# Open-roof Greenhouse Design and Operation

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## Abstract

An open-roof greenhouse production system with a heated ebb and flood floor irrigation system is being developed and evaluated. In addition to continuous roof vents, the greenhouse is equipped with sidewall vents to allow for ventilation during windy and rainy conditions. This paper discusses the design details as well as the instrumentation used for the evaluation. Preliminary data, collected over a 2.5-month period, of light and temperature conditions are presented. The greenhouse temperature closely followed outside temperature conditions for the entire measurement period when the inside temperature exceeded the set point. The inside light conditions were significantly affected by the greenhouse structure, and inside light intensities around solar noon could exceed outside light intensities due to reflection from the opened roof segments.

## Introduction

Growers have known for many years the value of growing outside in the spring to harden off plants. Cold frames were an important but labor-intensive part of that system. Plastic greenhouses gave growers a low-cost option of producing spring plants and largely replaced cold frames with a larger and more easily accessible form of plant production structure. Some form of ventilation is required however, to reduce high temperatures that occur in these and other glazed structures. Moving plants outside the greenhouse on rolling transportable benches is one solution and allows for growing in full sun under outside temperatures. The problem is the considerable labor involved with this method, especially in large production facilities. Recent greenhouse designs have provided for retractable roof greenhouses allowing hardening off while the crop remains in place. The early designs utilized thermal screens installed in greenhouses without glazing. Newer designs are traditional A-frame greenhouses with articulating roofs that either hinge at the gutters and open at the peak or hinge at one gutter and the peak while opening at the opposite gutter and moving across the greenhouse bay (Figure 1).

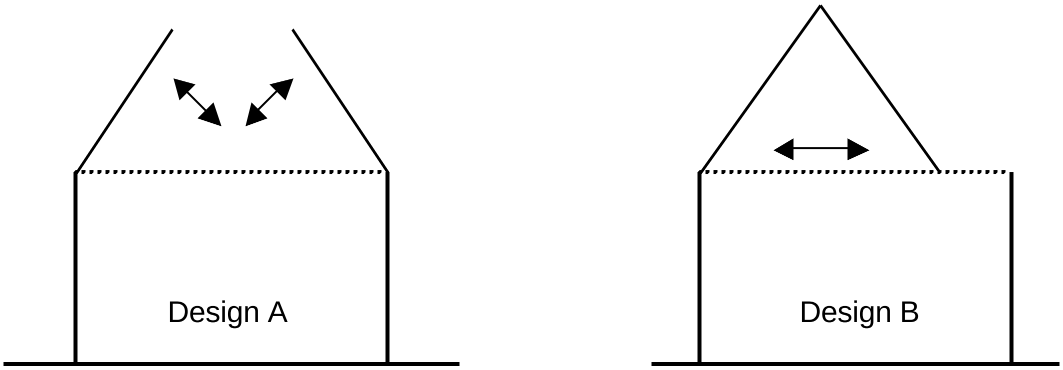

Figure 1. Two different designs of open-roof greenhouses.

There has been increased interest by growers in this new technology and many have begun utilizing it in their production facilities. One greenhouse manufacturer indicated that 75% of greenhouse construction inquiries deal with open-roof designs. The reaction from the growers is that they are very happy with the performance of these structures but there is a need to quantify this performance objectively. Many researchers have attempted to quantify the natural ventilation performance in different greenhouse designs (Boulard et al., 1997; Papadakis et al., 1996; Wang and Deltour, 1999), and different methods have been utilized, for example the tracer gas technique (Baptista et al., 1999; Kittas et al., 1996), which estimates air exchange rates only, and computational fluid dynamics (Boulard et al., 1999; Lee and Short, 2001), which can model the velocity and direction of airflow in a structure. Much of this work has been done on the Venlo-type greenhouse structures as well as many different styles of plastic-covered, tunnel-type houses, commonly used in Mediterranean climates.

