Light transmission and photosynthesis in greenhouses

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approach in estimating the light environment in a greenhouse will become more and more important as the commercial greenhouse industry expands.
At present, most of the models, however, concern only a single-span greenhouse and only a few models are available for calculating the light environment in a multispan greenhouse (Stoffers, 1971; Kirsten, 1973). Besides, the arrangement of structural members, the width and depth of these members, and the resulting uneven light distribution in the greenhouse have not been considered in most of the models. No model is available for calculating the net photosynthesis in the greenhouse mainly because of the complexity of constructing the model and the requirement of much computing time for the simulation run.

This book describes a computer simulation model for calculating the net photosynthesis in single-span and multispan greenhouses of finite length with solid, opaque struts and with non-diffusing covering materials both for the direct and diffuse solar light. To evaluate the net photosynthesis, the variations of the light environment in space and time within the canopy have been considered in some detail in the present model. Internal reflection from the glass within the greenhouse is not considered in the present model. The model is applied to both single-span and multispan greenhouses with different roof slopes in various orientations at different localities throughout the year. Throughout the chapters, emphasis is put on winter conditions, since these are the most difficult for the greenhouse grower.

The instruction manual for the use of the computer simulation program used in the present study together with the complete list of the program is given in Appendix A, so that the program can be used by greenhouse designers and researchers. The instructions are given in such a way that anyone who has the minimum knowledge of FORTRAN and CSMP languages can use the program. The program has been kept general so that it can be adapted to most conditions.

2 Description of the model

2.1 Transmissivity

2.1.1 Transmissivity of a multispan greenhouse

In a multispan greenhouse of finite length with solid structural members a light ray may pass through the glass roofs more than once before reaching the floor or the plants. After it has passed through one glass roof, a light ray may also be intercepted by some member, as shown in Fig. 1. Therefore it is more difficult and time consuming to develop an analytical model for predicting the light transmission by a multispan greenhouse than a numerical one. In this section a numerical model for greenhouse light transmission is described. In this model each light ray is traced until either the light ray reaches the floor or is intercepted by one of the struts before reaching the floor. The extinction of light intensity due to reflection and absorption is calculated by Fresnel's equations for each time the light ray passes through the glass. The extinction coefficient, index of refraction, thickness of the glass are assumed to be 0.076 cm^{-1}, 1.526, and 0.3 cm, respectively. When the angle of incidence changes from 0 to 90° at 10° intervals, the transmissivities of the glass are then, respectively, 0.86, 0.86, 0.86, 0.85, 0.85, 0.82, 0.77, 0.65, 0.40, and 0.00 (see Fig. 2). Thus, at angles greater than 40°, transmission begins to fall more and more rapidly. At 80° even more light is reflected than passes through the glass. To calculate the spatial average transmissivity of the greenhouse for light rays with a particular direction, many light rays with the same direction have to be traced in the computer. Each ray should fall on the floor at random to eliminate the possible bias of the transmissivity due to the regular and sparse arrangement of struts. This stochastic (Monte Carlo) method requires much computing time for the simulation, but it seems that there is no simple alternative deterministic method of predicting the spatial average transmissivity of a multispan greenhouse. Detailed computational procedures using a Monte Carlo method for predicting the greenhouse light environment are given in Section 2.1.4.

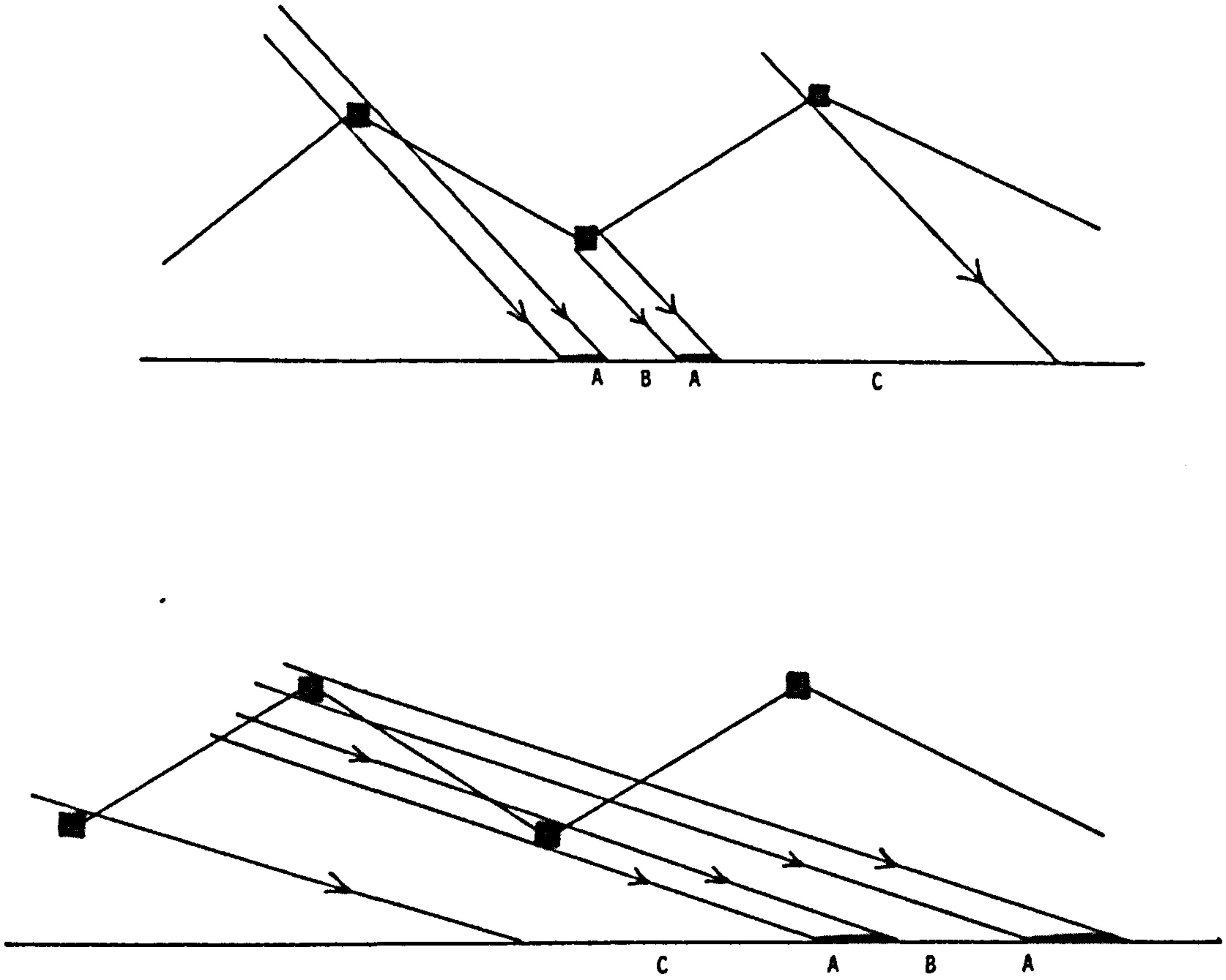


Fig. 1 | Schematic representation of direct solar light transmission into a multispan greenhouse.
upper: The sun's altitude relative to the roof not facing the sun is positive.
lower: The sun's altitude relative to the roof not facing the sun is negative. Here a part of the light passes through the roofs three times before reaching the floor or plants in the greenhouse

2.1.2 Total transmissivity of a greenhouse

The solar light reaching the Earth's surface can be divided into two components: direct light from the sun and diffuse light from the sky. The transmissivity of a greenhouse for direct light is generally different from that for diffuse light. Both depend on the shape and structure of the house, but only direct light transmission depends on the greenhouse orientation and the position of the sun in the sky. The transmissivity for the diffuse light may be considered a constant of the greenhouse itself.
Total light transmissivity, which is defined as the ratio of total (direct plus diffuse) light intensity or total light

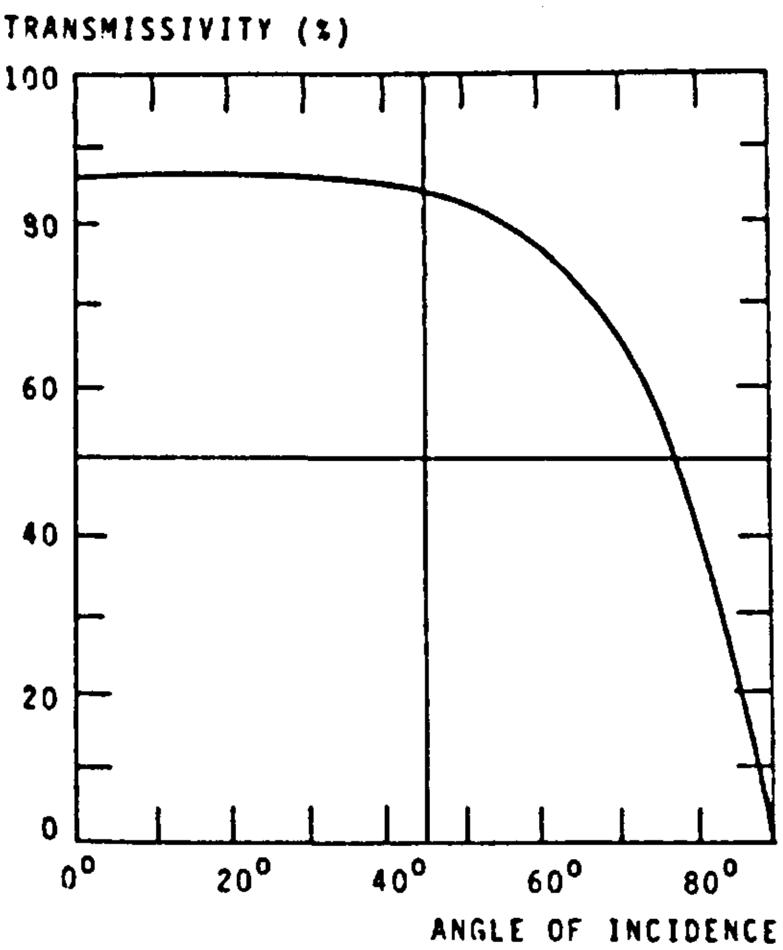


Fig. 2 | Relationship between the angle of incidence and transmissivity of glasspane for direct solar light.

integrals per unit area of the floor of the house to the light falling on unit area of the ground outside the house, TT, is given by the equation:

$$TT = FRDIF \times TRDIF + (1-FRDIF) \times T \qquad (2.1)$$

where FRDIF is the ratio of diffuse to total solar light outside typical for the time of year and the site of the greenhouse, T the transmissivity of the house for direct light, and TRDIF the transmissivity for diffuse light. Therefore, in order to establish the influences of the house orientation, the latitude, and time of year on the total transmissivity of the house, the determination of the transmissivity for direct light is of primary importance. The quantitiy FRDIF is a meteorological parameter and can be derived from appropriate measurements of the solar light components at a place in question.

A part of the direct light is scattered by a diffusive covering material or a non-diffusive material with water droplets and dirt. Furthermore, a part of the transmitted light is reflected by the glass within the greenhouse. The diffused light in the actual greenhouse, therefore, consists of transmitted diffuse light, scattered direct solar light, and reflected direct and diffuse solar light. Sometimes the diffuse light intensity inside the greenhouse may be larger than that outside (Uchijima et al., 1976; Kishida & Sonoyama, 1977).

2.1.3 Transmissivity of a greenhouse for direct and diffuse light

Suppose the hemispherical sky be equally divided into m x n segments and the transmissivity of a greenhouse for parallel light rays from a centre part of the (I,J)th segment be T(I,J).

Transmissivity for direct light

Thus, T(I,J) can be interpreted as the transmissivity of the house for direct light with the sun's altitude of (90I-45)/n degrees and sun's azimuth of (180J-90)/m degrees, if the numbers of m and n are large enough (m and n should be at least 36 and 18, respectively). Then the relative daily total of direct light is given by the equation:

$$AD = \frac{\sum_{t=\text{sunrise}}^{\text{sunset}} DRP(t) \cdot T(I_t, J_t) \cdot \Delta t}{\sum_{t=\text{sunrise}}^{\text{sunset}} DRP(t) \cdot \Delta t} \qquad (2.2)$$

where $I_t = (n \cdot H_t + 90)/90$, $J_t = (m \cdot A_t + 180)/180$ if the integers I_t and J_t are obtained after truncation of the floating point, $H_t (0^\circ < H < 90^\circ)$ the sun's altitude, $A_t (-180^\circ \leqq A_t \leqq 180^\circ)$ the sun's azimuth, and DRP(t) the direct light intensity outside at time t. The time interval for the integration, Δt in Eqn (2.2), was chosen as 1.0 hour in the present simulation. If the cross and longitudinal-sections of the house are symmetrical with respect to their centre axes, the transmissivity of the house for the solar azimuth of $A_t (0^\circ \leqq A_t \leqq 90^\circ)$ is equal to that for the solar azimuth of $(-A_t)$, $(A_t + 90^\circ)$, and $(A_t - 90^\circ)$ at any solar altitude. Then the transmissivities need only be calculated within the solar azimuth range between 0° and 90°, because those for the rest of the azimuths can be derived from this range.

Transmissivity for diffuse light

The transmissivity of the greenhouse for the isotropic diffuse sky light can be obtained by the equation:

$$TRDIF = \sum_{J=1}^{m} \sum_{I=1}^{n} T(I,J) \quad \sin^2(90\ I/n) - \sin^2(90(I-1)/n \quad /m \qquad (2.3)$$

where the second term of the equation is a weighting coefficient as a function of the altitude from which the light comes, the analytical form being $\int_{h_1}^{h_2} \sin(h) \cdot \cos(h)\, dh$.

The transmissivity of the greenhouse for non-isotropic diffuse sky light can also be obtained in a similar way simply by changing the weighting coefficients. Bowman (1970) gave the analytical method of calculating the transmissivity of diffuse light under non-isotropic (standard overcast) conditions and showed that it is worthwhile using the radiance distribution for a standard overcast sky in calculations relating to greenhouses, where differences in transmissivity of the order of 1% are of interest. He also showed the importance of the effect of greenhouse geometry on the transmission of diffuse light and that light reflected from the underside of a pitched roof makes a significant contribution to the total illumination.

2.1.4 Transmissivity of the greenhouse for light rays of particular direction

Once the direction from which the solar light rays come has been determined, the transmissivity (the inside solar light intensity relative to the one outside) of a greenhouse for the light rays can be calculated according to the following computational steps:

1. give the geometry and the arrangement of structural members of the greenhouse,
2. specify the number of light rays, I, which is used to calculate the transmissivity for the particular direction of the light rays (usually more than 10 000),
3. specify the range of calculation ($X1<X<X2$) along the length of the house, XL, within which the transmissivities for the light rays should be averaged, where $X1 \geq 0$, $X2 \leq XL$, and $X1<X2$,
4. assign values to YS and YE in the range for which the distribution of the transmissivities is calculated across the width, where $YS \geq 0$, $YE \leq$ width of the house, and $YS<YE$. Divide the range into J parts, and average the transmissivities in each division. The width of each division is $(YE-YS)/J$. Set the values of Y1 and Y2 to YS and $YS+(YE-YS)/J$, respectively,
5. initialize the value of integer variable i (the sequential number for pairs of random numbers, $1 \leq i \leq I$) at 1 and the value of n (the number of light rays intercepted by the structural members, $0 \leq n \leq I$) at 0,
6. produce a pair of uniform random numbers (XR,YR) within the ranges between X1 and X2, and between Y1 and Y2,
7. produce a light ray with the direction specified, which passes through the point (XR,YR),

8. initialize the transmissivity at the point (XR,YR), T, at 1.00,
9. initialize the value of the integer variable assigned to each of the greenhouse glass panes, k, at 1 ($1 \leq k \leq K$; K is the total number of greenhouse glass panes),
10. find whether the glass pane k intersects the light ray. If not, proceed to Step 15,
11. compute the point of intersection,
12. find whether the light ray is intercepted by any of the struts,
13. if so, set the value of T to zero and increase the value of n by one. Then, proceed to Step 17,
14, if not, compute the incidence angle of the light ray on the surface and the corresponding transmissivity of the surface. Calculate the new value of T by multiplying the old value of T by the transmissivity of the surface ($T_{new} \leftarrow T_{old} \times T_{current}$). T_{new} presents the relative intensity of light after passing through the glass pane k,
15. increase the value of k by one. If the value of k is less than K, return to Step 10,
16. add the value of T to CT ($CT_{new} \leftarrow CT_{old} + T$), where CT is the intermediate value to get the average spatial transmissivity at the segment (defined as X1 x X2 and Y1 x Y2) on the floor (see Step 18),
17. if the value of i is less than I, return to Step 6 after increasing the value of i by one,
18. divide the value of CT by I to get the space averaged transmissivity at the segment on the floor. Divide the value of n by I to get the ratio of the area shaded by the structural members to the segment area,
19. increase the values of Y1 and Y2 by (YE-YS)/J. If the new value of Y2 is less than or equal to the value of YE, proceed to Step 5.

The following assumptions were made:

- Internal reflection by the glass surface inside a greenhouse is ignored. The internal reflection of direct light in a single-span greenhouse with non-diffusing covering materials was studied by Kozai and Sugi (1972).
- Clear glass with parallel surfaces does not diffuse light. Basiaux et al. (1973) examined the effect of diffusion properties of greenhouse covers on the light balance in a greenhouse.
- The polarization of light, which was discussed by Bowman (1970) and Stoffers (1971), is not considered in the present

model, because it does not give rise to any appreciable difference in the daily integrals of light in the region considered in the present analyses (Morris, 1972).
- The direct light rays were considered to be completely parallel, although the solar disc actually subtends 0.5°. In other words the penumbra was ignored.

2.1.5 Calculation of daily solar light integrals in the greenhouse

The diurnal courses of the total solar light intensity and its daily integrals in the greenhouse were calculated as follows: The direct DRP and diffuse DSH solar light intensity outside for clear days and the diffuse light intensity DIFOV outside for overcast days were calculated by the following equations:

$$DRP = 580. * SIN(H) * (1.0-FRDIF) * TRAM \qquad (2.4)$$

$$DSH = 580. * SIN(H) * FRDIF * TRAM \qquad (2.5)$$

$$DIFOV = 116. * SIN(H) * TRAM \qquad (2.6)$$

$$TRAM = EXP(-0.1/SIN(H)) \qquad (2.7)$$

where H is the sun's altitude, TRAM the atmospheric transmission coefficient, and FRDIF the fraction of the diffuse to the total solar light, which is a function of the sun's altitude. The values of 1.0, 1.0, 0.4, 0.3, and 0.25 were assigned to FRDIF for the sun's altitudes of 0°, 5°, 15°, 25° and 90°, respectively. The intermediate values of FRDIF which are not specified above were calculated by linear interpolation. The fluxes DSH, DRP, and DIFOV only present the visible part of the spectrum and are expressed in $W\ m^{-2}$.
The values of DRP, DSH, and DIFOV are calculated at certain intervals for a whole day to obtain the daily integrals of the total light both for clear (CLT) and for overcast days (OVT). Fraction of overcast, f, for a given day, which is defined as:

$$f = (CLT-ADT)/(CLT-OVT), \qquad (2.8)$$

is then estimated, where ADT is the actual meteorological data of daily integral of total visible solar light at the place in question on the corresponding day.
Finally, the daily integral of the total light ATRT in the greenhouse is given by

$$ATRT = (1-f) \sum_{t=sunrise}^{sunset} (DSH \cdot TRDIF + DRP \cdot T(t)) \cdot \Delta t + f \cdot TRDIF \cdot OVT \qquad (2.9)$$

where TRDIF is the transmissivity of the greenhouse for diffuse light, T(t) the transmissivity of the house for direct light at each time of the day.

To illustrate the influence on light transmission by a greenhouse of the latitude where the greenhouse is built, two places were chosen: Tokyo (35°41'N) (or Osaka (34°39'N)) in Japan and Amsterdam (52°20'N) in the Netherlands. The actual monthly meteorological data of daily solar light integrals (ADT in Eqn (2.8)) for average years at the two places, which were used as the input data in the present simulation, are given in Fig. 3. The drop in daily solar light in June in Tokyo is due to the annual rainy season in early summer. Fig. 4 shows the average monthly ratios of diffuse to total light (FRDIF in Eqn (2.1)) at the two places, estimated by using Eqns (2.4) to (2.8). The diurnal courses of the altitude and azimuth of the sun on each day were calculated by using well-known formulae (e.g., Robinson, 1966). Fig. 5 illustrates, as examples, the changes in altitude and azimuth of the sun from noon till sunset on 22 December (the winter solstice), 21 March (the spring equinox), and 22 June (the summer solstice) in Amsterdam (52°20'N) and Tokyo (35°41'N). Solar altitudes at culmination on 22 December, 21 March, and 22 June are 14, 37, and 61°, respectively, in Amsterdam and are 31, 54, and 78°, respectively, in Tokyo.

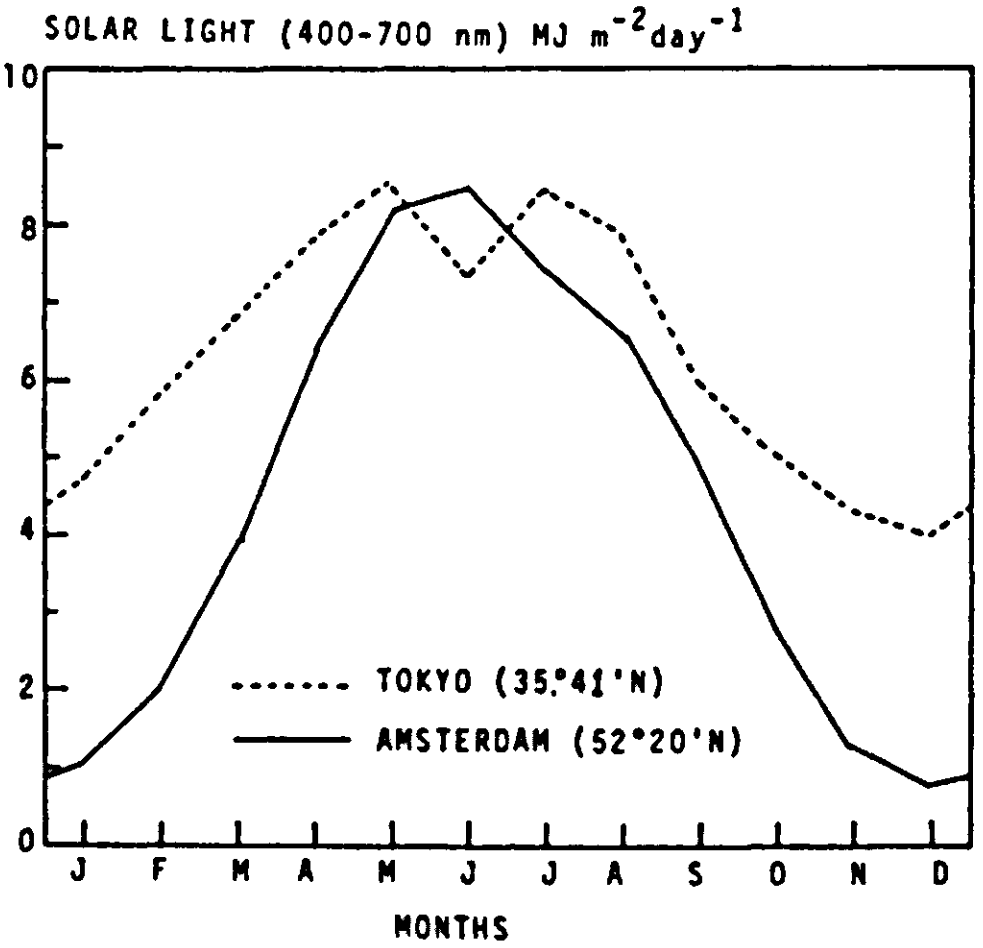


Fig. 3 | Mean daily values of total solar light (400-700 nm) throughout the year in Amsterdam and Tokyo. (After Manbeck and Aldrich and data from KNMI)

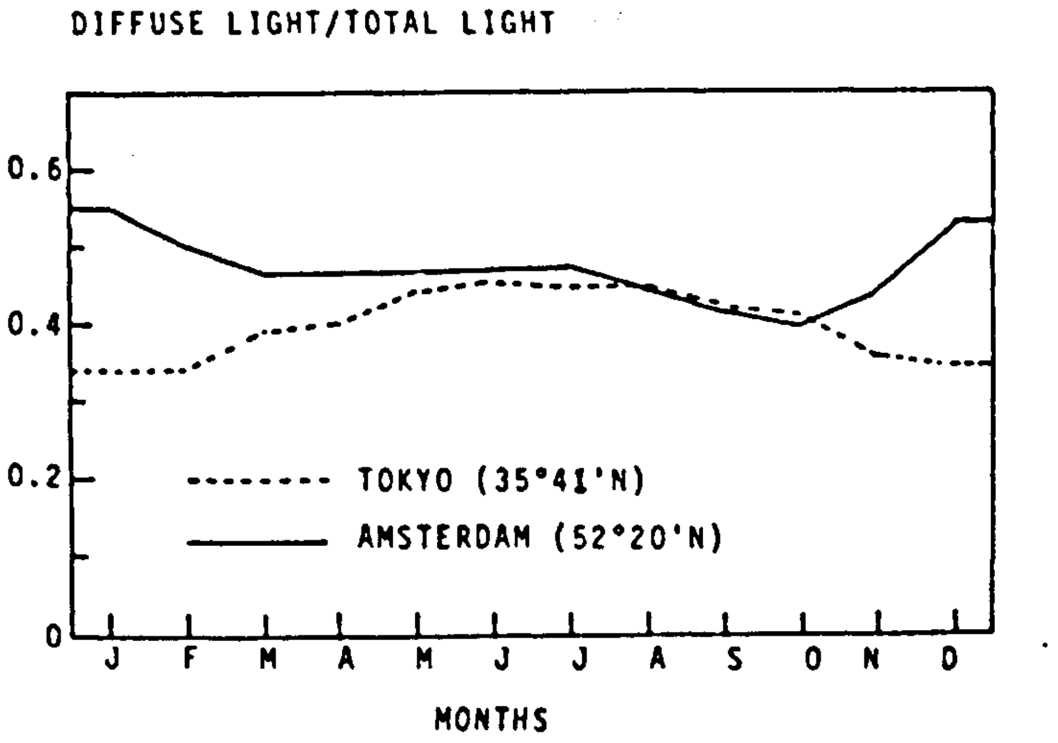


Fig. 4 | Mean monthly ratio of diffuse to total solar light (After Manbeck and Aldrich and data from KNMI)

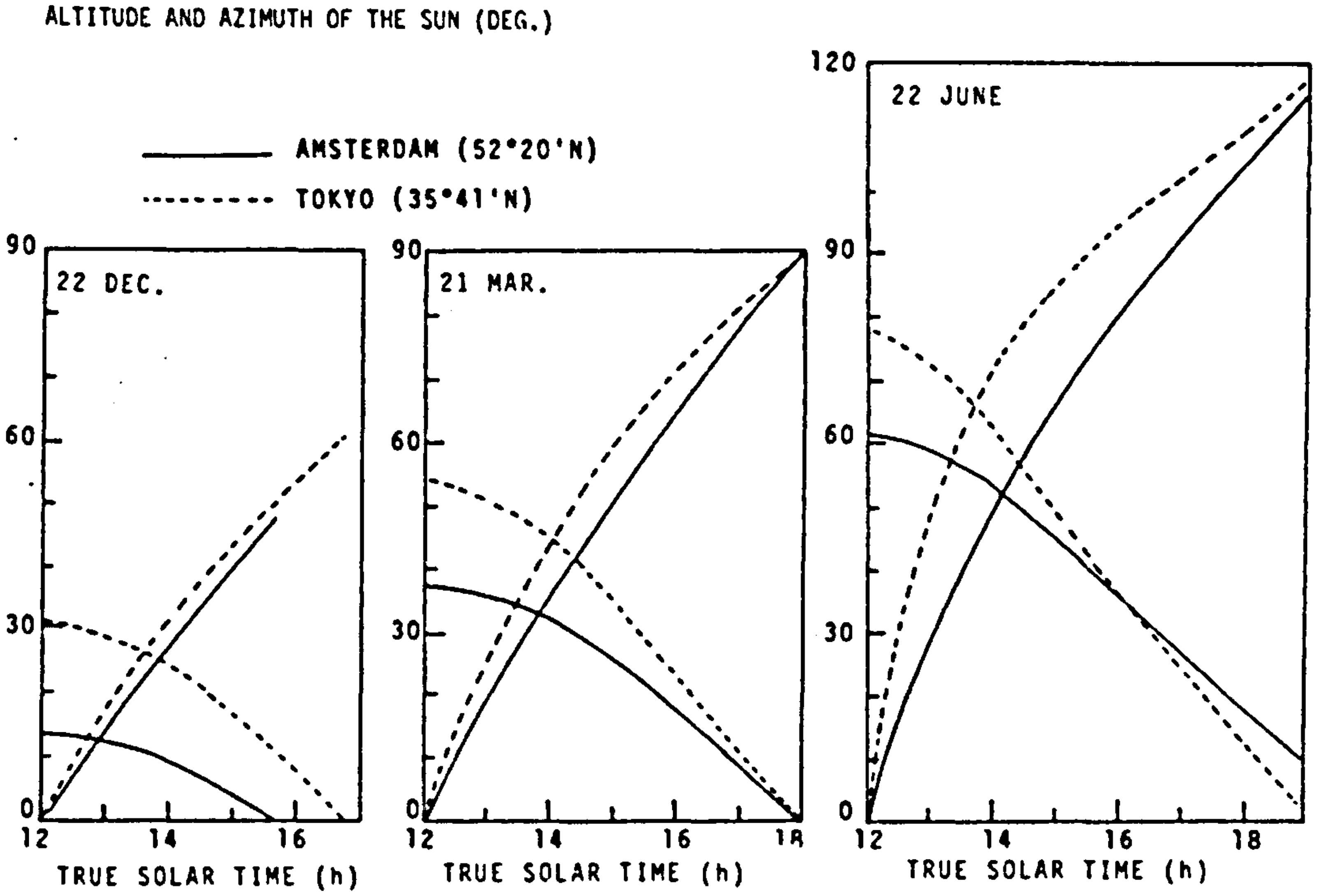


Fig. 5 | Changes in altitude and azimuth of the sun from noon till sunset on 22 December, 21 March, and 22 June in Amsterdam (52°20'N) and Tokyo (35°41'N).

2.2 Photosynthesis

In the previous chapter the model is discussed for the interception and transmission of the incident radiation by the greenhouse. The remaining transmitted radiative energy is used for photosynthesis, transpiration and sensible heat loss. The variation of light intensity in the horizontal direction, due to interception by the frame of the greenhouse and to transmission by differently oriented glass panes, makes the calculations more complicated than those for crops in the open.

2.2.1 The use of photosynthetic products

Before discussing the modelling of the photosynthesis itself, one should decide how to use the calculated increase in dry matter. It may be stored somewhere in a harvestable non-photosynthesizing plant organ, without affecting the leaf area index. However, it may be used for the formation of new leaves, so that there is feedback between photosynthesis and leaf area index.
The first method essentially assumes linear growth for constant environmental conditions. The growth equation is

$$\frac{dH}{dt} = a \; \mathrm{LAI} \qquad (2.10)$$

where H is the harvestable dry matter, LAI the leaf area index and a some proportionality constant, which depends on the light environment and is thus a function of transmissivity. Then the time required for the production of one crop is

$$t = (H_m - H_o)/(a \; \mathrm{LAI}) \qquad (2.11)$$

where H_m is the dry matter upon harvesting and H_o the initial dry matter. In the second method the LAI is proportional to H. The difference between the two methods is maximum, since a is not dependent on LAI. The resulting growth is exponential

$$H = H_o \exp{(a \; t/p)} \qquad (2.12)$$

where p is the specific leaf weight.
Now the time required is

$$t = \ln \left(\frac{H_m}{H_o}\right) p/a \qquad (2.13)$$

Thus in both methods the time requirement is inversely proportional to *a*, which factor contains the influence of the greenhouse geometry. Therefore the two methods discussed are equivalent for the purpose of comparing greenhouse performance, as long as an accurate prediction of the actual growth period is not required. Hence the simpler, linear method is used with a constant leaf area index.

2.2.2 Classification of the incoming radiation

The division of the visible radiation into direct and diffuse follows from the equations given in Section 2.1.5. The level of background radiation, uniform in the horizontal plane, is formed by the diffuse radiation from the sky, clear or overcast, after reduction by the greenhouse. The transmission coefficient for diffuse radiation is independent of greenhouse orientation. The direct radiation can be affected in three different ways: (Fig. 1)

a) It is intercepted by the frame (structural elements).

b) It passes through the roof side not facing the sun. Thus either the radiation is incident from above so that the sine of incidence is smaller than on the other roof side, or it is incident from below so that it has already passed the other roof side, and will do so another time, before reaching the soil or plants.

c) In all other situations it passes the roof side facing the sun only once. Then the transmissivity is largest. For each situation the fraction of projected area on the soil surface is calculated as is the corresponding transmissivity. These calculations are done by the program described in Chapter 2 for a series of sun inclinations and sun azimuths with respect to the azimuth of the glasshouse. Since the transmissivity of structural elements is always zero, and the fractions add up to one, four numbers characterize the transmissivity for each position of the sun. In the program these values are calculated and used for 19 inclinations and 19 relative azimuths, so that 1444 numbers characterize the transmissivity of a greenhouse. At a certain moment there are three classes of irradiation on the floor of the greenhouse, corresponding to situations a, b and c which all have the transmitted diffuse radiation in common. In the simulation program the penumbral effect is neglected. There is a distinct boundary between irradiation classes.

