solar radiation in a greenhouse. Kozai et al. (1978) divided the solar altitude into 19 segments and the sun’s azimuth relative to a greenhouse orientation into 37 segments to calculate the transmittance of diffuse solar radiation. However, Matsuda and Yoshikoshi (2019) concluded that the total number of dots or divisions in the DSVF must be set to $2 \times 10^5$ or more in order to ensure that the transmission absolute error of the diffuse solar radiation at any point in the greenhouse is less than 1%.

The purpose of this study is to calculate the solar radiation in a greenhouse with a complex structure using multi-point DSVF and compare it with the measured value. The methods of this study are expected to be useful for greenhouse designers to understand the spatial and temporal distribution of solar radiation in greenhouses with complex structures.

2. Theory and Methods

2.1 Study greenhouse

The single-span greenhouse used for this study was a timber-framed house (TF-house), whose main structural material was Cryptomeria. The TF-house was located at an altitude of 9 m in Rikuzentakata, Iwate Prefecture, Japan (39°01' N, 141°39' E). The width, length, ridge height, and eaves height of the TF-house were 7.0, 48.0, 5.4, and 3.9 m, respectively (Fig. 1). This was an even-span greenhouse connecting upper and lower rafters in oblique lattice patterns. The numerical values noted in Fig. 1 were used for the calculations in this study; however, in fact, the upper and lower rafters were bent slightly downward owing to their own weight. All spans of the north side pillars were 2.4 m. The spans of the south side pillars were 2.4 m, but the spans of both ends of the south side pillars were different from the others in order to connect the rafters accurately. The TF-house was constructed, and fixation of the film was carried out in September 2015. The TF-house is oriented 21° in a counterclockwise direction from an East–West greenhouse.

Table 1 shows a list of solar radiation obstacles and their cross-sectional sizes. Structural materials (such as side pillars and rafters), lock channels to fasten films, purlins and furring strips to fix lock channels, equal leg angles to combine upper and lower rafters, door frames, and ventilation fans were treated as sunshine obstacles. Lower rafters and equal leg angles were located in the inner spaces not in contact with films of the TF-house (Fig. 1). There were pipes and rolling drums as opening/closing internal

![Fig. 1. Sectional and side views of the timber-framed greenhouse used for calculating the irradiance of solar radiation (applicable unit: m). The spans of the north and south side pillars are all 2.4 m. However, the spans of both ends of the south side pillars are different from the others to connect the upper and the lower rafters together.](image-url)
covering materials and air circulation fans in the greenhouse; however, these were not included in Table 1 in order to limit the amount of calculation involved. The covering materials on the roofs were fluoropolymer films (F-CLEAN® Clear; AGC Green-Tech Co., Ltd., Tokyo, Japan; thickness: 0.08 mm), whereas those on the greenhouse side planes, gable ends, and door planes were polyolefin (PO) films (DiaStar; Mitsubishi Chemical Agri Dream Co., Ltd., Tokyo, Japan; thickness: 0.15 mm).

### 2.2 Numerical analysis method of solar radiation

Numerical analysis items were the total irradiance of direct, diffuse, and reflected solar radiation in the greenhouse. The reflected solar radiation was only calculated for the direct solar radiation reflected once on films. The reflection on other objects as well as the second reflection on films were not considered. The rays of radiation were assumed to be parallel, and diffraction and refraction by films were not taken into consideration. The calculations were programmed using FORTRAN.

Firstly, the outside direct and diffuse solar radiations were separately estimated from the observed outside global solar radiation. Many suggested models have estimated the outside direct and diffuse solar radiations from the outside global solar radiation. Soga et al. (1998) compared eight models and found that five (Erbis et al., 1982; Skartveit and Olseth, 1987; Reindl et al., 1990; Perez et al., 1992; Chandrasekaran and Kumar, 1994) presented better estimations than existing Japanese models. Of these five models, the Chandrasekaran and Kumar (1994) model is the most recent and has been adopted in this study.