Therefore, there is a need to more closely study the performance of greenhouse designs such as those illustrated in Figure 1 (Roberts et al., 1999). In addition to understanding ventilation rates and air movement within these structures, it is important to understand what effects these structures have on temperature and light conditions, and ultimately, the crop. Some of the other issues related to these structures, which require better understanding, are shade screening when ventilation is needed, insect exclusion, and energy consumption.

For this purpose, an open-roof greenhouse (Van Wingerden Greenhouse Company, MX-II) has been constructed at Cook College, Rutgers University to provide research and demonstration opportunities investigating (1) a novel natural ventilation system utilizing an open-roof greenhouse design, and (2) a heated ebb and flood floor irrigation system. The open-roof design allows for inside temperatures to closely track outside temperatures as well as for the crop to grow (during some of the time) in direct sunlight. This may result in a shorter production time and in plants that are hardened-off sufficiently. Reduced power consumption compared to mechanical ventilation systems may also be an added benefit. The ebb and flood irrigation system allows for excellent nutrient supply to the crop, and because of its closed-loop design, virtually eliminates runoff of the nutrient solution while optimizing nutrient and water use. We intend to study this system so we can take full advantage of its benefits and mitigate or eliminate problems such as the spread of plant disease that could be inherent in this type of system. This paper describes the design and construction of the open-roof greenhouse, the equipment and instrumentation currently in use, and reports on some preliminary data we have collected at this early stage of our investigations.

## Structure, Systems, and Instrumentation

### Structure

The particular open-roof greenhouse described in this paper has roof segments that are hinged at the gutter and open at the peaks (Figure 2). The entire roof area can be opened by engaging four electric motors to drive rack and pinion systems. The greenhouse is 18.3 m (60 ft) long (gutter direction) and 17.6 m (58 ft) wide (gable direction). The gutters are oriented 15° to the east of north (Figure 3). The greenhouse consists of two 7.3 m (24 ft) bays with 1.5 m (5 ft) wide lean-to additions along the east and west sides. The gutter-to-gutter distance is 3.7 m (12 ft), the top of the gutter is 4.0 m (13 ft) above the solid concrete floor, and the peaks of the greenhouse rise 4.9 m (16 ft) above the floor. The distance between the trusses is 3.0 m (10 ft).

All vertical sidewalls, as well as the two lean-to roofs, are glazed with 8 mm thick, double walled, acrylic panels. The opening roof sections are glazed with two layers of air inflated polyethylene film.

## Systems

### 1. Ventilation

Natural ventilation occurs when the roof sections are opened in continuous stages depending on the inside temperature deviation from the set point, and to a lesser extent on the outside temperature and solar radiation. When the roof sections are fully opened, approximately 215 $m^2$ (2,313 $ft^2$) of opening area is created, or 66% of the total greenhouse floor area. In addition to the open-roof, sidewall vents have been installed in the two 18.3 m (60 ft) long sidewalls. These side vents are 17.7 m (58 ft) long, hinge at the eaves of the lean-to roofs, and are 1.1 m (44 in.) high. Each side vent, when fully opened, provides approximately 19.5 $m^2$ (209 $ft^2$) of ventilation opening, or 6% of the total greenhouse floor area. The side vents can be utilized when opening the roof is prevented, by either high winds or rain. Six electric motors are used to open and close the four roofs (eight roof segments) and two side vents.