2.2.3 Leaf and canopy photosynthesis

For each class of irradiation the photosynthesis and transpiration for that part the canopy considered are calculated. This procedure is described extensively by Goudriaan (1977), but the essential elements are the following:
The fraction of sunlit leaves is

$$s = \{1 - \exp(-K_b\ LAI)\}/(LAI\ K_b) \tag{2.14}$$

where K_b is the extinction coefficient for direct radiation. The intensity of the direct radiation does not matter in this equation, so that it can be equally applied for all irradiation classes. The average absorbed direct light is now

$$\bar{R}_{v,d} = S_b\ (1 - \sigma_v)\ s \tag{2.15}$$

where S_b is the visible radiative flux through a horizontal surface and σ_v the scattering coefficient of the leaves in the visible region. Because also scattered radiation is partially absorbed upon a secondary interception, the average absorbed radiation originating from direct light is larger and is given by

$$R_{v,b} = S_b\ (1 - \sigma)\ (1 - \exp(-K\ LAI)/LAI \tag{2.16}$$

where σ and K are the reflection and extinction coefficients under direct irradiation. In these coefficients the secondary diffuse flux is included. The difference between the last equations represents the absorbed diffuse radiation, originating from direct radiation. Hence, the absorbed diffuse visible radiation, common to all leaves is

$$R_s = R_{v,c} + R_{v,b} - R_{v,d} \tag{2.17}$$

This is the absorbed visible radiation for shaded leaves. It must be noted that this irradiation is higher for the shaded leaves in the sunlit parts of the greenhouse than in the parts shaded by structural elements. Equations (2.15), (2.16) and (2.17) are applied for each of the three irradiation classes of the greenhouse floor.
For the sunlit leaves the direct radiation absorbed must be added to the amount given by Eqn (2.17). Sunlit leaves are classified according to the sine of incidence of the direct light. Ten classes are distinguished so that the direct radiation absorbed is

$$R_{v,d} = (0.1t - 0.05)\ (1 - \sigma_v)\ S_p \qquad (2.18)$$

where *t* is the index of the sine of incidence, running from 1 to 10 and S_p the direct flux through a surface perpendicular to the beam. The fraction of leaves in each class of incidence is 0.1. This simple distribution function holds for a spherical leaf angle distribution, the best guess for an imaginary crop (Goudriaan, 1977; Ross, 1975).
The leaf area index remains constant throughout the period studied and is here chosen to be 0.5. This is an arbitrary choice, which will not essentially affect the results.
The photosynthesis function of the individual leaves is chosen as the following equation

$$F_n = (F_m - F_d)\ (1 - \exp(-R_v \varepsilon / F_m)) + F_d \qquad (2.19)$$

which is close to most measured curves (van Laar & Penning de Vries, 1972). F_m is the maximum rate of net CO_2-assimilation, F_d the net CO_2 assimilation in the dark (negative dark respiration), R_v the absorbed visible radiation per leaf area and ε the slope of the curve at low light intensities. The latter can also be considered an efficiency and has an approximate value of $11.4\ 10^{-9}$ kg CO_2 per J absorbed visible light energy. This is the value for C_3 plants to which most plants belong that are cultivated in greenhouses (lettuce, tomatoes, cucumber, etc.). The maximum rate F_m and the dark rate F_d are both temperature-dependent. Therefore the temperature regime in the greenhouse is of some importance. It is simulated by first-order kinetics with a time constant of one hour. The equilibrium value is 10 °C during the night period and 20 °C during the day period, when the sun is above the horizon. In this temperature range the maximum rate F_m is made a linear function of air temperature.
At 10 °C it is 10 kg CO_2 $ha^{-1}h^{-1}$ (0.28×10^{-6} kg CO_2 $m^{-2}s^{-1}$) and at 20 °C it is 40 kg CO_2 $ha^{-1}h^{-1}$ (1.11×10^{-6} kg CO_2 $m^{-2}s^{-1}$).
The respiration rate is simply taken as one tenth of the maximum assimilation rate. This is a reasonable approximation for many plants (Tooming, 1967).
According to the simulation study a uniform temperature during day and night would mean an unreasonably long winter period in the Netherlands during which the 24 hours balance of CO_2 assimilation is negative; about four months. Lowering the night temperature to 10 °C reduces the respiration during the long nights to such an extent that the period of no growth is limited to the two darkest months.
The net CO_2-assimilation may be, and is often, improved by CO_2-fertilization. In this study, however, only an ambient

concentration of 300 vpm has been considered.
The fluxes per ground area are found by the following equations

$$F_{sh} = LAI\ (1-s)\ F(R_s) \qquad (2.20)$$

for the shaded leaves and for the sunlit leaves

$$F_{su} = LAI\ s \sum_{t=1}^{10} 0.1\ F(R_s + R_{v,d}) \qquad (2.21)$$

The variable F(R) means F according to Eqn (2.19) in which R_v should be replaced by R. These two fluxes are added to give the flux per ground area in one of the three main irradiation classes. This calculation is repeated for each class and then added according to the fractions following from the inclination and azimuth of the sun. The result is the average flux per ground area under a clear sky. For an overcast sky the procedure is simpler and only one equation is used:

$$F_{ov} = LAI\ F(R_{v,o})\ . \qquad (2.22)$$

where $R_{v,o}$ is found in the same way as in Eqn (2.16). The fluxes are integrated separately to give the daily totals for clear days and for overcast days. Finally the average daily total for standard conditions is found by the equation

$$\bar{F} = f \int F_{ov} + (1-f) \int F_{cl} \qquad (2.23)$$

where f is the average fraction overcast for the time of the year and the site of the greenhouse.

3 Influence of orientation in multispan greenhouses

Whittle and Lawrence (1959) measured natural light in single-span greenhouses differing in size and orientation to study the effect of greenhouse orientation on the transmission of winter light. They found that more direct light was transmitted by an E-W house than by a N-S one. They also found a more uniform distribution of light in E-W single-span houses. Their general conclusions about the orientation effect have been confirmed by measurements (e.g., Edwards, 1964) and by computer simulations (e.g., Nisen, 1962; Smith and Kingham, 1971).

However, it was uncertain which orientation is optimal in a multispan greenhouse. Morris (1972) suggested that in multispan greenhouses E-W orientation is likely to have fewer advantages because each span is shaded by its neighbor to the south. Moreover he indicated that the lack of uniformity of light in E-W greenhouses due to shadows and reflections remaining stationary during the important hours of the day, was more marked in multispan greenhouses. These suggestions provide an argument in favour of N-S orientated multispan greenhouses.

In this chapter the variation of light transmission by a multispan greenhouse with orientation, season, and latitude and of crop performance within the greenhouse are discussed in relation to our results of computer simulation. The simulated results demonstrate the dependence of the orientation effects on latitude and season.

3.1 Description of the greenhouse

Front and side views of the greenhouse used as an example in the present simulation are shown in Fig. 6. The cross-section and longitudinal-section of the house are symmetrical and the house is one of the most commonly used commercial greenhouses in Japan. The dimensions and technical details of the house are as follows:

number of spans	11	m
length of the spans	98	m
width of the spans	4	m
height of sides	2.2	m

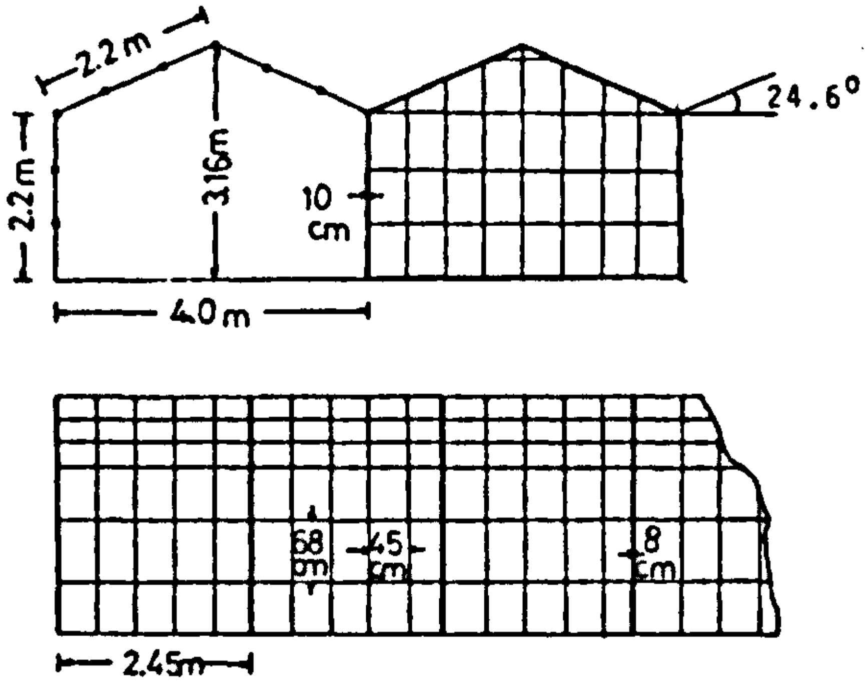


Fig. 6 | Front and side views of the multispan greenhouse analyzed in the present simulation.

height of ridge	3.16	m
roof slope	24.6°	
size of glass panes	0.68 x 0.48	m
thickness of glass panes	0.3	cm
depth of structural members	3.0	cm
width of structural members on roofs and sides	4.0	cm
width of horizontal structural members on gable ends	4.0	cm
width of vertical structural members on gable ends	5.0	cm
main structural members on the roofs and sides		
- distance apart	2.45	m
- width	8.0	cm
- depth	10.0	cm

The frame ratio (the ratio of the area covered by structural members to the total surface area) of the house is 0.16. This frame ratio is slightly higher than that for modern greenhouses with frames of steel and aluminium; The ratio for them usually ranges from 0.08 to 0.12. However, no other additional structural members such as trusses, ventilators, gutters, overhead heating pipes etc. are attached to the model greenhouse, so that the overall frame ratio including the additional structural members for an actual greenhouse is approximately equal to that of the model greenhouse. Simulations were made for the house in N-S and E-W orientations and in some cases at 15 degrees intervals between the two extreme orientations. For the purpose of the calculations, the house was assumed to be standing on an open, level site.

3.2 Transmission of diffuse light

The assumption of a uniformly bright sky for diffuse light implies that the transmissivity of the house should be independent of both orientation and season. The transmissivity may then be considered a constant of the greenhouse structure itself. The calculated value of the transmissivity was 60%. This is the space averaged value at the central part of the house ignoring effects from the sides and ends. Harnett (1975) reported that the transmissivity of diffuse light ranged from 59.7 to 61.9% in measurements on N-S and E-W multispan greenhouses throughout the year. His measurements were confined to the centre north-south strips in the greenhouses.

For diffuse light the shadows from the structural members of the house merge, so that the spatial variation in diffuse light is small and stationary. However, the transmissivity is generally slightly higher at the centre of each span than under the gutter or near the sides and ends (Edwards and Lake, 1965; Kozai and Sugi, 1972). The spatial variation in diffuse light was ignored in the present study and the space averaged value of 60% was used to simulate the diurnal course of the net rate of assimilation in the greenhouse.

The diffuse light at the floor of the greenhouse comes from the whole sky and is calculated as the sum of the contributions from each of the (m x n) subdivisions with a solid angle of 1/(m x n) steradian, as is explained in Eqn (2.3).

Table 1 gives the transmissivities of the house and weighting coefficients as a function of the sine of the altitudes from which the light comes; the interval of the calculation being 0.05. The product of the transmissivity and weighting coefficient at each altitude is summed for calculating the overall transmissivity of diffuse light. The transmissivity for each altitude is the average of those at 76 relative azimuths.

The transmissivity is greater at higher altitude except for that at the lowest altitude (4.3-7.2°). On an overcast day, nearly 30% of the diffuse light comes from overhead *i.e.* between 60° and 90° elevation and some 50% from between 30° and 60° (Lawrence, 1963). This fact, together with the higher transmissivity for higher altitude, emphasizes the importance of the diffuse light from overhead in contrast with direct light from the southern part of the sky, *i.e.* the greenhouse should be designed to give maximum transmission of both diffuse and direct light.

Bowman (1970) highlighted the importance of house geometry for the transmission of diffuse light, especially where about half of the total light received during a year is diffuse light as in England.

3.3 Transmission of direct light

Figs 7 and 8 show the changes in transmissivity of daily inte-

Table 1 Transmissivity of the multispan greenhouse and the weighting coefficients needed for the calculation of diffuse light transmission as a function of the sun's altitude (see Eqn (2.3)).

	Altitude							
I	$\sin(H_I)$	$\sin(H_{I+1})$	H_I	H_{I+1}	T_I*	WC_I**	$T_I x WC_I$	$\sum T_I x WC_I$***
1	0.075	0.125	4.3	7.2	0.222	0.010	0.002	0.002
2	0.125	0.175	7.2	10.1	0.178	0.015	0.003	0.005
3	0.175	0.225	10.1	13.0	0.297	0.020	0.006	0.011
4	0.225	0.275	13.0	16.0	0.377	0.025	0.009	0.020
5	0.275	0.325	16.0	19.0	0.446	0.030	0.013	0.030
6	0.325	0.375	19.0	22.0	0.497	0.035	0.017	0.051
7	0.375	0.425	22.0	25.2	0.529	0.040	0.021	0.072
8	0.425	0.475	25.2	28.4	0.540	0.045	0.024	0.096
9	0.475	0.525	28.4	31.7	0.551	0.050	0.028	0.124
10	0.525	0.575	31.7	35.1	0.568	0.055	0.031	0.155
11	0.575	0.625	35.1	38.7	0.587	0.060	0.035	0.190
12	0.625	0.675	38.7	42.5	0.607	0.065	0.039	0.230
13	0.675	0.725	42.5	46.5	0.627	0.070	0.044	0.274
14	0.725	0.775	46.5	50.8	0.642	0.075	0.048	0.322
15	0.775	0.825	50.8	55.6	0.661	0.080	0.053	0.375
16	0.825	0.875	55.6	61.0	0.675	0.085	0.057	0.432
17	0.875	0.925	61.0	67.7	0.692	0.090	0.062	0.495
18	0.925	0.975	67.7	77.2	0.706	0.095	0.067	0.562
19	0.975	1.000	77.2	90.0	0.730	0.050	0.037	0.598

* Transmissivity of the house for altitude I
** Weighting coefficient $(\sin^2(H_{I+1})-\sin^2(H_I))$ for altitude I
*** Cumulative transmissivity

grated direct light in Tokyo and Amsterdam, respectively, during the period from 20 December to 1 July. The transmissivities for the rest of the year are symmetrical with respect to 22 December (the winter solstice). The calculation of transmissivity was confined to the central part of a 11-span house so that effects from the sides and ends would be negligible except when the sun's altitude is very low. The transmissivity would then approach that of a multispan house with an infinite number of spans with an infinite lenght.

In Tokyo, around the shortest day the E-W multispan transmits 59% of daily direct light compared with 50% from the identical structure orientated N-S. But the transmissivity of the E-W house coincides with that of N-S house on 20 February and the position is reversed afterwards. The advantage of an E-W over a N-S orientation, therefore, exists only between 20 October

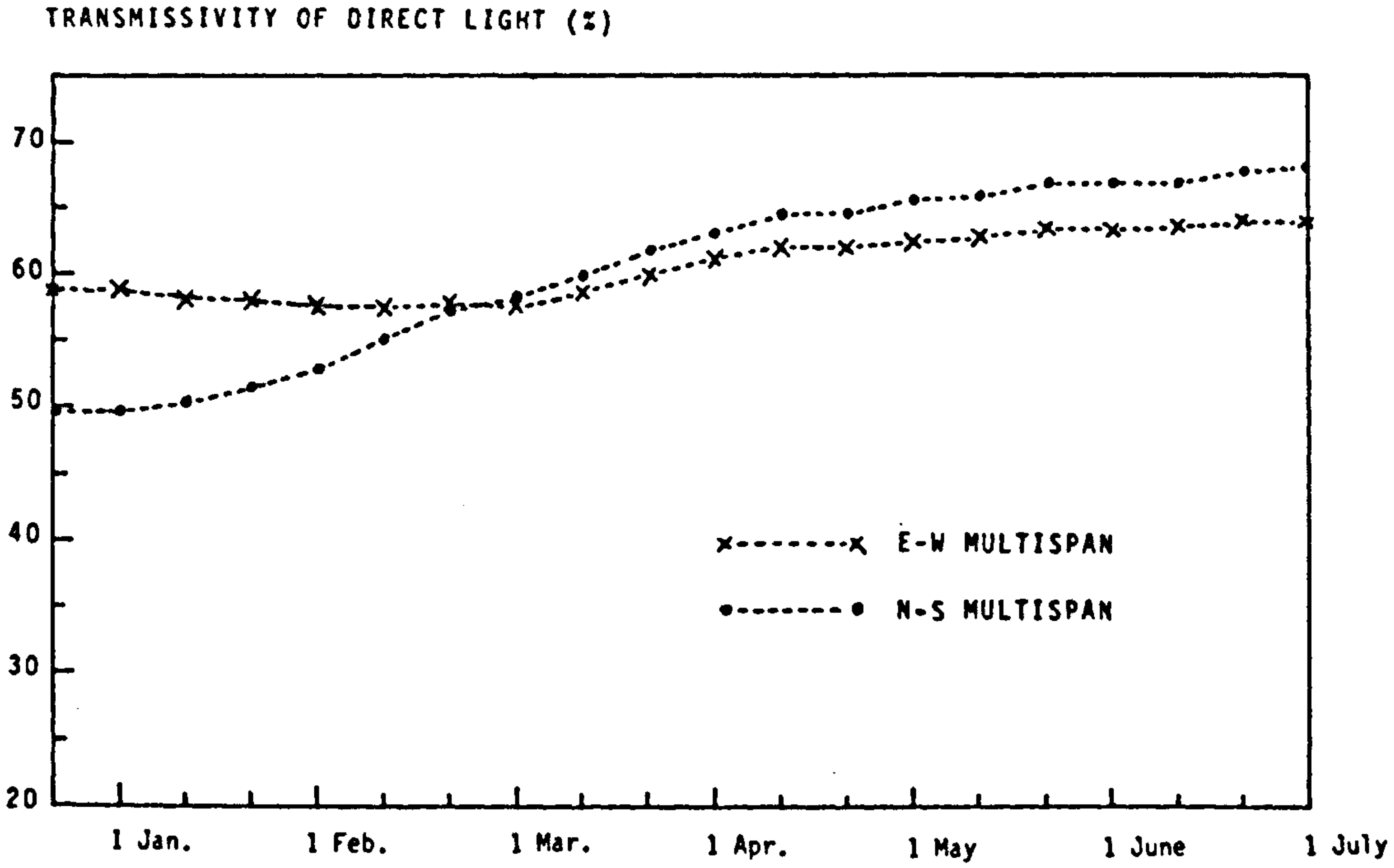


Fig. 7 | Seasonal variations of transmissivity of daily direct light for the N-S and E-W multispan greenhouses in Tokyo (35°41'N).

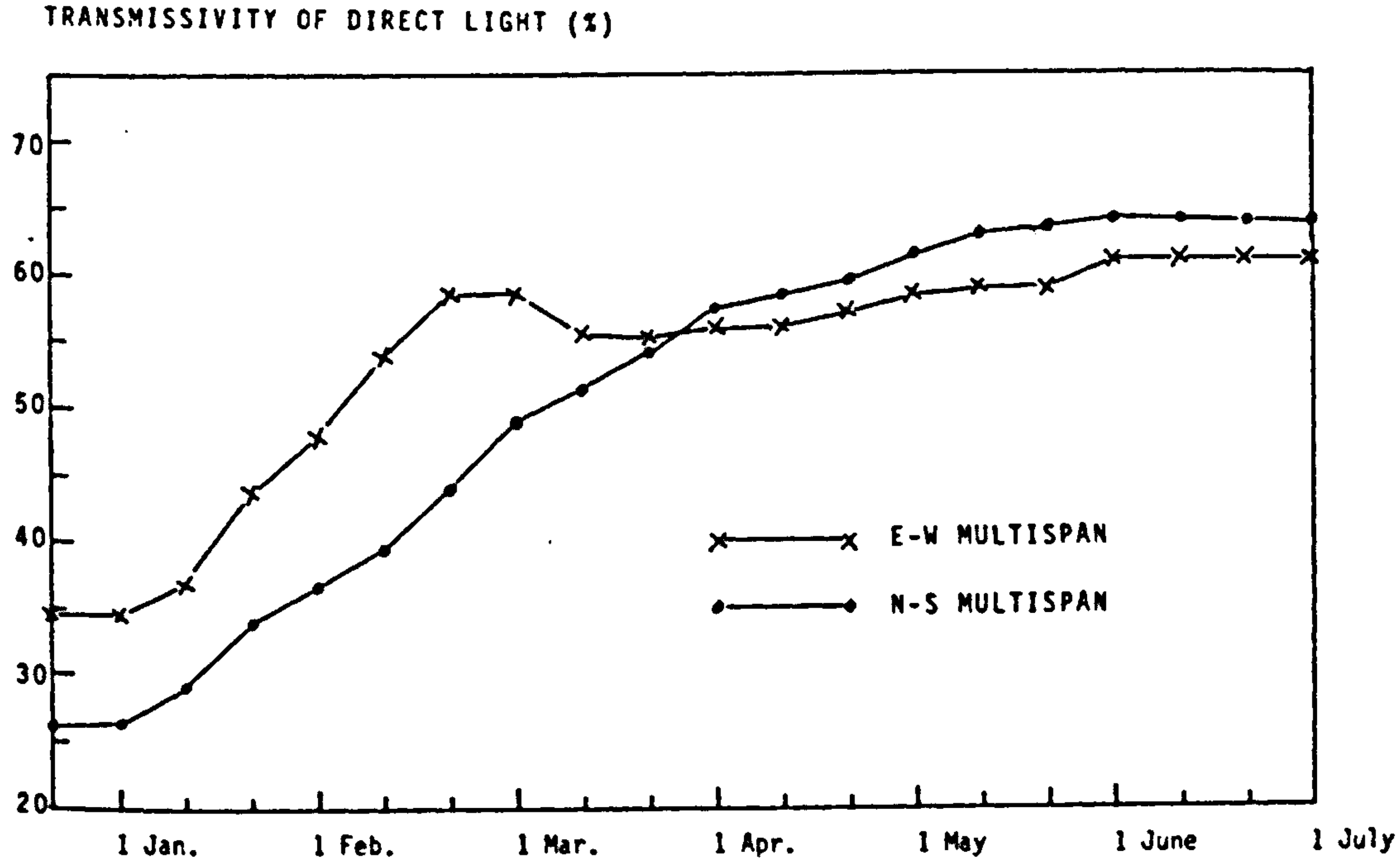


Fig. 8 | Seasonal variations of transmissivity of daily direct light for the N-S and E-W multispan greenhouses in Amsterdam (52°20'N).

and 20 February (for four months) and a greater light intensity is obtained with greenhouses orientated N-S for the rest of the year.

In Amsterdam the N-S multispan transmits only 26% of daily direct light compared with 35% for the E-W multispan house in the winter solstice, as is shown in Fig. 8. The transmissivity of N-S house steadily increases with time and approaches a maximum of 64% at the beginning of June. The transmissivity of E-W house, on the other hand, has a maximum of 58.5% at the end of February. The advantage of an E-W over a N-S orientation exists between 20 September and 20 March (for six months).

The duration of this advantage is two months longer in Amsterdam (52°20'N) than in Tokyo (35°41'N), that is, the duration is longer at higher latitudes. It is also noted that in Amsterdam the maximum difference of about 15% in transmissivity between the two orientations appears in February, not in the winter solstice.

The transmissivity of direct light in Amsterdam in the winter is surprisingly low for both E-W and N-S orientations. These low values of transmissivity are mainly due to the low incidence angle of direct light to the roofs and to the extensive shadows cast by solid structural members. The transmissivity of total light is, of course, higher than that of direct light because of the low proportion of direct light to total light (see Fig. 4) and of the relatively high transmissivity of diffuse light (60%).

The transmissivities of direct light for the greenhouse are given in Table 2 for 19 classes of the sun's altitudes and 19 azimuths relative to the house orientation. These 361 numbers characterize all aspects of direct light transmission into the greenhouse. Since the cross-section and the longitudinal-section of the greenhouse are assumed to be symmetrical, the transmissivity for the azimuth of 80° is, for example, the same as those for the azimuths of -80°, 100°, and -100°.

As can be seen from Table 2, the transmissivity is generally low when the sun is low and is much dependent upon the azimuth angle of the sun. The minimum and maximum values of transmissivity for each class of the altitudes are underlined in the table. The maximum difference in transmissivity for different azimuths is, for instance, 23% at the sun's altitude of 13-16° and is 7% at the sun's altitudes of 38.7-42.5°. Greenhouse orientation, therefore, becomes more important at lower altitudes of the sun. The low transmissivity is generally obtained for the relative azimuth around 90° at the sun's altitudes of 4.3-42.5° so that the transmissivity of a N-S multispan greenhouse is low around noon, the most important time of the day. (Relatively high transmissivities for the altitudes

Table 2 Transmissivity of the multispan greenhouse with a roof pitch of 24.6° as a function of the sun's altitude and the sun's azimuth relative to the house orientation.

The sun's altitude (deg.)	Azimuth with respect to orientation (deg.)																		
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	180	175	170	165	160	155	150	145	140	135	130	125	120	115	110	105	100	95	90
4.3 - 7.2	65	52	51	48	41	39	31	18	10	3	2	6	10	12	12	14	11	6	3
7.2 - 10.1	26	17	16	13	13	12	13	16	18	20	19	22	24	26	27	21	14	11	11
10.1 - 13.0	35	30	31	30	32	31	28	29	30	32	34	36	37	37	29	25	20	18	18
13.0 - 16.0	43	38	39	38	39	39	40	41	42	44	45	47	42	37	33	29	26	24	24
16.0 - 19.0	54	49	49	48	49	49	49	51	52	53	51	46	42	39	36	34	32	31	31
19.0 - 22.0	62	59	57	57	58	58	57	57	56	52	49	47	44	42	39	39	38	37	37
22.0 - 25.2	70	67	64	63	61	58	58	56	54	52	51	48	47	45	44	44	43	42	43
25.2 - 28.4	68	64	62	62	60	59	56	56	55	53	51	50	48	48	49	48	47	47	47
28.4 - 31.7	64	62	62	60	59	58	57	56	55	54	53	52	51	52	52	51	50	50	52
31.7 - 35.1	65	62	62	60	58	59	58	57	57	56	54	55	54	55	55	54	54	54	54
35.1 - 38.7	65	63	62	61	60	60	59	58	58	59	58	57	57	58	57	57	57	57	57
38.7 - 42.5	66	64	64	62	62	62	62	59	60	59	59	60	60	60	60	60	59	60	60
42.5 - 46.5	67	64	65	65	62	63	62	63	63	63	62	63	62	62	62	61	62	62	61
46.5 - 50.8	68	66	65	66	65	65	64	64	65	64	64	64	63	63	63	64	62	64	63
50.8 - 55.6	69	68	68	67	67	66	67	66	65	66	67	65	65	65	65	64	65	66	65
55.6 - 61.0	70	70	70	69	68	68	67	67	66	67	68	67	67	67	67	67	67	67	68
61.0 - 67.7	72	71	70	70	70	70	69	69	69	69	69	69	68	68	69	69	68	68	69
67.7 - 77.2	72	72	72	71	71	71	70	71	71	70	70	69	69	70	70	70	70	71	70
77.2 - 90.0	73	73	73	73	73	73	73	73	73	73	73	73	73	73	73	74	73	73	73

of 4.3-7.2° and for the azimuths of 0-25° are due to the effects of light from the sides.)

3.4 Daily net assimilation of carbon dioxide in the greenhouse

Fig. 9 shows daily net CO_2-assimilation in the N-S and E-W greenhouses under clear and overcast conditions and that in the N-S greenhouses under hazy conditions (f=0.5 in Eqn (2.23) in Amsterdam during the period from 20 December to 1 May. Those in Tokyo are also shown in Fig. 10. The calculation method and all the values of parameters used are given in Section 2.2. The net assimilation under overcast conditions is independent of greenhouse orientation, as stated in the preceding chapter. The daily net assimilation on overcast days has a negative value until the middle of March in Amsterdam and until the beginning of February in Tokyo.
The maximum difference in the daily net CO_2-assimilation on clear days between the two greenhouses is 5 kg CO_2 ha^{-1} day^{-1} at the most. However, the ultimate difference in plant growth between the two houses is not necessarily small, because the accumulation of these daily differences might become large during the growth period.
If a lettuce is planted at the middle or end of February in Amsterdam, it will grow faster in the E-W greenhouse than in the N-S greenhouse until the end of March. Thereafter the growth will become faster in the N-S greenhouse than in the E-W house and the difference in plant growth between the two houses will become gradually less.
In our model of net CO_2-assimilation a constant value of LAI (leaf area index) is assumed, so that the plant growth (the accumulation and translocation of photosynthate in the plant body) cannot be simulated. We must, therefore, estimate the plant growth by some other means. However, comparison of greenhouse performances in N-S and E-W orientations can be based on the calculation of net CO_2-assimilation rates of the crops with a constant LAI within the greenhouses.
Let us assume now that a lettuce plant needs 100 MJ m^{-2} of solar light between transplantation and harvest. Then, for Amsterdam, a lettuce transplanted on 10 December can be harvested on 14 March in an E-W greenhouse, but on 19 March in a N-S greenhouse, a difference of five days.

3.5 Total solar light integral and plant growth

As far as the amount of light is a limiting factor to the plant growth, the plant growth is said to be nearly proportional to the total solar light integral during the growth period

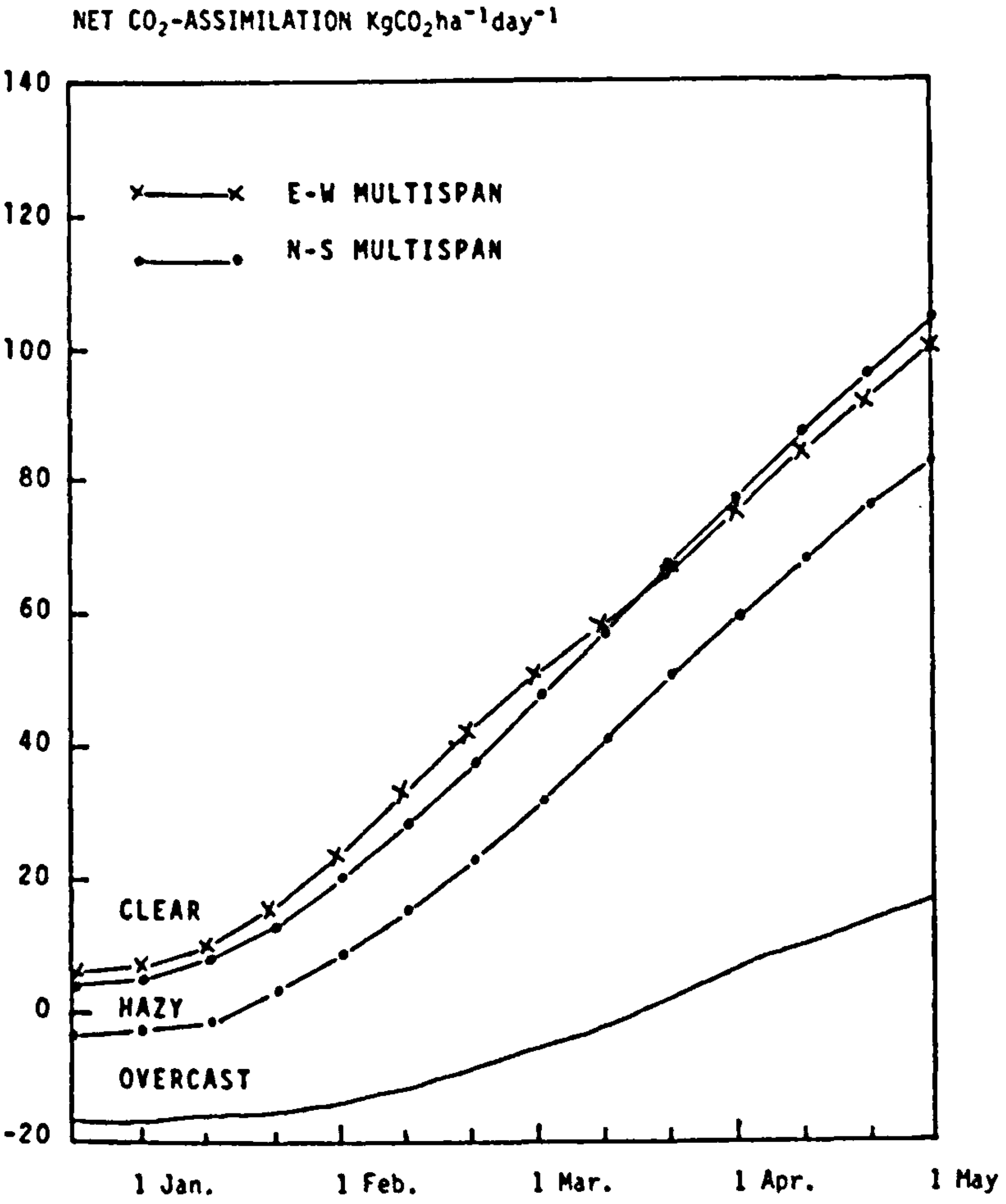


Fig. 9 | Daily net CO_2-assimilation in the N-S and E-W multispan greenhouses in Amsterdam under clear, hazy and overcast conditions.

