Some Thoughts on Supplemental Lighting for Greenhouse Crop Production

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Introduction

The light environment inside a greenhouse structure is primarily determined by the amount of solar radiation received at the location. The introduction of electric lighting started the use of artificial light sources for plant irradiation. Artificial light sources (e.g., incandescent, fluorescent, and especially high intensity discharge lamps) can be used to supplement the (limited) amount of solar radiation received by a crop on darker days. Therefore, a discussion on supplemental lighting should consider the effects of solar radiation on the light environment experienced by greenhouse crops. In addition, the greenhouse structure and a possible shading system will reduce the amount of solar radiation reaching the top of the plant canopy. The successful use of supplemental lighting for greenhouse plant production requires a careful design incorporating such elements as light intensity, light distribution and uniformity, cost of operation, and system maintenance. When measuring light for plant production, it is important to use the correct unit of measurement, the appropriate type of sensor, and the desired placement of light sensors. Computer control of the greenhouse light environment usually involves both lighting and shading systems, but in some cases also includes carbon dioxide enrichment.

Solar Radiation

Just outside the atmosphere, the earth is receiving an almost constant amount of solar radiation from the sun. The amount of radiation that penetrates the atmosphere and reaches the surface of the earth depends on the composition of the atmosphere (clouds, dust particles, and gaseous constituents), the location on earth (latitude and elevation), and the season (solar elevation above the horizon and daylength). The radiation the earth receives from the sun is usually called short-wave radiation and includes radiation with a wavelength between roughly 300 and 3,000 nanometer (nm, or 10^{-9} meter). All bodies with a temperature above absolute zero Kelvin (-273.15°C or -459.67°F) radiate energy to each other. Bodies at temperatures which are common on earth (15°C or 59°F) radiate so-called long wave radiation (approximately 3,000-100,000 nm). The magnitude of long-wave radiation depends on the temperature difference between radiating objects and their surface emittance (a material specific coefficient). The amount of solar radiation is usually much larger than the long-wave radiation (except at night). However, only part of the solar radiation is used by plants for photosynthesis. This so-called photosynthetically active radiation (PAR) contains the wavelengths between 400 and 700 nm and falls just within the so-called visible spectrum (380-770 nm) which we can see with our human eyes. The total visible spectrum is perceived by humans as white light, but with the help of a prism white light can be separated into a continuous spectrum of colors: from violet to indigo, blue, green, yellow, orange, and red (from the smaller to the larger wavelengths). Plants roughly use from blue to red light as their energy source for photosynthesis. The amount of energy contained in light is inversely proportional to the wavelength (in other words: the larger the wavelength, the less energy). This means that blue light contains more energy than red light and that plants would need less blue light compared to red light for the same photosynthetic response. However, plants are less sensitive to blue light compared to red (the maximum sensitivity for photosynthesis is at approximately 675 nm).

On a clear and sunny day, the solar radiation starts off slowly at sunrise, followed by a rapid increase till the sun reaches its highest position above the horizon (solar noon). Solar noon does not always coincide with noon on the (local) clock because of our conventions for keeping time (e.g., time zones and possible daylight saving time). After solar noon, the solar radiation declines rapidly. The decline continues more gradual towards sunset. The bell-shaped curve of solar radiation on a clear and sunny day is shown in Figure 1. The shape of this curve changes depending on the location on earth and the season. Of course, not all days of the year are clear and sunny, so the amount of solar radiation received varies from day to day. Therefore, it is sometimes easier to consider the total amount of light received during, e.g., a 24-hour period compared to instantaneous (e.g., minute-by-minute) light levels. The total amount of light is usually referred to as the integrated (or summed) light. Figure 1 also shows the integrated light for a clear and sunny day (it starts at zero at sunrise and reaches its maximum at sunset).