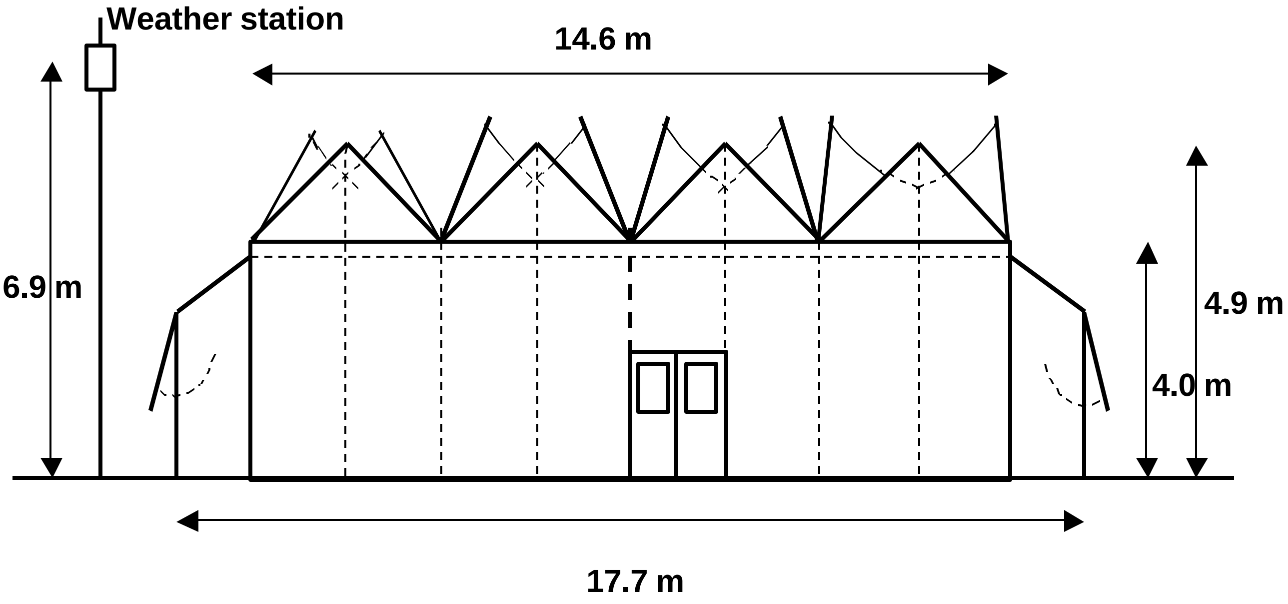

Figure 2. Side view of the greenhouse south wall (not to scale).

### 2. Heating

A 10 cm (4 in.) thick concrete floor was constructed with 2.5 cm (1 in.) polypropylene pipe placed on 30 cm (12 in.) centers embedded in the lower third of the concrete (Figure 3). Once completed, warm water (approximately 38º C, or 100º F) will circulate through the floor heating pipe providing heat close to a crop grown directly on the floor. The floor is divided into two heating zones (east and west), each with its own circulating pump and mixing valve so that the temperature of each floor can be individually controlled. Overhead and perimeter heating pipe will be used to provide the balance of the total heat requirement for the greenhouse. Hot water will be provided by a 139 kW (475,000 Btu/hr) gas-fired boiler.

## 3. Water and Nutrient Supply

Integrated in the floor heating system is an ebb and flood irrigation system. The greenhouse was divided into two independent growing areas, each measuring 100 $m^2$ (1,080 $ft^2$; 45 by 24 ft). Each growing area was connected to a 1,500-gallon concrete tank, which was installed just below the floor of the south walkway, to hold the nutrient solution. Underneath each growing area, two 10 cm (4 in.) diameter PVC pipes (spur lines) were placed just below the floor at a distance of 1.83 m (6 ft) from the sides of the growing area, and running parallel to the gutters. These spur lines are connected to the nutrient solution tanks by a 15 cm (6 in.) diameter PVC header pipe. The concrete floor was poured over these distribution pipes in such a way that the top of the floor's cross section is in the shape of a "W", with the lowest elevation of the floor surface positioned directly on top of the spur lines (Figure 4). The floor rises 1.6 cm (5/8 in.) towards the sides and the middle of the floor. After the floor was poured, 3.8 cm (1.5 in.) diameter holes positioned 46 cm (18 in.) apart, were drilled through the concrete floor and into the top of the spur lines. In each nutrient solution tank, two (2 HP) submersible pumps, each capable of pumping 8.8 L $s^{-1}$ (140 gpm) at 3 m (10 ft) of head, pump the solution through the header pipe, spur lines, and finally out the drain holes onto the floor. A 7.5 cm (3 in.) tall rubber

