MEASUREMENT OF NATURAL IRRADIANCE IN GREENHOUSES : THE EFFECT OF AVERAGING PERIOD AND NUMBER OF SENSORS ON MEASUREMENT RELIABILITY

Graham, Michael E. D.
Departement de phytologie Faculte des sciences de l'agriculture et de l'alimentation Universite Laval

Dube, Pierre-Andre
Departement de phytologie Faculte des sciences de l'agriculture et de l'alimentation Universite Laval

Phenix, Maurice
Departement de phytologie Faculte des sciences de l'agriculture et de l'alimentation Universite Laval

http://hdl.handle.net/2324/8164

出版情報：BIOTRONICS. 19, pp.83-91, 1990-12. Biotron Institute, Kyushu University
バージョン：
権利関係：

BIOTRONICS **19**, 83–91, 1990

MEASUREMENT OF NATURAL IRRADIANCE IN GREENHOUSES: THE EFFECT OF AVERAGING PERIOD AND NUMBER OF SENSORS ON MEASUREMENT RELIABILITY

Michael E. D. GRAHAM, Pierre-André DUBÉ and Maurice PHÉNIX

Département de phytologie, Faculté des sciences de l'agriculture et
de l'alimentation, Université Laval, Québec City, Qué.,
Canada G1K 7P4

(Received January 17, 1990; accepted February 16, 1990)

GRAHAM M. E. D., DUBÉ P.-A. and PHÉNIX M. *Measurement of natural irradiance in greenhouses: The effect of averaging period and number of sensors on measurement reliability.* BIOTRONICS **19**, 83–91, 1990. Measurements of natural photosynthetic photon flux (PPF) at 1 m above the floor in glass and polyethylene greenhouses obtained using a mobile sampling system are compared to data obtained by 6 stationary sensors at the same height. Analysis of the data shows that the use of multiple stationary sensors does not lead to an accurate value of the spatial average irradiance under sunny conditions in either glass or polyethylene greenhouses when integration times are short (1 to 3 h). With longer integration times (up to 10 h), these inaccuracies are insignificant under glass. Under polyethylene, systematic differences in PPF occur across the greenhouse. In our region, calculations using data from this experiment indicate that average differences in total radiation accumulations during February can be as large as those induced in typical supplemental irradiation experiments. These systematic gradients should be taken into account in experiments where the parameters being studied may be sensitive to radiation integrals.

Key words: light transmission; gradient; mobile sampling; systematic error; PPF.

INTRODUCTION

For many greenhouse crops, the irradiance received by the plant canopy is an important factor controlling growth and development. It is well known that the addition of supplemental irradiation can increase earliness and yield of many greenhouse plants, and the addition of supplementary lighting is recommended for many species (*1*). Research in this field is continuing worldwide, including in eastern North America (for example, *2–4*, *11*).

A knowledge of the irradiance inside a greenhouse is usually required both in studies of energy transfer in the greenhouse and in studies of crop production and water use. Where dynamic interactions are being studied (e.g. *8*, *15*), the short-term (e.g. 1 h) integrals of radiation received by the crop are required. In these dynamic studies the cover transmission and/or radiation integrals inside the greenhouse are usually obtained from a single, stationary radiation sensor placed inside the greenhouse (*8*, *9*, *12*), although in some cases, multiple stationary sensors are used (*15*). Where radiation levels are reported in crop growth studies, they are usually obtained from a single stationary sensor, and comparisons of radiation accumulations between experimental blocks of an experiment are rarely given.

While models exist to predict light transmission in greenhouses, these are generally intended as design aids to determine factors such as optimal roof slopes, gutter heights and house widths (*5–7*). Although many include shading produced by repeated structural members (e.g. gutters, trusses etc.) and the effect of adjacent houses in a gutter-connected array, they are often complex, and do not easily account for non-repeated structures and the variations in cover transmission caused by dirt and age.