Greenhouse Structure

Once the solar radiation reaches the surface of the earth, the greenhouse structure is the next obstacle it has to pass through. Framing members and glazing bars are usually opaque and absorb or reflect all the light that falls on them. The same is true for the gutters. In addition, shade curtains, electric conduits, water lines, heating equipment and pipes, horizontal airflow fans, and supplemental lighting are installed near the top of the greenhouse, all of which block light from reaching the plants inside. In some cases, evaporative cooling pads and ventilation fans are installed in the sidewalls, which further reduce the amount of solar radiation. All added up, a very significant amount of solar radiation available outside the greenhouse will never reach the plants inside (30% for newer, 50% and higher for older greenhouses). Especially during the darker months of the year when the solar elevation above the horizon is low and the days are short, the greenhouse structure and the various systems installed can block large amounts of light from reaching the plants. Finally, the choice of greenhouse cover (glass or plastic) will have an impact on the amount of light transmitted.

Shading

Most greenhouse growers use some kind of shading technique to grow their crops successfully. The goal is to reduce the amount of sunlight reaching a crop or to shorten the photoperiod. The latter technique requires a heavy-duty shade cloth that blocks all outside light from entering the greenhouse. Whether the cloth is applied manually or with a (computer controlled) mechanical system, it is important that all entry points for light are completely covered. The technique for reducing the amount of sunlight in the greenhouse is usually simpler. One can apply a shading compound or fabric on the inside or outside of the greenhouse. The shading compounds are frequently applied in the Spring and removed in the Fall. Fabrics can be installed to remain in place part or most of the year and can be operated manually or mechanically (in that case usually controlled by a computer system). Some shade fabrics are designed so that they, once deployed, act as an energy curtain by preventing warm greenhouse air from rising all the way to the greenhouse roof and cooling down against the colder cladding material.

Supplemental Lighting

Especially at the higher latitudes, and during the darker months of the year, the amount of solar radiation reaching the plants in a greenhouse is insufficient to sustain adequate growth rates. Some growers decide not to use the greenhouse during such conditions, while others use supplemental lighting to boost plant production. Without careful analysis of all economic factors involved, the use of supplemental lighting is frequently perceived as too expensive. It is true that these systems are expensive to install and operate, but crops grow considerably faster during a period of the year when prices are generally (much) higher. If a grower is not convinced the use of supplemental lighting can be profitable, a small-scale trial might be a good way to investigate the possibilities without major capital expenses.

When installing supplemental lighting systems in greenhouses, several factors should be considered. First, the (average) amount of solar radiation for the location should be investigated. This will give an idea of the range of solar radiation conditions at the site. An example of such radiation data is given in Figure 2 for Ithaca, NY. Second, as discussed before, the type of greenhouse structure and cover will have an impact on the transmission of sunlight. Third, the type of crop (or crops) grown in the greenhouse will point to the plant requirements (such as light intensity, duration, or light integral), and the available space in the greenhouse to hang lamps (less space is available for taller crops in lower greenhouses resulting in loss of light uniformity). Next, the plant requirements should be compared to the available amounts of sunlight to calculate the necessary amounts of supplemental lighting. It is usually not economical to install lighting systems which provide high light intensities in greenhouses because of the large number of lamps required. Therefore, supplemental lighting systems can be designed to provide a certain light integral during a 24-hour period such that the sum of the supplemental light integral and the solar radiation integral meet the plant requirements for even the darkest day of the year. The light integral supplied by the supplemental lighting system depends on the average light intensity provided by the lamps and the duration of operation. The light intensity supplied by commercial supplemental lighting systems usually is not higher than 200 $\mu mol\text{-}m^{-2}\text{-}s^{-1}$ (or 0.72 $mol\text{-}m^{-2}\text{-}hr^{-1}$, or 17.3 $mol\text{-}m^{-2}\text{-}(24\ hour)^{-1}$). These units of measurement will be explained in the next section.

In addition to light intensity, light uniformity is an important factor to consider when designing lighting systems for greenhouses. In general, except when clouds are passing overhead or when structural elements create shading patterns, sunlight is uniform from one location to the next inside a greenhouse. However, due to the distance between lamps and the distance between the lamps and the crop, supplemental lighting systems will always provide non-uniform lighting patterns over a plant canopy. It is the task of the designer to optimize light uniformity by carefully calculating the light distribution from each lamp and the different paths the light can travel from each lamp to the crop underneath. Fortunately, computer software programs exist to assist the designer with this complicated task and, in general, a careful design results in very acceptable light distribution and uniformity over a crop canopy.