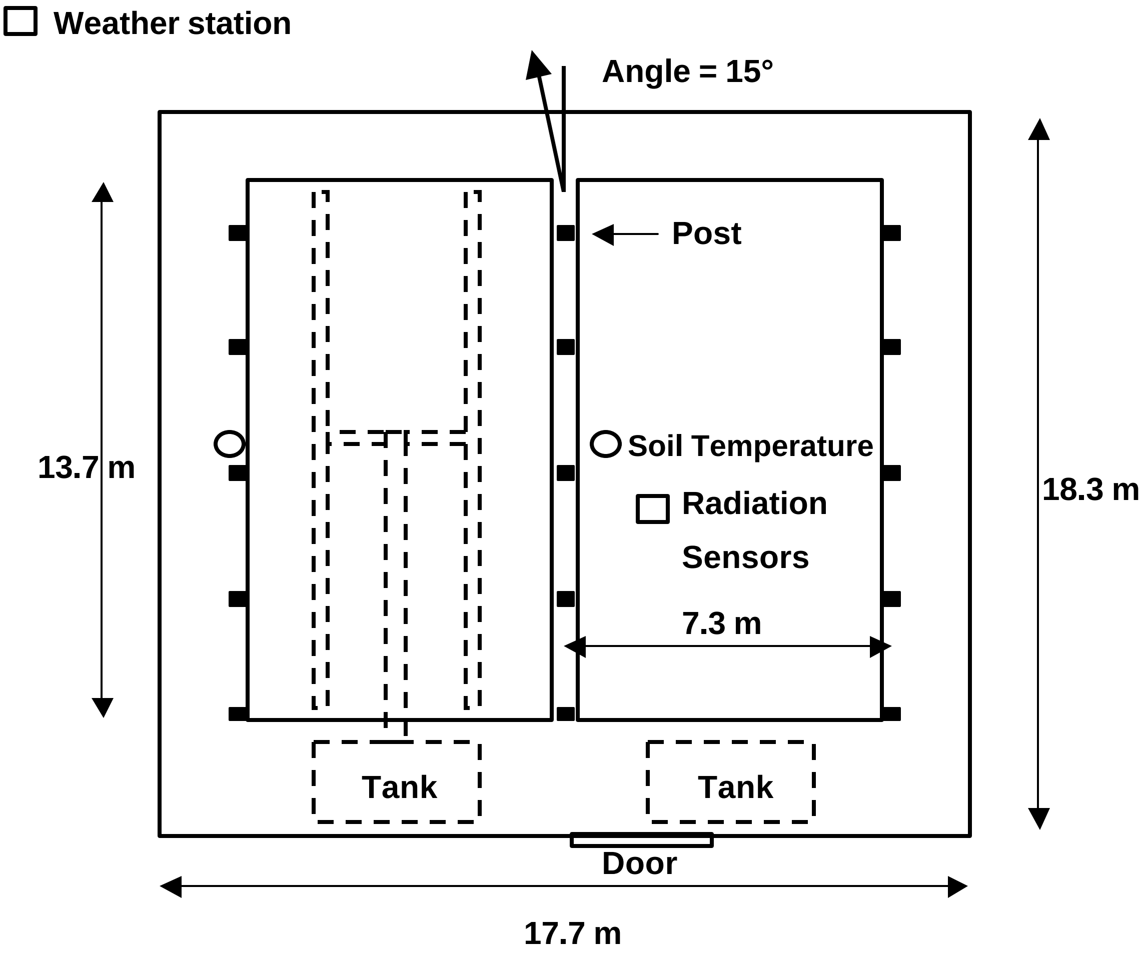

Figure 3. Greenhouse layout (not to scale).

dam placed in a groove cut in the concrete floor along the perimeter of the growing area contains the nutrient solution once it has been pumped onto the floor. After the floor is flooded, the pumps shut off, and an air actuated valve located inside the nutrient solution tank opens and allows the solution to return to the tank by the force of gravity. After each irrigation cycle, make-up water is added to the tanks after it is enriched with nutrients by a concentrated stock solution injector system. The two completely independent nutrient solution systems allows each growing area to have its own nutrient solution concentration, flooding frequency, flooding duration, and flood depth.