Secondly, the presence or absence of the respective direct, diffuse, and reflected solar radiations at a solar radiation calculation point (hereinafter referred to as “calculation point”) was simulated, considering the three-dimensional structures of the sunlight obstacles. The program was processed as follows. The altitude (elevation angle relative to horizontal plane) and the azimuth angle of the direction of radiation at the calculation point were calculated. Furthermore, the coordinates of an intersection between plane A’ including a surface A of an obstacle listed in Table 1 and the radiation direction at the calculation point were computed (Fig. 2). Given that the coordinates were within the surface A (\( y_1 \leq y \leq y_2, z_1 \leq z \leq z_2 \)), there was no solar radiation from this direction. If no intersection was noted within surface A, it was determined whether there was an intersection in the surface of another obstacle on plane A’. If no intersection point was noted, the same procedure was followed for different planes (for example \( x - z \) plane in \( y = y_2 \) in Fig. 2). This process was applied to all the surfaces of each obstacle listed in Table 1. No intersection on all surfaces of all the obstacles indicates the penetration of sunlight from that direction.

Lastly, the irradiance of total solar radiation was obtained from the sum of the irradiance of direct, diffuse, and reflected solar radiations calculated by the following methods. The irradiance of non-direct solar radiation was determined from the sum of the irradiance of diffuse and reflected solar radiations.

#### 2.2.1 Calculation method of the irradiance of direct solar radiation

The radiation direction of direct solar radiation indicates the solar direction at the calculation point. If there was a sunshine obstacle in the solar direction, the film transmittance was considered to be zero. Equation (1) shows the calculation of the irradiance of direct solar radiation on a horizontal surface at a given calculation point in the greenhouse.

\[
S_{da} = I_{da} \tau_c
\]

where \( S_{da} \) is the irradiance of direct solar radiation on a horizontal surface at a given calculation point in the greenhouse, \( I_{da} \) is the irradiance of outside direct solar radiation on a horizontal surface (both units are W m\(^{-2}\)), and \( \tau_c \) is the film transmittance in the solar direction at the calculation point.

#### 2.2.2 Calculation method of the irradiance of diffuse solar radiation using a DSVF

The radiation direction for calculating the diffuse solar radiation in the greenhouse was simulated using the DSVF. The total number of dots in the DSVF is generally 1000 in Japan (e.g.,

| Obstacle                        | size (mm)  |
|--------------------------------|------------|
| Side pillar                     | 120 × 105  |
| Upper/Lower rafter              | 120 × 60   |
| Sill, Gable pillar, Gable rafter, Gable beam, Tie beam, Side girdler | 105 × 105  |
| Brace                          | 90 × 60    |
| Purlin                         | 75 × 60    |
| Furring strip                   | 60 × 45    |
| Lock channer                    | 30 × 10    |
| Door frame, Equal leg angle     | 50 × 50    |
| Ventilation fan                 | 950 × 950  |

### Table 1. List of solar radiation obstacles and their cross-sectional sizes.

![Fig. 2. Schematic diagram used to determine the presence/absence of solar radiation in a radiation direction at the solar radiation calculation point.](image-url)
Architectural Institute of Japan, 1977). However, Matsuda and Yoshikoshi (2019) concluded that the total number of dots or divisions in the DSVF must be set to $2 \times 10^3$ or more in order to ensure that the transmission absolute error of the diffuse solar radiation at any point in the greenhouse is less than 1%. In this study, to increase the number of dots in the DSVF, these dots were arranged according to the following method. The center of the DSVF was defined as the first layer, the periphery as the second layer, and so on, where the number of dots in the DSVF was 1 for the first layer and 6 ($i - 1$) for the $i$th layer ($i \geq 2$). If the cumulative number of dots exceeded the set total number of dots, the number of dots in the outermost layer was the difference between the set total number of dots and the cumulative number of dots of the inner layers. Incidentally, the number of layers were changed according to the total number of dots in the DSVF. The total number of dots was $1 \times 10^3$ in this study.

The position of the dot in the first layer was the center of the circular segment (Fig. 3). The positions of the dots in annular sector segments were the centers of each segment on the circumference whose radius was the average value of the inner and the outer circle radiuses. Equations (2) and (3) show the calculation method of the outer circle radius $r_i$ of the annular sector segment in the $i$th layer.

$$\Delta S = \frac{\pi}{n_{act}}$$

$$r_i = \frac{\Delta S}{\pi} \sum_{k=1}^{i-1} n_k$$

where $\Delta S$ is the occupied area of a dot (= the area of a divided segment), $\pi$ is the circular constant (= the area of a DSVF with radius 1), $n_{act}$ is the set total number of dots in the DSVF, $n_k$ is the number of dots in the $k$th layer in the DSVF, and $i$ and $k$ are layer numbers in the DSVF. The arrangement of the dots in the circumferential direction in the same layer in the DSVF followed the equiangular center angle in Equation (4).

$$\Theta_i = \frac{2\pi}{n_i}$$

(4)

where $\Theta_i$ is the center angle between adjacent points in the $i$th layer. Incidentally, the first dot in the $i$th layer was arranged by rotating $\Theta_i/2$ counterclockwise from the base line (Fig. 3).