In order to make the operation of a supplemental lighting system as economical as possible, these systems are sometimes operated exclusively during periods of the day with off-peak electricity rates (e.g., from 10:00 pm to 6:00 am). However, during the darker months, this could result in two light periods for a crop during every 24-hour period (one starting at sunrise, ending at sunset, and followed by a (short) dark period; the other continuing with the supplemental lighting period, and followed by a brief dark period before sunrise). Not every crop might thrive under these conditions. Some crops require an extended dark period (e.g., tomatoes), resulting in the use of supplemental lighting during hours of the day with more expensive electricity rates. Careful (computer) control of the operation of lighting systems will help reduce electricity costs.

Maintenance of supplemental lighting systems is important and should not be overlooked. Just like any other piece of equipment, failures do occur and need to be corrected as soon as possible. Lamp failures create non-uniform light distribution patterns, which can quickly lead to non-uniform plant production. In addition to incidental failures, the light output of lamps slowly degrades over time. The rate of degradation depends on the type of lamp used and the operating conditions (e.g., temperature). Knowing the approximate rate of degradation (check with the manufacturer), a lamp replacement schedule can be developed such that the overall light intensity does not drop below acceptable levels. Instead of replacing all the lamps at once (which can be expensive), lamps can be replaced in groups (e.g., one greenhouse bay at-a-time, or, better yet, every other lamp or every other third lamp, etc.).

Units of Measurement

The currently preferred unit of measurement for light is $\mu mol\text{-}m^{-2}\text{-}s^{-1}$ (pronounced: 'micromol per meter squared per second'). This unit expresses an amount of photons (or quanta) of light incident on a unit area (m^2) per unit time (second). A photon is defined as the smallest particle (or unit) of light. In order for a common light sensor to display a meaningful reading, a very large number of photons are needed to sufficiently activate the sensing element. Therefore, Avogadro's number ($6.023 * 10^{23}$) of photons is defined as a 'mol' of light. A 'micromol' (μmol) is defined as one millionth (10^{-6}) of a mol.

The amount of PAR (400-700 nm) the plants receive is expressed in the unit of $\mu mol\text{-}m^{-2}\text{-}s^{-1}$. The sensors used to measure PAR are called quantum sensors and have carefully designed filters such that no light outside the PAR waveband is measured. As explained before, the human eye is able to detect light in a slightly larger waveband of approximately 380-770 nm. To measure light in this waveband a foot-candle meter (or a lux meter) can be used. But measurements with a foot-candle meter include some light with a wavelength which falls outside the waveband used by plants for photosynthesis (PAR). Therefore, using a foot-candle meter introduces some error when interested in only measuring the amount of light available to plants for photosynthesis. It is for this reason that the use of a foot-candle meter is not recommended when evaluating the light environment for plant production. It is possible to convert a measurement taken with a foot-candle meter into a $\mu mol\text{-}m^{-2}\text{-}s^{-1}$ value, but the correct conversion factor depends on the light source and is, in the case of mixed light sources, not always easily determined.

Sensors

As with all sensors in the harsh outdoor and greenhouse environments, light sensors need to be checked and calibrated on a frequent schedule. Usually, important decisions about closing a shade curtain or starting the supplemental lighting system are based on readings performed with a light sensor. Errors in sensor readings will result in erroneous decisions, which can lead to (subtle) changes in plant growth and development. And, since a sensor reading error is usually not the first suspected cause of a particular production problem, it is clear that sensor errors should be avoided as much as possible. Usually, the manufacturer recommends certain maintenance procedures (e.g., cleaning and removal of obstructions) and indicates the time between and procedures for calibrations. When light sensors are a critical part of the greenhouse operation, it can make sense to install more than one sensor for redundancy or for a better approximation of the light environment (when the sensor readings are averaged).