(Lawrence, 1963). The total solar light integrals inside and outside the houses in Amsterdam are given in Fig. 11. The integration of solar light was assumed to start on 10 December. The calculations were based on Eqn (2.9) and on the meteorological data presented in Figs 3 and 4.
The five-day gain in the E-W greenhouse is valid only for the lettuce transplanted on 10 December. If it is transplanted one month earlier, the gain in days will become larger. While, if it is transplanted one month later, the gain in days becomes smaller. Similar results are obtained for the houses in Tokyo in Fig. 12, except that the absolute values of the light integrals are much greater in Tokyo than in Amsterdam.
Harnett (1975) found experimentally that the cropping performance of lettuce in multispan houses follows closely the solar light measurements and that a lettuce weighing 170 g was

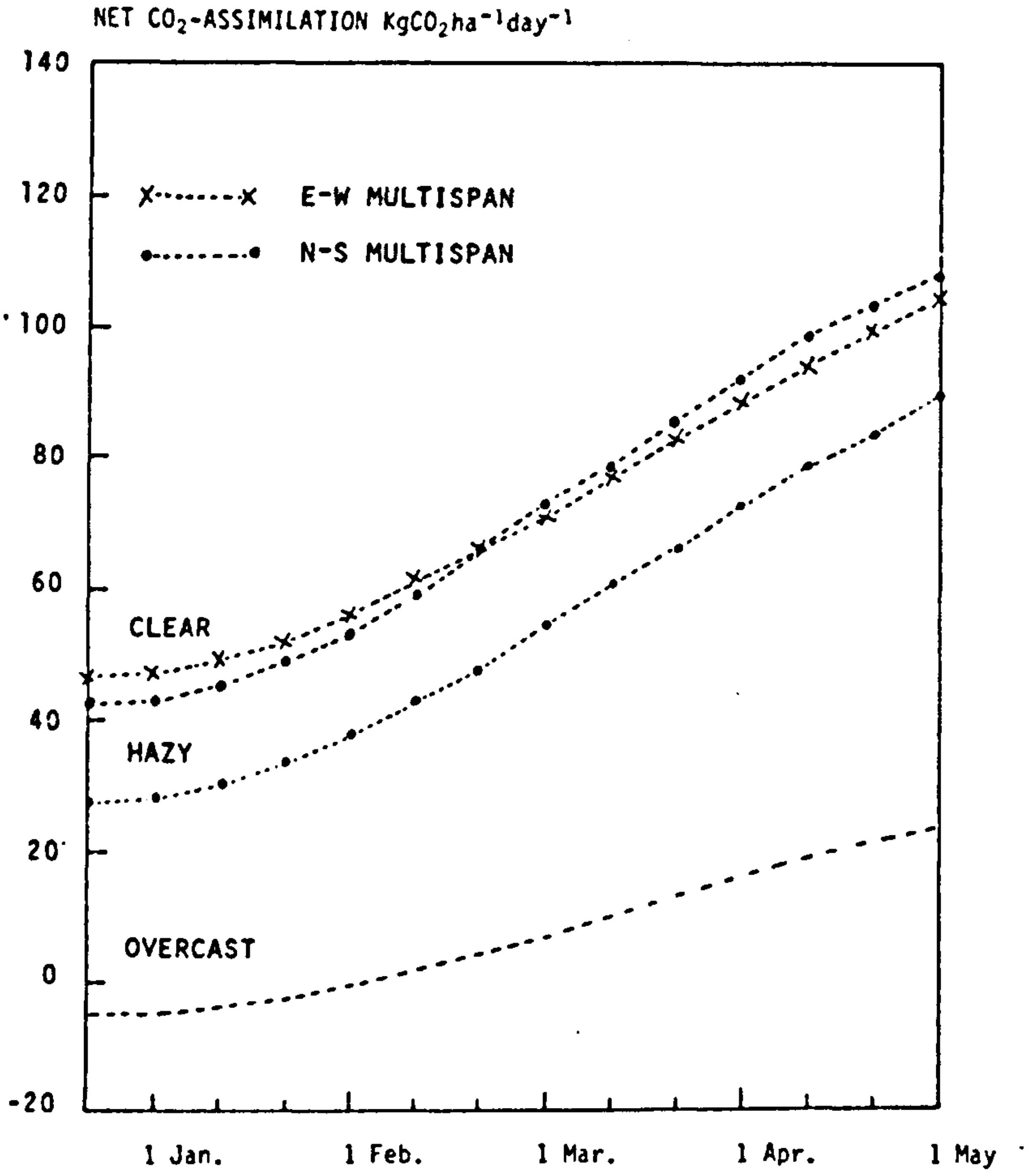


Fig. 10 | Daily net CO_2-assimilation in the N-S and E-W multispan greenhouses in Tokyo under clear, hazy and overcast conditions.

attained seven days earlier in the E-W multispan than in the N-S multispan when harvested during late December and January. He also found that there was no significant difference in maturity of crops between the two greenhouses when harvested during April. His experiments were carried out on the south coast of England (Efford, Hants, 50°50'N) where the total light integral during the winter months was only a little higher than that in Amsterdam. Our simulated results are in agreement with his experimental results.

The difference in days of plant growth between greenhouses is discussed in some detail in Chapter 6.

3.6 The effects of orientation intermediate between N-S and E-W

Fig. 13 presents the effects of house orientation between E-W and N-S on 20 March, 28 July, and 20 December. Vertical axis

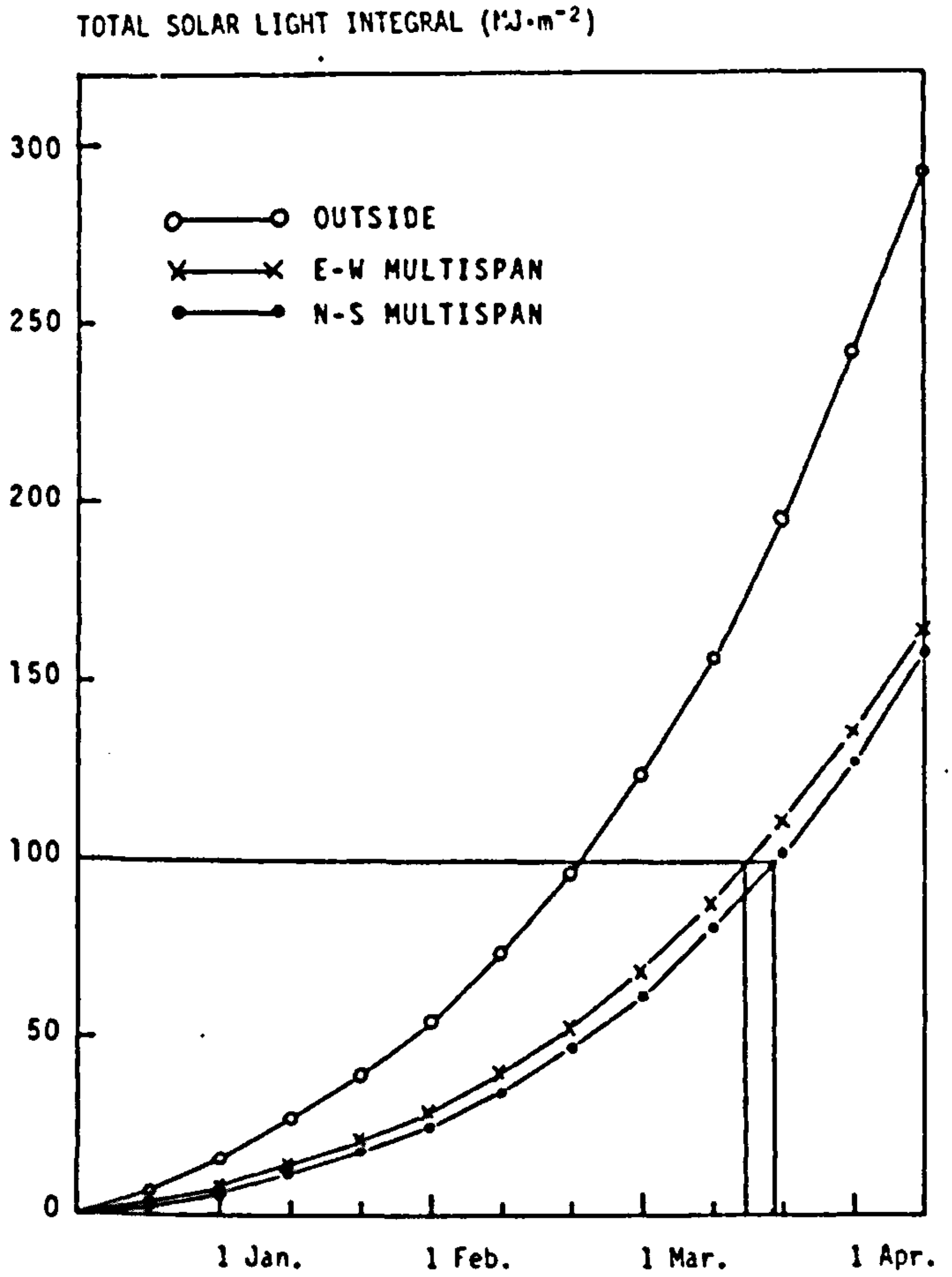


Fig. 11 | Total solar light integrals outside and inside the N-S and E-W multispan greenhouses in Amsterdam (52°20'N) (The integration was started on 10 December).

indicates the transmissivity of mean total light (see Eqn (2.1)), not of direct light. An exact E-W orientation does not give the maximum winter light transmission in Amsterdam, although the transmission losses at E-W orientation are quite small compared with those at orientations from 30 to 45° from E-W. In fact, there is little difference in transmissivity between the houses orientated in the range from 0 to 45° from E-W. Thereafter, however, the light transmission drops more steeply. The difference in transmissivity between the house orientated 45° from E-W and the N-S house is about 5% in Amsterdam. In Tokyo, on the other hand, an exact E-W orientation is ideal for winter light transmission and the light transmission drops more rapidly up to 60° from E-W, while the lowest winter light transmission is seen at 15° from N-S, not at an exact N-S orientation. The difference in transmissivity between the E-W house and the house with orientation of 15° from N-S is about 7%.

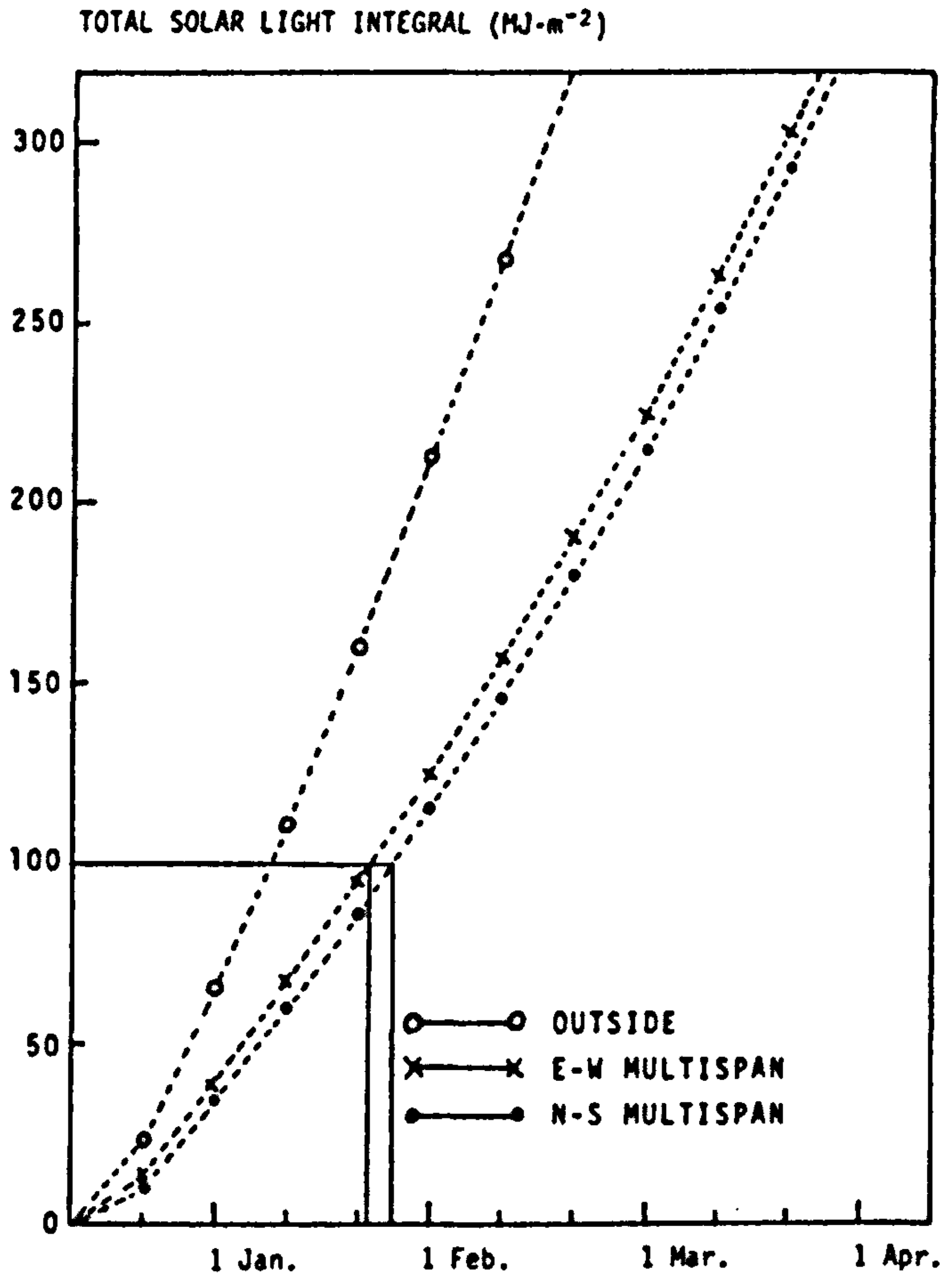


Fig. 12 | Total solar light integrals outside and inside the N-S and E-W multispan greenhouses in Tokyo (35°41'N) (The integration was started on 10 December).

The orientation effect on direct light transmission alone is stronger at higher altitude as stated in Section 3.3. However, the ratio of diffuse to total light in winter is higher in Amsterdam than in Tokyo and therefore the orientation effect on the total light transmission is actually more pronounced in Tokyo than in Amsterdam. It is also noted that the transmissivity of the E-W house on 20 December in Amsterdam is 49.5% which is about 10% lower than that in Tokyo. Thus the transmissivity in winter is lower at higher altitudes.

As is suggested by Kingham and Smith (1971), a multispan house is less sensitive to orientation in winter than a single-span house, because the transmission of walls is generally more sensitive than that of roofs. Nevertheless, there is still a significant orientation effect in multispan greenhouses.

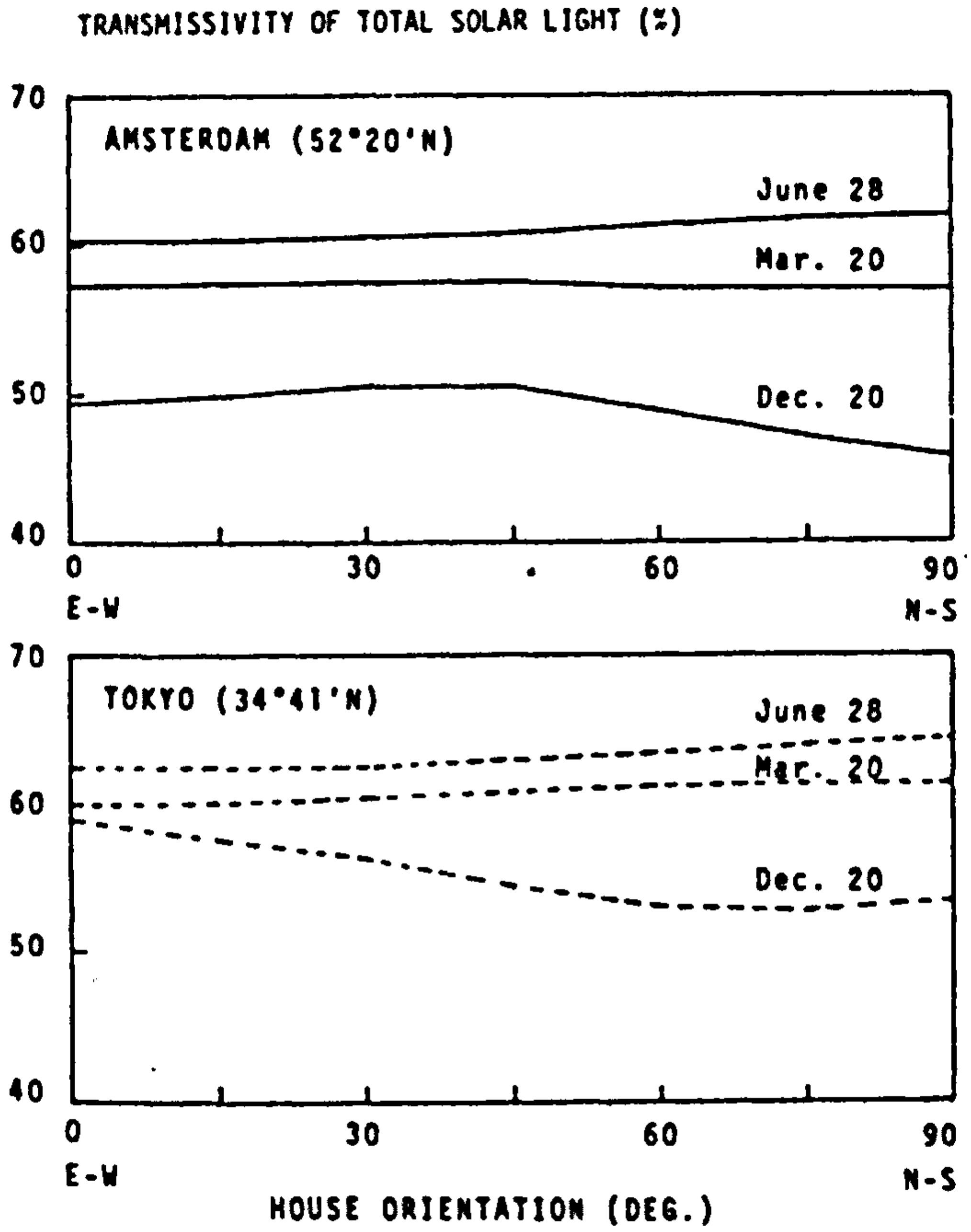


Fig. 13 | Transmissivity of daily total solar light for the multispan greenhouse as a function of house orientation, for two sides and three dates.

4 Influence of roof slope

To illustrate the influence of roof slope on the light transmission, both direct and diffuse light transmission into multispan greenhouses with roof pitches of 15, 20, 30, 35° were calculated as well as the greenhouse with a roof pitch of 24.6°, which had been analysed in the previous chapter. Widths of spans for these houses were 4.25, 4.14, 3.81, 3.60, and 4.00 m, respectively. Other dimensions of the houses such as length of spans, height of sides, width and depth of structural members, number of spans etc remained unchanged. The transmissivities of daily integrated direct light for these houses in E-W and N-S orientations were calculated at two latitudes (in Amsterdam and Tokyo) throughout the year.

4.1 Transmission of diffuse light

Transmissivities of diffuse light for the houses with roof pitches of 15, 20, 24.6, 30, and 35° were 60.3, 60.0, 59.8, 59.1, 58.1%, respectively. Thus, the gentler the roof slope the higher the transmissivity of diffuse light obtained in the greenhouse. In the region considered, the steepest roof slope should be avoided when designing greenhouses but for the rest the differences are negligible.

4.2 Transmission of direct light

E-W greenhouse

Fig.14 presents the changes in transmissivity of daily integrated direct light for the E-W greenhouses with different roof slopes in Amsterdam during the period from 20 December to 1 July. The calculation of transmissivity was confined to the central section of 11-span houses so that the effect from the sides and ends could be neglected except when the sun's altitude was very low.

In Amsterdam, the transmissivities of an E-W greenhouse during winter months are largely dependent on roof slope. The transmissivities of the houses with roof pitches of 15, 24.6, and 35° in the winter solstice are 49, 34, and 26%, respectively, *i.e.* the gentler the roof slope the higher the

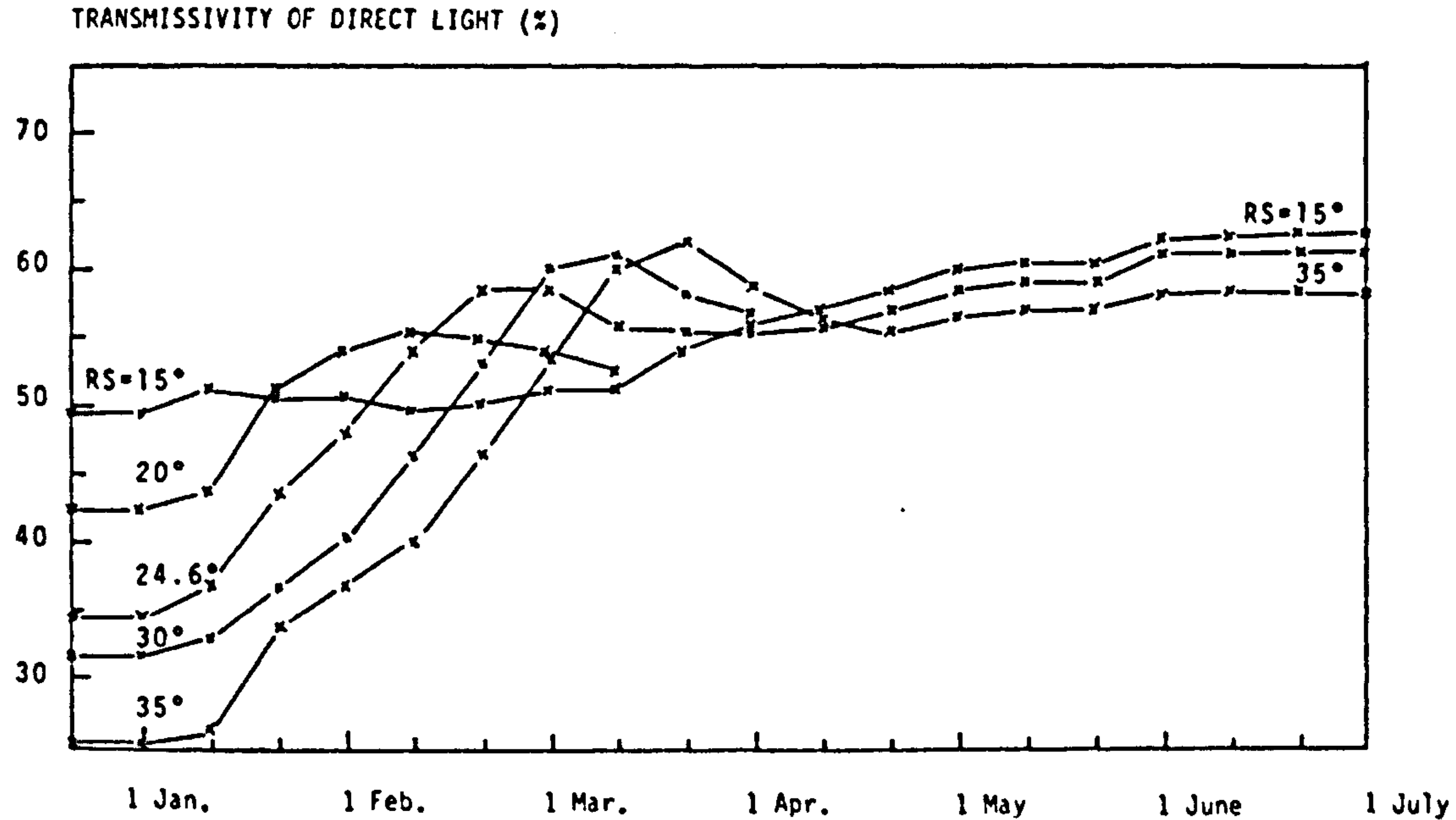


Fig. 14 | Seasonal variations of transmissivity of daily direct solar light for the E-W greenhouses with different roof slopes in Amsterdam ($52^{\circ}20'$N)

transmissivity around the winter solstice. The curve of transmissivities for each house has a maximum point in the range of from January to April. The peak is higher and clearer and is observed later in spring in the greenhouse with a steeper roof slope. The date when the local peak appears is approximately equal to the date when solar altitude at culmination (the maximum solar altitude in the day) coincides with the roof angle of the corresponding E-W greenhouse (see Fig. 15). This phenomenon can be explained as follows: (a) When the sun's altitude relative to the roof side not facing the sun is greater than zero, some part of the incident light passes through that side with low transmissivity. (b) When the relative sun's altitude has a negative value, some part of the light passes through the roofs three or more times before reaching the soil or plants. Consequently, the transmissivity is very low. (c) When the relative sun's altitude is just or nearly equal to zero, all or most of the light passes through the roof facing the sun only once. Then the transmissivity is largest. The peak is not clear for greenhouses with a gentler roof slope because the sun is never so low around noon.

This phenomenon is illustrated in Tables 3 and 4 for roof pitches of 15 and 35° where transmissivities are given as a function of altitude and relative azimuth of the sun. The transmissivities for the house with a roof pitch of 24.6° have been listed in Table 2 in Chapter 3.

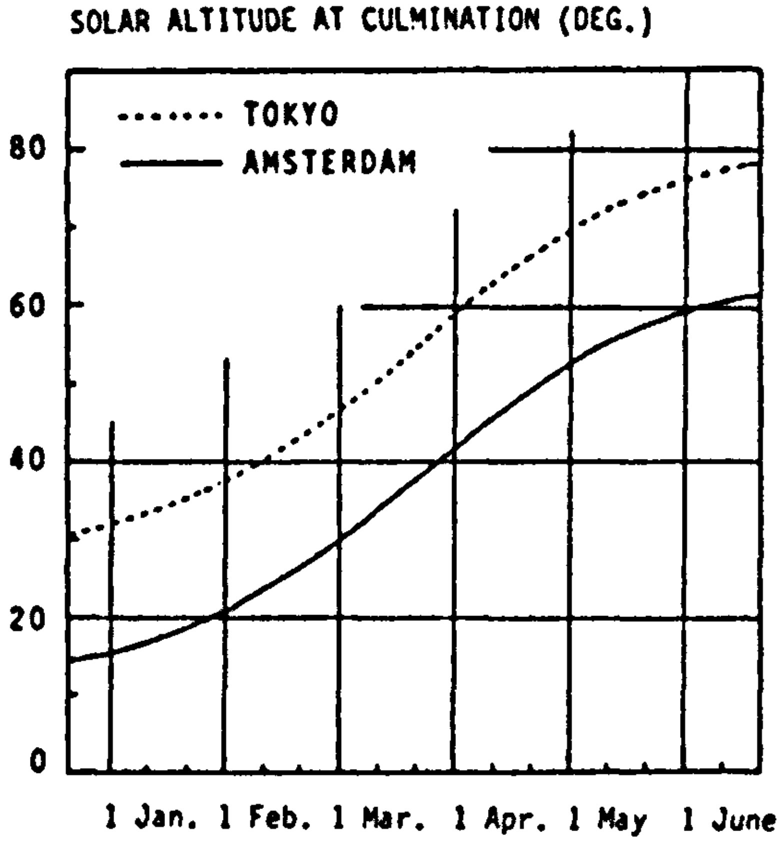


Fig. 15 | Seasonal variations of solar altitude at culmination in Amsterdam (52°20'N) and Tokyo (35°41'N).

The transmissivities at relative azimuth of 0° has a local maximum value at the sun's altitudes of 13-16° in the house with a roof pitch of 15°, at the sun's altitudes of 22-25.2° in the house with 24.6° roof angle, and at the sun's altitudes of 31.7-35.1° in the house with 35° roof angle. The peak is very weak for the house with a roof pitch of 15° and the transmissivity of this house steadily increases with increasing the sun's altitude. (The high transmissivity at the sun's altitudes of 4.3-7.2° is due to the transmission by the side walls.) The low transmissivities for daily direct light for the house with a roof pitch of 35° in winter are due to the low transmissivities of the house at the sun's altitude of 7.2-25.2° and at the relative azimuth angles of 0-30°, as can be seen from Table 4.

Transmissivities of all the E-W houses give approximately the same value (about 57%) on 10 April. Later the transmissivity is slightly higher in the greenhouse with gentler roof slope. The variations in transmissivity by season for the E-W houses with different roof slopes in Tokyo are presented in Fig. 16. The roof slope has less influence on the transmissivity of daily direct light in Tokyo than in Amsterdam. The house with a roof pitch of 15° gives the lowest transmissivity in winter months and the house with a roof pitch of 20° gives the highest transmissivity around the winter solstice. The house with a roof pitch of 35° gives the highest transmissivity from 20 January to the end of February. The transmissivity reaches a maximum of 63% in the house with a roof pitch of 35° on 10 February when the sun's altitude at noon is 40°.

Table 3 Transmissivity of the multispan greenhouse with a roof pitch of 15° as a function of the sun's altitude and the sun's azimuth relative to the house orientation.

	Azimuth with respect to house orientation (deg.)																		
The sun's altitude	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
(deg.)	180	175	170	165	160	155	150	145	140	135	130	125	120	115	110	105	100	95	90
4.3 - 7.2	49	38	37	37	29	21	17	11	15	12	13	14	16	15	13	10	7	5	3
7.2 - 10.1	31	26	27	25	24	26	29	26	27	28	28	27	21	18	14	13	12	12	12
10.1 - 13.0	49	43	42	42	42	41	41	40	40	37	33	31	28	25	23	21	19	18	19
13.0 - 16.0	62	55	51	50	49	47	47	44	41	39	36	33	33	30	29	27	27	26	27
16.0 - 19.0	59	54	53	52	50	47	47	45	44	42	40	37	36	36	34	33	34	32	34
19.0 - 22.0	58	54	53	51	50	50	47	47	45	44	42	42	41	39	39	40	39	39	40
22.0 - 25.2	58	56	55	53	52	51	50	50	48	48	46	45	46	45	45	45	45	44	46
25.2 - 28.4	60	56	55	55	53	53	51	52	51	49	50	50	49	49	49	48	48	48	50
28.4 - 31.7	62	58	58	57	57	55	55	54	54	54	53	53	53	53	53	52	53	53	55
31.7 - 35.1	64	61	61	61	59	58	58	57	57	57	57	56	55	55	56	56	56	56	57
35.1 - 38.7	65	64	63	62	61	61	61	60	59	58	59	59	59	59	60	58	59	58	60
38.7 - 42.5	66	65	64	63	62	62	62	62	62	61	61	61	60	60	61	62	61	62	62
42.5 - 46.5	68	67	66	65	64	65	65	63	63	63	64	64	62	63	64	63	64	63	64
46.5 - 50.8	69	68	67	68	67	66	66	65	66	64	65	64	63	65	64	65	65	64	66
50.8 - 55.6	71	69	70	69	68	67	67	68	67	67	68	67	67	66	67	66	66	66	68
55.6 - 61.0	71	71	71	70	70	70	69	70	69	68	70	68	69	69	68	68	68	67	69
61.0 - 67.7	73	72	71	72	71	70	69	70	70	70	70	70	69	70	70	69	69	69	70
67.7 - 77.2	73	73	73	72	71	72	71	72	71	72	71	71	71	70	71	70	71	71	72
77.2 - 90.0	74	74	74	74	74	74	74	74	74	74	74	74	74	74	74	75	74	73	74

Table 4 Transmissivity of the multispan greenhouse with a roof pitch of 35^{o} as a function of the sun's altitude and the sun's azimuth relative to the house orientation.

The sun's altitude (deg.)	Azimuth with respect to house orientation (deg.)																		
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	180	175	170	165	160	155	150	145	140	135	130	125	120	115	110	105	100	95	90
4.3 - 7.2	77	61	56	51	49	48	45	52	32	17	6	2	3	2	9	10	13	7	2
7.2 - 10.1	35	22	22	17	14	11	8	9	8	8	7	9	15	18	22	24	19	12	8
10.1 - 13.0	29	19	21	18	21	18	16	16	16	20	24	26	26	31	34	31	22	16	15
13.0 - 16.0	35	26	26	26	27	26	29	30	33	20	33	35	39	41	40	33	26	22	20
16.0 - 19.0	45	38	38	39	38	39	36	36	38	41	43	46	49	47	40	35	31	27	27
19.0 - 22.0	48	45	42	41	42	43	43	45	47	49	52	54	52	47	41	38	35	33	33
22.0 - 25.2	55	51	50	50	50	50	52	53	54	57	58	55	51	48	44	42	39	37	39
25.2 - 28.4	61	58	57	56	58	58	58	60	60	59	57	54	50	49	46	45	44	42	43
28.4 - 31.7	66	62	64	63	64	64	64	64	62	60	56	54	53	51	50	48	47	45	47
31.7 - 35.1	73	69	69	68	66	65	64	62	59	57	56	54	53	54	52	51	50	51	51
35.1 - 38.7	71	68	66	66	65	63	62	60	60	58	57	56	55	54	55	54	53	53	54
38.7 - 42.5	68	65	66	64	63	62	61	59	60	59	58	59	56	57	56	56	56	56	57
42.5 - 46.5	68	64	64	63	63	63	62	62	60	60	60	60	59	58	59	59	58	59	58
46.5 - 50.8	67	64	64	64	62	63	62	62	62	62	62	61	61	61	61	61	60	60	61
50.8 - 55.6	68	66	65	65	66	65	64	63	63	64	63	63	63	63	63	63	63	62	64
55.6 - 61.0	69	67	68	66	66	66	66	65	65	65	65	66	64	65	65	65	65	64	66
61.0 - 67.7	70	69	68	67	67	68	67	67	68	66	66	66	67	66	66	66	67	67	67
67.7 - 77.2	71	71	69	70	70	69	69	69	69	69	68	68	68	69	69	67	69	69	70
77.2 - 90.0	72	71	71	72	72	72	72	71	72	71	71	71	71	72	71	72	72	72	71

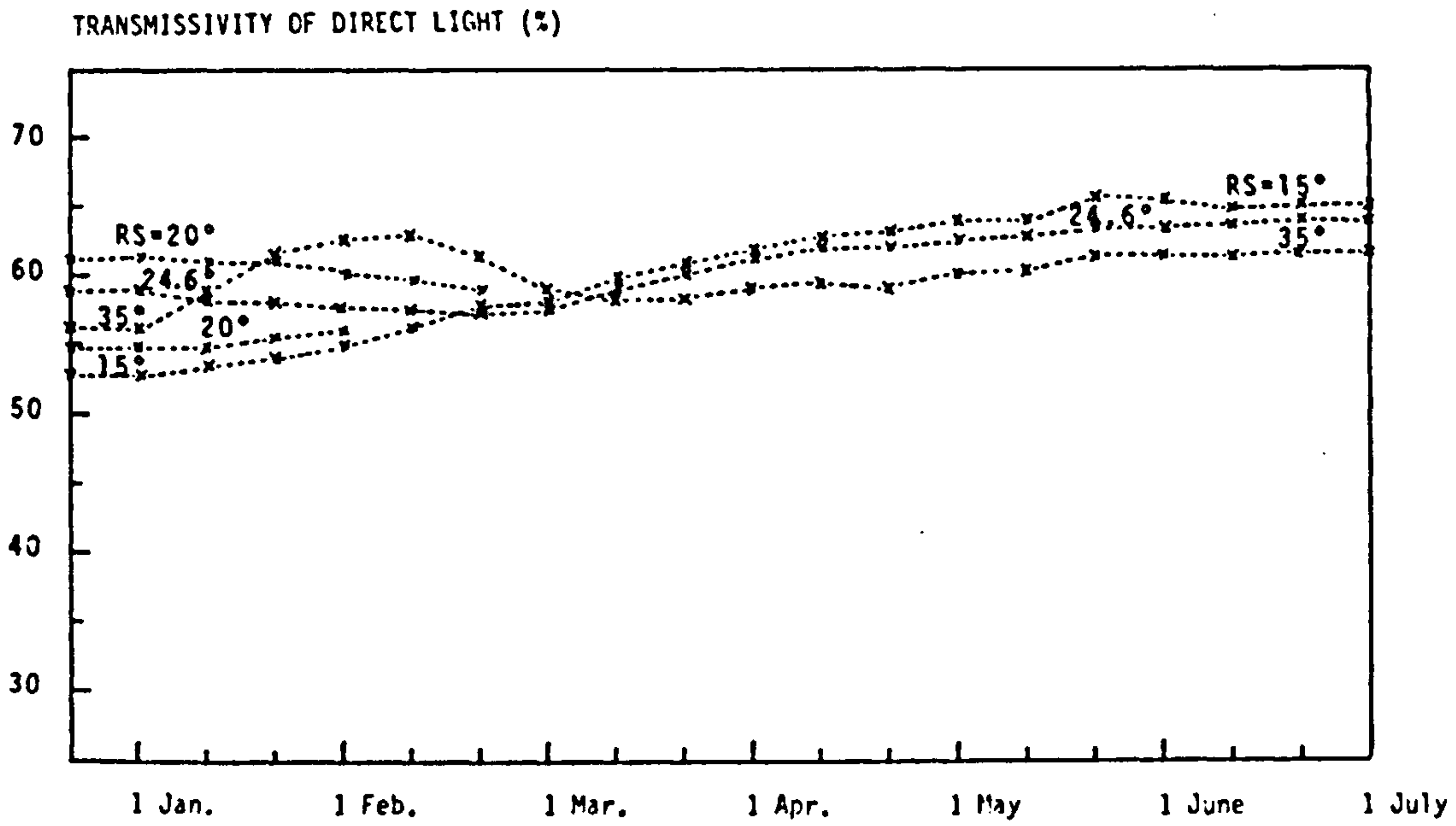


Fig. 16 | Seasonal variations of transmissivity of daily direct light for the E-W multispan greenhouses with different roof slopes in Tokyo.