For the calculation of the radiation direction using a DSVF, the following method was used. A hemisphere of radius 1 was placed around a solar radiation calculation point and a DSVF of radius 1 was set on the bottom (Fig. 4). Furthermore, the coordinates of an intersection between the vertically upward direction at a dot in the DSVF and the hemispherical surface were simulated. The direction of the intersection at the calculation point was set as the radiation direction. If there was a sunshine obstacle in a radiation direction, the film transmittance in the direction was considered to be zero. The radiation direction and transmittance at all dots in the DSVF were computed. Incidentally, the distribution of diffuse solar radiation from the sky was assumed to be uniform.

Equation (5) shows the calculation of the irradiance of diffuse solar radiation at a given calculation point in the greenhouse.

$$I_D = \frac{I^0}{4\pi}$$

(5)

where $I_D$ is the irradiance of diffuse solar radiation at the calculation point, $I^0$ is the solar irradiation at the calculation point, and $4\pi$ is the area of a hemisphere.
where $S_{diff}$ is the irradiance of diffuse solar radiation at a given calculation point in the greenhouse, $I_{ini}$ is the irradiance of outside diffuse solar radiation (both units are W m$^{-2}$), $t_0$ is the film transmittance in the direction of an intersection between the perpendicular of the $i$th layer and $j$th dot counterclockwise from the base line in the DSVF and the hemisphere surface centered at the calculation point, and $i_{out}$ is the outermost layer number in the DSVF.

2.2.3 Calculation method of reflected solar radiation

Two radiation directions were considered when reflected solar radiation was simulated; one is the solar direction at a reflection point and the other is the direction of the reflection point at the calculation point. Figure 5 shows a schematic diagram for calculating reflected solar radiation, and Fig. 6 shows a calculation flow chart of the irradiance of reflected solar radiation. First, with a film surface in the greenhouse as a symmetry plane, the coordinates of a symmetric point of the calculation point were simulated. Next, a point of intersection between the sun direction at the symmetric point and the symmetry plane was taken as a reflection point. Given that there was no obstacle in the solar direction at the reflection point and between the calculation point and the reflection point, reflected sunlight was considered to be on the symmetry plane (e.g., film plane $B$ in Fig. 5). If one or more of the following conditions was true, there was no reflection by the film surface: (1) no reflection point was detected at the symmetry plane (e.g., film plane $C$ in Fig. 5), (2) a sunshine obstacle was detected in the solar direction at the reflection point, and (3) a sunshine obstacle was detected between the calculation point and the reflection points. Using these methods, the irradiance of reflected solar radiation on all film surfaces in the TF-house was calculated.

Equation (6) shows the calculation of the irradiance of reflected solar radiation at a given calculation point in the greenhouse.

$$S_{ref} = I_{ini} \sum_{k=1}^{6} (\tau_k \rho_k)$$

where $S_{ref}$ is the irradiance of reflected solar radiation at a given calculation point in the greenhouse (W m$^{-2}$). $\tau_k$ is the film transmittance in the solar direction at the reflection point, $\rho_k$ is the film reflectance on the $k$th film, and $6$ refers to the number of film planes of the greenhouse (roof plane, greenhouse side plane, and gable end each have two planes).

2.2.4 Calculation of transmittance and reflectance of the film

The incident angle to the film was calculated as follows: simulating the altitude and azimuth angle of the radiation direction at a calculation point, finding the film that the radiation direction intersects, and computing the incident angle to the film from the azimuth and tilt angles of the film using equation (7).

$$\cos \theta = \sin h \cos \mu + \cos h \sin \mu \cos (\alpha \beta)$$

![Symmetry plane = film plane $B$, $C$, ...](image)

Compute the coordinates of the symmetric point against the solar radiation calculation point

Calculate the coordinates of the reflection point (the intersection of the sun direction at the symmetric point and the symmetry plane)

Is the reflection point within the region of the symmetry plane?