To obtain accurate values for light levels inside a greenhouse, or of the average transmission of the cover, measurements of the spatial average irradiance incident on an area of the floor or crop are required. The major objective of this study was to determine the number of PPF sensors and length of the averaging period required to obtain a representative value of the average irradiance incident on the floor or crop. A horizontal radiation averaging system was used to obtain spatial average PPF levels for comparison to values reported by six stationary quantum sensors. The experiments were performed in both glass and polyethylene houses, during both sunny and cloudy weather.

MATERIALS AND METHODS

Measurements of the photosynthetic photon flux (PPF) incident on a plane 1 m above the floor, made by six stationary sensors randomly placed across the width of the greenhouse, were compared to the horizontal average as measured by two mobile sampling systems similar to that described by Péch (*14*).

The comparisons were conducted in two experimental greenhouses: an inflated polyethylene Harnois Nordic greenhouse oriented east-west (30×6 m) and a Lord and Burnham single pane glass structure (7×6 m) with its axis north-south. The polyethylene house was a central member of a gutter-connected array, and the glass compartment was the northernmost end of a free standing structure. Both greenhouses are located on the campus of Université Laval (47°N).

Instantaneous readings from both the mobile and stationary PPF sensors were taken every 20 s with a 1 s integration time using an Adtek DLX-100 data acquisition and control system (Adtek Inc., Sillery, Que.). The mobile sampling systems were placed across the width of the greenhouse and the six stationary quantum sensors (model Li-190SB, Li-Cor, Inc., Lincoln, Neb.) were randomly placed at the same height near the mobile systems (Fig. 1). Zero-offsets for each channel-sensor combination were determined by measurements made at night of the outputs

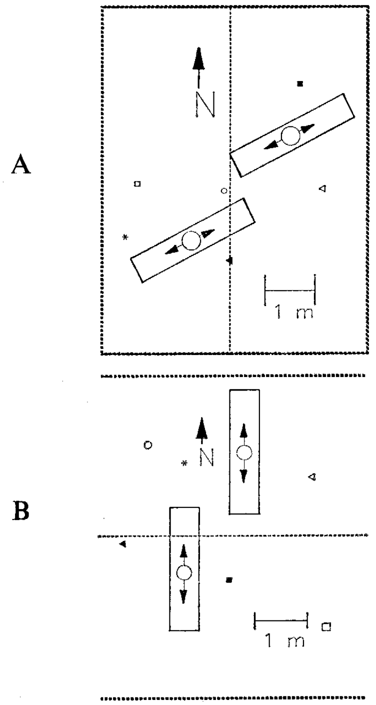

Fig. 1. Scale drawings of floor plan of test greenhouses. Rectangles indicate area measured by mobile sensors (circles with arrowheads). Light dotted line indicates position of greenhouse peak; heavy dotted line indicates the position of greenhouse walls where they occur within the scale of the drawings. Other symbols refer to individual sensors for which data is plotted using identical symbols in Fig. 2. A) glasshouse; B) polyethylene greenhouse.

of aluminium foil-covered sensors. All sensors were calibrated by Li-Cor, Inc. immediately prior to the experiment (specified accuracy$\pm 3\%$). Outside radiation was measured by a similar quantum sensor placed on the roof of a nearby building.

Each mobile sampling system consisted of a 2.5 m long track on which a wheeled instrument platform equipped with a PPF sensor was placed. The sensor was mounted on the instrument platform at a height of 1 m in a mastic-filled hole in a machined gimbal. This device allowed automatic horizontal leveling of the sensor (the mastic allowed leveling of the sensor in the free-hanging gimbal). Level was checked using a 1.5-cm diameter spirit level placed on top of the sensor several times a day at several positions on the track. Adjustment of the level was found to be necessary about once every 3 days. While the instrument platform was moving, the gimbal-mounted sensor tended to "rock". During experiments, therefore, at least 20 s were allowed between the positioning of the sensor and the taking of readings (visible gimbal oscillation stopped within 10 s).