As explained earlier, the unit of light is expressed in $\mu mol\text{-}m^{-2}\text{-}s^{-1}$, or in other words, in the number of photons incident on a unit area per unit of time. A parallel beam of light of a fixed cross-sectional area (e.g., 1 m^2) will cover the same cross-sectional surface area (1 m^2) when it hits the surface perpendicularly. But when this light beam with the same cross-sectional area intersects the surface at an angle, the illuminated surface area will be larger. In fact, the larger illuminated area is inversely proportional to the cosine of the angle between the beam and a plane normal (i.e., perpendicular) to the surface. And, since the same number of photons are spread out over a larger area, the light intensity is less and proportional to the cosine of the angle between the beam and a plane normal to the surface. Sunlight or supplemental light reaches the plants at different angles and, therefore, the intensity is proportional to the cosine of the angle between the incoming light and a plane normal to the (leaf) surface. Light sensors, which are able to account for the directionality of the incoming light, are said to be "cosine-corrected" and are highly recommended for accurate light measurements.

Placement of the Sensors

In general, light sensors inside the greenhouse should be placed at the top of the canopy. This is a challenge for tall growing crops when the sensor has to be moved as the crop matures. However, failure to position the sensor at the top of the canopy results in readings, which are influenced by the shape and structure of the foliage. Since the foliage is changing continuously, the influence on the sensor reading changes continuously. This will make any interpretation of the readings difficult at best. Placement of an outdoor sensor is usually straightforward as long as any adjacent structure or trees will not shade the sensor. Maintenance on outdoor sensor is usually a little more complicated because the sensors are more difficult to reach. However, outdoor sensors will have the same problems as indoor sensors and their maintenance and calibration should not be neglected.

Figure 3 shows the instantaneous light level measurements with two light sensors at two different locations (East and West) inside a new greenhouse equipped with overhead heating pipes, retractable shade screen, horizontal airflow fans, and supplemental lighting. The sensors are placed asymmetrically within two different greenhouse segments (each segment measures 12 by 21 feet) and away from the end walls so that the shading of the sensors due to structural elements occurs at different times of the day. The measurements of the sensors are averaged in order to estimate the overall light intensity in the entire greenhouse. A symmetric placement of the sensors within two different greenhouse segments would result in the sensors being shaded or fully exposed to the sunlight at the same time. The asymmetric placement of the sensors ensures the average measurement is a better approximation of the light intensity in the entire greenhouse. Using even more light sensors in the greenhouse would further improve the characterization of the true light environment, but is usually too costly and would further increase sensor maintenance (calibration).

Light and Shade Control

For some crops, and especially for the vegetative growth phase, a (linear) relationship exists between total amount of light received and plant growth. This relationship brought forth the idea of providing plants with the same light integral (or light sum) every day of the year and independent of the amount of solar radiation received. Whenever the amount of light provided by sunlight would be less than the target light integral, the remainder would be added with a supplemental lighting system. And whenever a crop would be in danger of receiving more than the target light integral, a shade curtain would be deployed. Controlling such a lighting system with the goal of providing the exact same light integral every day of the year is only feasible with the help of computer software. Such software was recently developed and it enables the computer to keep track of the amount of light received since sunrise. By comparing the amount of light received with a calculated prediction of the total amount of sunlight received at sunset and knowing the desired daily light integral, the computer determines when to operate the lighting or shading system. It was found that such a control program needs to decide which system to operate only once every hour, minimizing the daily number of on/off cycles for these systems. Simulation runs with the developed software were very successful and the system is currently being tested in a commercial greenhouse operation. In addition to making sure the plants receive the same light integral every day, the control system also makes maximum use of the hours of the day with off-peak electricity rates to operate the supplemental lighting system.