Yes

No

Is there an obstacle in the solar direction at the reflection point?

With obstacles

No obstacles

Is there an obstacle between the solar radiation calculation point and the reflection point?

With obstacles

No obstacles

Calculate the irradiance of reflected solar radiation considering incident angle

Symmetry plane

Sum up irradiance of reflected solar radiation by each symmetry plane

Fig. 5. Schematic diagram for calculating reflected solar radiation, where the reflection point for film plane $B$ was within the plane, and reflected solar radiation on film plane $C$ was absent due to the lack of the reflection point at the film plane $C$. 

Fig. 6. Flow chart used for the calculation of the irradiance of reflected solar radiation.
where $\theta$ is the incident angle to the film, $h$ is the altitude of the radiation direction, $\alpha$ is the azimuth angle of the radiation direction, $\beta$ is the azimuth angle of the film, and $\mu$ is the tilt angle of the film (all units are $^\circ$).

In equations (1), (5), and (6), $\tau_\text{t}$, $\tau_\text{e}$, and $\tau_\text{c}$ is the transmittance of the fluoropolymer film shown in Fig. 7. The transmittance was considered as zero at an incident angle of $90^\circ$, and transmittances between adjacent points within the incident angle ranging from $0^\circ$ to $90^\circ$ were interpolated by linear interpolation. Absorption by films was not taken into consideration, and, therefore, the film reflectance was the remainder from subtracting the transmittance from 1.0. The transmittances of fluoropolymer film were substituted for the transmittance of the PO film used at the greenhouse side planes, gable ends, and door planes. The reason is that the relationship between incident angles and transmittances of the PO film was not published.

2.3 Verification of the validity of calculation results

The validity of calculation results was verified using the following three criteria: (1) validity in shadow distribution on the ground caused by the direct solar radiation, (2) validity in radiation directions using the DSVF for calculation of the diffuse solar radiation, and (3) validity of the calculation methods of the irradiance of total solar radiation (the sum of direct, diffuse, and reflected solar radiation) and non-direct solar radiation (the sum of diffuse and reflected solar radiation).

In the calculation of shadow distribution, the ground in the greenhouse was divided into 1-cm grid squares, and the existence of shadows caused by the direct solar radiation was confirmed at the center of each grid. If there was a shadow, the grid was painted black. The shadow distributions at 09:00 Japan Standard Time (JST) on June 21 (summer solstice) and 09:00 JST on December 22 (winter solstice), 2017 were calculated.

To verify the validity of the radiation direction using the DSVF, a mapping of obstacles in radiation directions using the DSVF was compared with an actual fisheye image captured using a digital camera (E995; Coolpix, Nikon, Tokyo, Japan) and a fisheye lens (FC-E8; fisheye converter, Nikon). The projection method of the lens was equidistant, but the projection method of the DSVF used in this calculation was orthogonal, as shown in Fig. 4. Therefore, the coordinates of the intersection in the orthogonal projection in Fig. 4 were converted into the equidistant projection. Further, a mapping image of obstacles in the radiation direction using the DSVF was compared with the actual fisheye image. The coordinates of an intersection between the perpendicular line at a point in the DSVF and a hemisphere centered at the calculation point were simulated in order to determine if there was a sunshine-blocking obstacle in the direction of the intersection at the calculation point. If an obstacle was identified, the intersection was projected equidistantly within the same circle as the DSVF, and a black dot was marked at that point. The number of dots set in the DSVF was $1 \times 10^5$.

Two pyranometers (SR05-DA1; Hukseflux, Delft, Netherlands) were installed at a height of 2.5 m at the center of the TF-house, and a shading ring (MB-11L; EKO Instruments Trading, Tokyo, Japan) was attached to one of the pyranometers to verify the validity of the calculation of the irradiance of total and non-direct solar radiations. The irradiance of solar radiation observed by the respective pyranometers without and with the shading ring were compared with the calculated irradiance of total solar radiation (the sum of direct, diffuse, and reflected solar radiations) and non-direct solar radiation (the sum of diffuse and reflected solar radiations). The validity of the reflected solar radiation blocked by the shading ring was estimated to be negligible, and, therefore, was not taken into consideration. The number of dots in the DSVF was $1 \times 10^5$.