To move the sensors along the tracks, the instrument platforms were connected by a chain drive system to a reversible 12 V DC motor. The motor speed and chain sprocket size were selected so that the instrument platform could be advanced at 1 m s^{-1}. Limit switches at either end of the track were used to reverse the direction of the motor. The motor could be turned off and on, either manually at the track or remotely by computer. The motor control system included an electronic circuit preventing rapid acceleration of the instrument platform. The position of the instrument platform on the track was detected by measuring the resistance of a 10-turn variable resistor mounted on the motor drive shaft.

During operation, the instrument platforms were advanced every 40 s about 60 cm, the distance varying with different friction in different areas of the track. This resulted in 10 complete traverses of each track in 15 min. The system was designed so that, during the same 15 min averaging period, the sensor rarely stopped at the same position twice, and at least two measurements were obtained in each 20 cm section of the track.

The stored data from each sensor were averaged for various time periods in multiples of 15 min using a running-mean procedure in order to compare the effect of averaging period on the difference between the mobile and stationary sensors. For each period, the average value for one to six stationary sensors was calculated. The precision of the various combinations of averaging periods (15 to 600 min) and number of sensors (1 to 6) was then examined by comparing the averaged values of the PPF level reported by the stationary sensors to that reported by the two mobile sensors for the same period. For n stationary sensors, an error value was calculated as

$$E=\frac{1}{\mathrm{n}}\sum_{\mathrm{i}=1}^{\mathrm{n}}\left|\frac{S_{\mathrm{i}}-M}{M}\right| \tag{1}$$

where E is the error value, S_1 is the PPF value reported by the i^th sensor, and M the average PPF value reported by the two mobile sensors. Maximum error values were then examined as a function of integration period, with the period length ranging from 15 min to the length of the data set (10–11 h), and values of n ranging from 1 through 6.

The resolution of the data acquisition system was 5 μmol m^{-2} s^{-1}. Periods for which light levels were less than 50 μmol m^{-2} s^{-1} (i.e. error greater than $\pm 10\%$) were therefore discarded. The above analysis is essentially a Fourier frequency analysis on the difference between the mobile and stationary sensors.

Experiments in the polyethylene house were carried out on six cloudless days between 12 and 28 February 1988. In the glasshouse measurements were made on four cloudless days between 6 and 12 March. Both houses contained neither plants nor lighting fixtures.

RESULTS AND DISCUSSION

The effect of averaging period and number of sensors on measurement reliability

On overcast days, the difference between the mobile and stationary sensors was less than 10% of the mobile value, regardless of the averaging period and of the number of stationary sensors used in the calculation of the average. At integration times longer than 2 h, the differences between sensors in both houses were within the specified accuracy of the sensors (3%, data not shown).