Carbon Dioxide and Light

For photosynthesis, plants need both light (PAR) and carbon dioxide. Both need to be available in sufficient quantities for either one not to become the limiting factor (if there is enough light but not enough carbon dioxide, carbon dioxide becomes the limiting factor and vice versa). Therefore, when using supplemental lighting to increase plant production, it is important to maintain sufficiently high carbon dioxide concentrations inside the greenhouse. Especially during the colder months of the year, when (very) low ventilation rates are needed to maintain the desired greenhouse temperature, the carbon dioxide concentration inside the greenhouse can drop significantly because little or no fresh air (with more carbon dioxide) enters the greenhouse. Under these low ventilation conditions, it may be economically feasible to boost the carbon dioxide concentration inside the greenhouse to levels as high as three times the ambient concentration (from 350 to 1000 parts per million) resulting in increased photosynthesis and, thus, plant growth. Research indicated that, within certain limits, it is possible to reduce the daily required light integral, while, at the same time, increasing the carbon dioxide concentration for the same overall plant production. This result points to possible significant savings because adding carbon dioxide to the greenhouse environment is cheaper than adding supplemental light (needed to reach the required light integral). Computer control software is needed to assist the grower with the decision when to add carbon dioxide to the greenhouse, what target concentration should be used, and when to operate the supplemental lighting system. During the warmer months of the year, when (significant) ventilation is required to maintain the target greenhouse temperature, carbon dioxide enrichment is not cost effective because the released carbon dioxide would be immediately exhausted from the greenhouse.

Additional Reading

Albright, L.D. 1998. Method for controlling greenhouse light. United States Patent number 5,818,734.

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Both, A.J., L.D. Albright, R.W. Langhans, B.G. Vinzant, and P.N. Walker. 1997. Electric energy consumption and PPF_i output of nine 400 watt high pressure sodium luminaires and a greenhouse application of the results. Acta Horticulturae 418:195-202.

Both, A.J. 1994. HID lighting in horticulture: a short review. Presented at the Greenhouse Systems: Automation, Culture, and Environment (ACESYS I) Conference, July 20 - 22. New Brunswick, NJ. Northeast Regional Agricultural Engineering Service Publication No. 72. Riley-Robb Hall, Cornell University, Ithaca, NY 14853. pp. 208-222.

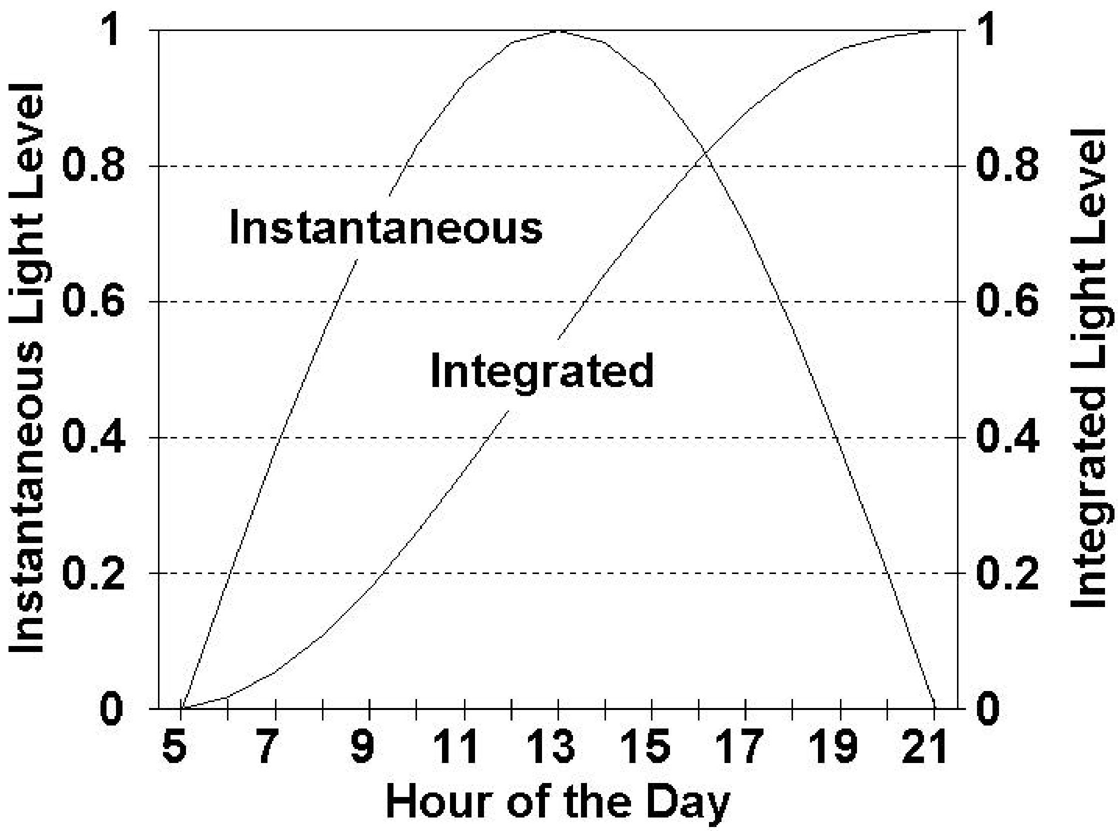

Figure 1. Normalized instantaneous and integrated light levels (sunlight only) for a clear and sunny day with a 16-hour light period.