The outputs from the pyranometers were measured every 10 s, and the 180-s average values were recorded with a datalogger (CR10X; Campbell, Logan, Utah, U.S.A.). The shading ring was a black band with a diameter of 40 cm and a width of 40 mm, and the band position was adjusted manually. Because the shading ring also blocked some of the diffused radiation, the irradiance of diffuse solar radiation was corrected using equations (8) to (10) (Drummond, 1956; Kondo et al., 1991).

$$S_\text{pycom} = c \cdot S_\text{pyout}$$  \hspace{1cm} (8)

$$c = \frac{1}{1 - \frac{2h}{\pi R} \cos^5 \delta \left(\sin \phi \sin \delta + \sin \omega \cos \phi \cos \delta\right)}$$  \hspace{1cm} (9)

$$\sin \frac{\omega}{2} = \left(\frac{\sin \left(\frac{\pi}{4} + \frac{\phi - \delta + \gamma}{2}\right) \sin \left(\frac{\pi}{4} - \frac{\phi - \delta - \gamma}{2}\right)}{\cos \phi \cos \delta}\right)^{1/2}$$  \hspace{1cm} (10)

where $S_\text{pycom}$ is the correction value of the irradiance of solar radiation observed by the pyranometer with the shading ring, $S_\text{pyout}$ is the output value of the irradiance of solar radiation observed by the pyranometer with the shading ring (both units are W m$^{-2}$), $c$ is the correction factor, $h$ is the width of the shading ring (mm), $R$ is the radius of the shading ring (mm), $\delta$ is the declination (rad), $\phi$ is the latitude of the observation point (rad), $\omega$ is the hour angle of the sun at sunset (rad), and $\gamma$ is the
atmospheric refraction of the sun at sunset (= 0.01 rad). The outside global solar radiation was measured every 10 s using a pyranometer (LP02; Hukseflux; height: 2.5 m) and 60-s average values were recorded with a datalogger (CR1000; Campbell). Based on these recorded values, solar radiation in the greenhouse was simulated and averaged every 180 s. The time period and days used for the calculation ranged from 04:00 to 20:00 JST on August 10 (cloudy day) and 13 (sunny day), 2016.

3. Results and discussion

Figure 8 shows the distribution of shadows on the ground in the TF-house at 09:00 JST on summer solstice (June 21) and winter solstice (December 22) in 2017; no unnatural shadow was observed on both days. However, the results could not be compared with the actual shadow distribution in the greenhouse. Hence, in this respect, it was insufficient to verify the validity of the results. At 09:00 on June 21, 2017, the projected area of the roof occupied most of the area on the ground. In contrast, the projected areas of the gable end and the greenhouse side plane on the ground were relatively small; however, the proportions of shadows in each projected area were high. There were many sunshine obstacles at the gable end and the side plane of the greenhouse, and the areas of the shadows of the side pillars, sills, and side girders were large in the projected greenhouse side plane. Conversely, at 09:00 on December 22, 2017, the projected area of the greenhouse side plane occupied most of the ground, in which the shadow areas by the sills were large. In this greenhouse, high-transmittance fluoropolymer films were used only on the roof; however, it is better to also use fluoropolymer films on the greenhouse side plane taking sunshine into account if the plants that develop leaves near the ground are grown in the winter.

Figure 9 shows an actual fisheye image (left figure) and a mapping image of obstacles in radiation directions using the DSVF (right figure). Since the mapping did not incorporate some actual objects (e.g., air circulation fans, iron braces, and pipes and rolling drums for opening/closing internal covering material), there were some differences between both images. However, overall, the calculation of radiation direction using the DSVF yielded a good result. Incidentally, the distribution of dots in the right figure was dense in the center part and sparse in the peripheral part, indicating the characteristic of the equidistant projection method. The method of dot arrangement in the DSVF assigns one dot to the first layer and 6 \((i-1)\) dots to the \(i\)th layer \((i \geq 2)\). However, it is difficult to determine whether this method was best suited for the most equable arrangement of dots. Although the mapping image was compared with the actual

![Fig. 8. Calculation result of shadow distribution on the ground as a result of direct solar radiation at 09:00 JST on June 21 (summer solstice) and December 22 (winter solstice), 2017.](image)

![Fig. 9. (Left) An actual fisheye image of vertical upward direction taken using an equidistant projection lens. (Right) A mapping image of solar radiation obstacles using the DSVF in the greenhouse, output with the same projection method for comparison with the actual fisheye image. The number of dots in the DSVF was \(1 \times 10^5\).](image)
image, the fitness could not be expressed as a numerical value; there is room for consideration.