N-S greenhouse

Fig. 17 shows the variations in transmissivity by season for the N-S greenhouse in Amsterdam and Tokyo. The transmissivity of the greenhouse with a roof pitch of 15° is always about 0.5-3.0% higher than that of the greenhouse with a roof pitch of 35° at both places. Thus the N-S greenhouse is much less sensitive to the roof slope than the E-W greenhouse at both places. The transmissivities of the greenhouses with roof pitches of 15, 24.6, and 35° at culmination on 20 December, 20 March, and 20 July are listed in Table 5. For each date the differences in transmissivity around noon between the three greenhouses at the two places are negligible mainly because the incidence angles of light to differently pitched roofs facing the west and east are about the same.

4.3 The effect of roof slope on the spatial distribution of daily direct light

The cross-sectional distributions of the transmissivity across the floors of E-W greenhouses with roof pitches of 20 and 30° are given in Fig. 18 for Osaka (34°39'N) in Japan and Amsterdam. (Kozai and Kimuara, 1977). The ratio of height of side walls to width of one span was assumed to be 0.66. The calculations were made only for the northerly spans so that the effect from

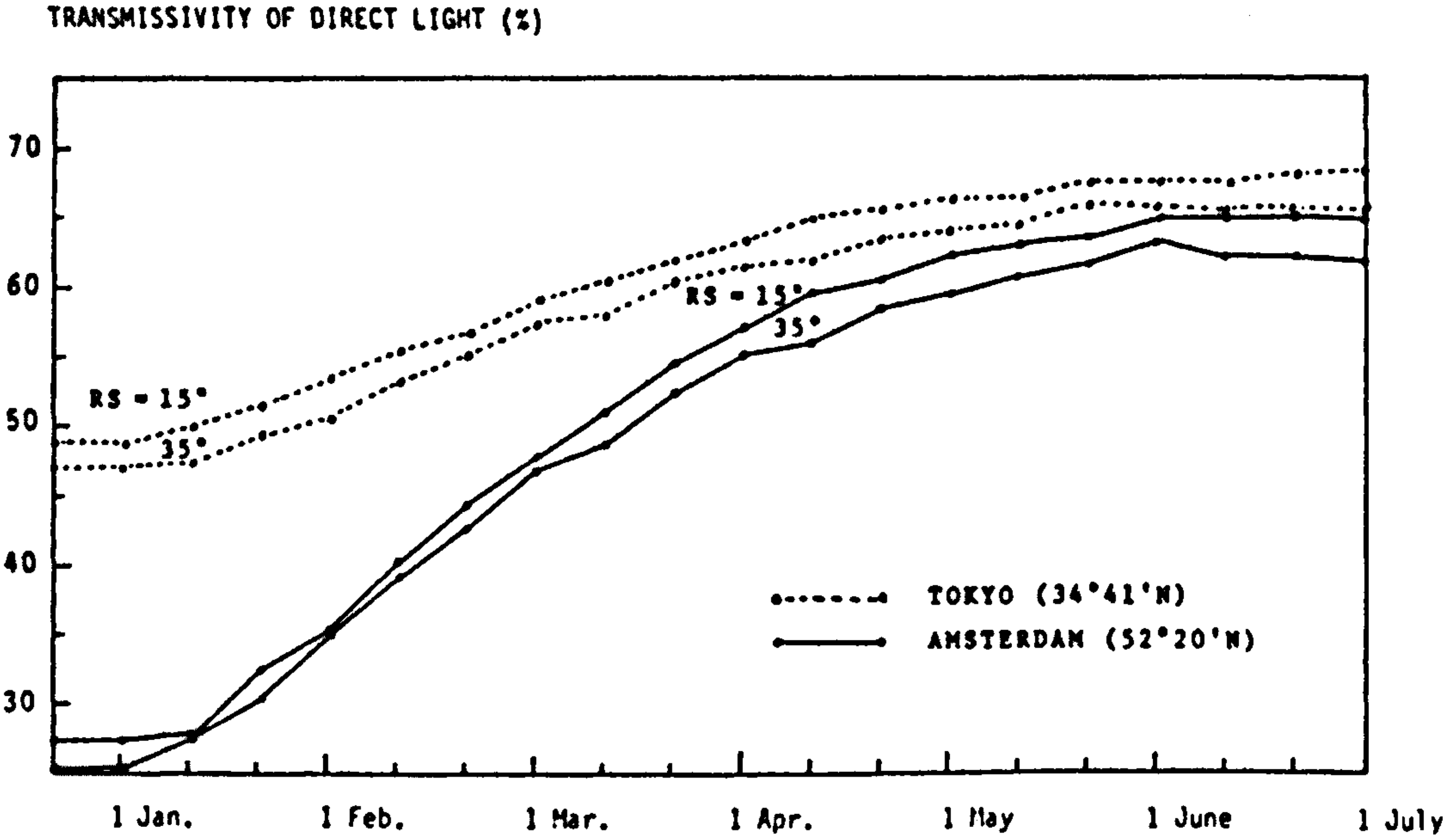


Fig. 17 | Seasonal variations of transmissivity of daily direct light for the N-S multispan greenhouses in Amsterdam and Tokyo.

Table 5 Seasonal variations in transmissivity of daily direct light for the E-W houses with different roof slopes in Tokyo and Amsterdam

		Tokyo (35°41'N)		Amsterdam (52°20'N)	
date	roof angle (deg.)	the sun's altitude at noon (deg.)	trans-missiv-ity at noon (%)	the sun's altitude at noon (deg.)	trans-missiv-ity at noon (%)
20 Dec.	15.0	31	55	14	27
	24.6		52		24
	35.0		51		20
20 Mar.	15.0	54	68	37	60
	24.6		65		57
	35.0		64		54
20 June	15.0	77	74	61	70
	24.6		73		69
	35.0		71		67

the south side wall could be neglected. The distribution in the N-S greenhouse with a roof pitch of 20° on 22 December is also shown for reference.

This house was assumed to be composed of glass panes alone (*i.e.* without any opaque structural member). Therefore, the absolute value of the transmissivity is much higher than that of an actual greenhouse with structural members and the uneven light distribution was simply due to the reflection and absorption of the glass pane.

The even distribution is observed in the N-S greenhouse at both of the two places (and the distribution is not affected by the roof slope). In Osaka, the light distribution in the E-W greenhouse is more uniform with a roof pitch of 30° than with one of 20°. In Amsterdam, the opposite is true. The horizontal arrows in Fig. 18 indicate how far the centre of the low

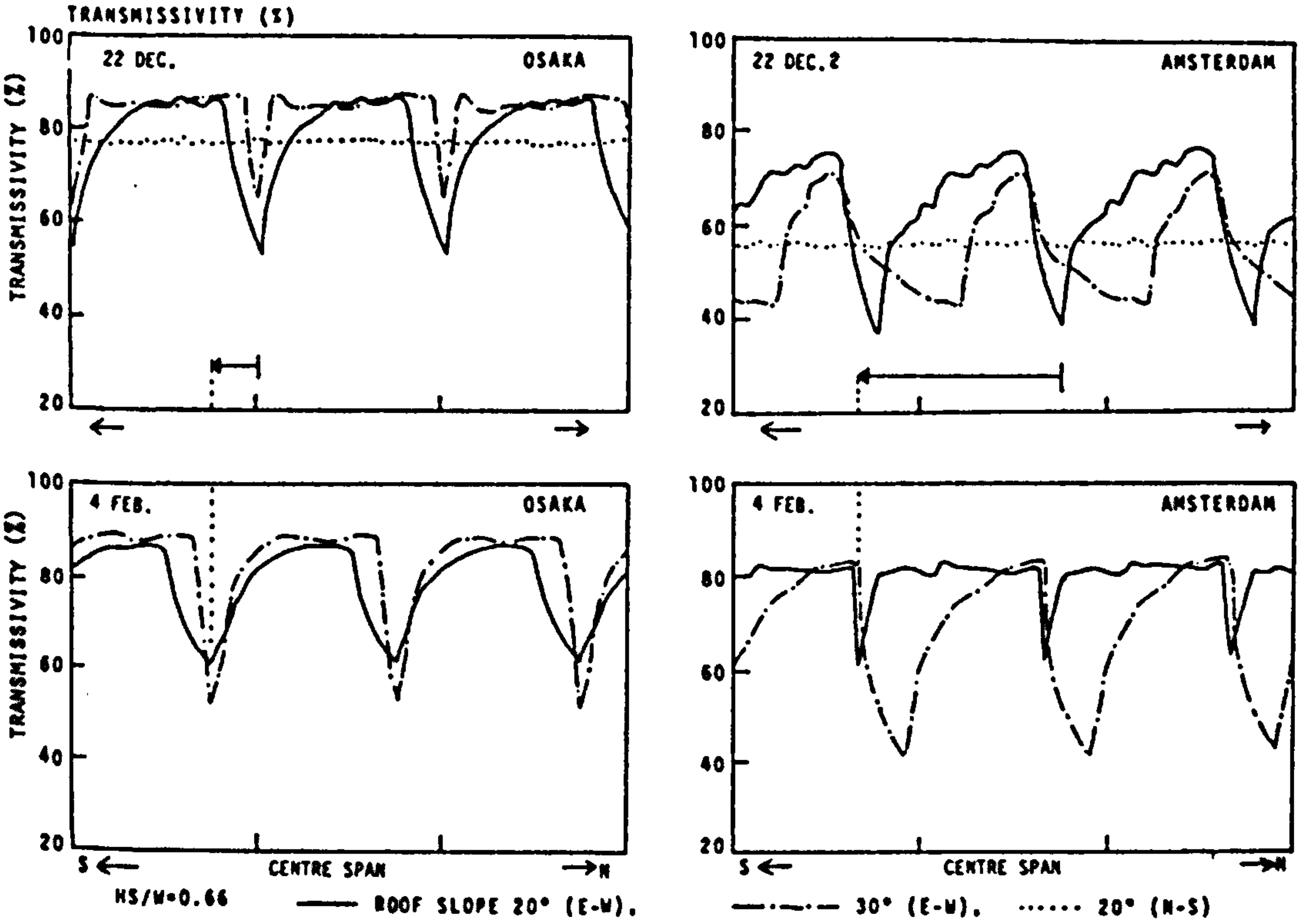


Fig. 18 | Cross-sectional distributions of transmissivity for daily direct light on the floor of E-W multispan greenhouses with roof pitches of 20 and 30° in Osaka (34°39'N) and Amsterdam (52°20'N) on 22 December and 4 February (The greenhouse was assumed to be constructed with glasspanes only, i.e. without structural members).

transmissivity region has moved in the greenhouse with a roof pitch of 20° over a period of 46 days (from 20 December to 4 February). During the winter the low transmissivity region remains almost stationary in Osaka whereas it moves over one span in Amsterdam. Hence in Osaka growers should use the low transmissivity region as a path if only short height crops such as lettuce are grown in the E-W house with a roof pitch of 20°.

This lack of uniformity of light in the E-W multispan house provides an argument in favour of a N-S multispan house, although an E-W multispan house generally gives a higher mean transmissivity in the winter (Morris, 1972).

5 Single-span vs multispan greenhouses

In the previous chapters the light transmission by multispan greenhouses and the plant growth within them were discussed. Under these conditions the light that enters through the side walls or gable ends is practically negligible. In the single-span or twin-span greenhouses, however, the light transmitted through the sides and ends often plays an important role in total light transmission. In this chapter the effect of the number and the length of spans on the light transmission, its variation with time and space, and the plant growth will be discussed.
The dimensions and structure of the greenhouses analysed in this chapter are basically the same as those given in Section 3.1 unless otherwise stated.

5.1 Transmission of diffuse light

The transmissivity was 64% for the single-span greenhouse with the same dimensions and structure as those described in Section 3.1 (except for the number of spans being unity). The transmissivity of the corresponding multispan greenhouse was 60%, as stated previously in Section 3.2: that is, the transmissivity of the single-span house is 4% higher than that of the multispan house.
For a large E-W single-span greenhouse on the Hampshire coast (51°N) in England, Edwards and Lake (1964) give a measured value of 64.5% for diffuse light throughout the year. This figure was obtained on cloudy days. Edwards (1963) reported a percentage transmission of 57% in wooden-framed greenhouse for vines orientated N-S under overcast conditions at Efford (50°45'N), Hants.

5.2 Transmission of direct light

Fig. 19 shows the seasonal variations in transmissivity of daily integrated direct light for single-span and multispan greenhouses in Amsterdam from 20 December to 1 July. Those in Tokyo are shown in Fig. 20. The multispan house was assumed to have an infinite. length and an infinite number of spans. The differences in transmissivity between single-span and multi-

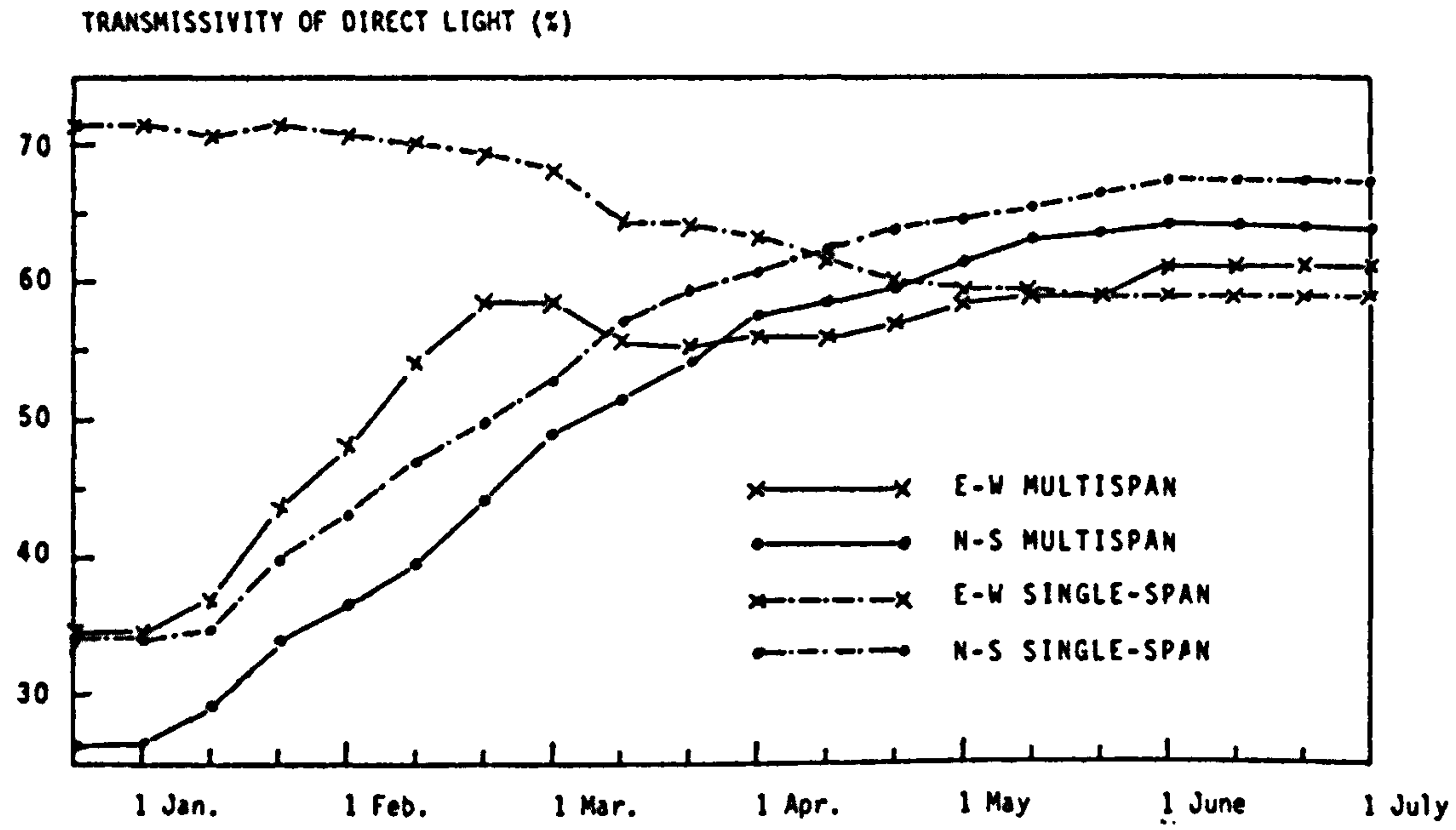


Fig. 19 | Seasonal variations of transmissivity of daily direct light for the single-span and multispan greenhouses in N-S and E-W orientations in Amsterdam (52°20'N).

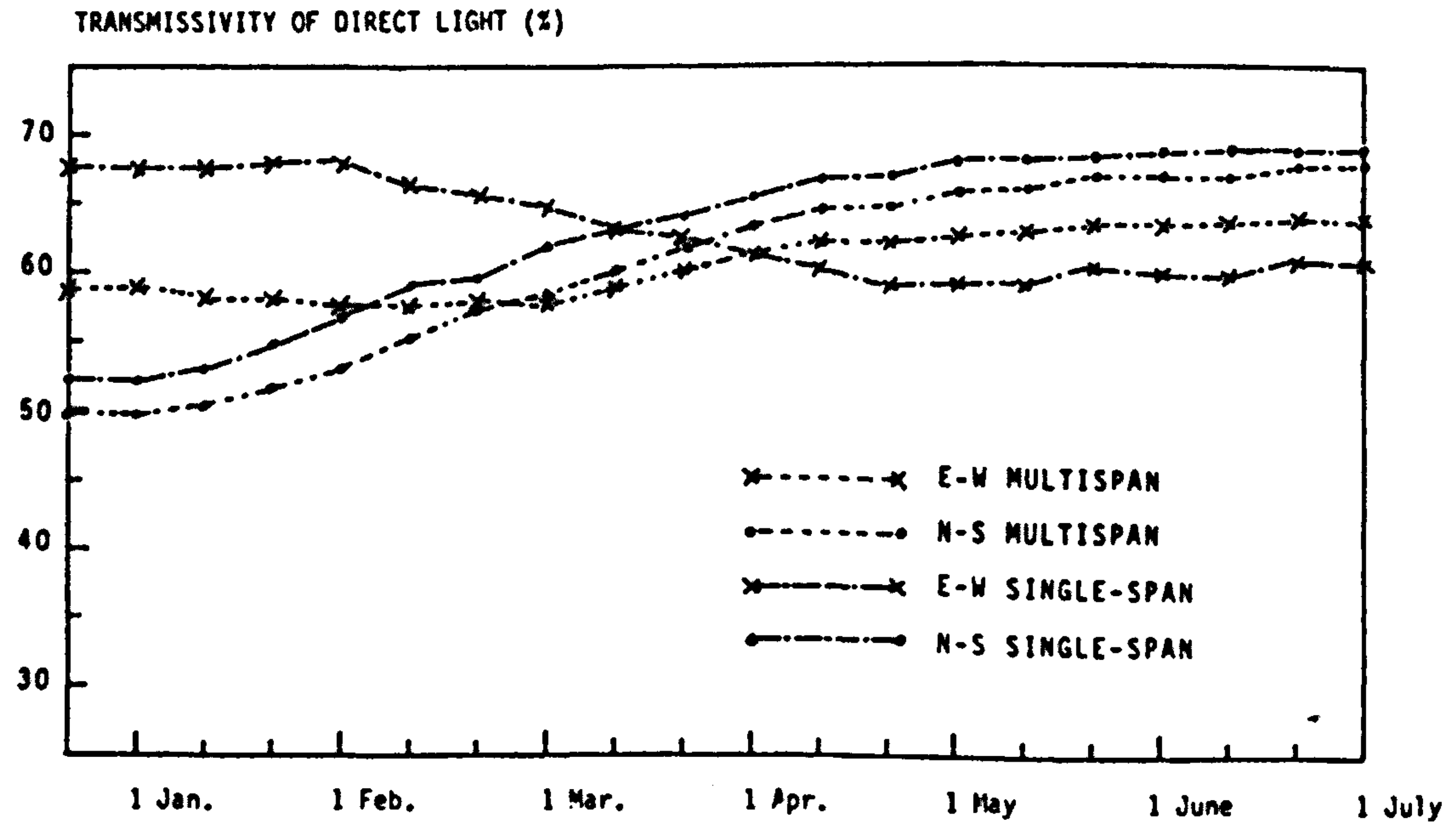


Fig. 20 | Seasonal variations of transmissivity of daily direct light for the single-span and multispan greenhouses in N-S and E-W orientations in Tokyo (35°41'N).

span greenhouses orientated N-S are 2-7% in Amsterdam and are 1-4% in Tokyo. The reduction in light transmission due to the shading by neighbouring spans is relatively small in the N-S greenhouse throughout the year.

In the winter solstice for a greenhouse orientated E-W the transmissivity of a single-span house is 36% higher than that of a multispan house in Amsterdam and 9% higher in Tokyo.

The reduction in light transmission due to the shading by the neighbouring spans to the south is very large in the E-W multispan house around the winter solstice especially at higher latitudes. The floor of the E-W single-span house, on the other hand, receives the light transmitted through the south side wall with high transmissivity most of the day during the winter. The benefits of E-W orientation in the winter are, therefore, much larger in single-span than in multispan greenhouses.

Smith and Kingham (1971) calculated the transmissivity of direct light for a wide single-span alloy house at two orientations, N-S and E-W, at latitude 51 °N. Their results are listed in Table 6. The variations by season and orientation are similar to our calculations, shown in Fig. 19. For the summer, the results of both calculations are very close. In winter, the transmissivity of an E-W house as calculated by Smith and Kingham is 5-6% lower than our value. For a N-S house, on the contrary, our results are 10% lower. Part of these discrepancies for the winter months can probably be attributed to, Smith and Kingham's assumption of a constant value for the ratio of the freely transmitting area to its overall area of the surface of the house (in their simulation the ratio was 0.82 for a wall surface and 0.8 for a roof surface). In other words, they assumed no depth for the structural members. As one can see from Fig. 1, such an assumption erroneously increases the transmissivity at low solar angles. Hence when the sun is in the south, the transmissivity is overestimated in a N-S greenhouse and underestimated in an E-W house.

The diurnal courses of the space averaged transmissivity of the single-span and multispan houses for the direct light in Osaka (34°39'N), Japan, in the winter solstice are given in Fig. 21. The length of the houses was assumed to be infinite. In both orientations the transmissivity of the multispan house increases at 9h00 and drops again at 15h00 because of the shading by the neighbouring spans. In E-W orientation the transmissivity of the single-span house is higher than that of the multispan house all day. In N-S orientation the advantage of the single-span house is less. At noon there is no difference because the light passes through the roofs only. Just before and after noon the transmissivity of the single-span house is

Table 6 Seasonal variations in transmissivity of daily direct light for the N-S and E-W single-span greenhouses (Smith and Kingham, 1971).

Orientation	Calculated percentage transmission of direct radiation											
	J	F	M	A	M	J	J	A	S	O	N	D
0° (E-W)	65.7	65.1	65.0	59.6	59.5	59.0	59.5	59.8	61.0	64.4	65.1	65.4
90° (N-S)	49.7	57.7	63.4	65.6	65.8	65.8	65.8	65.7	64.9	62.3	50.6	48.7

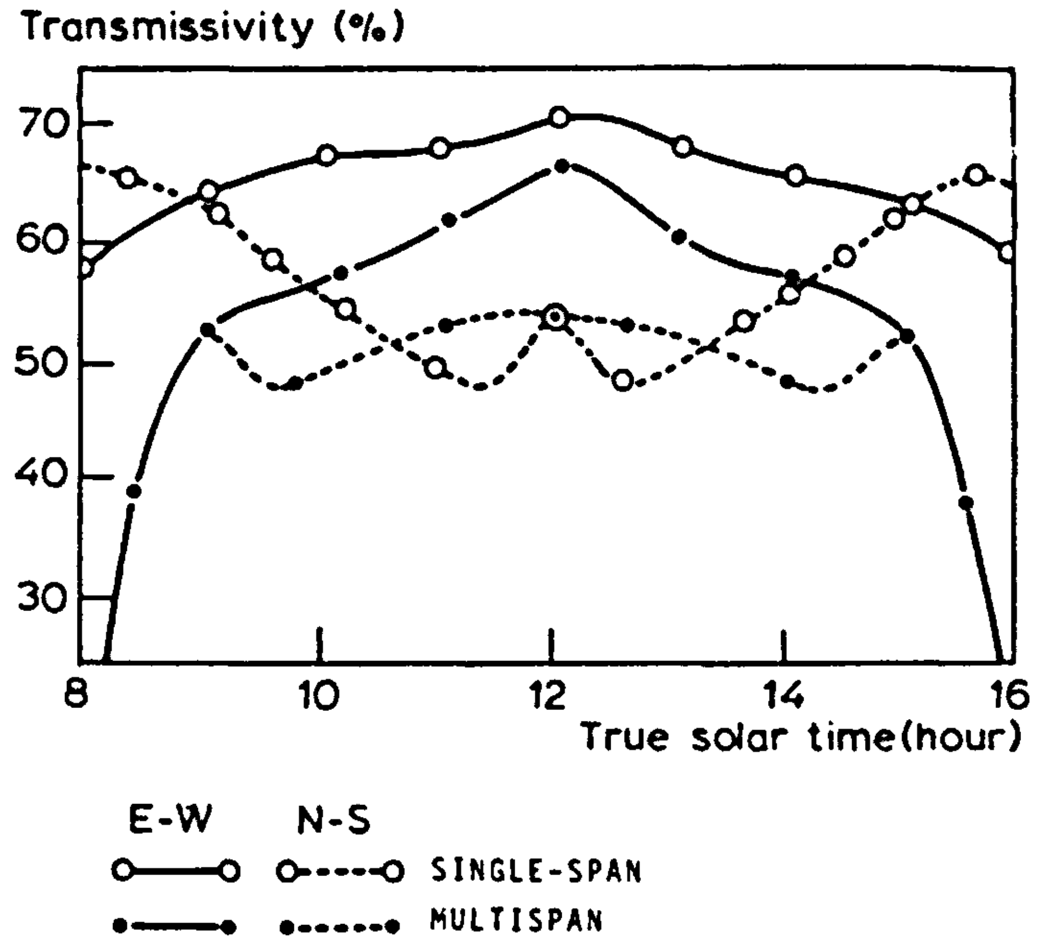


Fig. 21 | Diurnal courses of space averaged transmissivity in the single-span and multispan greenhouses in N-S and E-W orientations in Osaka ($34^{\circ}39'$N) on 22 December.

even lower than that of the multispan house because then the transmission of direct light by the side walls is very low. Therefore, the daily average transmissivity of a N-S single-span house is only higher than that of a N-S multispan house on overcast days, when the light level is relatively low.

The transmissivities of the single-span house for direct light are listed in Table 7 as a function of the altitude and relative azimuth of the sun. At relative azimuths of 0-30°, the transmissivities range between 65 and 75% without a clear relation with the sun's altitude. At relative azimuths of 60-90° (grazing incidence on the walls) the transmissivities range between 3 and 73% and increase gradually with the sun's altitude.

5.3 *Total solar light integrals*

The total solar light integrals in the E-W and N-S single-span greenhouses together with the N-S multispan house in Amsterdam are given in Fig. 22 and those for Tokyo in Fig. 23. The curve for the E-W multispan house is omitted from the figure because it is very close to that for N-S single-span house. The total solar light was integrated from 10 December. The calculations were made based on Eqn (2.9) and the meteorological data presented in Figs 3 and 4.

If we assume now that lettuce seedlings just transplanted can be harvested after receiving 100 MJ m^{-2} of solar light, as al-

Table 7 Transmissivity of the single-span greenhouse with a roof pitch of 24.6^o as a function of the sun's altitude and the sun's azimuth relative to the house orientation.

The sun's altitude (deg.)	Azimuth with respect to house orientation																		
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90
	180	175	170	165	160	155	150	145	140	135	130	125	120	115	110	105	100	95	90
4.3 - 7.2	72	71	70	70	69	69	69	68	66	64	63	60	53	47	39	28	16	5	3
7.2 - 10.1	75	74	73	73	71	71	71	68	64	64	61	58	55	50	40	28	18	11	11
10.1 - 13.0	70	70	70	69	69	69	68	67	67	64	61	59	54	48	39	29	22	17	17
13.0 - 16.0	72	73	71	71	70	69	69	68	68	64	61	59	55	47	39	33	28	22	23
16.0 - 19.0	74	74	72	72	71	70	70	66	64	63	61	57	62	47	42	37	31	27	31
19.0 - 22.0	72	71	70	70	69	69	67	67	66	65	59	57	54	49	44	40	35	33	38
22.0 - 25.2	73	72	71	71	69	69	68	68	63	62	60	57	54	50	47	42	40	38	42
25.2 - 28.4	74	73	72	71	71	68	66	64	64	63	60	58	55	51	49	45	43	43	46
28.4 - 31.7	70	71	69	68	68	68	66	65	65	63	62	60	56	54	60	46	46	47	49
31.7 - 35.1	72	71	71	70	69	69	65	65	65	62	61	59	58	56	53	50	49	51	54
35.1 - 38.7	72	72	71	69	69	67	67	65	66	63	62	61	59	57	54	52	52	54	56
38.7 - 42.5	72	71	71	69	69	69	67	67	65	63	63	61	59	57	55	55	55	56	59
42.5 - 46.5	73	71	71	70	69	67	66	66	65	63	64	63	59	58	57	57	58	58	61
46.5 - 50.8	71	70	69	70	68	68	68	66	66	64	62	62	59	59	58	59	59	61	63
50.8 - 55.6	71	70	70	70	69	69	68	65	66	64	63	62	62	60	60	61	61	63	64
55.6 - 61.0	70	69	69	69	69	67	67	66	65	63	64	64	63	63	61	61	63	64	67
61.0 - 67.7	70	68	68	67	67	67	66	66	66	65	65	65	63	64	63	65	66	66	67
67.7 - 77.2	68	68	68	67	68	67	67	66	66	66	65	66	66	66	66	67	69	69	69
77.2 - 90.0	72	71	71	71	72	71	72	72	72	71	71	72	72	72	72	73	72	71	71

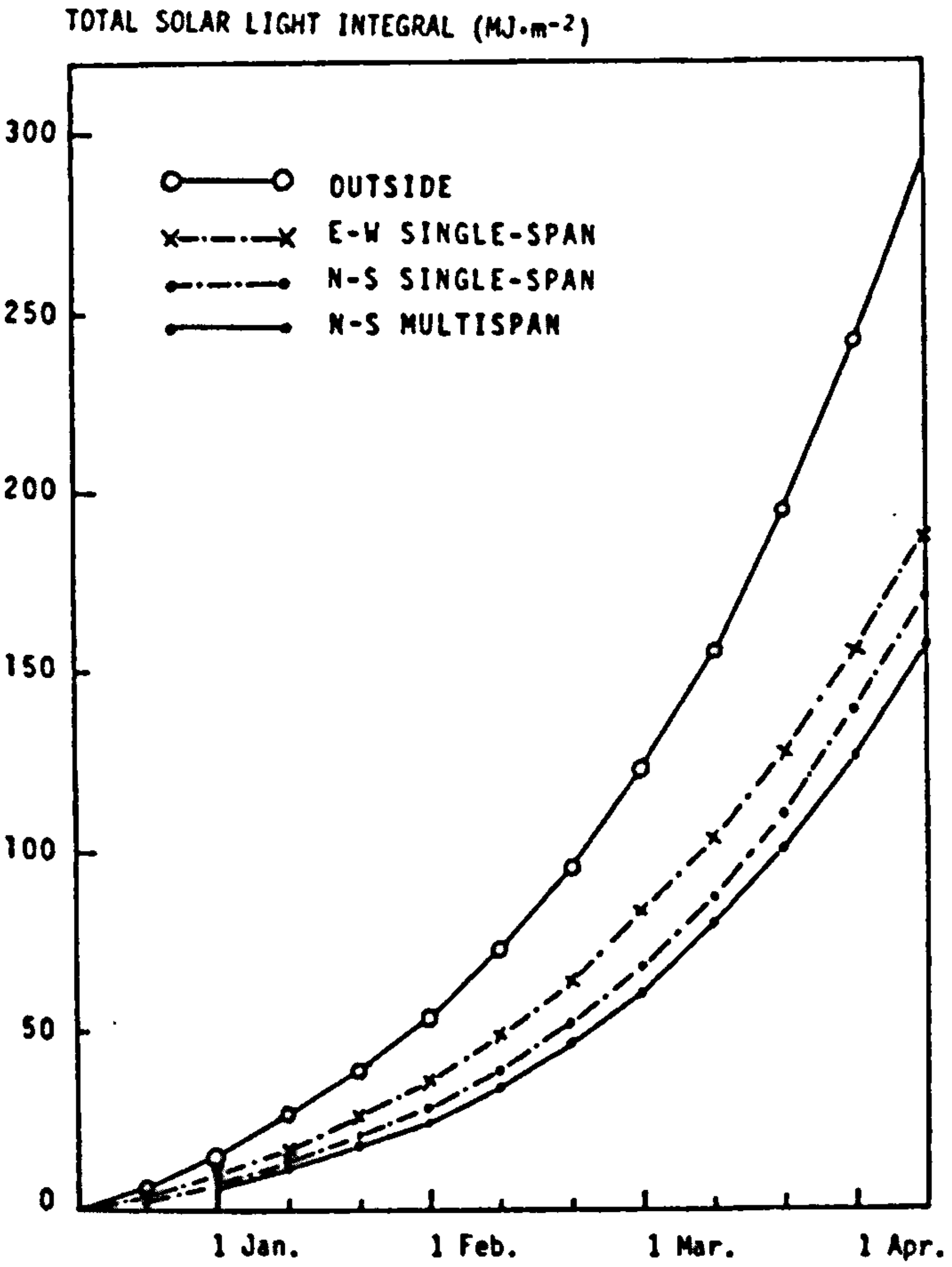


Fig. 22 | Total solar light integrals outside and inside the N-S and E-W single-span greenhouses in Amsterdam (52°20'N) (The integration was started on 10 December).

ready assumed in Section 3.5, lettuce transplanted on 10 December in Amsterdam can be harvested on 9 March in the E-W single-span house, on 15 March in the N-S single-span house, and on 19 March in the N-S multispan house. The corresponding dates in Tokyo are 19, 23, and 25 February.