The magnitude of the differences between mobile and stationary sensors and

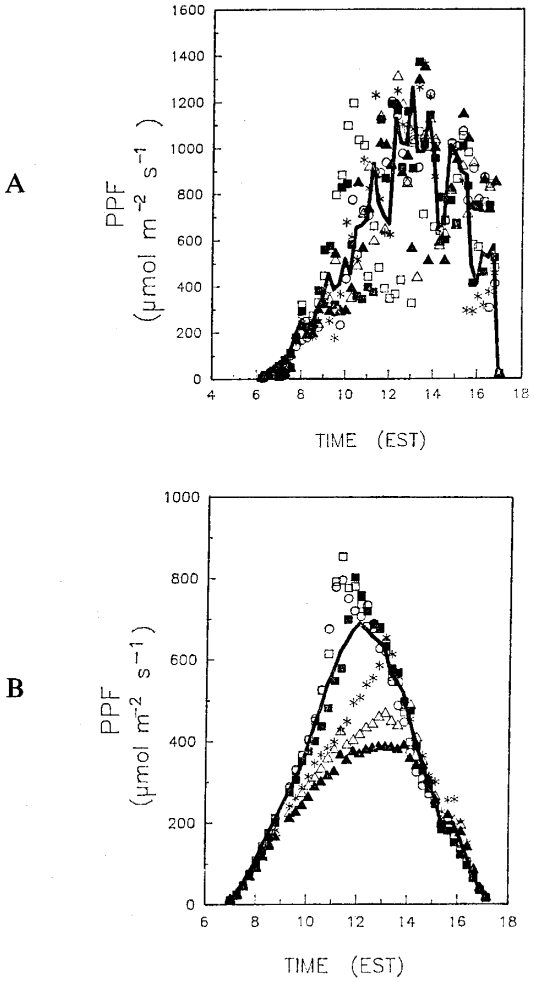

Fig. 2. PPF data as measured in (A) glasshouse on 9 March 1988 and in (B) an inflated double polyethylene greenhouse on 18 February 1988. Symbols represent 15-min averages from individual stationary sensors (positions as indicated in Fig. 1); line is average of two mobile sensors.

the pattern of the non-uniformities observed inside a particular house during sunny weather did not change detectably from day to day during the measurement period. Data are presented, therefore, for only one full day of measurements in each house. During sunny weather, measurements made in both the glass and polyethylene houses (Fig. 2) showed that large differences between the mobile and stationary sensors are common. The analysis of the effect of averaging period (Eq. (1)) for the same 2 days are presented in Fig. 3.

Glasshouse

At noon in the glasshouse, the different stationary sensors reported 15 min average PPF values ranging from 300 to 1300 μmol m^{-2} s^{-1}, while the mobile sensors reported a spatial average of about 1000 μmol m^{-2} s^{-1} at the same time (Fig. 2A). It should be noted that this data was obtained on a cloudless day; the

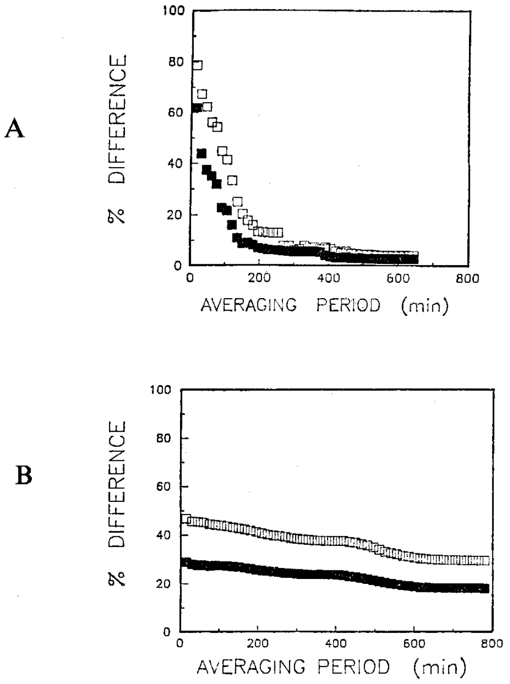

Fig. 3. Percent differences between mobile and stationary sensors as defined by Eq. (1) for 1 (open symbols) and six (filled symbols) sensors as a function of averaging time in (A) glass and (B) polyethylene greenhouses for the data shown in Fig. 2.

variability in the mobile sensors with time resulted from shading by structural members running parallel to the tracks. The analysis of the effect of averaging period (Eq. (1)) for the same data (Fig. 3A) showed that the maximum difference encountered was reduced as averaging period increased. This non-uniformity of light levels in the glasshouse results from shading by structural members, leading to short-term variations in PPF over a particular point. This produces large differences between instantaneous measurements made by adjacent sensors. The large point-to-point variation encountered using short averaging periods (max. 80% with 15-min averaging) is reduced if enough time is given to allow a representative amount of sun and shadow to pass the sensor (differences of 10% with 3-h averaging). Little improvement was found through using additional point measurements (Fig. 3A).