Figure 10 shows diurnal changes of the calculated and observed values of total and non-direct solar radiations at the same spatial positions as recorded by pyranometers in the greenhouse on a sunny and on a cloudy day. The observed values of non-direct solar radiation in Fig. 10b and d were correction values, \( S_{\text{pycor}} \), obtained from Eq. (8). There was a relatively good agreement between the observed and calculated values in the overall fluctuation and sharp drops of total solar radiation on the sunny day (Fig. 10a) due to the diurnal change of the solar elevation and sunshine obstacles, respectively. However, in the early morning hours, from 06:00 to 07:00, the calculated values were higher than the observed values because buildings standing on the east side of the greenhouse were not considered in the calculation. This calculation will be improved by including the coordinates of surrounding buildings. The calculation of the diurnal change in non-direct solar radiation on the sunny day (Fig. 10b) was a good representation of the observed values. However, as compared with the observed values, the calculated values were slightly higher from 05:00 to 09:30 and 16:00 to 18:00. The reason will be described later.

As shown in Fig. 10a, the calculated values of the total solar radiation were lower than the observed values during the time periods when the solar radiation dropped sharply as a result of sunshine obstacles in the greenhouse. In contrast, differences between the calculated and the observed values for non-direct solar radiation were negligible during these times (Fig. 10b). This result suggests that the underestimation of the direct solar radiation during these times can be determined by neglecting the diffraction when obstacles block direct solar radiation.

Figures 10c and d show diurnal changes in total and non-direct solar radiation on a sunny day (August 13, 2016) and a cloudy day (August 10, 2016). The number of dots in the DSVF was \( 1 \times 10^5 \).

Fig. 10. Diurnal changes of calculated and observed values of total and non-direct solar radiations in the timber-framed greenhouse on a sunny day (August 13, 2016) and a cloudy day (August 10, 2016). The number of dots in the DSVF was \( 1 \times 10^5 \).
solar radiations on the cloudy day. Both figures show relatively good results, although there were slight shifts in the time of the rising value and some differences between the calculated and observed values for the same time. In Fig. 10d, the calculated values were slightly higher than the observed values from 09:00 to 13:00. This could be attributed to the fact that the component of diffuse solar radiation estimated from the observed outside global solar radiation was slightly higher than the actual value on this day.

The proportions of direct, diffuse, and reflected solar radiations in the greenhouse were 73.2%, 26.8%, and 0.0% on August 13, and 10.2%, 89.8%, and 0.0% on August 10, respectively. The ratio of the irradiance of reflected solar radiation was low. This is because the calculation point was set at a high position in the TF-house and there was almost no reflection from the greenhouse side plane. If the calculation point was set on the ground, it was inferred that the irradiance of reflected solar radiation would increase.

The relative error in each calculated value of the irradiance of daytime (from 04:00 to 20:00) total and non-direct solar radiations to the measured value was (a) 4.3% for the total radiation on the sunny day, (b) 5.5% for the non-direct radiation on the sunny day, (c) 1.1% for the total radiation on the cloudy day, and (d) 0.3% for the non-direct radiation on the cloudy day, where the calculated values were higher than the measured values except for (c). The non-direct solar radiation on the sunny day (Fig. 10b), the day with the highest relative error between Fig. 10a–d, could be attributed to the low accuracy in the estimation of the outside direct and diffuse solar radiation from the outside global solar radiation during low solar elevation on the sunny day. This can be improved by directly measuring the outside diffuse solar radiation in addition to observing the outside global solar radiation.

The results of the calculation of the irradiance of total and non-direct solar radiations in the greenhouse were in reliable agreement. This agreement indicated that the DSVF can be useful for calculating solar radiation in a greenhouse with a complex structure. The expected improvement points suggested in this study are as follows: goodness of fit between calculated and observed shadow distribution and the mapping image using the DSVF and an actual fisheye image.