### 4. Control

An Argus control system was installed to provide computerized environment control as well as data acquisition from the various sensors located in and outside the greenhouse. The Argus system controls all mechanical systems and provides a record of, for example, mixing valve position, vent window opening, or how long a pump or motor is on. Each day all data logged by Argus is written to a file and stored for future retrieval.

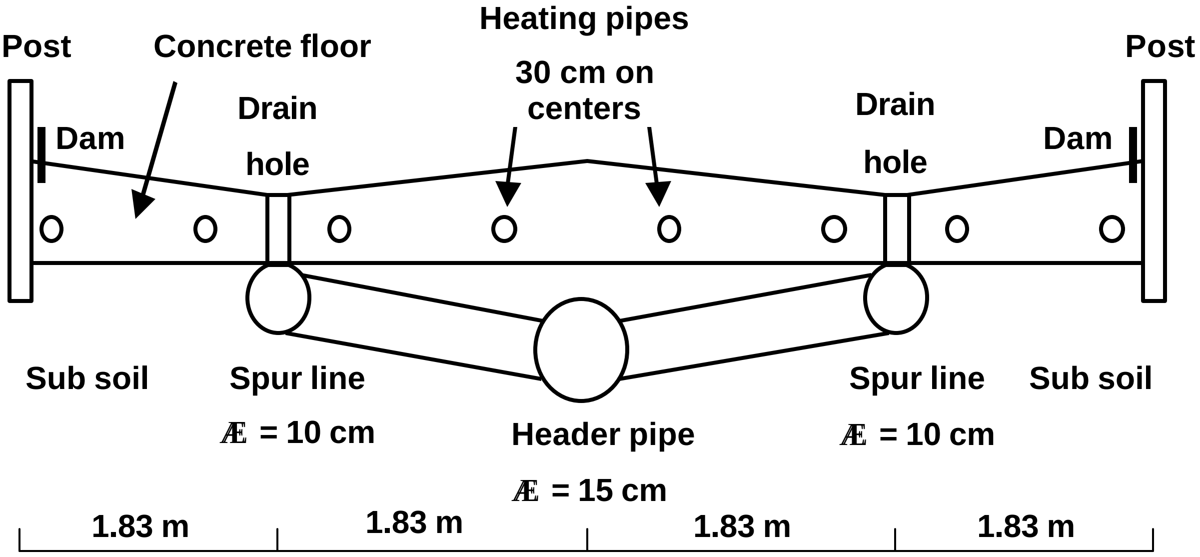

Figure 4. Cross sectional view through the heated concrete ebb and flood floor (not to scale).

### *Instrumentation*

A weather station mast was installed to hold a variety of sensors to measure outdoor conditions. The 7.9 m (26 ft) mast is equipped with instrumentation to measure the following parameters: temperature, relative humidity, wind speed and direction, and rain detection. In addition, a LI-COR quantum sensor was installed to measure photosynthetically active radiation (PAR, with wavelengths between 400 and 700 nm), as well as an Eppley precision pyranometer to measure total solar radiation (short wave, with wavelengths between 280 and 2,800 nm). Inside the greenhouse, temperature is measured at three different heights: 1.2, 2.4, and 3.6 m (4, 8, and 12 ft) above the floor. A LI-COR quantum sensor, an Eppley precision pyranometer, and a Micromet net radiometer (measuring wavelengths between 250 and 60,000 nm) are mounted at 1.2 m (4 ft) above the floor, and underneath one of the roof ridges, to measure radiation conditions inside the greenhouse. All radiation sensors have been calibrated in the summer of 2000 using the “Instrument Package” provided by the NCR-101 Committee on Controlled Environment Technology and Use. At two locations, one near the center of the greenhouse and one near the west wall, temperature sensors were installed below the floor surface. In each of these two locations, the temperature is measured at the outside surface of a heating pipe, as well as soil temperatures at the following depths: soil surface (just below the concrete floor), 15 cm, 30 cm, and 60 cm (0.5 ft, 1 ft, and 2 ft) below the soil surface. In the center location, an additional sensor was placed at 90 cm (3 ft) below the soil surface.