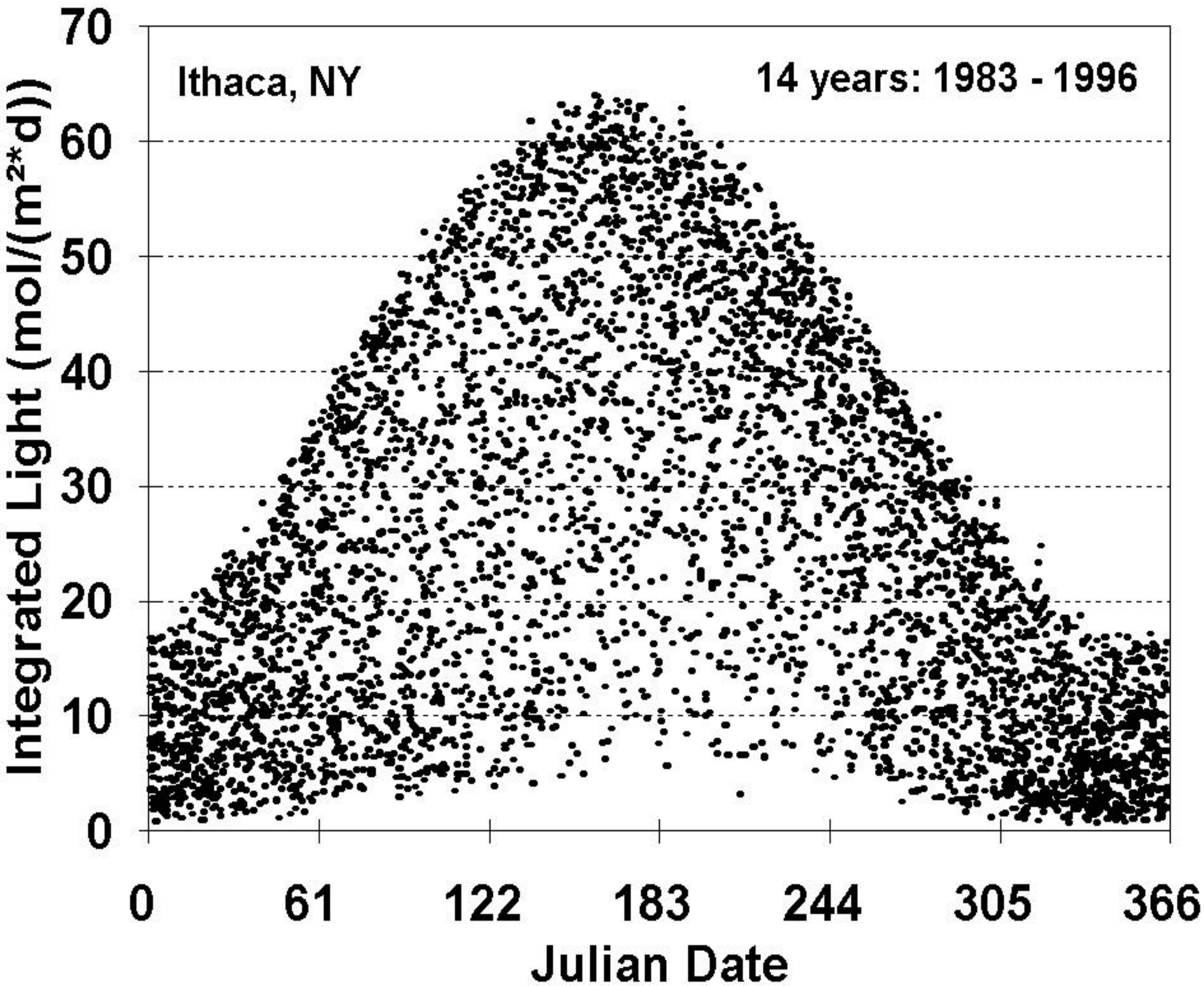

Figure 2. Daily outdoor integrated light levels for a 14-year period for Ithaca, NY. Note especially the large difference between the very darkest and brightest measurements, and the fact that some summer days can be just as dark as some of the darker winter days.