According to Harnett (1974), a lettuce weighting 170 g was attained seven days earlier in the E-W single-span house than with the E-W multispan house and 14 days earlier than in the N-S multispan house when harvested during late December and January at Efford (50°45'N) in England. In our calculation, if the integration was started earlier than on 10 December, the gain in days in Amsterdam (50°20'N) would have been greater than those mentioned above, and the results would then be comparable to those of Harnett.

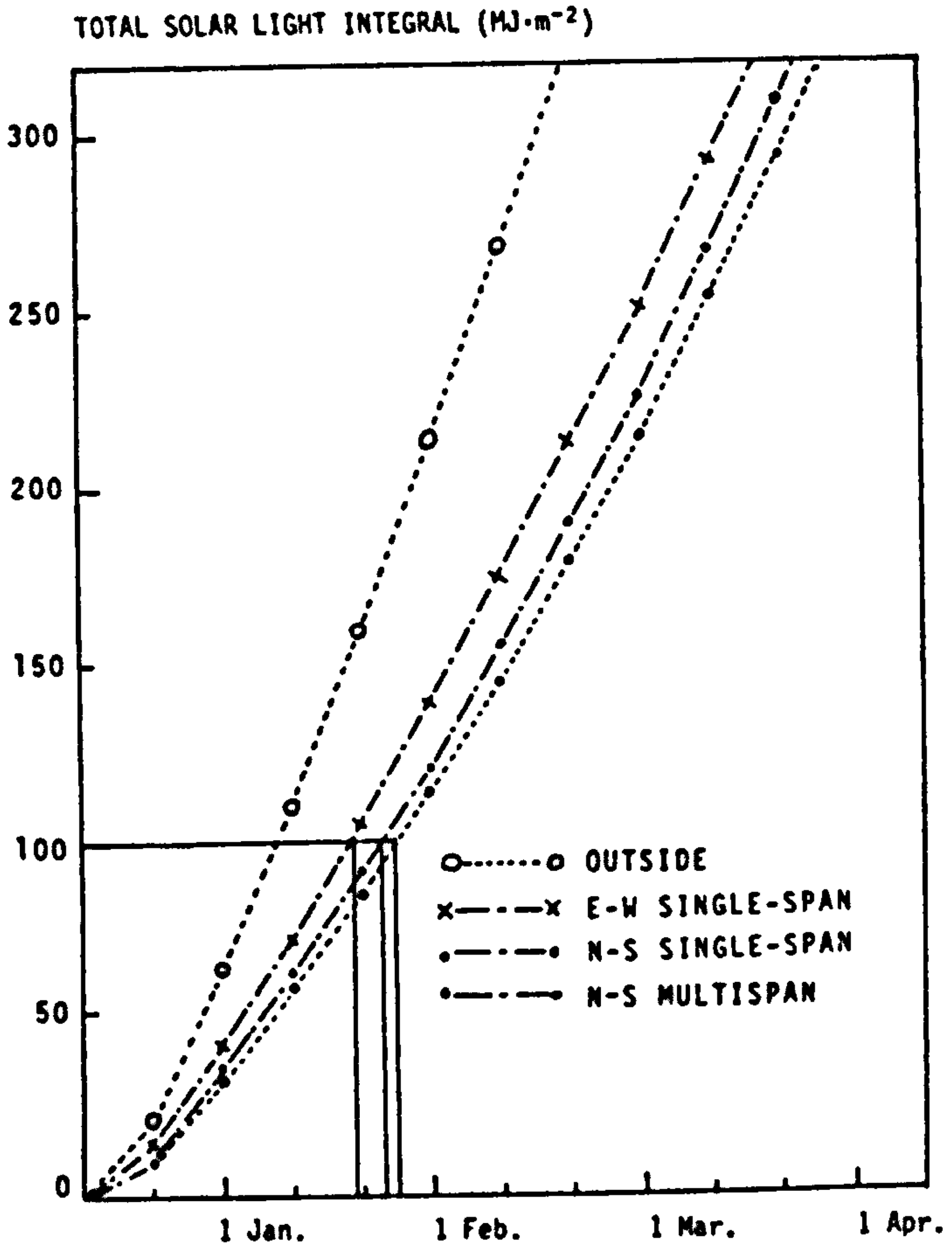


Fig. 23 | Total solar light integrals outside and inside the N-S and E-W single-span greenhouses in Tokyo (35°41'N) (The integration was started on 10 December).

5.4 Effect of the number of spans

Fig. 24 shows the effect of the number of spans on the transmissivity of daily direct light in Osaka (34°39'N) in the winter solstice. The dimensions of the house are the same as those described in Section 3.1 except that the length of the house is 49.0 m. The transmissivity of E-W houses are higher than those of N-S houses regardless of the number of spans. The transmissivity of E-W houses decreases with the increase of the number of spans, whereas that of N-S houses is hardly affected by the number of spans. The high transmissivity of E-W houses with a small number of spans is due to the high transmission of light through the south side wall. This dependence of the transmissivity of E-W houses on the number of spans is more remarkable at higher latitudes. The cross-sectional distributions of daily direct light on the floor of the E-W and N-S greenhouse with four spans in Osaka in the winter

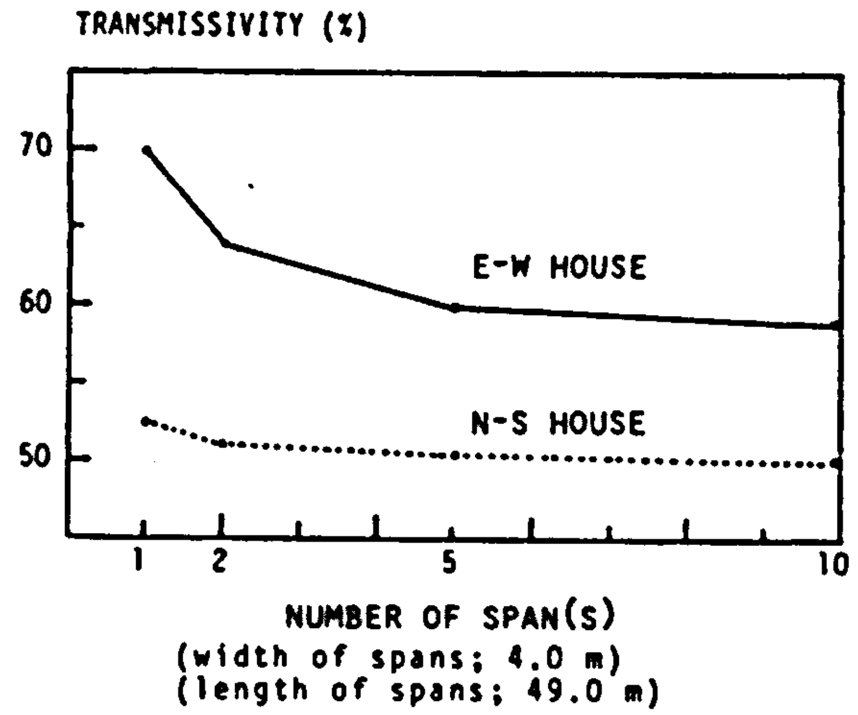


Fig. 24 | Effect of the number of spans on the transmissivity of daily direct light in Osaka (34°39'N) on 22 December.

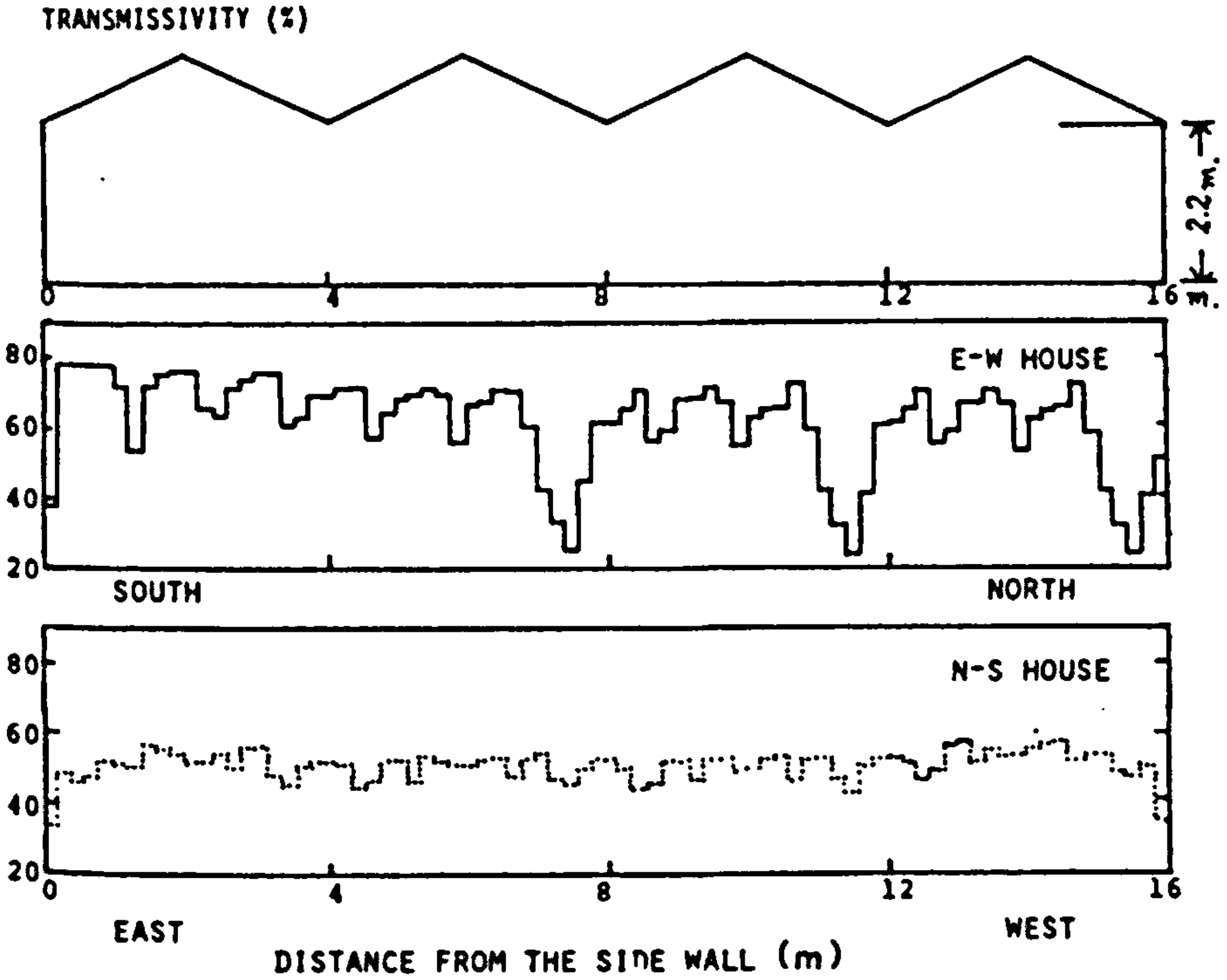


Fig. 25 | Cross-sectional distributions of daily direct light on the floor of 4-span N-S and E-W greenhouses in Osaka (34°39'N) on 22 December.

solstice are given in Fig. 25. The distribution in the N-S house is more uniform than that in the E-W house and there is only a little difference in distribution pattern among the four spans. Apparently the effect of the sides is negligible so that the spatial transmissivity is not affected by the number of spans.

On the other hand, the transmissivity at the most southerly spans in the E-W house is higher than that at the most northerly spans, because the light transmitted through the south wall reaches the second span from the south for almost a whole day and reaches the fourth span only during the morning and evening in Osaka in the winter solstice.
It should also be noted that a part of the floor under the northerly spans in the E-W house receives only 25% of the daily direct light outside in the winter solstice. This large reduction of light is attributable both to the shadow by the structural members of the neighbouring roof to the south and to the low light transmission of the roof not facing the sun.

5.5 Effect of length of spans

The effect of the length of a ten-span house on the space averaged transmissivity of daily direct light in Osaka in the winter solstice is illustrated in Fig. 26. The transmissivity of the E-W house does not vary with the length of the house, whereas that of the N-S house decreases with the increase of the length. The transmissivity of a N-S house is strongly affected by the incident light through the south gable end when the length is relatively short. A N-S greenhouse of very short lenght gives about the same value of transmissivity as that for an E-W house. This effect of the length on the transmissivity is, of course, dependent upon the height of ridge and side walls, the latitude, and the season. Kozai (1977) discussed this dependence in some detail.

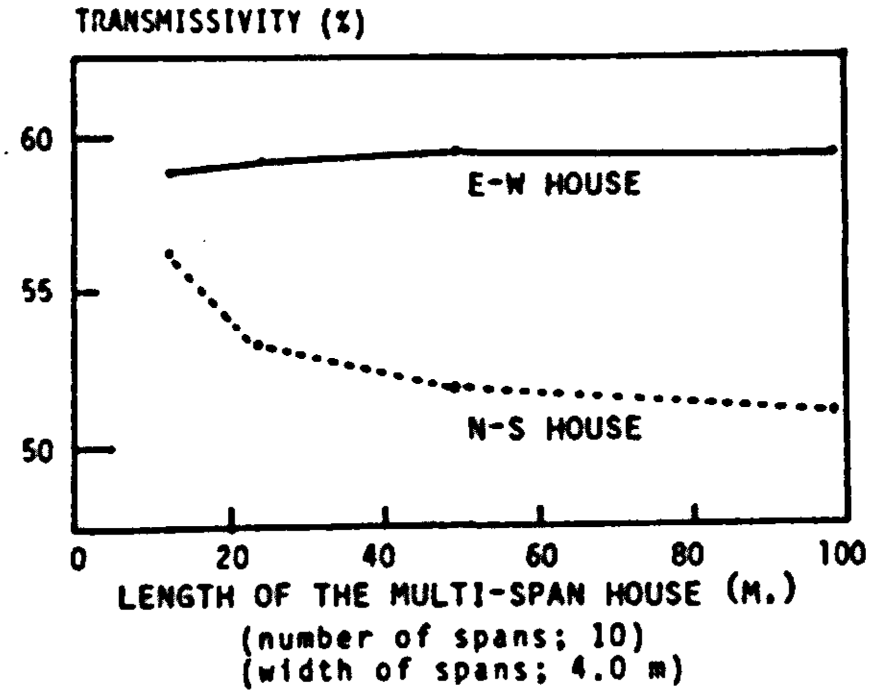


Fig. 26 | Effect of the length of the N-S and E-W multispan greenhouses on the transmissivity of daily direct light in Osaka ($34^{o}39'$N).

5.6 The spacing between the E-W single-span houses

So far the single-span house was assumed to be standing on an open field, although this assumption is not always realistic. Fig. 27 shows the cross-sectional distributions of the transmissivity (relative daily integrated direct light) in the E-W single-span greenhouse with infinite length on 22 December when two identical single-span greenhouses stand parallel at intervals of 1, 2, and 3 m. The distribution in the E-W single-span house built on an open field is also shown in the figure for reference. The width of span, height of side walls, and roof slope were assumed to be 4.0 m, 1.48 m and 24.6°, respectively. The letter M in Fig. 27 denotes the average transmissivity across the floor.

The transmissivity on the southern part of the floor is largely reduced by the shadows of the neighbouring houses to the south when the distance between the houses is less than 2.0 m. The reduction in transmissivity is considerable if the distance is less than 1.0 m. The effect of a neighbouring greenhouse is, of course, not only dependent on the distance between the houses, but also on the height of sides, roof slope, and house orientation. The effect of the neighbouring greenhouse is not larger in a N-S orientation than in an E-W orientation (Kozai, 1974).

The transmissivity of diffuse light will also be affected by neighbouring houses to a certain extent when the distance between the houses is, for example, less than 2.0 m.

The diurnal courses of the space averaged transmissivity for these houses in the winter solstice are presented in Fig. 28. If the distance between the houses is less than 2.0 m, the northern house is shaded by the neighbouring house to the south all day. The transmissivity of the greenhouse 1.0 m away from the neighbouring house is worse than that of the multispan house with the same structure for each span.

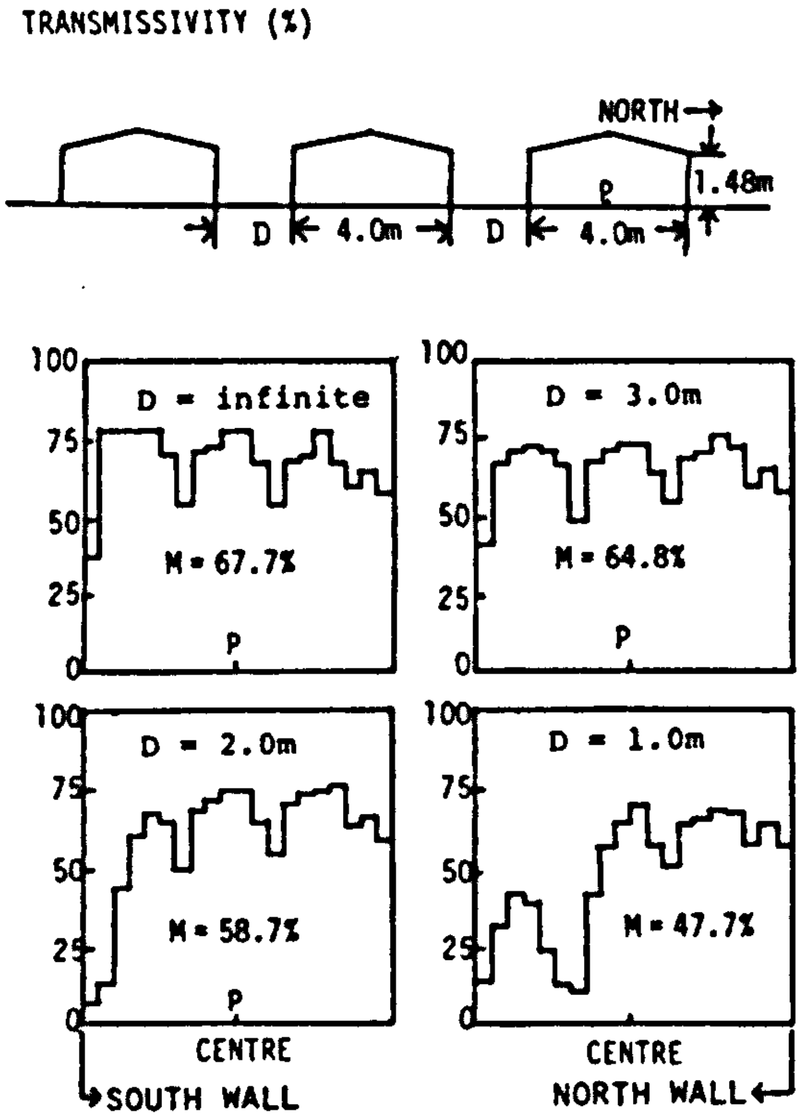


Fig. 27 | Effect of the shadows of neighbouring E-W single-span greenhouses running parallel on the cross-sectional distribution of daily direct light in the E-W single-span greenhouses in Osaka on 22 December.

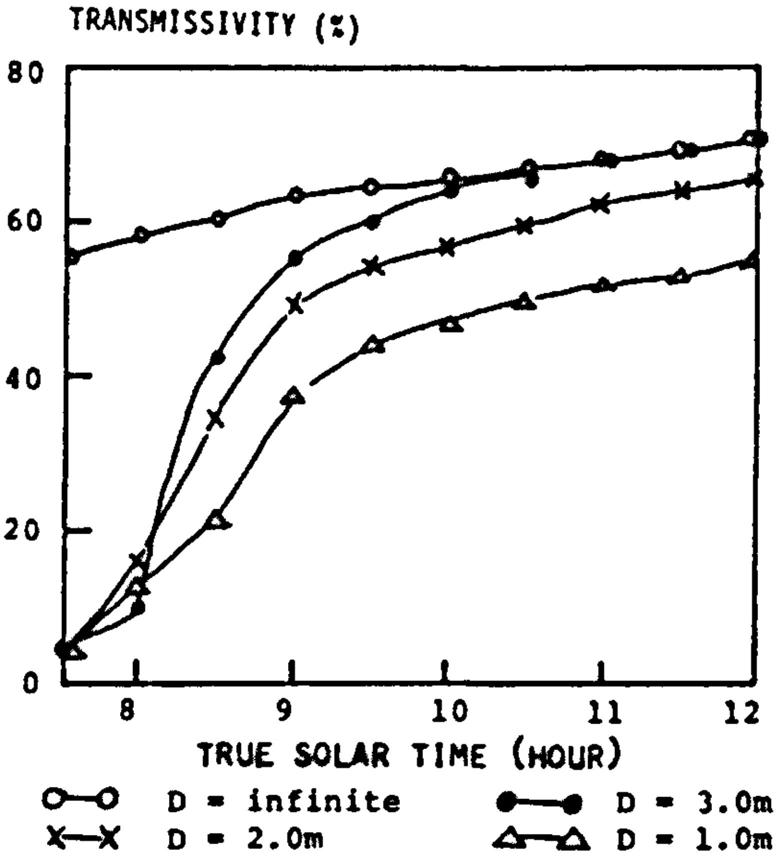


Fig. 28 | Effect of the shadows of neighbouring single-span greenhouses running parallel on the diurnal courses of space averaged transmissivity of direct light for the E-W single-span greenhouse in Osaka ($34^{\circ}39'$N) on 22 December.

6 Concluding remarks

6.1 The light integral inside the greenhouse

In Section 3.5 we discussed the total solar light integral in N-S and E-W greenhouses and the difference in days for plant growth. In this section this problem will be discussed in more detail.

Fig. 29 shows the increase of total solar light integrals inside single-span and multispan houses in N-S and E-W orientations in Tokyo. The total light was integrated from the end of each month during the winter. The calculations were based on Eqn (2.9) and the meteorological data presented in Figs 3 and 4. The total light integrals for the houses in Amsterdam are also given in Fig. 30. As can be seen from the figures, the differences in the integral for a certain period between N-S and E-W houses, or between single-span and multispan houses are largely dependent upon the date on which the integration was started.

Tables 8 and 9 summarize the number of days from the start of integration to attaining the light integral of 100 MJ m^{-2} in those houses. In Amsterdam, when the integration is started on 29 August, it takes 35 days to attain the total light integral of 100 MJ m^{-2} on the floor in the N-S and E-W multispan houses, 32 days in the N-S single-span house, and 31 days in the E-W single-span house. Thus, the total light integral of 100 MJ m^{-2} is attained four days earlier in the E-W single-span than in the N-S and E-W multispan houses, and one day earlier compared with the N-S single-span house. This gain in days becomes the largest when the integration is started at the end of October in Amsterdam and at the end of November in Tokyo. On the other hand, if the integration is started at the end of January in Amsterdam, or at the end of February in Tokyo, there is only a little or no difference between the houses.

Table 10 shows the experimental results of the number of days from planting to attaining 170 g head of a lettuce plant in N-S and E-W multispan houses and an E-W single-span (wide-span) house at Hants (51°N), England (Harnett, 1974). The experimental results of lettuce growth by Harnett correspond approximately to our simulated results of the total light integral, therefore, the total light integral is a major factor influencing the

Table 8 Number of days from the start of integration to attaining the total light integral of 100 MJ m^{-2} in Amsterdam (52°20'N).

Planted	Days from planting to receiving the light quantity of 100 MJ m^{-2}				(a)-(b)	(c)-(d)	(b)-(d)	(a)-(d)
	multispan		single-span					
	N-S (a)	E-W (b)	N-S (c)	E-W (d)				
Aug 29	35	35	32	31	0	1	4	4
Sept 28	73	59	63	47	14	6	12	26
Oct 29	120	111	112	94	9	18	17	26
Nov 28	90	83	82	64	7	18	19	26
Dec 29	78	72	72	63	6	9	9	15
Jan 29	61	58	58	55	3	3	3	6

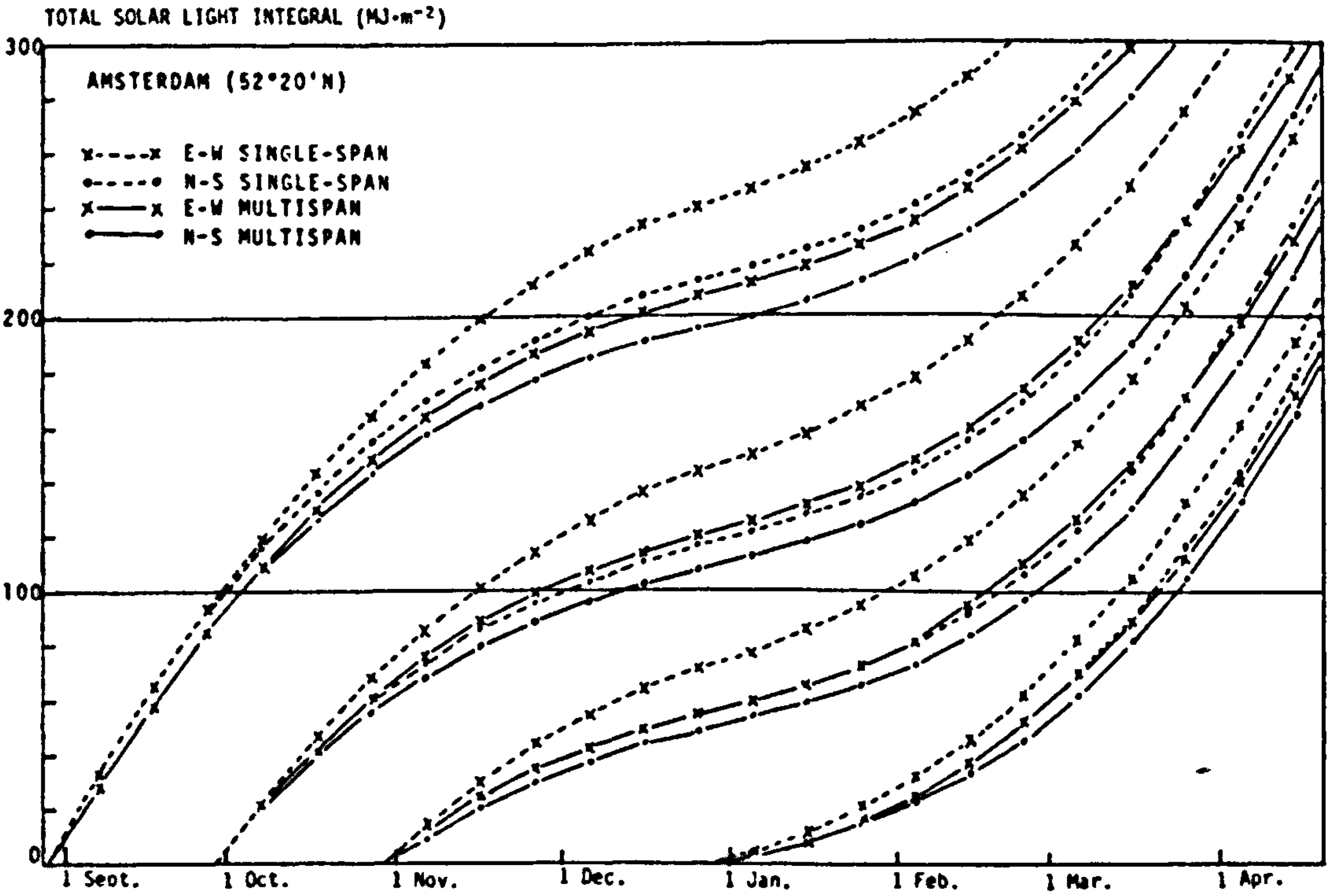


Fig. 29 | Total solar light integrals in the single-span and multispan houses in N-S and E-W orientations in Tokyo (The integration was started at the end of each month).

Table 9 Number of days from the start of integration to attaining the total light integral of 100 MJ m^{-2} in Tokyo. (35°41'N)

Planted	Days from planting to receiving the light quantity of 100 MJ m^{-2}				(a)-(b)	(c)-(d)	(b)-(d)	(a)-(d)
	Multispan		Single-span					
	N-S (a)	E-W (b)	N-S (c)	E-W (d)				
Aug 29	25	26	24	25	-1	-1	1	0
Sept 28	30	30	28	27	0	1	3	3
Oct 29	37	35	36	31	2	5	4	6
Nov 28	42	37	39	33	5	6	4	9
Dec 29	37	34	34	31	3	3	3	6
Jan 29	30	30	28	27	0	1	3	3
Feb 27	27	27	25	25	0	0	2	2

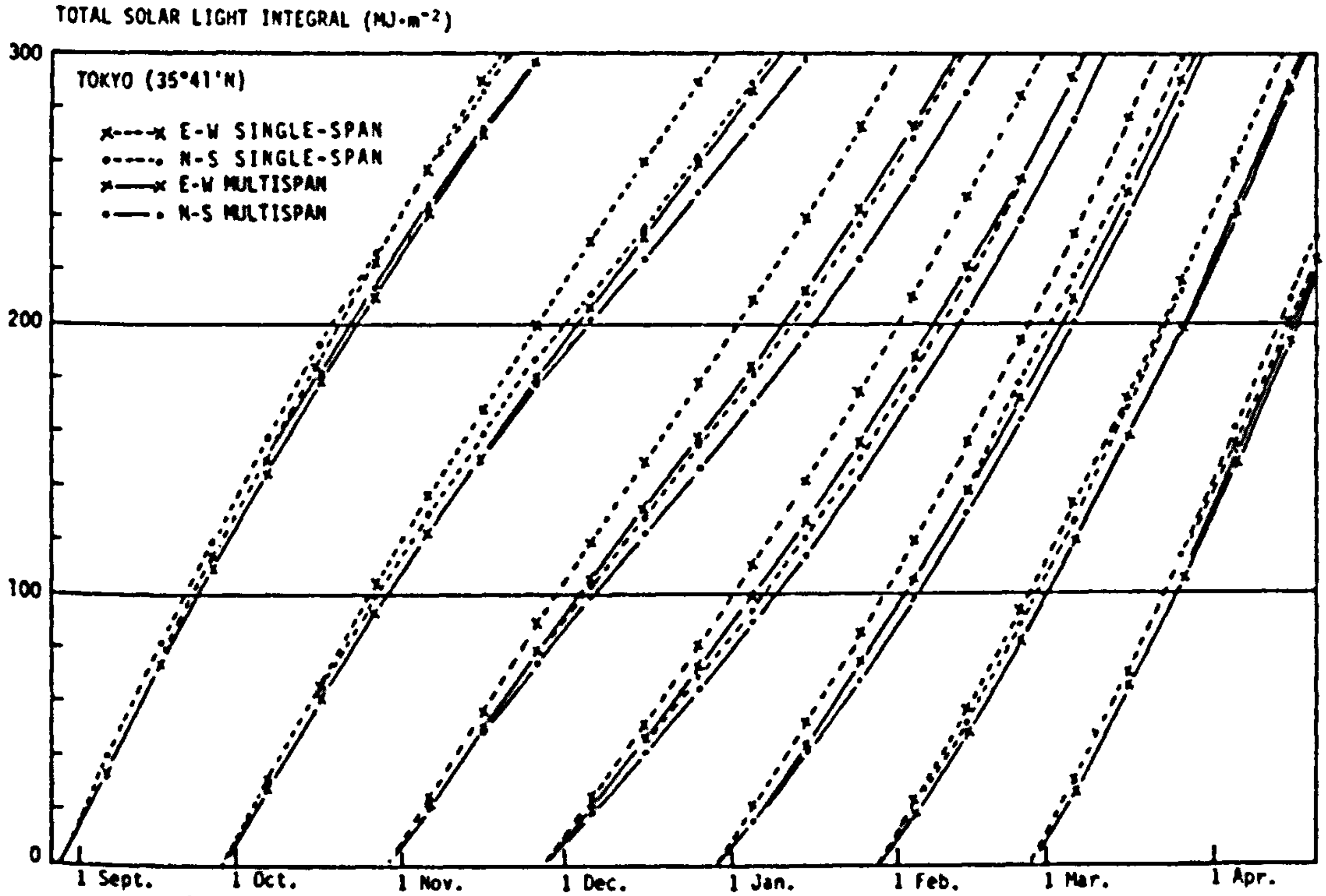


Fig. 30 | Total solar light integrals in the single-span and multispan houses in N-S and E-W orientations in Amsterdam (The integration was started at the end of August, September, October, and December).