Polyethylene house

In the polyethylene house, differences between instantaneous PPF readings made by adjacent sensors were smaller, but the variability of the daily totals was larger than those obtained in the glasshouse. As the radiation received on the floor changed smoothly with time (Fig. 2B), this variability between the stationary sensors was evidently not caused by shading from opaque structural members. However, at a given solar elevation, light beams striking the different positions on the floor must pass through the curved roof with different angles of incidence (hence different reflectivities), while some pass through the roof of the adjacent bay and subsequently through the polyethylene wall of the test greenhouse. Transmission models are not as yet, however, sufficiently advanced to verify whether or not this differential transmission is sufficient to account for the observed gradients.

In practical terms for the experimenter in such a greenhouse, the data indicates that a true spatial average of PPF over the width of the polyethylene greenhouse cannot be accurately determined with point measurements under sunny conditions. Figure 3B shows that summations over the whole day using six sensors still gave a 15% difference between the point measurements and the spatial average (mobile sensors). With 15-min averaging periods, this difference was 25% for six sensors and 45% using one point measurement. Also, this difference is non-random, the maximum radiation received by particular sensors were both different in magnitude and offset in time (Fig. 2B). Our data indicates that, on a sunny day, one position on the floor of the polyethylene greenhouse received a total insolation 35% different from the spatial average (Fig. 3B).

Implications for crop growth and experimental design

The data in Fig. 3B can be used to calculate the differences in total insolation over the crop growth period. The daily total irradiation inside the polyethylene greenhouse for the data shown in Fig. 2B was 12.4 mol m^{-2} day^{-1} (an average of 343 μmol m^{-2} s^{-1} over 10.5 h). The outside daily integral was 21 mol m^{-2} day^{-1} (an average cover transmission of 59%). Hay (*10*) reports that 50% of the days in February in our region have solar radiations equal to or greater than 9 MJ m^{-2} day^{-1}. Using a conversion based on solar spectral data (*13*), this represents 22 mol m^{-2} day^{-1} of PPF.

The total spatial variation in PPF occurring in the greenhouse over a period of several days or weeks can be calculated as:

$$D = R \times V \times N \qquad (2)$$

where D is the difference in radiation received between two points in the greenhouse averaged over the whole period (mol m^{-2} day^{-1}), R is the minimum radiation received inside the greenhouse at which gradients in PPF begin to appear (again in mol m^{-2} day^{-1}), V is the variation (expressed as a fraction of the mean) which occurs on days with radiation levels higher than R, and N is the number of days (also expressed as a fraction) in the growth period that show radiation levels equal to or higher than R. If it is assumed that the gradients only appear on sunny days (i.e. days with radiation levels equal to or higher than 21 mol day^{-1}), then for February in our region, $R = 12.4$ mol m^{-2} day^{-1}, $V = 0.35$ and $N = 0.5$. This yields a maximum point-to-point variation of 2.2 mol m^{-2} day^{-1} in our polyethylene greenhouse when averaged over the whole month. In most supplemental lighting experiments, such as those cited in the introduction, differences between lighting treatments are on the order of 50 μmol m^{-2} s^{-1}, with photoperiods of 10 to 24 h. Based on a supplemental lighting period of 17 h, the daily integral of the difference between artificial light treatments would be 3 mol m^{-2} day^{-1}. Thus, monthly averaged gradients in natural irradiance can be as large as 73% of the difference between lighting treatments, this value increasing with the number of sunny days in the month. It should be emphasized that this variation is apparently a property of the geometry of the greenhouse, and is therefore non-random. Although the pattern of the non-unformities may change with seasonal changes in the maximum solar angle encountered, large differences in the total radiation absorbed by particular plants could occur if the growth period is on the order of 2 to 3 months. If the effects being studied are responding to the daily radiation integral (and not affected by photoperiod), the gradients in natural light level could introduce considerable variation in the experiment. The data indicates that, in the type of polyethylene greenhouses studied here, a blocking should be added to the experimental design and statistical analysis which takes the variation of radiation environment into account.