Acknowledgements

This study was supported by a Grant-in-Aid from the Ministry of Agriculture, Forestry and Fisheries of Japan (A project to apply advanced technologies for regenerating a food production area). We thank Dr. Yoshitaka Kurose of WARC/NARO for lending the digital camera and the fisheye lens.

References

AGC Green-Tech Co., Ltd., 2019: <https://www.f-clean.net/f-clean-uv-open/> (accessed on 15 February 2019). Architectural Institute of Japan, 1977: Nissha no sokutei to kentou, Shokokusha Publishing, Tokyo, pp. 87 (in Japanese).

Bowman GE, 1970: The transmission of diffuse light by a sloping roof. Journal of Agricultural Engineering Research 15(2), 100–105.

Cabrera FJ, Baille A, López JC, González-Real MM, Pérez-Parra J, 2009: Effects of cover diffusive properties on the components of greenhouse solar radiation. Biosystems Engineering 103, 344–356.

Chandrasekaran J, Kumar S, 1994: Hourly diffuse fraction correlation at a tropical location. Solar Energy 53(6), 505–510.

Cossu M, Ledda L, Urracci G, Sirìfu A, Cossu A, Murgia L, Pizzonia A, Yano A, 2017: An algorithm for the calculation of the light distribution in photovoltaic greenhouses. Solar Energy 141, 38–48.

Critten DL, 1983: A computer model to calculate the daily light integral and transmissivity of a greenhouse. Journal of Agricultural Engineering Research 28, 61–76.

Drummond AJ, 1956: On the measurement of sky radiation. Archiv für Meteorologie, Geophysik und Bioklimatologie, Serie B7, 413–436.

Erbs DG, Klein SA, Duffie JA, 1982: Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. Solar Energy 28(4), 293–302.

Kondo J, Nakamura T, Yamazaki T, 1991: Estimation of the solar and downward atmospheric radiation. Tenki 38, 41–48 (in Japanese).

Kozai T, Sugi J, 1972: Studies on the solar irradiation in greenhouses (2). Journal of Agricultural Meteorology 27(3), 105–115 (in Japanese with English summary).

Kozai T, Goudriaan J, Kimura M, 1978: Light Transmission and Photosynthesis in Greenhouses. Centre for Agricultural Publishing and Documentation, Wageningen, pp. 99.

Kurata K, 1990: Role of reflection in light transmissivity of greenhouses. Agricultural and Forest Meteorology 52, 319–331.

Manbeck HB, Aldrich RA, 1967: Analytical determination of direct visible solar energy transmitted by rigid plastic greenhouses. Transactions of the ASAE 10(4), 564–567 and 572.

Matsuda S, Yoshikoshi H, 2019: Relationship between the number of dots in a sky view factor diagram and the absolute error of the transmittance of diffuse solar radiation in a greenhouse, Transactions of the 2019 International joint conference on JSAM, SASS and 13th CIGR VI technical symposium joining FWNWG and FSWG workshops, pp. 117 (in Japanese).

Nisen A, 1962: Calculation of natural light for horticulture structure. Proceedings of the 16th International Horticultural Congress (Aug. 31– Sep. 8, Brussels), 4, 283–289 (in French).

Perez RR, Ineichen P, Maxwell EL, Seals RD, Zelenka A, 1992: Dynamic global-to-direct irradiance conversion models. ASHRAE Transactions 98, 354–369.

Reidt DT, Beckman WA, Duffie JA, 1990: Diffuse fraction correlations. Solar Energy 45(1), 1–7.

Skartveit A, Olseth JA, 1987: A model for the diffuse fraction of hourly global radiation. Solar Energy 38(4), 271–274.

Soga K, Akasaka H, Nimiya H, 1998: A comparison of models to estimate hourly direct and diffuse irradiation from hourly global irradiation. Journal of Architecture, Planning, and Environmental Engineering 512, 17–24 (in Japanese with English summary).

Soriano T, Montero JI, Sánchez-Guerrero, Medrano E, Antón A, Hernández J, Morales MI, Castilla N, 2004: A study of direct solar radiation transmission in asymmetrical multi-span greenhouses using scale models and simulation models. Biosystems Engineering 88(2), 243–253.

Takakura T, Jordan KA, Boyd LL, 1971: Dynamic simulation of plant growth and environment in the greenhouse. Transactions of the ASAE 14(5), 964–971.