Table 10 Number of days from planting to attaining 170 g head of Lettuce cultivar Deci minor (Harnett, 1975).

Planted	Days from planting to attaining 170 g head			(a)-(b)	(b)-(d)	(a)-(d)
	Multispan		Single-span			
	N-S (a)	E-W (b)	E-W (d)			
Sept 25	42	40	37	2	3	5
Sept 29	44	41	38	3	3	6
Oct 4	51	47	45	4	2	6
Oct 9	63	60	60	3	0	3
Oct 13	66	56	56	10	0	10
Oct 22	66	54	52	8	2	10
Oct 27	73	66	61	7	5	12
Oct 31	91	82	78	9	4	13
Nov 6	90	85	85	5	0	5
Nov 11	90	85	80	5	5	10
Nov 23	81	78	70	3	8	11
Dec 15	71	68	61	3	7	10
Dec 31	62	61	56	1	5	6
Jan 8	60	58	54	2	4	6
Jan 24	52	50	45	2	5	7
Feb 8	41	39	38	2	1	3

growth of lettuce. The light integral changes considerably with the design and orientation of the greenhouse, although growth cannot be considered to be proportional to the total light integral.

6.2 *Summary of some factors influencing transmissivity*

The results of the present simulation study indicate quantitatively the influence of various climatic and design factors on the transmissivity of direct and diffuse light and, to a certain extent, on the net CO_2-assimilation of a crop within the greenhouse.

For the efficient use of greenhouses during the winter, it is essential to obtain maximum transmissivity and uniformity of solar light. Siting, orientation, and design of greenhouses should be based on these criteria. The following results show the advantages and disadvantages of N-S and E-W houses, and are summerized in Table 11.

The daily average of direct solar light transmissivity in an E-W house is, in general, higher than that in a N-S house. This phenomenon is more pronounced

- when the ratio of the height of side walls to the width of the span is greater than about 0.5. The transmissivity of an E-W house decreases with the number of spans, whereas that of a N-S house is almost independent of the number of spans (Fig. 24).
- when the ratio of the length of house to the width of the span is greater than about 5. The transmissivity of a N-S house decreases with the increase of the ratio, whereas the transmissivity of an E-W house is less dependent on the ratio (Fig. 26).
- at higher latitudes (Figs 19, 20, 29, and 30).

The cross-sectional distribution of daily integrated direct light on the floor in a E-W multispan house is less uniform than in a N-S multispan house. However, for a E-W single-span house or for the southerly spans of an E-W multispan house, the cross-sectional distribution on the floor is as uniform as in a N-S house (Figs 25 and 27).

The longitudinal gradient of the daily integrated direct light on the floor is considerable in a N-S house with a relatively high pitch, especially at higher latitudes (Kozai, 1977).

Diffusive covering materials increase the uniformity of the light on the floor.

As stated above, there is much variation in the average transmissivity of direct light with latitude, although it is not shown in Table 11. Figures 31 and 32 illustrate the variation in the average transmissivity of both single-span and multispan houses with latitude and orientation. The transmissivity of a single-span house is more sensitive to orientation than that of a multispan house, especially at higher latitudes. These effects are, of course, confined to sunny periods. The more direct light, the greater the effects.

6.3 Design factors not discussed in the present study

So far we discussed mainly the influences of orientation, latitude, time of the year, greenhouse shape (roof slope, length, width, and the number of spans of the house) on the light environment and the net CO_2-assimilation rate of a crop within the greenhouse. However, there are many other design factors influencing the light environment and plant growth in the greenhouse:

1. The influences of diffusive covering materials (including transparent material with condensed water droplets), corrugated materials, or materials of unusual optical characteristics

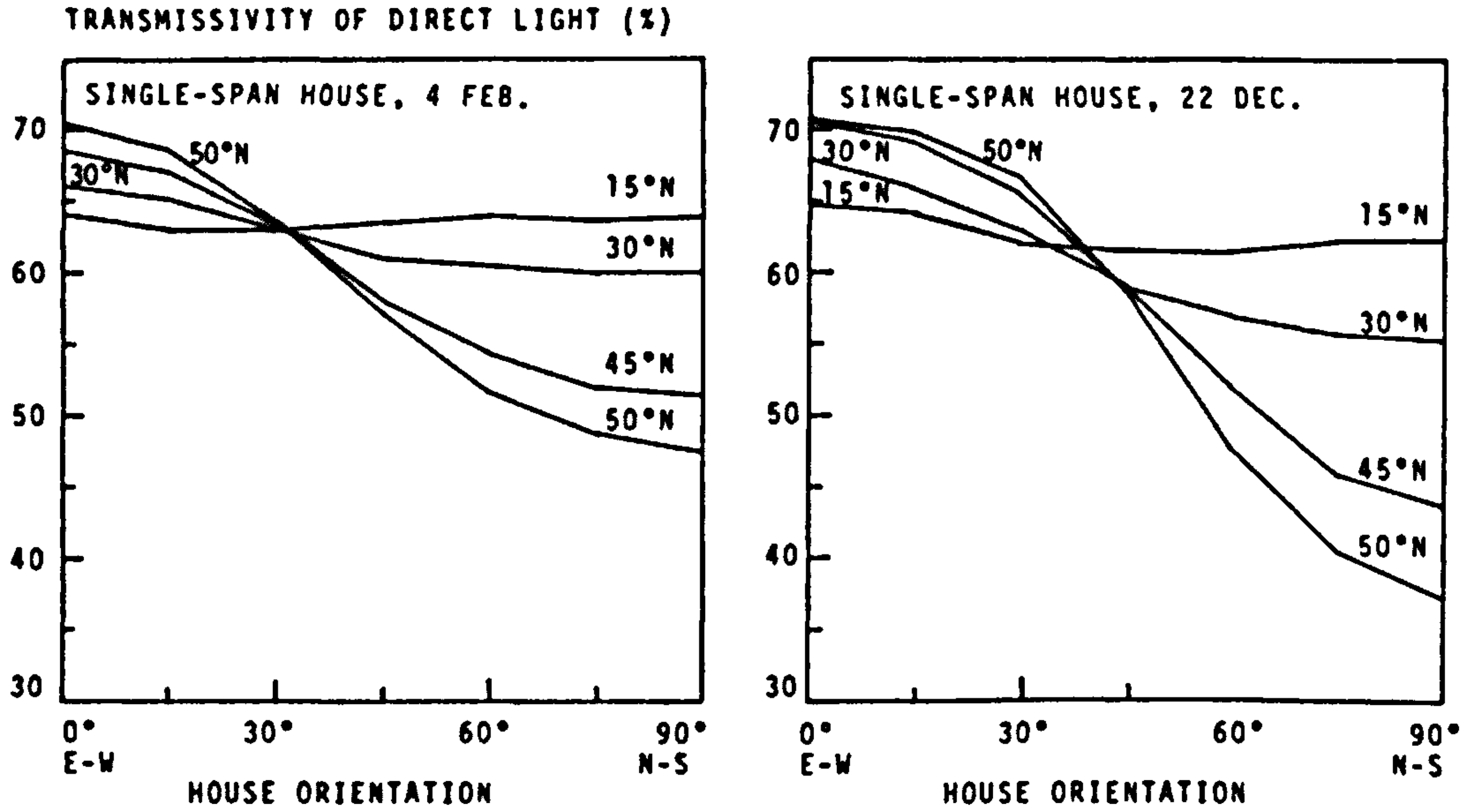


Fig. 31 | The transmissivity of the single-span house for daily direct light on 4 February and 22 December as a function of latitude and orientation.

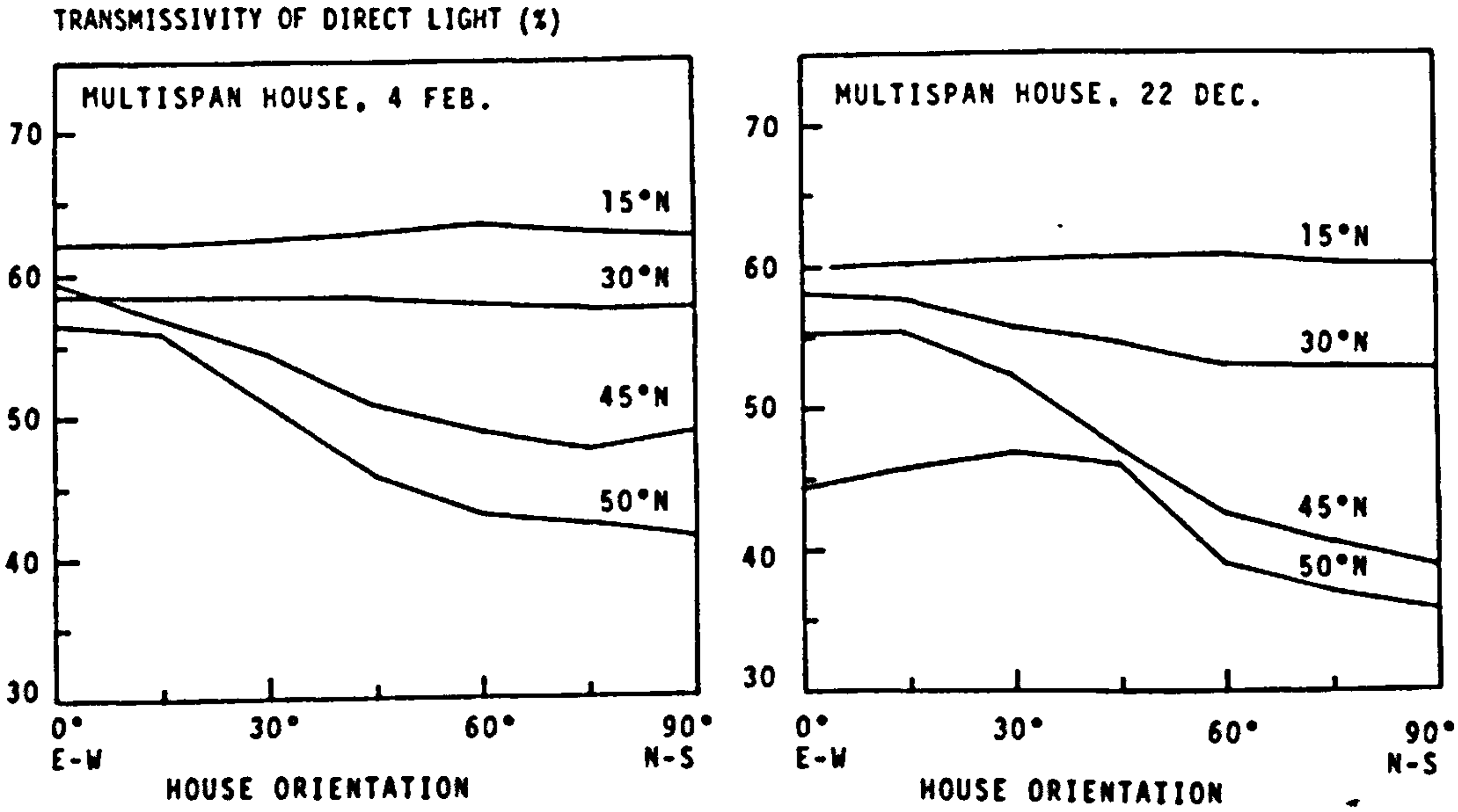
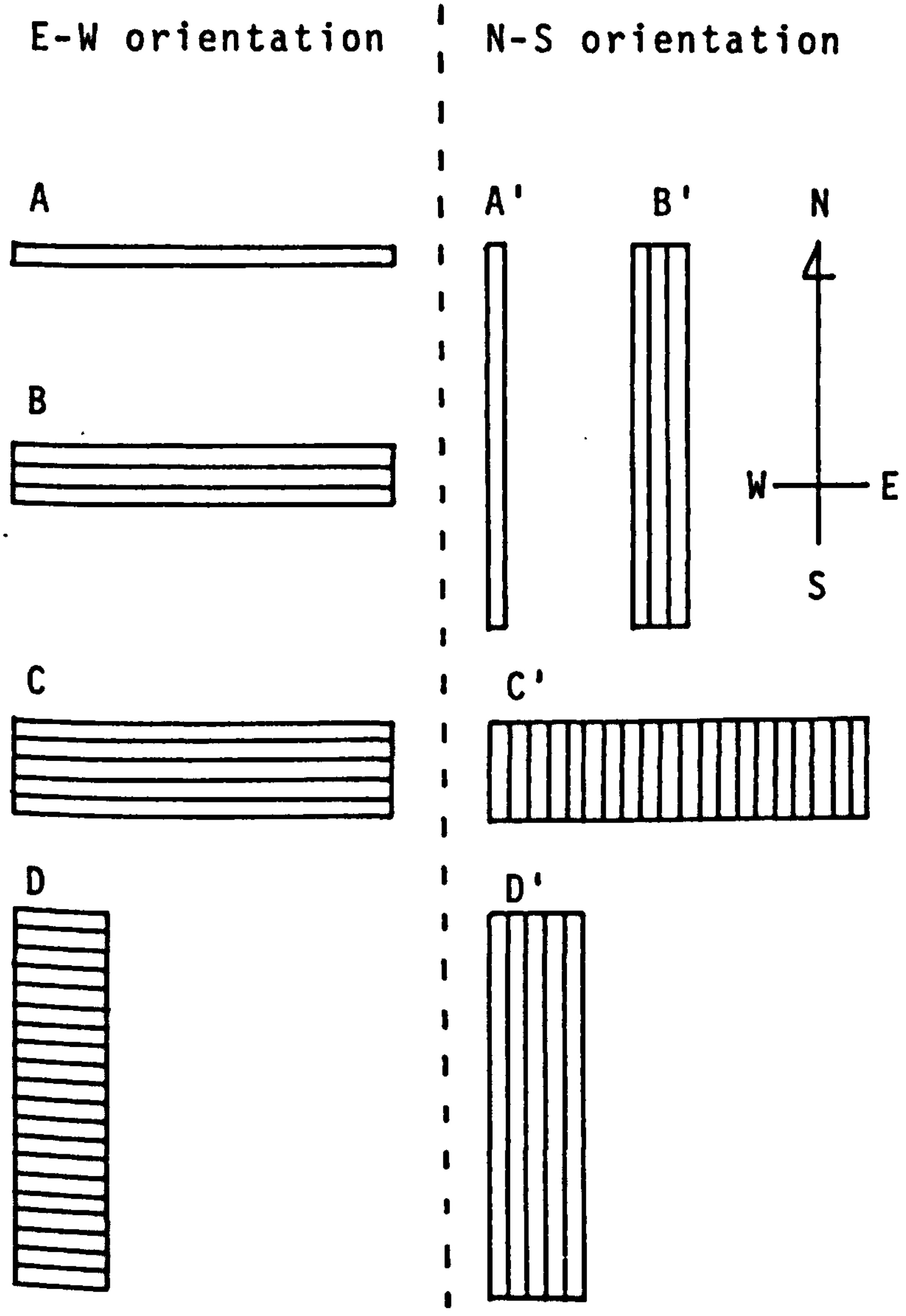


Fig. 32 | The transmissivity of the multispan house for daily direct light on 4 February and 22 December as a function of latitude and orientation.

(selective transmission or selective reflection for radiation) on the light environment in the greenhouse,
2. The loss of light due to the weathering of covering materials (including the deposit of dirt on them),

Table 11 The advantages and disadvantages of N-S and E-W houses.

Number of spans	length/ width	orien- tation	unifor- mity	transmis- sivity	notation of the house given below
1	20	E-W	good	very high	A
3	20	E-W	bad	very high	B
5	20	E-W	worse	high	C
20	5	E-W	worse	hight	D
1	20	N-S	good	low	A'
3	20	N-S	good	low	B'
20	5	N-S	good	medium	C'
5	20	N-S	good	low	D'



3. The loss of light due to the shadows of electric fans and polythene ducts for mechanical ventilation,
4. The influence of spacing and dimensions of roof bars on the light environment in the greenhouse,
5. The light transmission into dome-shaped, semi-circular, mansard-type and cylindrical greenhouses.

The effect of diffusive covering materials on the light environment in the greenhouse has been studied by Nisen (1971), Nisen and Deltour (1971) and Basiaux et al. (1973). The loss of light due to the shadows of electric fans for ventilation was studied by Kozai (1977). He also studied the effect of the spacing and dimensions of roof and wall bars on the light environment (Kozai, 1974). The use of reflective mirror to increase the light in the greenhouse was studied by Kozai and Sugi (1972). The light transmission into semi-circular or other unconventional greenhouses has been studied by Manbeck and Aldrich (1967) and Kirsten (1973).

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Appendix A1 - A program for calculating the transmissivity of a greenhouse as a function of solar altitude and relative solar azimuth

```
      DIMENSION      YP(99),ZP(99),BK(50),CK(50),DK(50),FRQ(101)
      DIMENSION TRAM(50),DOMY1(50),DOMY2(50),BKK(50),DKK(50)
      DIMENSION SDOMY1(50),SDOMY2(50),SDOMX1(50),SDOMX2(50),SHADS(50)
      DIMENSION SMODY(50),BCKK(50),SHADY(50),SHADX(50)
      DIMENSION STYP(25),STZP(25),SSDOM1(25),SSDOM2(25),SSYP(25)
      DIMENSION YPERTR(300),SPERTR(300),PERY(300),STPERT(300),STPY(300)
      DIMENSION N1(300),N2(300), DOMX1(30)
      DIMENSION         DSTR(50,101),ITBL(20,20)
      IRANDY=584287
      RI=0.194/2.54
      READ(5,5000)HLENGT,HLX1,HLX2
      READ(5,5000)HLY1,HLY2
      CALL HOUSE(KEND,YYW,YP,ZP,BK,CK,DK,KBNKT,HSIDE,KSPAN)
C
C           ************************************************
C
C   GL          THICKNESS OF GLASS-PANE
C   RI          EXTINCTION COEFFICIENT FOR GLASS
C   IRANDY      INITIAL VALUE OF RANDOM NUMBER
C   IRAST       NUMBER OF RANDOM NUMBERS USED AT EACH TIME STEP
C               MORE THAN 1000 AND LESS THAN 10000 RANDOM NUMBERS SHOULD
C               BE USED FOR ONE SPAN OF A MULTISPAN GREENHOUSE
C   HLENGT      LENGTH OF THE HOUSE (METER)
C   HLX1        DISTANCE FROM GABLE END (METER)
C   HLX2        DISTANCE FROM GABLE END (METER)
C                THE LENGTH OF THE HOUSE IS HLENGT, CALCULATION
C                IS PERFORMED FOR THE RANGE HLX1 TO HLX2.
C   HLY1        DISTANCE FROM A SIDE WALL
C   HLY2        DISTANCE FROM THE SIDE WALL
C               CALCULATION IS PERFORMED FOR THE RANGE HLY1 TO HLY2.
C
C       *******      AN EXAMPLE OF INPUT DATA
C
C     10000     (NUMBER OF RANDOM NUMBERS USED)
C     100.0     50.0      75.0     (THE LENGTH OF THE HOUSE IS 100 METRES,
C                                   BUT THE LIGHT DISTRIBUTION IS CALCULAT
C                                   ONLY IN A RANGE FROM 50 TO 75 METRES.
C                                   TO CALCULATE FOR THE WHOLE LENGTH,
C                                   HLX1 AND HLX2 SHOULD BE 0. AND 100.,
C                                   RESPECTIVELY).
C      16.       24.                HLY1 AND HLY2 (THE SAME AS IN HLX1 AND
C                                   BUT, IN TERMS OF THE WIDTH OF THE HOUS
      HHABA=YYW*FLOAT(KBNKT)
      YYY=HHABA/FLOAT(KSPAN)
      KDIV=KBNKT/KSPAN
      WRITE(6,6307) HLENGT,HHABA,YYY,KSPAN,YYW,KBNKT,HSIDE,KDIV
      WRITE(6,6308)HLX1,HLX2,HLY1,HLY2
      READ(5,5000)AHH,AHW,BHH,BHW,GHH,GHW
      READ(5,5000)AHHX,AHWX,BHHX,BHWX,GHHX,GHWX
      READ(5,5000)SAHH,SBHW,SGHW
```

```
      READ(5,5000) GL
      READ(5,6305)IRLAST
      WRITE(6,6502)AHH,AHW,BHH,BHW,GHH,GHW
      WRITE(6,6503)AHHX,AHWX,BHHX,BHWX,GHHX,GHWX
      WRITE(6,6506)SAHH,SBHW,SGHW
      WRITE(6,9908) GL
      WRITE(6,6306)IRLAST
      GL=GL*100.
                              WRITE(6,9904)
C
C         **********************************
C
C   AHH          DEPTH OF HORIZONTAL STRUTS FOR ROOF OR SIDE WALL
C   BHH          WIDTH OF HORIZONTAL STRUTS FOR ROOF OR SIDE WALL
C   BHW          WIDTH OF VERTICAL STRUTS FOR ROOF AND SIDE WALL
C   AHW          DEPTH OF VERTICAL STRUTS FOR ROOF OR SIDE WALL
C   GHH          LENGTH OF EACH GLASS-PANE FOR ROOF SIDE WALL
C   GHW          WIDTH  OF EACH GLASS-PANE FOR ROOF SIDE WALL
C   AHHX         DEPTH OF HORIZONTAL STRUTS FOR GABLE END
C   AHWX         DEPTH OF VERTICAL STRUTS FOR GABLE END
C   BHHX         WIDTH OF HORIZONTAL STRUTS FOR GABLE END
C   BHWX         WIDTH OF VERTICAL STRUTS FOR GABLE END
C   GHHX         LENGTH OF EACH GLASS-PANE FOR GABLE END
C   GHWX         WIDTH OF EACH GLASS-PANE FOR GABLE END
C   SAHH         DEPTH OF DEEPER ELEMENTS LOCATED ALONG THE LENGTH OF
C                ROOF AND SIDE WALL
C   SBHW         WIDTH OF DEEPER ELEMENTS LOCATED ALONG THE LENGTH OF
C                ROOF AND SIDE WALL
C   SGHW         DISTANCE BETWEEN THE DEEPER ELEMENTS
C   STRYP        DISTANCE OF MAIN VERTICAL STRUCTURAL ELMENTS MEASURED
C                FROM A SIDE WALL
C   STRZP        HEIGHT OF MAIN VERTICAL STRUCTURAL ELEMENTS
C                FOR A N-SPAN HOUSE, (N-1) CARDS ARE REQUIRED.
C
C   KEND         NUMBER OF WALLS EXCLUDING GABLE ENDS
C   YYW          WIDTH OF ONE SPAN
C   KBNKT        NUMBER OF SPANS
C   HHABA        WIDTH OF THE HOUSE
C   BK(K)        -SIN(AA(K))
C   DK(K)        -(BK(K)*Y(K)+CK(K)*Z(K))
C   CK(K)        COS(RK))
C
C         *****     NORMALIZATION OF HOUSE DIMENSIONS   **********
C
      AH=AHH/YYW
      AW=AHW/YYW
      BH=BHH/YYW
      BW=BHW/YYW
      GH=GHH/YYW
      GW=GHW/YYW
      SMODX=GW+BW
      SMODH=GH+BH
      AHX=AHHX/YYW
      AWX=AHWX/YYW
      BHX=BHHX/YYW
      BWX=BHWX/YYW
      GHX=GHHX/YYW
      GWX=GHWX/YYW
      SMODTY=GWX+BWX
      SMODTZ=GHX+BHX
      SAH=SAHH/YYW
```

```
      SBH=SBHW/YYW
      SGH=SGHW/YYW
      SMODS=SGH+SBH
      SMAH=SAH/2.
      XLAST=HLENGT/YYW
      XL1=HLX1/YYW
      XLAM=HLX2/YYW-XL1
      YL1=HLY1/YYW
      YL2=HLY2/YYW
      IY2=YL2+0.5
      YLAM=YL2-YL1
      IY1=YL1+1.0000001
      II=KSPAN-1
      STRZP=HSIDE
      DO 1234 NSS=1,II
      STRYP=YYY*FLOAT(NSS)
      STYP(NSS)=STRYP/YYW
      STZP(NSS)=STRZP/YYW
 1234 CONTINUE
      DO 1080 IQ=1,20
      DO 1080 II=1,20
      ITBL(IQ,II)=0
 1080 CONTINUE
C
C
C  SA          SIN(AA)
C  CA          COS(AA)
C  SH          SIN(HH)
C  CH          COS(HH)
C              AA AND HH ARE SOLAR AZIMUTH AND SOLAR ALTITUDE RELATIV
C              TO THE GLASS WALL
C  ANX         ANGLE OF INCIDENCE OF LIGHT TO GLASS
C  RI          EXTINCTION COEFFICIENT FOR GLASS
C  TRAX        TRANSMISSIVITY OF GLASS SHEET
C
C  DAPE        RELATIVE DAILY TOTALS OF LIGHT AT IYY
C  T           SPACE AVERAGE OF RELATIVE LIGHT INTENSITY AT TIME T
C
      KHH=20
      KAA=19
                     KK=KHH*KAA
      LLL=0
                     WRITE(6,5410)
      DO 300 K=20,KK
      DO 555 IQ=1,101
  555 FRQ(IQ)=0.
      DO 556 JD=1,50
      DO 556 IQ=1,101
  556 DSTR(JD,IQ)=0.
      KKD=(K-1)/KAA
      IF(KKD.NE.LLL) WRITE(6,9905)
      LLL=KKD
      SH=(1.+FLOAT(KKD))/FLOAT(KHH)
      IF(SH.GE.0.999) SH=0.999
      CH=SQRT(1.-SH**2)
      MMD=MOD(K,KAA)-1
      IF(MMD.LT.0) MMD=KAA-1
      FMMD=(90.*FLOAT(MMD)/FLOAT(KAA-1)+0.001)*0.0174533
      SA=SIN(FMMD)
      CA=COS(FMMD)
      XSL=CH*SA
```

```
      YSL=CH*CA
      ZSL=-SH
      YOX=YSL/XSL
      ZOX=ZSL/XSL
      YOZ=YSL/ZSL
      ANX=FATAN(XSL)
      CALL GLASS(ANX,RI,GL,TRAX)
      STMYL=YOX*AWX
      STMZL=ZOX*AHX
      SHADTY=ABS(STMYL)+BWX
      SHADTZ=ABS(STMZL)+BHX
      IF(STMYL)45,45,41
   45 STMY1=0.
      STMY2=STMYL
      GO TO 42
   41 STMY1=-STMYL
      STMY2=0.
   42 IF(STMZL)46,46,43
   46 STMZ1=0.
      STMZ2=STMZL
      GO TO 44
   43 STMZ1=-STMZL
      STMZ2=0.
   44 NNN=0
      DO 501 NII=IY1,IY2
  501 N1(NII)=10000
      DO 50 NOM=1,KEND
      BKN=BK(NOM)
      CKN=CK(NOM)
      SAY=AH*(YOZ*CKN-BKN)
      SSAY=SAH*SAY/AH
      YTL1=-YOZ*ZP(2*NOM-1)+YP(2*NOM-1)
      YTL2=-YOZ*ZP(2*NOM)+YP(2*NOM)
      IF(YTL1.LT.YTL2) GO TO 51
      IF(SAY.GT.0.) GO TO 52
      YLIT=YTL2+SAY
      YLAG=YTL1
      SYLIT=YTL2+SSAY
      SYLAG=YTL1
      GO TO 53
   52 YLIT=YTL2
      YLAG=YTL1+SAY
      SYLIT=YTL2
      SYLAG=YTL1+SSAY
      GO TO 53
   51 IF(SAY)59,59,54
   59 YLIT=YTL1+SAY
      YLAG=YTL2
      SYLIT=YTL1+SSAY
      SYLAG=YTL2
      GO TO 53
   54 YLIT=YTL1
      YLAG=YTL2+SAY
      SYLIT=YTL1
      SYLAG=YTL2+SSAY
   53 IF(SYLIT-YL2)57,57,50
   57 IF(SYLAG-YL1)50,58,58
   58 NNN=NNN+1
      IYI=SYLIT+1.
      IYE=SYLAG+1.
      IF(IYI.LT.IY1) IYI=IY1
```

```
      IF(IYE.GT.IY2) IYE=IY2
      DO 502 NIY=IYI,IYE
      N2(NIY)=NNN
      IF(N2(NIY)-N1(NIY))503,502,502
  503 N1(NIY)=NNN
  502 CONTINUE
      COSANG=YSL*BKN+ZSL*CKN
      ANG=FATAN(COSANG)
      CALL GLASS(ANG,RI,GL,TR)
      DOMY1(NNN)=YLIT
      TRAM(NNN)=TR
      DOMY2(NNN)=YLAG
      SDOMY1(NNN)=SYLIT
      SDOMY2(NNN)=SYLAG
      BKK(NNN)=BKN
      DKK(NNN)=DK(NOM)
      SBY=BH*(YOZ*BKN+CKN)
      SMODY(NNN)=ABS(SMODH)*SBY/BH
      SHADY(NNN)=ABS(SAY)+ABS(SBY)
      BCKK(NNN)=BKN*YOX+CKN*ZOX
      SAX=AW/BCKK(NNN)
      SSAX=SAH/BCKK(NNN)
      SHADX(NNN)=ABS(SAX)+BW
      SHADS(NNN)=ABS(SSAX)+SBH
      IF(SAX)55,55,56
   55 DOMX1(NNN)=SAX
      SDOMX1(NNN)=SSAX
      SDOMX2(NNN)=XLAST
      GO TO 50
   56 DOMX1(NNN)=0.
      SDOMX1(NNN)=0.
      SDOMX1(NNN)=0.
      SDOMX2(NNN)=XLAST+SSAX
   50 CONTINUE
      SHAD=-SMAH/YOX
      SSHAD=ABS(SHAD)
      SSHADS=SSHAD+SBH
      XRLAST=XLAST+SSHAD
      NOW=0
      DO 10 NST=1,NSS
      IF(YOZ.LT.0.) GO TO 11
      SY1=-YOZ*STZP(NST)+STYP(NST)-SMAH
      SY2=STYP(NST)+SMAH
      GO TO 12
   11 SY1=STYP(NST)-SMAH
      SY2=-YOZ*STZP(NST)+STYP(NST)+SMAH
   12 IF(SY1-YL2)13,13,10
   13 IF(SY2-YL1)10,14,14
   14 NOW=NOW+1
      SSYP(NOW)=STYP(NST)
      SSDOM1(NOW)=SY1
      SSDOM2(NOW)=SY2
   10 CONTINUE
      DO 80 IYY=IY1,IY2
      SPERTR(IYY)=0.
      YPERTR(IYY)=0.
      STPERT(IYY)=0.
      STPY(IYY)=0.
   80 PERY(IYY)=0.
      IF(XSL)100,100,200
  200 DO 60 IRNOM=1,IRLAST
```

```
      PERTR=1.
      TRW=1.
      YI=YLAM*RAND20(IRANDY)+YL1
C
C        RAND20 IS THE FUNCTION SUBPROGRAM WHICH PRODUCES
C        UNIFORM RANDUM NUMBER IN THE RANGE ZERO TO ONE.
C        IF THE COMPUTER SYSTEM  YOU ARE USING DOES NOT HAVE
C        THE FUNCTION SUBPROGRAM, YOU MUST PREPARE IT YOURSELF.
C
      IY=YI+1.0
      IDY=YL1
      IDY=IY-IDY
      IF(IDY.LE.0.OR.IDY.GE.51) WRITE(6,5300) IDY
      IF(IDY.LE.0) IDY=1
      IF(IDY.GE.51) IDY=50
      XI=XLAM*RAND20(IRANDY)+XL1
      NCHEK=0
      NI1=N1(IY)
      NI2=N2(IY)
      DO 70 NNOM=NI1,NI2
      IF(YI-SDOMY1(NNOM))70,71,71
   71 IF(YI-SDOMY2(NNOM))75,75,70
   75 XR=XI-(BKK(NNOM)*YI+DKK(NNOM))/BCKK(NNOM)
      SPOINT=XR-SDOMX1(NNOM)
      IF(SPOINT)72,76,76
   76 IF(AMOD(SPOINT,SMODS)-SHADS(NNOM))86,86,89
   89 YPOINT=YI-DOMY1(NNOM)
      IF(YPOINT)70,78,78
   78 IF(YI-DOMY2(NNOM))79,79,70
   79 IF(AMOD(YPOINT,SMODY(NNOM))-SHADY(NNOM))86,86,88
   88 XPOINT=XR-DOMX1(NNOM)
      IF(AMOD(XPOINT,SMODX)-SHADX(NNOM))86,86,85
   85 NCHEK=NCHEK+1
      PERTR=PERTR*TRAM(NNOM)
      GO TO 70
   72 IF(TRW-1.)70,21,21
   21 ZR=-ZOX*XI
      ZPOINT=ZR-STMZ1
      IF(AMOD(ZPOINT,SMODTZ)-SHADTZ)82,82,83
   83 YR=YI-YOX*XI
      YPOINT=YR-STMY1
      IF(AMOD(YPOINT,SMODTY)-SHADTY)82,82,84
   84 TRW=TRAX
      GO TO 70
   82 TRW=0.
   70 CONTINUE
      IF(MOD(NCHEK,2).EQ.1) TRW=1.
      IF(TRW)86,86,23
   23 DO 20 NOS=1,NOW
      IF(YI-SSDOM1(NOS))20,24,24
   24 IF(YI-SSDOM2(NOS))25,25,20
   25 XR=(SSYP(NOS)-YI)/YOX+XI
      SPOINT=XR-SSHAD
      IF(SPOINT)20,27,27
   27 IF(AMOD(SPOINT,SMODS)-SSHADS)86,86,20
   20 CONTINUE
      GO TO 87
   86 PERTR=0.
       STPERT(IY)=STPERT(IY)+1.
   87 PERTR=PERTR*TRW
      IF(PERTR.LT.0.0.OR.PERTR.GT.1.) WRITE(6,999) PERTR
```

```
      IQ=PERTR*100.+1.
      FRQ(IQ)=FRQ(IQ)+1,
      YPERTR(IY)=YPERTR(IY)+PERTR
      SPERTR(IY)=SPERTR(IY)+1.
      DSTR(IDY,IQ)=DSTR(IDY,IQ)+1.
   60 CONTINUE
      GO TO 201
  100 DO 160 IRNOM=1,IRLAST
      PERTR=1.
      TRW=1.
      YI=YLAM*RAND20(IRANDY)+YL1
      IY=YI+1.0
      IDY=YL1
      IDY=IY-IDY
      IF(IDY.LE.0.OR.IDY.GE.51) WRITE(6,5300) IDY
      IF(IDY.LE,0) IDY=1
      IF(IDY.GE,51) IDY=50
      XI=XLAM*RAND20(IRANDY)+XL1
      NCHEK=0
      NI1=N1(IY)
      NI2=N2(IY)
      DO 170 NNOM=NI1,NI2
      IF(YI-SDOMY1(NNOM))170,171,171
  171 IF(YI-SDOMY2(NNOM))175,175,170
  175 XR=XI-(BKK(NNOM)*YI+DKK(NNOM))/BCKK(NNOM)
      IF(XR-SDOMX2(NNOM))177,177,173
  177 SPOINT=XR-SDOMX1(NNOM)
      IF(AMOD(SPOINT,SMODS)-SHADS(NNOM))186,186,189
  189 YPOINT=YI-DOMY1(NNOM)
      IF(YPOINT)170,178,178
  178 IF(YI-DOMY2(NNOM))179,179,170
  179 IF(AMOD(YPOINT,SMODY(NNOM))-SHADY(NNOM))186,186,188
  188 XPOINT=XR-DOMX1(NNOM)
      IF(AMOD(XPOINT,SMODX)-SHADX(NNOM))186,186,185
  185 NCHEK=NCHEK+1
      PERTR=PERTR*TRAM(NNOM)
      GO TO 170
  173 IF(TRW-1.)170,122,122
  122 ZR=ZOX*(XLAST-XI)
      ZPOINT=ZR-STMZ2
      IF(AMOD(ZPOINT,SMODTZ)-SHADTZ)182,182,183
  183 YR=YI+YOX*(XLAST-XI)
      YPOINT=YR-STMY2
      IF(AMOD(YPOINT,SMODTY)-SHADTY)182,182,184
  184 TRW=TRAX
      GO TO 170
  182 TRW=0.
  170 CONTINUE
      IF(MOD(NCHEK,2).EQ.1) TRW=1.
      IF(TRW)186,186,123
  123 DO 120 NOS=1,NOW
      IF(YI-SSDOM1(NOS))120,124,124
  124 IF(YI-SSDOM2(NOS))125,125,120
  125 XR=(SSYP(NOS)-YI)/YOX+XI
      IF(XR-XRLAST)126,126,120
  126 SPOINT=XR-SSHAD
      IF(AMOD(SPOINT,SMODS)-SSHADS)186,186,120
  120 CONTINUE
      GO TO 187
  186 PERTR=0.
       STPERT(IY)=STPERT(IY)+1.
```

```
  187 PERTR=PERTR*TRW
      YPERTR(IY)=YPERTR(IY)+PERTR
      IF(PERTR.LT.0.0.OR.PERTR.GT.1.) WRITE(6,999) PERTR
      IQ=PERTR*100.+1.
      FRQ(IQ)=FRQ(IQ)+1.
      SPERTR(IY)=SPERTR(IY)+1.
      DSTR(IDY,IQ)=DSTR(IDY,IQ)+1.
  160 CONTINUE
  201 TOTYP=0.
      DO 90 IYY=IY1,IY2
      TOTYP=TOTYP+YPERTR(IYY)
      PERY(IYY)=YPERTR(IYY)/SPERTR(IYY)
      STPY(IYY)=STPERT(IYY)/SPERTR(IYY)
   90 CONTINUE
      DO 101 IQ=1,101
  101 FRQ(IQ)=FRQ(IQ)/FLOAT(IRLAST)
      LMD=MMD+1
      ITBL(1,LMD)=FRQ(1)*100.+0.5
      LL=2
      DO 1020 IQ=2,101
      IF(FRQ(IQ).GE.0.004) ITBL(LL,LMD)=FRQ(IQ)*100.+0.5
      IF(FRQ(IQ).GE.0.004) ITBL(LL+10,LMD)=IQ-1
      IF(FRQ(IQ).GE.0.004) LL=LL+1
      IF(LL.GE.11) WRITE(6,6600) LL
 1020 CONTINUE
      IF(LMD.NE.KAA) GO TO 1060
      DO 1030 IQ=1,20
      IQQ=IQ
      IF(IQ.GT.10) IQQ=IQQ-10
      DO 1040 II=1,KAA
      IF(ITBL(IQ,II).GT.0) GO TO 1050
 1040 CONTINUE
      GO TO 1030
 1050 IF(IQ.LT.10) WRITE(6,6620) SH,IQQ,(ITBL(IQ,II),II=1,KAA)
      IF(IQ.GE.10) WRITE(6,6610) SH,IQQ,(ITBL(IQ,II),II=1,KAA)
 1030 CONTINUE
      DO 1181 IQ=1,20
      DO 1181 II=1,KAA
 1181 ITBL(IQ,II)=0
 1060 CONTINUE
      JIY=IY2-IY1+1
      IF(JIY.GE.50) WRITE(6,5500) JIY
  300 CONTINUE
  999 FORMAT(1H ,6HPEPTR=,F10.4)
 5000 FORMAT(8F10.0)
 5300 FORMAT(1H ,4HIDY=,I10,5X,15H*****ERROR*****)
 5410 FORMAT(1H ,34X, 52HAZIMUTH OF THE SUN RELATIVE TO THE HOUSE ORIENT
     *ATION/1H ,27X,  91H0     5    10    15    20    25    30    35    40    45
     * 50    55    60    65    70    75    80    85    90/)
 5500 FORMAT(1H ,4HJIY,I9,5X,15H*****ERROR*****)
 6305 FORMAT(I10,F10.0,I10)
 6306 FORMAT(1H0,48HNUMBER OF RANDOM NUMBERS USED AT EACH TIME STEP ,
     * I10)
 6307 FORMAT(1H ,/1H ,15HLENGTH OF HOUSE,F10.3,5X,14HWIDTH OF HOUSE,
     *F10.3/1H ,18HWIDTH OF EACH SPAN,F10.3,5X,15HNUMBER OF SPANS,I4/1H
     * 4HYYW=,F8.2,3X,6HKBNKT=,I5,3X,6HHSIDE=,F8.2,3X,5HKDIV=,I5)
 6308 FORMAT(1H0,5HHLX1=,F8.2,3X,5HHLX2=,F8.2,3X,5HHLY1=,F8.2,3X,
     * 5HHLY2=,F8.2,3X,39HSEE COMMENTS IN THE PROGRAM FOR DETAILS)
 6502 FORMAT(1H0,4HAHH=,F7.2,3X,4HAHW=,F7.2,3X,4HBHH=,F7.2,3X,4HBHW=,
     * F7.2,3X,4HGHH=,F7.2,3X,4HGHW=,F7.2)
 6503 FORMAT(1H0,5HAHHX=,F6.2,3X,5HAHWX=,F6.2,3X,5HBHHX=,F6.2,3X,5HBHWX=
```

```
     ¥,F6.2,3X,5HGHHX=,F6.2,3X,5HGHWX=,F6.2/)
 6506 FORMAT(1H ,5HSAHH=,F6.2,3X,5HSBHW=,F6.2,3X,5HSGHW=,F6.2)
 6600 FORMAT(1H ,3HLL=,I5,15H*****ERROR*****)
 6610 FORMAT(1H ,7HSIN(H)=,F7.3,3X,2HTR,I1,3X,19I5)
 6620 FORMAT(1H ,7HSIN(H)=,F7.3,3X,2HFR,I1,3X,19I5)
 9904 FORMAT(1H1)
 9905 FORMAT(1H )
 9908 FORMAT(1H0,33H    THICKNESS OF THE GLASS-PANE =,F8.4)
    1 STOP
      END
```

```
C
      SUBROUTINE GLASS(R,RC,GL,U)
      REFN=1.526
      GLP1=SIN(R)**2
      GLP=GL/SQRT(1.0-GLP1/REFN**2)
      A=EXP(-RC*GLP)
      IF(R.EQ.0.0) GO TO 1
      AB=SIN(R)/REFN
      AANG=ATAN(AB/SQRT(1.0-AB**2))
      DDAN=R-AANG
      ADAN=R+AANG
      Q=((SIN(DDAN)/SIN(ADAN))**2+(TAN(DDAN)/TAN(ADAN))**2)/2.0
      GO TO 2
    1 Q=(1.-REFN)**2/(1.+REFN)**2
    2 TU=(1.-Q)**2*A
      TL=(1.0-Q**2*A**2)
      U=TU/TL
      RETURN
      END
```

```
C
      FUNCTION FATAN(X)
      SINA=SQRT(1.-X**2)
      FATAN=ATAN(SINA/X)
      RETURN
      END
```

```
C
      FUNCTION TAN(X)
      TAN=SIN(X)/COS(X)
      RETURN
      END

      SUBROUTINE HOUSE(K,YYW,YP,ZP,B,C,D,KBNKT,HSIDE,KSPAN)
      DIMENSION B(50),C(50),D(50),Y(99),Z(99),YP(99),ZP(99)
C
C       ****************************************
C
C   R            WIDTH OF EACH WALL
C   AA           SLOPE OF EACH WALL (DEGREES) ( ASSUME E-W MULTISPAN)
C                THE ANGLE IS MEASURED COUNTERCLOCKWISE.
C                FOR SOUTH SIDE WALL, AA=90.
C                FOR NORTH SIDE WALL, AA=-90.
C                FOR SOUTH FACING ROOF, AA=20, FOR EXAMPLE.
```

```
C              FOR NORTH FACING ROOF, AA=-20., FOR EXAMPLE.
C              FOR A N-SPAN HOUSE, 2*N+2 INPUT CARDS ARE NEEDED.
C              THE VALUES OF R AND AA FOR EACH ROOF OR SIDE WALL
C              SHOULD BE PUNCHED ON A SEPARATE CARD.
C         DETERMINATION OF COEFFICIENTS B(K),C(K), AND D(K) FOR EACH WAL
C
C         PLANE EQUATION     A*X+B(K)*Y+C(K)*Z+D(K)=0.
C
C         WHERE, A=0. FOR ALL SIDE WALLS AND ROOFS.
C  K      NUMBER OF WALLS WITH A=0.
C  KBNKT         NUMBER OF DIVISIONS
C  KSPAN         NUMBER OF SPANS
C  YYY           WIDTH OF ONE SPAN
C  YYW           WIDTH OF ONE DIVISION
C
C       **************************************
C
C
      Y1=0.
      Z1=0.
      READ(5,5102) KSPAN,KDIV,HSIDE
      KBNKT=KDIV*KSPAN
      KK=2*KSPAN+2
      READ(5,5101) RR,AAA
      WRITE(6,5104) RR,AAA
      DO 30 K=1,KK
      AA=AAA
      R=RR
      IF(K.EQ.1.OR.K.EQ.KK) R=HSIDE
      IF(K.EQ.1) AA=90.
      IF(K.EQ.KK) AA=-90.
      IF(K.NE.1.AND.MOD(K,2).EQ.1) AA=-AAA
      AN=AA*0.0174533
      C(K)=COS(AN)
      M=2*K-1
      B(K)=-SIN(AN)
      N=2*K
      Y(M)=Y1
      Y(N)=Y(M)+C(K)*R
      Z(M)=Z1
      Z(N)=Z(M)-B(K)*R
      D(K)=-B(K)*Y(N)-C(K)*Z(N)
      Y1=Y(N)
      Z1=Z(N)
   30 CONTINUE
      YYW=Y1/FLOAT(KBNKT)
      K=KK
      DO 10 I=1,KK
      M=2*I-1
      N=2*I
      YP(M)=Y(M)/YYW
      YP(N)=Y(N)/YYW
      ZP(M)=Z(M)/YYW
      ZP(N)=Z(N)/YYW
      D(I)=D(I)/YYW
 5101 FORMAT(2F10.0)
   10 CONTINUE
 5102 FORMAT(2I5,F10.0)
 5104 FORMAT(1H1,14HWIDTH OF ROOF=,F9.2,3X,11HROOF SLOPE=,F9.2)
      RETURN
      END
```