For short-term measurements in the polyethylene house, point measurements may well be representative of smaller areas around the sensor (e.g. the size of one plot), because there is little structural shading. Our experiment compared point measurements to the spatial averages across the whole greenhouse; further research is required to find the size of the area that a single point measurement represents. In glass greenhouses, it is unlikely that point measurements made over short periods can be representative of large areas, as most of the variability results from sharp changes between sun and shadow. If, in either type of greenhouse, short-term PPF values are required, and the permanent installation of a spatial averaging system is impossible, a direct and diffuse transmission model calibrated for the particular greenhouse might yield data more representative of the spatial average than is possible from point measurements inside the greenhouse.

CONCLUSIONS

Measurements of light levels made at a single point and integrated for short periods (e.g. 15 min to 1 h) do not represent spatial averages in either type of house during sunny weather. The addition of extra point measurements does not appreciably alter this conclusion.

For short-term measurements of interior light levels, a linear averaging system that is capable of taking measurements every few centimeters over the width of the greenhouse appears necessary. Systematic gradients that exist in polyethylene greenhouses must be accounted for in the layout of the plot replications in the experimental design.

ACKNOWLEDGEMENTS

The authors wish to thank the "Conseil des Recherches en pêche at agro-alimentaire du Québec" (CORPAQ) for the financial support of this research. We would also like to thank Mme. F. Chrochetière and Dr. L. Smeets for their aid and comments during the preparation of the manuscript.

REFERENCES

1. Anonymous (1987) *Artificial Lighting in Horticulture.* 40 pages, Philips Lighting Division, Eindhoven, The Netherlands.

2. Balazsovits J., Dansereau B., Gagnon S. and Beeson R. C., Jr. (1989) Effets à long terme de l'enrichissement carboné et d'un appoint de lumière sur la productivité de la rose cultivée en serre. *Can. J. Plant Sci.* **69**, 979–989.

3. Blain J. A., Gosselin A. and Trudel M. J. (1987) Influence of HPS supplementary lighting on growth and yield of greenhouse cucumbers. *Hortscience* **22**, 36–38.
4. Boivin C., Trudel M. J. and Gosselin A. (1986) Influence du niveau d'irradiance d'appoint (HPS) en pépinière sur la croissance et la productivité d'une culture de tomate de serre. *Can. J. Plant Sci.* **66**, 961–970.
5. Coffin W. L., Skelton A. M. and Jackson H. A. (1988) Light levels in multispan greenhouse models. *Can. Agric. Eng.* **30**, 143–149.
6. Critten D. L. (1983) Greenhouse light transmission: The shading effect of infinite parallel cylinders under diffuse light. *J. Agric. Eng. Res.* **28**, 569–572.
7. Critten D. L. (1986) A general analysis of light transmission in greenhouses. *J. Agric. Eng. Res.* **33**, 289–302.
8. de Halleux D. (1988) Modélisation des échanges thermodynamiques d'une serre. PhD thesis, Faculté des Sciences Agronomiques de Gembloux (Belgique).
9. Froehlich D. P., Albright L. D., Scott N. R. and Chandra P. (1979) Steady-periodic analysis of glasshouse thermal environment. *Trans. Am. Soc. Agric. Eng.* **22**, 387–399.
10. Hay J. E. (1977) An analysis of solar radiation data for selected locations in Canada. *Fish. Environ. Can., Climatological Studies Bull.* **32.**
11. Hicklenton P. R. (1989) Effects of supplemental lighting and root-zone temperature on growth of chrysanthemums in nutrient film. *Can. J. Plant Sci.* **69**, 585–590.
12. Hunt R., Warren Wilson J., Hand D. W. and Sweeney D. G. (1984) Integrated analysis of growth and light interception in winter lettuce I. Analytical methods and environmental influences. *Ann. Bot.* **54**, 743–757.
13. Nisen A. (1972) *L'eclairement naturel des serres.* Les presses agronomiques de Gembloux, Gembloux, Belgium.
14. Péch G. (1986) Mobile sampling of solar radiation under conifers. *Agric. For. Meteorol.* **37**, 15–28.
15. Stanghellini C. (1987) *Transpiration of Greenhouse Crops: An Aid to Climate Management.* 150 pages, IMAG Press, Wageningen, The Netherlands.