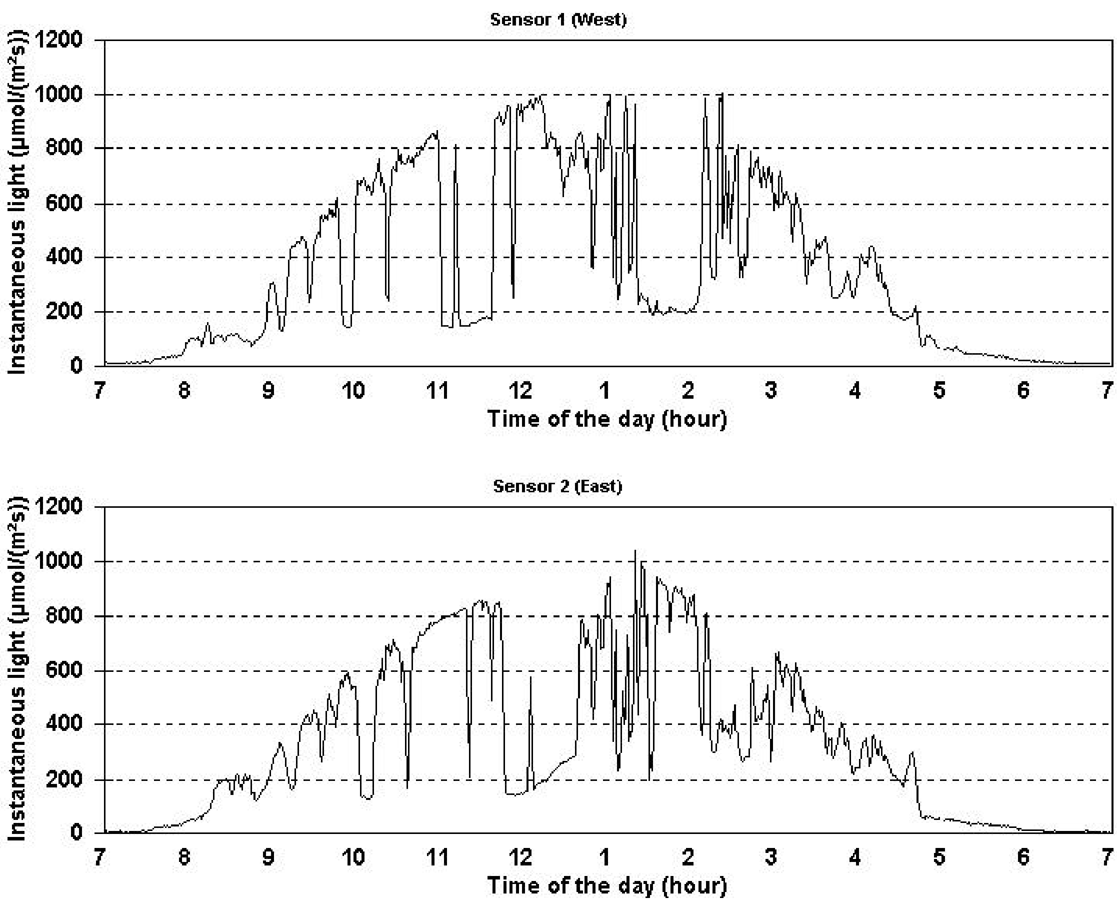

Figure 3. Instantaneous light levels measured with two light sensors in two different locations inside a greenhouse and for a 12-hour measuring period. Note that the sensors are, for the most part, not shaded (by the greenhouse structure) at the same time so that their averaged reading gives a better approximation of the overall light environment in the greenhouse.