Appendix A2 - A program for calculating diurnal courses of direct and diffuse light in a greenhouse and their daily integrals

```
      DIMENSION LA(13),TSL(13),X(2527)
      DATA LA/0,31,59,90,120,151,181,212,243,273,304,334,365/
      II=2527
      II=1805
      READ(5,5000) RFSLP,TRDIF
      READ(5,1100)(X(I),I=1,II)
      READ(5,5000)G
      RH=1./G
      WRITE(6,1250) RFSLP,TRDIF
      WRITE(6,1300) (X(I),I=1,II)
      WRITE(6,9902)G
  555 READ(5,5005) (TSL(I),I=1,12)
      WRITE(6,1000)
      WRITE(6,5007)
      WRITE(6,5006) (I,TSL(I),I=1,12)
      TSL1=(TSL(1)+TSL(12))/2.
      TSL(13)=TSL1
      DO 5100 I=2,12
 5100 TSL(I)=(TSL(I-1)+TSL(I))/2.
      TSL(1)=TSL1
    5 READ(5,5200)PHA1,ORIT,M1,M2,M3,M4,MINT
      FMI=MINT
      IF(PHA1.LE.0.) GO TO 555
      IF(PHA1.GE.100.) STOP
      WRITE(6,1000)
      YTT=0.
      YTD=0.
      ATI=0.
      ATT=0.
      TATRT=0.
      LD12=LA(M1)+M2
      LD34=LA(M3)+M4
      IF(LD12.GT.LD34) LD34=LD34+365
   98 CONTINUE
      IQI=0
      IF(YTT.LE.0.) IQI=1
      IF((LD12+MINT).GE.LD34) IQI=1
      IF(LD12.GT.LD34) GO TO 5
      LD=LD12
      IF(LD.GT.365) LD=LD-365
      WRITE(6,6200)PHA1
      PHAI=PHA1*0.0174533
      CALL FORDAY(LD,DELTA,EOT,W)
      CALL FORTIM(PHAI,DELTA,KK,RH,TAU)
      CALL RADIUS(W,RS)
      TTAU=12.-TAU
      MM=LD
      WRITE(6,6302)ORIT
      WRITE(6,6202) TTAU
      MXM=12.*FLOAT(MM)/366.+1.
```

```
      FXM=MM-LA(MXM)
      FYM=LA(MXM+1)-LA(MXM)
      ADT=TSL(MXM)+(TSL(MXM+1)-TSL(MXM))*FXM/FYM
      ATI=RECT(ATI,ADT,FMI,IQI)
      DO 94 MO=1,12
      MD=LD-LA(MO+1)
      IF(MD) 96,96,94
   94 CONTINUE
   96 MD=LD-LA(MO)
      WRITE(6,6201)MO,MD,MM
      LD12=LD12+MINT
      LD=LD+MINT
      IF(LD,GT,365) LD=LD-365
      DRO=0,
      DAVTYP=0,
      TTOTAL=0,
      DFO=0,
      TDIF=0,
      RH=1./G
C
C  PHAI        LATITUDE OF THE PLACE ( DEGREES)
C  MO          MONTH
C  MD          DAY
C  ORIT        HOUSE ORIENTATION
C  DELTA       DECLINATION OF THE SUN
C  EOT         EQUATION OF TIME DIFFERENCE
C  TAU         SUNRISE TIME (HOUR)
C  KK          NUMBER OF TIME STEPS FOR A WHOLE DAY
C  RH          INVERSE OF TIME INTERVAL
C              KK = TAU * 2 * RH
C  TA          TIME ANGLE
C  DAVTYP      SPACE AVERAGE OF RELATIVE DAILY TOTALS OF LIGHT INSIDE
C  DRO                  DAILY TOTALS OF LIGHT OUTSIDE
C  DRP                  LIGHT INTENSITY OUTSIDE AT TIME T
C
      DO 300 K=1,KK
      JQJ=0
      IF(K.EQ.1.OR.K.EQ,KK) JQJ=1
      PK=K-KK/2-1
      TA=FK*G
      TIME=TA+12,
      TA=TA*15.*0.0174533
      IF(TA,EQ,0.) TA=0,0000001
      CALL ALTITH(PHAI,DELTA,TA,SA,CA,SH,CH,ORIT,HH,AA)
      AB=AA
      IF(AA.LT,0.) AA=-AA
      IF(AA,GT,180) AA=360.-AA
      IF(AA,GT.90.) AA=180.-AA
      FRDIF=AFGENI(HH)
      TRATM=EXP(-0.1/AMAX1(0,05,SH))
      DIFOV=116,*SH*TRATM
      DSH=580,*SH*FRDIF*TRATM
      DRP=580.*SH*(1.-FRDIF)*TRATM
      WRITE(6,5103) K,TIME,DRP,DSH,DIFOV,HH,AA,AB
      IF(SH,LT.0.075) GO TO 1200
      I=20.*(SH-0,025)+0,0001
      J=0,2*(AA+7,5)
      IF(II,EQ,2527) GO TO 800
          T=AV(J,I,X)
      GO TO 1200
  800     T=AT(J,I,X)
```

```
 1200 CONTINUE
      TRD=TRDIF*DSH
      CAD=T*DRP
      CAT=CAD+TRD
      TRT=CAT/(DSH+DRP)
      WRITE(6,6303)     T,CAD,CAT,TRT
      GG=3600.*G
      DFO=RECT(DFO,DSH,GG,JQJ)
      DRO=RECT(DRO,DRP,GG,JQJ)
      TDIF=RECT(TDIF,DIFOV,GG,JQJ)
      DAVTYP=RECT(DAVTYP,CAD,GG,JQJ)
      TTOTAL=RECT(TTOTAL,CAT,GG,JQJ)
  300 CONTINUE
      WRITE(6,6500)
      DDD=DRO+DFO
      FOV=(DDD-ADT)/(DDD-TDIF)
      BTRT=DAVTYP*(1.-FOV)
      ABC=TDIF*FOV+DFO*(1.-FOV)
      RDL=ABC/ADT
      YTD=RECT(YTD,DRO,FMI,IQI)
      YTT=RECT(YTT,DDD,FMI,IQI)
      ATT=RECT(ATT,TDIF,FMI,IQI)
      DAVTYP=DAVTYP/DRO
      ATRT=TTOTAL*(1.-FOV)+FOV*TRDIF*TDIF
      TATRT=RECT(TATRT,ATRT,FMI,IQI)
      TBTRT=RECT(TBTRT,BTRT,FMI,IQI)
      DAB=ATRT/ADT
       TTOTAL=TTOTAL/DDD
C
C  DAVTYP      RELATIVE DAILY INTEGRAL OF DIRECT LIGHT (SPACE AVERAGE
C              OVER A WHOLE FLOOR
C
       WRITE(6,9906) DAVTYP,TTOTAL,ATRT,FOV,RDL
      WRITE(6,9909) DRO,DFO,DDD,TDIF,ADT
      WRITE(6,9910) YTD,YTT,ATT,ATI,TATRT
      WRITE(6,9911) DAB
      GO TO 98
 1000 FORMAT(1H1)
 1100 FORMAT(6X,19F3.0)
 1250 FORMAT(12H0ROOF SLOPE=,F9.2,5X,6HTRDIF=,F9.2//)
 1300 FORMAT(1H ,19F6.2)
 5000 FORMAT(8F10.0)
 5005 FORMAT(8F10.2)
 5006 FORMAT(1H ,I10,E15.6)
 5007 FORMAT(1H ,5X,5HMONTH,3X,11HTOTAL LIGHT)
 5103 FORMAT(1H ,2HK=,I3,2X,5HTIME=,F6.2,2X,4HDRP=,F7.0,2X,4HDSH=,
     *F7.0,3X,6HDIFOV=,F8.0,3X,3HHH=,F5.1,3X,3HAA=,F6.1,3X,3HAB=,F6.1)
 5200 FORMAT(2F10.0,5I5)
 6200 FORMAT(1H0,46HLATITUDE OF THE PLACE WHERE THE HOUSE IS BUILT,F15.
     ¥)
 6201 FORMAT(1H ,5HDATE ,5X,6HMONTH=,I4,3X,4HDAY=,I4,3X,3HLD=,I4)
 6302 FORMAT(1H ,17HHOUSE ORIENTATION,F10.1,3X,9H(DEGREES))
 6202 FORMAT(1H ,46HTHE TIME THE SUN RISES ABOVE THE HORIZON (HR.),
     ¥F10.5)
 6303 FORMAT(1H ,14HSPACE AVERAGE=,F8.3,3X,4HCAD=,E13.5,3X,4HCAT=,E13.5
     ¥3X,4HTRT=,E12.4)
 6500 FORMAT(1H ,14HDAILY AVERAGES)
 9902 FORMAT(1H0,20HTIME INTERVAL (HOUR),F10.2/)
 9906 FORMAT(1H ,7HDAVTYP=,E12.4,3X,7HTTOTAL=,E12.4,3X,5HATRT=,E12.4,3X
     ¥4HFOV=,E12.4,3X,4HRDL=,E12.4)
 9909 FORMAT(1H ,4HDRO=,E12.4,3X,4HDFO=,E12.4,3X,4HDDD=,E12.4,3X,
```

```
     *5HTDIF=,E12.4,3X,4HADT=,E12.4)
 9910 FORMAT(1H ,4HYTD=,E12.4,3X,4HYTT=,E12.4,3X,4HATT=,E12.4,3X,4HATI=,
     *E12.4,3X,6HTATRT=,E12.4)
 9911 FORMAT(1H ,4HDAB=,E12.4/)
      END
```

```
C
      SUBROUTINE FORDAY(LD,DELTA,EOT,W)
      W=2.*3.141592*FLOAT(LD)/366.
      DELTA=0.3622133-23.24763*COS(W+0.153231)-0.3368908*COS(2.*W+
     10.2070988)-0.1852646*COS(3.*W+0.6201293)
      DELTA=DELTA*0.0174533
      EOT=-0.0002786409+0.1227715*COS(W+1.498311)-0.1654575*COS(2.*W-
     11.261546)-0.00535383*COS(3.*W-1.1571)
      RETURN
      END
```

```
C
      SUBROUTINE FORTIM(PHAI,DELTA,KK,RH,TAU)
      TAU=-TAN(PHAI)*TAN(DELTA)
      TUA=SQRT(1.-TAU**2)
      TAU=ATAN2(TUA,TAU)
      TAU=TAU*180./3.141592/15.
      KK=TAU*2.*RH
      IF(MOD(KK,2).NE.1) KK=KK-1
      RETURN
      END
```

```
C
      SUBROUTINE RADIUS(W,RS)
      DIMENSION A(11)
      DATA A/-105.06,2.958,-0.194,0.983,-0.333,-1.131,0.972,1.207,-0.08,
     *-0.531,-0.613/
      RS=6.2776/2.
      DO 10 I=1,11
      RS=RS/3.141592
   10 RS=RS+0.0001*A(I)*COS(FLOAT(I)*W)
      RETURN
      END
```

```
C
      SUBROUTINE ALTITH(PHAI,DELTA,T,SINAA,COSAA,SINHH,COSHH,D,HHH,AAA)
      SINHH=SIN(PHAI)*SIN(DELTA)+COS(PHAI)*COS(DELTA)*COS(T)
      HH=ATAN(SINHH/SQRT(1.-SINHH**2))
      COSHH=COS(HH)
      SINAA=COS(DELTA)*SIN(T)/COSHH
      COSAA=(SINHH*SIN(PHAI)-SIN(DELTA))/(COSHH*COS(PHAI))
      AA=ATAN2(SINAA,COSAA)+D*0.0174533
      SINAA=SIN(AA)
      COSAA=COS(AA)
      HHH=HH*180./3.141592
      AAA=AA*180./3.141592
      RETURN
      END
```

```
C
      FUNCTION AFGENI(HH)
      IF(HH.LE.5.) AFGENI=1.0
      IF(HH.GT.5..AND.HH.LE.15.) AFGENI=1.-0.06*(HH-5.)
      IF(HH.GT.15..AND.HH.LE.25.) AFGENI=0.4-0.01*(HH-15.)
      IF(HH.GT.25.) AFGENI=0.3-0.05*(HH-25.)/65.
      RETURN
      END
```

```
C
      FUNCTION TAN(X)
      TAN=SIN(X)/COS(X)
      RETURN
      END
```

```
C
      FUNCTION AV(J,I,X)
      DIMENSION X(2527)
      K=J+95*(I-1)
       AV=X(K+19)*X(K+57)+X(K+38)*X(K+76)
      SUMF=X(K)+X(K+19)+X(K+38)
      IF(SUMF.LT..985.OR.SUMF.GT.1.15) WRITE(6,880) J,I,SUMF
  880 FORMAT(30H SUM OF FRACTIONS NE 1 IN J,I~,2I4,F10.2)
      RETURN
      END
```

```
C
      FUNCTION AT(J,I,X)
      DIMENSION X(2527)
      K=J+133*(I-1)
       AT=X(K+19)*X(K+76)+X(K+38)*X(K+95)+X(K+57)*X(K+114)
      SUMF=X(K)+X(K+19)+X(K+38)+X(K+57)
      IF(SUMF.LT..985.OR.SUMF.GT.1.15) WRITE(6,880) J,I,SUMF
  880 FORMAT(30H SUM OF FRACTIONS NE 1 IN J,I~,2I4,F10.2)
      RETURN
      END
```

```
C
      FUNCTION RECT(Y,X,H,K)
      Z=X
      IF(K.EQ.1) Z=0.5*X
      RECT=Y+Z*H
      RETURN
      END
```

Appendix A3 - A program for calculating the transmissivity of a greenhouse for the diffuse light

```
      DIMENSION X(2527)
      II=1805
      II=2527
    1 READ(5,700)RFSLP
      IF(RFSLP.LE.0,) STOP
      READ(5,800) (X(K),K=1,II)
      WRITE(6,850) (X(K),K=1,II)
      TRDIF=0,
      DO 2 M=2,20
      I=M-1
      SUM=0,5*AV(1,I,X,II)
      DO 4 L=2,18
      J=L
    4 SUM=SUM+AV(J,I,X,II)
      SUM=SUM+0,5*AV(19,I,X,II)
      SUM=SUM*0,0025*FLOAT(2*M)/18.
      IF(M.EQ.20) SUM=0,5*SUM
      TRDIF=TRDIF+SUM
      WRITE(6,950) M,SUM,TRDIF
    2 CONTINUE
      WRITE(6,1000) RFSLP,TRDIF
      GO TO 1
  700 FORMAT(F10.0)
  800 FORMAT(6X,19F3,0)
  850 FORMAT(1H ,19F6,2)
  950 FORMAT(1H ,2HM=,I3,3X,4HSUM=,F8,3,5X,6HTRDIF=,F8,3)
 1000 FORMAT(1H0,11HROOF SLOPE=,F6.1,5X,6HTRDIF=,F9,3/1H1)
      END
```

```
C
      FUNCTION AV(J,I,X,II)
      DIMENSION X(2527)
      IF(II,EQ,2527) GO TO 10
      K=J+95*(I-1)
       AV=X(K+19)*X(K+57)+X(K+38)*X(K+76)
      SUMF=X(K)+X(K+19)+X(K+38)
      IF(SUMF.LT.,985,OR.SUMF.GT.1.15) WRITE(6,880) J,I,SUMF
      RETURN
   10 K=J+133*(I-1)
       AV=X(K+19)*X(K+76)+X(K+38)*X(K+95)+X(K+57)*X(K+114)
      SUMF=X(K)+X(K+19)+X(K+38)+X(K+57)
      IF(SUMF.LT.,985,OR.SUMF.GT.1.15) WRITE(6,880) J,I,SUMF
  880 FORMAT(30H SUM OF FRACTIONS NE 1 IN J,I:,2I4,F10,2)
      RETURN
      END
```

Appendix A4 - A program for the calculation of net assimilation of carbon dioxide in a greenhouse

```
TITLE PHOTOSYNTHESIS IN GLASSHOUSE
/      DIMENSION X(1805)
FIXED I,J,K,NUMLL
METHOD RECT
TIMER FINTIM=86400.,PRDEL=21600.,DELT=300.
PARAM START=0.
PRINT LTC,LTO,ASC,ASO,AS4,CRC,CRO,LHC,LHO,SHC,SHO,DCRC,DCRO, ...
      DASC,DASO,DAS4,FR1,FR2,FR3,TA ,TR2,TR3,SNHSS,RAZ,HOUR
MACRO EHL,SHL,TL,NPHOT=TRPH(VIS,NIR,TA,RA,SLOPE,DRYP)
PROCEDURAL
      ABSRAD=VIS+NIR
      AMAX=AMAX1(0.001,AFGEN(AMTB,TA))
      DPLO=0.1*AMAX
      NPHOT=(AMAX+DPLO)*(1.-EXP(-VIS*EFF/AMAX))-DPLO
      CO2OPP=ECO2C-RA*1.3*NPHOT/68.4
      SRESL=(CO2OPP-RCO2I)*68.4/(AMAX1(.001,NPHOT)*1.66)
      IF(SRESL.GT.SRW) GO TO 700
      SRESL=SRW
      NPHOT=AMIN1(NPHOT,68.4*(ECO2C-RCO2I)/(1.66*SRW+1.3*RA))
  700 CONTINUE
      SRES=RESCW*SRESL/(SRESL+RESCW)
      ENP=0.3*NPHOT
      EHL=(SLOPE*(ABSRAD-ENP)+DRYP)/((RA*0.93+SRES)/RA*PSCH+SLOPE)
      SHL=ABSRAD-EHL-ENP
      TL=TA+SHL*RA/RHOCP
ENDMAC
PARAM SRW=130.
PARAM ECO2C=330.
PARAM LAI=0.5
PARAM DLONG=0.
FUNCTION AMTB=0.,0.001,10.,10.,20.,40.,30.,40.
PARAM RCO2I=210.
PARAM EFF=0.48,RESCW=2000.
PARAM SCV=0.2,SCN=0.85
PARAM WIDTH =0.05
INITIAL
NOSORT
      NUMLL=LAI+1.
      DL=LAI/NUMLL
      ZISSN=0.1
      SONI=SQRT(1.-SCN)
      SQSC=SQRT(1.-SCV)
      REFNI = (1.-SQNI)/(1.+SQNI)
      REFLOV=(1.-SQSC)/(1.+SQSC)
      RDRV=REFLOV
      RDFV=REFLOV
      RDRN=REFNI
      RDFN=REFNI
PARAM PI=3.141592,SIGMA=5.668E-8,RAD=1.745329E-2
      KBL=0.7
```

```
      KDFV=0.95*KBL*SQSC+0.035
      KDFN=0.95*KBL*SQNI+0.035
      XNDF=EXP(-KDFN *DL)
      XVDF=EXP(-KDFV*DL)
      XL=EXP(-KBL*DL)
PARAM LAT=52.
      SNLT=SIN(2.*PI*LAT/360.)
      CSLT=COS(2.*PI*LAT/360.)
I-CON ISW=0.
      IF(ISW.GT.0.5) GO TO 60
      ISW=1.
      READ(5,800) (X(K),K=1,1805)
  800 FORMAT(6X,19F3.2)
   60 CONTINUE
DYNAMIC
      HOUR=AMOD(TIME/3600.+START,24.)
*     CALCULATION OF SUN ALTITUDE
      SNHSS=SNLT*SIN(RAD*DEC)+CSLT*COS(RAD*DEC)*COS(RAD*15.*(HOUR+12....
      -DLONG))
      SNHS=AMAX1(0.,SNHSS)
      FLIS=180.*ATAN(SNHS/SQRT(1.-SNHS*SNHS))/PI
      KDR=0.5/AMAX1(0.1,SNHSS)
      KDRV=0.95*KDR*SQSC+0.035
      KDRN=0.95*KDR*SQNI+0.035
      DEC=-23.4*COS(2.*PI/365.*(DAY+10.))
PARAM VPA=10.
      TA=INTGRL(10.,(TAE-TA)/3600.)
      TAE=INSW(SNHSS,10.,20.)
       VPD=SVPA-VPA
      SVPA=6.11*EXP(17.4*TA/(TA+239.))
      SLOPE=17.4*SVPA/(TA+239.)*(1.-TA/(TA+239.))
PARAM RHOCP=1240.,PSCH=0.67
PARAM WIND=.2
      RA=185.*SQRT(WIDTH/WIND)*0.5
      DRYP=VPD*RHOCP/RA
PARAM TR1=0.,TRDIF=0.6
***     1 MEANS SHADED BY STRUCTURAL ELEMENTS
** 2 MEANS LOWER TRASNMISSIVITY
** 3 MEANS HIGHER TRANSMISSIVITY
** 4  MEANS THAT TRANSMISSIVITIES ARE AVERAGED
SAZ=COS(RAD*DEC)*SIN(RAD*15.*(HOUR+12.-DLONG))/SQRT(1.-SNHSS*SNHSS)
      AZ=(180./PI)*ATAN(SAZ/SQRT(1.-SAZ*SAZ))
PARAM AZGH=0.
* THE AZIMUTG AZGH IS MEASURED ALONG THE GUTTERS WITH RESPECT TO THE SOU
TH
**    TURNING TO THW WEST IS POSITIVE
      RAZ=ABS(AMOD(ABS(AZ-AZGH),180.)-90.)

PROCEDURE FR1,FR2,FR3,TR2,TR3=GLASH(SNHS,RAZ)
      I=20.*(AMAX1(.075,SNHS)-0.025)
      J=0.2*(ABS(RAZ)+7.5)
      K=J+95*(I-1)
      FR1=X(K)
      FR2=X(K+19)
      FR3=X(K+38)
      TR2=X(K+57)
      TR3=X(K+76)
ENDPRO
      TR4=SUMX(FR'1,3',TR'1,3')

      FRDIF=AFGEN(FRDIFT,FLIS)
```

```
FUNCTION FRDIFT=0.,1.,5.,1.,15.,0.4,25.,0.3,90.,0.25
      TRATM=EXP(-0.1/AMAX1(0.05,SNHSS))
      DIFOV=116.*SNHS*TRATM
      DIFCL=580.*SNHS*FRDIF*TRATM
      SUNDCL=580.*SNHS*(1.-FRDIF)*TRATM
      FVDR'1,4'=(1.-RDRV)*SUNDCL*TR'1,4'*(1.-XVDR)/DL
      FNDR'1,4'=(1.-RDRN)*SUNDCL*TR'1,4'*(1.-XNDR)/DL
      VDIR'1,4'=(1.-SCV)*SUNDCL*TR'1,4'*(1.-XD)/DL
      NDIR'1,4'=(1.-SCN)*SUNDCL*TR'1,4'*(1.-XD)/DL
      VISDF=(1.-RDFV)*DIFCL*(1.-XVDF)/DL*TRDIF
      NIRDF=(1.-RDFN)*DIFCL*(1.-XNDF)/DL*TRDIF
      VISDFO=VISDF*DIFOV/(DIFCL+NOT(DIFCL))
      NIRDFO=NIRDF*DIFOV/(DIFCL+NOT(DIFCL)) * 0.7
      VISF'1,4'=VISDF+FVDR'1,4'-VDIR'1,4'
      NIRF'1,4'=NIRDF+FNDR'1,4'-NDIR'1,4'
      VPER'1,4'=(1.-SCV)*SUNDCL*TR'1,4'/SNHSS
      NPER'1,4'=(1.-SCN)*SUNDCL*TR'1,4'/SNHSS
      FSR=(1.-XD)/(DL*KDR)
      PHOT'1,4'=0.
      SHLL'1,4'=0.
      LHLL'1,4'=0.
      LT'1,4'=0.
      LTO=0.
      ASO=0.
      SHO=0.
      LHO=0.

      XD=EXP(-KDR*DL)
      XNDR=EXP(-KDRN*DL)
      XVDR=EXP(-KDRV*DL)
NOSORT
      IF(SNHSS.LT.0.) GO TO 100
      DO 154 I=1,NUMLL
      DO 260 SN=1,10
      SNINC=-0.05+0.1*SN
      VIS'1,4'=VISF'1,4'+VPER'1,4'*SNINC
      NIR'1,4'=NIRF'1,4'+NPER'1,4'*SNINC
      LH'1,4',SH'1,4',LTS'1,4',PH'1,4'=TRPH(VIS'1,4',NIR'1,4',TA,RA...
      ,SLOPE,DRYP)
      SHLL'1,4'=SHLL'1,4'+ZISSN*SH'1,4'*FSR
      LHLL'1,4'=LHLL'1,4'+ZISSN*LH'1,4'*FSR
      PHOT'1,4'=PHOT'1,4'+ZISSN*PH'1,4'*FSR
      LT'1,4'=LT'1,4'+LTS'1,4'*FSR*ZISSN
  260 CONTINUE
      LH5,SH5,LT5,PH5=TRPH(VISDFO,NIRDFO,TA,RA,SLOPE,DRYP)
      LHO=LHO+LH5
      SHO=SHO+SH5
      ASO=ASO+PH5
      LTO=LTO+LT5
      LH'1,4',SH'1,4',LTS'1,4',PH'1,4'=TRPH(VISF'1,4',NIRF'1,4',TA,...
      RA,SLOPE,DRYP)
      SHLL'1,4'=SHLL'1,4'+(1.-FSR)*SH'1,4'
      LHLL'1,4'=LHLL'1,4'+(1.-FSR)*LH'1,4'
      PHOT'1,4'=PHOT'1,4'+(1.-FSR)*PH'1,4'
      LT'1,4'=LT'1,4'+(1.-FSR)*LTS'1,4'
      FSR=FSR*XD
      VISDF=VISDF*XVDF
      NIRDF=NIRDF*XNDF
      VISDFO=VISDFO*XVDF
      NIRDFO=NIRDFO*XNDF
      FVDR'1,4'=FVDR'1,4'*XVDR
```

```
      FNDR'1,4'=FNDR'1,4'*XNDR
      VDIR'1,4'=VDIR'1,4'*XD
      NDIR'1,4'=NDIR'1,4'*XD
      VISF'1,4'=VISDF+FVDR'1,4'-VDIR'1,4'
      NIRF'1,4'=NIRDF+FNDR'1,4'-NDIR'1,4'
  154 CONTINUE
      SHLL'1,4'=SHLL'1,4'*DL
      LHLL'1,4'=LHLL'1,4'*DL
      PHOT'1,4'=PHOT'1,4'*DL
      LT'1,4'=LT'1,4'/NUMLL
      LHO=LHO*DL
      SHO=SHO*DL
      ASO=ASO*DL
      LTO=LTO/NUMLL
      LTC=SUMX(FR'1,3',LT'1,3')
      ASC  =SUMX(FR'1,3',PHOT'1,3')
      SHC  =SUMX(FR'1,3',SHLL'1,3')
      LHC  =SUMX(FR'1,3',LHLL'1,3')
      AS4=PHOT4
      CRC=2.*(SUNDCL+DIFCL)
      CRO=1.7*DIFOV
      GO TO 101
  100 ASC=-0.1*AFGEN(AMTB,TA)*LAI
      AS4=ASC
      ASO=ASC
      SHC=0.
      LHC=0.
      CRC=0.
      CRO=0.
  101 CONTINUE
      DCRC=INTGRL(0.,CRC)
      DCRO=INTGRL(0.,CRO)
      DASC=INTGRL(0.,ASC/3600.)
      DASO=INTGRL(0.,ASO/3600.)
      DAS4=INTGRL(0.,AS4/3600.)
PARAM DAY=(-10.,20*10.)
END

*      ROOF SLOPE IS 15 DEGREES
DATA
      .30.45.46.46.54.65.70.77.70.78.77.74.69.68.70.74.79.84.86
      .65.53.54.54.02.04.06.06.07.02.01.26.31.32.30.26.21.01.14
      .05.02.00.00.43.31.25.17.23.20.23.00.00.00.00.00.00.15.00
      .69.69.68.68.16.15.13.11.09.07.05.54.51.48.44.39.35.18.24
      .89.89.00.00.67.66.65.63.62.59.57.00.00.00.00.00.00.30.00
      .44.57.56.60.61.61.57.61.58.58.57.54.55.62.66.70.70.68.65
      .17.10.09.05.06.03.02.01.41.42.43.46.45.38.34.02.04.09.35
      .39.34.35.34.33.36.41.38.00.00.00.00.00.00.00.28.26.23.00
      .15.15.14.13.12.11.09.07.67.66.64.61.59.56.52.20.25.30.35
      .73.73.73.72.72.71.70.69.00.00.00.00.00.00.00.49.45.40.00
      .35.43.45.45.45.45.44.45.45.48.52.54.56.58.59.59.60.61.57
      .01.01.55.55.55.55.56.55.55.52.48.46.01.02.05.08.11.15.43
      .63.56.00.00.00.00.00.00.00.00.00.00.43.40.36.33.29.25.00
      .09.09.77.76.76.75.74.73.72.71.69.67.16.22.27.32.36.41.45
      .77.77.00.00.00.00.00.00.00.00.00.00.65.62.60.57.53.49.00
      .22.31.36.37.38.40.40.43.46.47.49.51.50.51.52.52.52.53.50
      .78.69.64.63.62.60.60.57.54.01.02.04.06.08.11.13.15.18.50
      .00.00.00.00.00.00.00.00.00.52.49.45.44.40.37.34.33.29.00
      .80.80.79.79.79.78.78.77.76.16.20.24.29.33.38.42.46.50.54
      .00.00.00.00.00.00.00.00.00.75.73.72.70.68.66.63.60.57.00
```

```
.28.34.34.37.37.40.39.42.42.43.44.47.47.46.47.47.46.47.44
.72.66.65.01.01.02.02.03.04.05.06.09.11.12.14.16.19.22.56
.00.00.00.63.62.58.58.55.54.52.49.45.43.42.39.36.35.30.00
.82.82.82.12.14.16.19.22.25.29.32.36.40.44.48.51.55.58.61
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.32.32.32.32.32.33.32.32.34.32.34.33.34.35.35.36.38.76.78
.49.48.48.47.47.46.46.47.44.45.45.44.44.43.42.41.39.00.00
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.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.00.00
```

```
      .18.19.20.19.20.20.21.21.21.21.21.21.22.21.21.22.22.22.21
      .35.34.34.34.34.33.34.34.34.35.35.35.36.36.37.78.78.78.79
      .47.47.46.47.46.46.44.45.45.44.44.44.42.43.42.00.00.00.00
      .88.88.88.88.88.88.88.88.88.88.88.88.88.88.88.89.89.89.89
      .89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.00.00.00.00
      .18.18.18.19.20.19.20.19.20.19.20.20.20.21.20.21.20.20.19
      .82.82.82.81.80.81.80.81.80.81.80.80.80.79.80.79.80.80.81
      .00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00
      .89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89
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      .83.83.83.83.83.83.83.83.83.83.83.83.83.83.83.84.83.82.83
      .00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00
      .89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89.89
      .00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00.00
ENDDATA
STOP
ENDJOB
```

Appendix B1 - An input example for Program A1

FORMAT specifications of the input data

An example of the input data make-up for Program A1 is given in Table B1, and the corresponding greenhouse geometry and the arrangement of the structural members are shown in Figs B1 and B2, respectively. In the following explanations, item number *n* in parenthesis corresponds to the *n*th input data card in Table B1. All input variables having the dimension of length are expressed in metres and the angle in degrees.

(1) The length of the greenhouse, HLENGT, and the range of calculation along the length, HLX1 and HLX2 in this order, within which the light transmissivities should be averaged to get a space avereaged transmissivity, where $0 \leqq HLX1 < HLX2 \leqq HLENGT$; FORMAT(3F10.0). Thus the calcutation need not be done for the whole length of the house.
(2) The range of calculation as for the width of the greenhouse, HLY1 and HLY2 in this order; FORMAT(2F10.0). The calculation need not be done in the whole range of the width, instead, it can be done in the range from HLY1 to HLY2, where $0 \leqq HLY1 < HLY2 \leqq$ width of the house.
(3) The number of spans, KSPAN, the number of divisions, KDIV, for one span at each of which the light transmissivities should be averaged, and the height of the side walls HSIDE; FORMAT (2I5,F10.0). Each span of the house is divided into KDIV segments across the width and the light transmissivities on the floor are averaged at each of the divisions in the range

Table B1

(1)		98.0	46.55	51.45			
(2)		0.01	3.99				
(3)	1	1	2.2				
(4)		2.2	24.62				
(5)		0.03	0.03	0.04	0.04	0.68	0.45
(6)		0.03	0.03	0.04	0.05	0.68	0.45
(7)		0.10	0.08	2.37			
(8)		0.003					
(9)		8000					

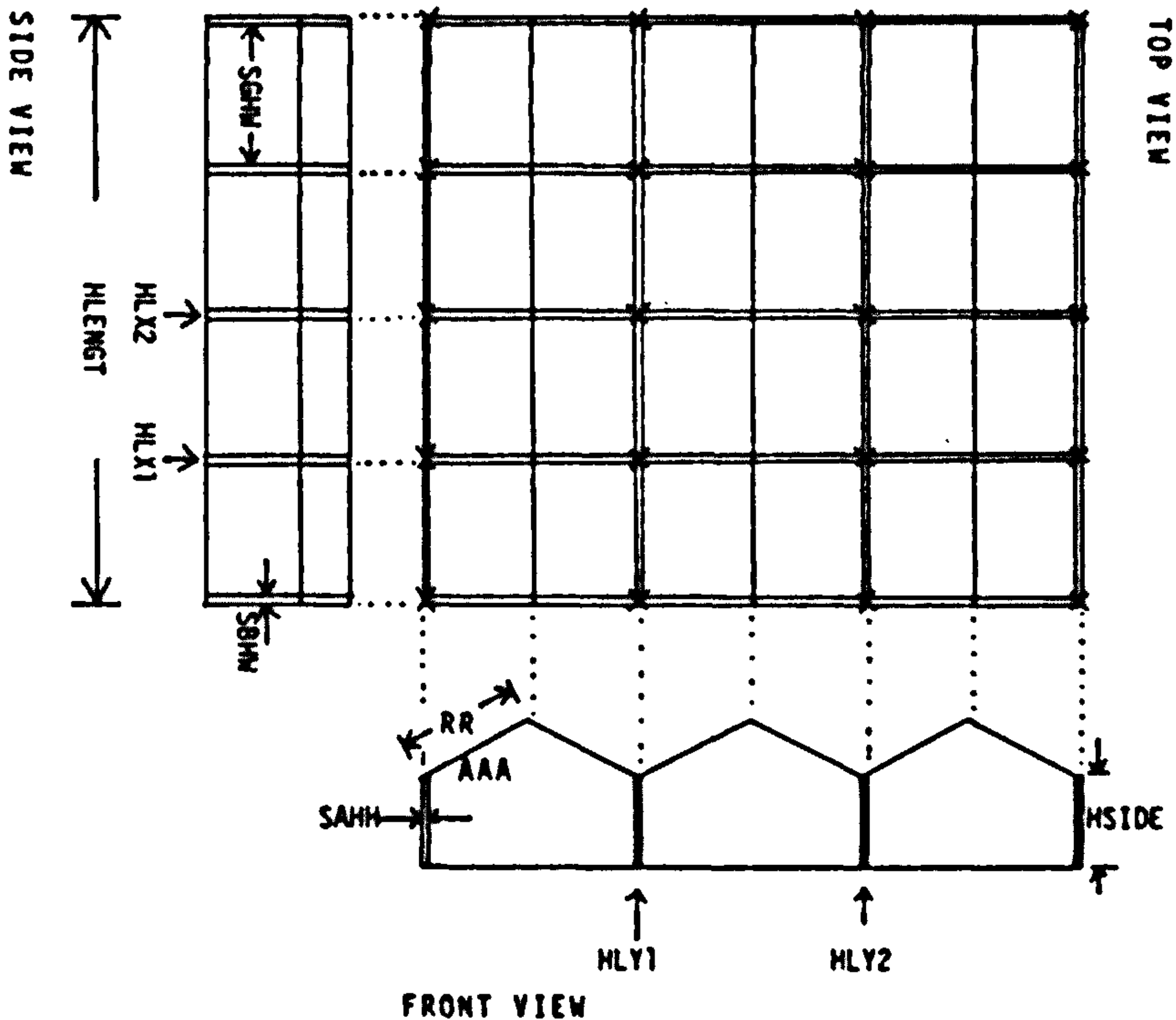


Fig. B1

from HLY1 to HLY2. The product of KSPAN and KDIV must be less than 300 to meet the DIMENSION limitation of the corresponding ARRAY variables in the program.

(4) The width of the roof, RR, and the slope of the roofs, AAA; FORMAT(2F10.0). All the spans are assumed to have the same cross-section and to have even roofs. The side walls and gable ends are assumed to be vertically constructed to the ground. Thus, the whole width of the house should be equal to 2*KSPAN*RR*COS(AAA).

(5) The thickness of horizontal AHH and non-horizontal AHW structural members, the width of horizontal BHH and non-horizontal BHW structural members, and the width GHH and length GHW of each glass pane for the roofs and side walls (see Fig. B2); FORMAT(6F10.0). The following relationships should hold between the input data:

HSIDE = k*(BHH + GHH) + BHH
RR = m*(BHH + GHH) + BHH
HLENGT = n*(BHH + GHW) + BHW

where k, m, and n are arbitrary integer numbers.

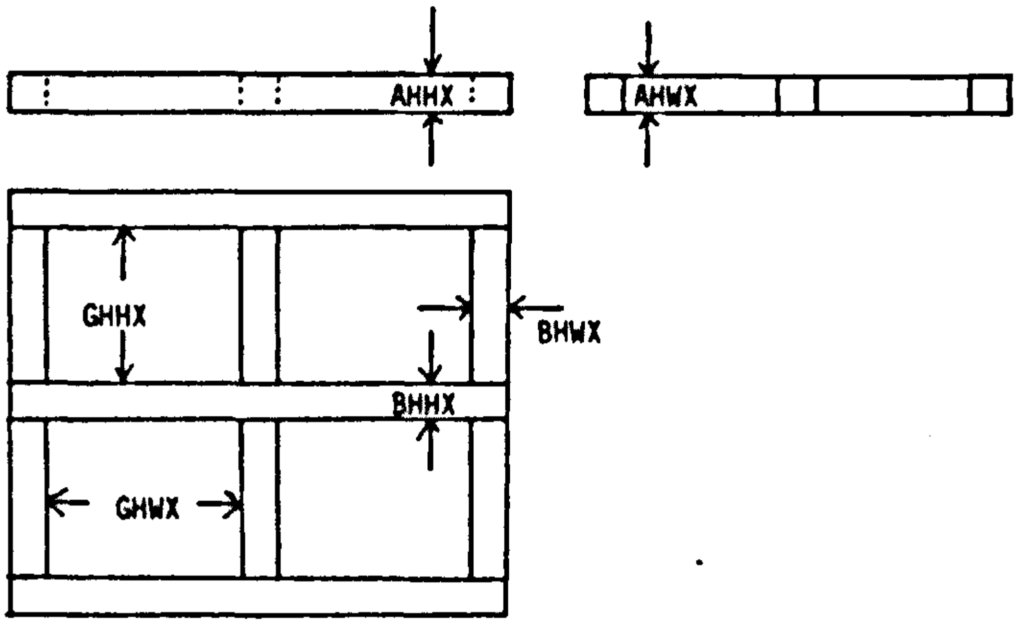
(6) The thickness of horizontal AHHX and vertical AHWX structural members, and the width GHHX and length GHWX of each glass pane at the gable ends; FORMAT(6F10.0). The following relationship should hold between the input data:

the width of one span (= 2*RR*COS(AAA)) = m*(BHHX + GHHX) + BHHX

where m is an arbitrary integer number.

(7) The thickness SAHH and width SBHW of the main structural

GABLE ENDS



SIDES AND ROOFS

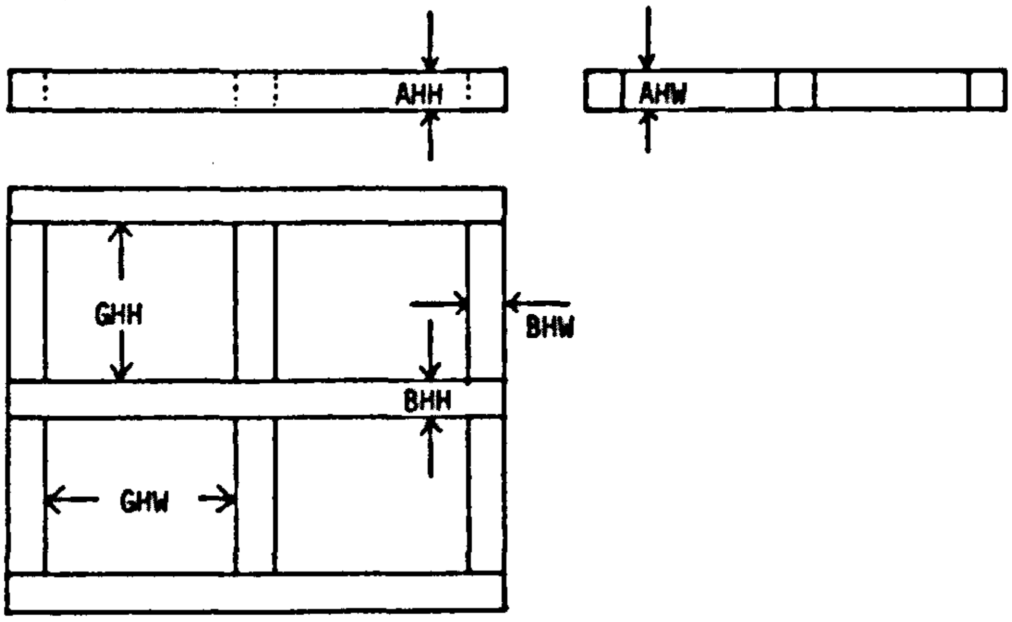


Fig. B2

members (which are supposed to be thicker and wider than those specified on the fifth and sixth input data cards) a distance of SGHW apart along the side walls and roofs. The same main structural members are assumed to be placed vertically along the joints of the spans at the interval of SGHW. The crosses in Fig. B1 indicate the places where the vertical main structural members are positioned.
(8) The thickness of the glass pane GL; FORMAT(F10.0), which is used to calculate the transmissivity of the glass pane as a function of incidence angle.
(9) The total number of random numbers used in the calculation of the average transmissivity of the greenhouse at each time step IRLAST; FORMAT(I5). For each division (with the width of 2*RR*COS(AAA)/KDIV) on the floor, more than about 2 000 and less than 10 000 random numbers are usually required to get

the reasonable accurarcy. Thus, the number which should be specified here is between 2 000*KDIV*(HLY2 - HLY1)/(2*RR*COS(AAA)), and 10 000*KDIV*(HLY2 - HLY1)/(2*RR*COS(AAA)).

Appendix B2 - An input example for Program A2

An example of the input data make-up for Program A2 is given in Table B2. In the following explanations, item number *n* corresponds to the *n*th input data card given in the table.

(1) The slope of roofs in degrees, RFSLP, and the transmissivity of the house for diffuse light, TRDIF; FORMAT(2F10.0).

(2 - *n* + 1) Transmissivities of the house as a function of solar altitude and relative solar azimuth X(I); FORMAT(6X, 19F3.0). The value of II given on the fourth line in the program should be changed into an appropriate number according to the number of the corresponding data. The value is usually 1805 (= 19 x 19 x 5) for a multispan house and is 2527 (= 19 x 19 x 7) for a single-span house. In Program A1, the transmissivities are calculated for 19 solar altitudes and 19 relative azimuths, and five or seven values are given for each combination of solar altitude and relative azimuth, showing the spatial light distribution in the house as follows:

FR1	the fraction of the floor area shaded by the structural members,
TR2	the second lowest transmissivity for the direct light (The lowest is always zero where no direct light is received by that fraction of the floor area.),
FR2	the fraction of the floor area with the transmissivity of TR2,
TR3	the third lowest transmissivity for the direct light,
FR3	the fraction of the floor area with the transmissivity of TR3,
TR4	....
FR4	....

(*n* + 2) The time interval for integration in hours to get the daily light integral G; FORMAT(F10.0). A value between 0.4 and 1.0 is adequate.

(*n* + 3, *n* + 4) The monthly average of daily total light (300 - 400 *nm*) outside, TSL, from January to December in this order (J $m^{-2}day^{-1}$); FORMAT (8F10.0).

(*n* + 5) The latitude of the place where the greenhouse is built, PHA1, the house orientation, ORIT, the month, M1, and the day, M2, from which the simulation starts, the month, M3, and the day, M4, at which the simulation ends, and the increment of the day, MINT; FORMAT(2F10.0, 5I5). The value of ORIT should be zero

Table B2

```
(1)  24.6
(2)      .24.38.39.42.49.50.56.70.79.86.88.87.79.78.76.69.72.82.88
(3)      .43.36.40.45.49.50.08.12.14.14.12.06.05.01.24.31.28.18.12
         ...........
         ...........
(n+2)  1.00
(n+3)4665000.  5855000.  6845000.  7685000.  8580000.  7325000.  8455000.  7890000.
(n+4)5965000.  5065000.  4330000.  4020000.
(n+5)35.7          0.0     9    1    5    1    5
```

for E-W orientation and be 90.0 for N-S orientation, and intermediate values for intermediate orientations.
The same kind of data cards should follow in the same FORMAT specification if you want to get the output for different ORITs or different dates in succession. If the value of zero is given to PHA1, the simulation will stop.

Appendix B3 - An output example for Program A1

A part of the output example for Program A1 is shown in Table B3. The transmissivities are calculated every five degrees of relative solar azimuth from 0^o to 90^o, and every 0.05 of sine of solar altitude (SIN(H)) from 0.075 to 0.975 and are given in tabular form.

```
                                        AZIMUTH OF THE SUN RELATIVE TO THE HOUSE ORIENTATION
                             0   5  10  15  20  25  30  35  40  45  50  55  60  65  70  75  80  85  90

SIN(H)=  0.100  FR1         19  21  21  21  21  23  24  24  24  26  27  28  35  36  40  50  61  80  88
SIN(H)=  0.100  FR2         81  79  79  79  79  77  76  76  76  74  73  72  65  64  60  50   1   5  12
SIN(H)=  0.100  FR3          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  38  15   0
SIN(H)=  0.100  TR2         89  89  89  89  89  89  89  88  88  87  86  83  80  75  67  56  39  22  23
SIN(H)=  0.100  TR3          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  41  31   0

SIN(H)=  0.150  FR1         16  18  18  18  20  20  21  23  27  28  29  29  32  34  40  50  59  70  69
SIN(H)=  0.150  FR2         84  82  82  82  80  80  79  77  73  72  71  71  68  66  60   2  25   3  31
SIN(H)=  0.150  FR3          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  48  16   1   0
SIN(H)=  0.150  FR4          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  26   0
SIN(H)=  0.150  TR2         89  89  89  89  89  89  89  88  88  87  85  83  80  75  67  54  41  22  34
SIN(H)=  0.150  TR3          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  56  48  25   0
SIN(H)=  0.150  TR4          0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0   0  41   0
```

Appendix B4 - An output example for Program A2

A part of the output example is shown in Table B4. The output variables can be classified into three groups. The meanings of the output variable names in each group are listed below:

(1) Current values at the Kth time step

K	the sequential number of the time step counting from the sunrise time on the day in question
TIME	true solar time of the day
DRP	direct visible solar light (400 - 700 *nm*) outside for clear days (W$\cdot$m^{-2})
DIFOV	diffuse visible solar light outside for overcast days
HH	solar altitude
AA	solar azimuth

(2) Current values at each division on the floor at the Kth time step (Some of them are not printed out in the example)

IYY	sequential number of the division in question on the floor counting from one of the side walls
SPERTR	total number of direct light rays actually used at the IYYth division
STPERT	number of the direct light rays intercepted by the structural members from transmitting at the IYYth division
STPY	average transmissivity for the direct light at the IYYth division
PERY	ratio of shaded area due to the structural members to the area of the IYYth division (= STPERT/SPERTR)
SPACE	space averaged transmissivity of the house for the direct light
CAD	space averaged direct light intensity in the greenhouse for clear days (= SPACE * DRP)
CAT	space averaged total light intensity in the greenhouse for clear days (= CAD + TRDIF * DSH)

(3) Daily integrals and cumulative values of the daily integrals

DRO	daily integral of DRP
DFO	daily integral of DSH
TDIF	daily integral of DIFOV
DDD	daily integral of (DRO + DFO)
DAPE	daily averaged transmissivity at the IYYth division

	of the direct light for clear days
DPE	daily averaged transmissivity at the IYYth division of the total light for clear days
DAVTYP	space averaged daily transmissivity of the direct light for clear days
TTOTAL	space averaged daily transmissivity of the total light for clear days
YTD	cumulative value of DRO during the specified period
YTT	cumulative value of DDD during the specified period
ATT	cumulative value of TDIF
ADT	daily integral of the total light on the day in question outside, calculated from the input data, TSL
ATI	cumulative value of ADT
ATRT	daily integral of the total light in the greenhouse
TATRT	cumulative value of ATRT
FOV	fraction of overcast (= (DDD - ADT)/(DDD - TDIF))

```
LATITUDE OF THE PLACE WHERE THE HOUSE IS BUILT        50.0000
HOUSE ORIENTATION      90.0   (DEGREES)
THE TIME THE SUN RISES ABOVE THE HORIZON (HR.)   7.37792
DATE       MONTH=   2   DAY=   4   LD=  35
K=  1  TIME=  8.00  DRP=      0.  DSH=     17.   DIFOV=       3.    HH=  5.2   AA=  33.5    AB=  33.5
SPACE AVERAGE=   0.175   CAD=  0.36527E-01   CAT=  0.10372E 02   TRT=  0.5949E 00
K=  2  TIME=  9.00  DRP=     37.  DSH=     44.   DIFOV=      16.    HH= 12.6   AA=  46.0    AB=  46.0
SPACE AVERAGE=   0.320   CAD=  0.11694E 02   CAT=  0.37806E 02   TRT=  0.4722E 00
K=  3  TIME= 10.00  DRP=     85.  DSH=     49.   DIFOV=      27.    HH= 18.4   AA=  59.6    AB=  59.6
SPACE AVERAGE=   0.415   CAD=  0.35208E 02   CAT=  0.64536E 02   TRT=  0.4828E 00
K=  4  TIME= 11.00  DRP=    113.  DSH=     55.   DIFOV=      34.    HH= 22.2   AA=  74.5    AB=  74.5
SPACE AVERAGE=   0.438   CAD=  0.49491E 02   CAT=  0.82588E 02   TRT=  0.4911E 00
K=  5  TIME= 12.00  DRP=    123.  DSH=     57.   DIFOV=      36.    HH= 23.5   AA=  90.0    AB=  90.0
SPACE AVERAGE=   0.427   CAD=  0.52649E 02   CAT=  0.86666E 02   TRT=  0.4815E 00
K=  6  TIME= 13.00  DRP=    113.  DSH=     55.   DIFOV=      34.    HH= 22.2   AA=  74.5    AB= 105.5
SPACE AVERAGE=   0.438   CAD=  0.49491E 02   CAT=  0.82588E 02   TRT=  0.4911E 00
K=  7  TIME= 14.00  DRP=     85.  DSH=     49.   DIFOV=      27.    HH= 18.4   AA=  59.6    AB= 120.4
SPACE AVERAGE=   0.415   CAD=  0.35208E 02   CAT=  0.64536E 02   TRT=  0.4828E 00
K=  8  TIME= 15.00  DRP=     37.  DSH=     44.   DIFOV=      16.    HH= 12.6   AA=  46.0    AB= 134.0
SPACE AVERAGE=   0.320   CAD=  0.11694E 02   CAT=  0.37806E 02   TRT=  0.4722E 00
K=  9  TIME= 16.00  DRP=      0.  DSH=     17.   DIFOV=       3.    HH=  5.2   AA=  33.5    AB= 146.5
SPACE AVERAGE=   0.175   CAD=  0.36527E-01   CAT=  0.10372E 02   TRT=  0.5949E 00
DAILY AVERAGES
DAVTYP=  0.4145E 00   TTOTAL=  0.4857E 00   ATRT=  0.9892E 05   FOV=  0.1250E 01   RDL=  0.3557E 04
DRO=  0.2132E 07   DFO=  0.1329E 07   DDD=  0.3460E 07   TDIF=  0.6921E 06   ADT=  0.1498E 03
YTD=  0.1066E 08   YTT=  0.1730E 08   ATT=  0.3460E 07   ATI=  0.7491E 03   TATRT=  0.4946E 06
DAB=  0.6602E 03
```

Appendix C - List of symbols

a	Growth rate per leaf area index	kg $m^{-2}d^{-1}$
A	Azimuth of the sun	
AD	Average daily transmissivity for direct light	
ADT	Actual daily light integral	J $m^{-2}d^{-1}$
ATRT	Actual daily light integral inside the greenhouse	J $m^{-2}d^{-1}$
CLT	Daily light integral for a clear day	J $m^{-2}d^{-1}$
DIFOV	Diffuse light intensity outside on a standard overcast day	J $m^{-2}s^{-1}$
DRP	Direct light intensity outside on a standard clear day	J $m^{-2}s^{-1}$
DSH	Diffuse light intensity outside on a standard clear day	J $m^{-2}s^{-1}$
$\bar{F}$	Daily total of net CO_2-assimilation	kg $m^{-2}d^{-1}$
F_d	F_n in the dark	kg $m^{-2}s^{-1}$
F_m	F_n under light saturation	kg $m^{-2}s^{-1}$
F_n	Net CO_2-assimilation per leaf area	kg $m^{-2}s^{-1}$
F_{cl}	Net CO_2-assimilation per ground area under a clear sky	kg $m^{-2}s^{-1}$
F_{ov}	Net CO_2-assimilation per ground area under an overcast sky	kg $m^{-2}s^{-1}$
F_{sh}	Net CO_2-assimilation of shaded leaves per ground area	kg $m^{-2}s^{-1}$
F_{su}	Net CO_2-assimilation of sunlit leaves per ground area	kg $m^{-2}s^{-1}$
f	Fraction overcast	
FRDIF	Fraction of diffuse light outside	
h	Inclination or altitude	
H	Altitude of the sun	
H	Harvestable dry matter	kg m^{-2}
I	Index of the sun's altitude	
I	Number of light rays to be traced in the program	
J	Index of the sun's relative azimuth	
J	Number of divisions in the width of a span	
K	Total number of glass panes	
K	Extinction coefficient for total light under direct irradiation, in a plant canopy	
K_b	Extinction coefficient for direct radiation in a plant canopy	

LAI	Leaf area index	m^2 leaf m^{-2} ground
m	Number of azimuth zones	
n	Number of altitude zones	
n	Number of rays, intercepted by a strut	
OVT	Daily light integral for an overcast day	$J\ m^{-2}d^{-1}$
p	Specific leaf weight	$kg\ m^{-2}$
R_v	Absorbed visible radiation per leaf area	$J\ m^{-2}s^{-1}$
R_s	R_v for shaded leaves	$J\ m^{-2}s^{-1}$
$R_{v,b}$	R_v originating from direct light, averaged over all leaves	$J\ m^{-2}s^{-1}$
$R_{v,c}$	Absorbed diffuse visible radiation	$J\ m^{-2}s^{-1}$
$R_{v,d}$	Absorbed direct visible radiation (sunlit leaves)	$J\ m^{-2}s^{-1}$
$\bar{R}_{v,d}$	$R_{v,d}$, averaged over all leaves	
s	Fraction of sunlit leaves	
S	Visible radiative flux on a horizontal surface	$J\ m^{-2}s^{-1}$
S_b	Direct visible radiative flux	$J\ m^{-2}s^{-1}$
S_p	Direct visible radiative flux, through a surface perpendicular to the solar beam	$J\ m^{-2}s^{-1}$
t	Index of sine of incidence	
t	Time, also time required for harvesting	
T	Transmissivity of the greenhouse for direct light	
TRAM	Atmospheric transmission coefficient	
TRDIF	Transmissivity of the greenhouse for diffuse light	
TT	Transmissivity of the greenhouse for total light	
X	Distance along the length of the house	
Y	Distance over the width of the house	
ε	Maximum efficiency of light utilization for CO_2-assimilation	$kg\ J^{-1}$
ρ	Reflection coefficient of the plant canopy	
σ_v	Scattering coefficient of the leaves for visible radiation	