## Preliminary results

Shortly after the re-glazing of the greenhouse sidewalls was completed, measurements of the greenhouse and outside environment conditions were collected over a period of approximately 2.5 months (April 2–June 19, 2001, with the exception of some data on June 6). The environment control system recorded 15-minute averages of most relevant environment parameters. Figure 5 shows the daily light integrals, which were calculated from 15-minute averaged instantaneous light intensity readings. In addition to the daily inside and outside light integrals, the ratio of the daily light integrals is shown in Figure 5. Due to the fact that, usually around solar noon and during some time period of the day, the inside light sensor received direct sunlight (without passage through the glazing), this ratio cannot be defined as the greenhouse light transmission.

Figure 6 shows the set point temperature during the data collection period: 18.3°C or 65°F. In addition, Figure 6 shows the average daytime greenhouse temperature (calculated from 15-minute average temperature readings and for the duration of the natural daylength). Finally, Figure 6 shows the average daytime roof opening (0% is fully closed, 100% is fully opened, i.e., in an almost vertical upright position). Note that the control system operated the position of the roof based on the temperature deviation from the temperature set point (18.3°C or 65°F), and to a lesser extend based on the outside temperature and solar radiation.

Figure 7 shows a correlation between the ratio of the inside and outside light integral and the average daytime roof opening. The calculated regression equation has an $R^2$ value of 0.60.

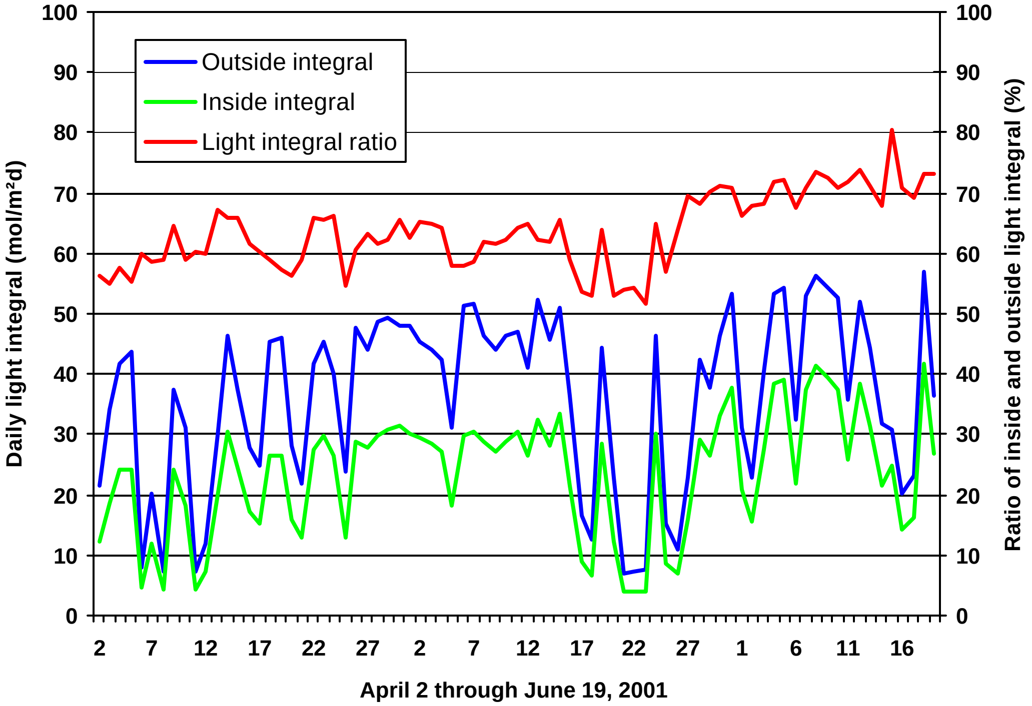

Figure 5. Daily inside and outside light integral and their ratio for a 2.5-month period.

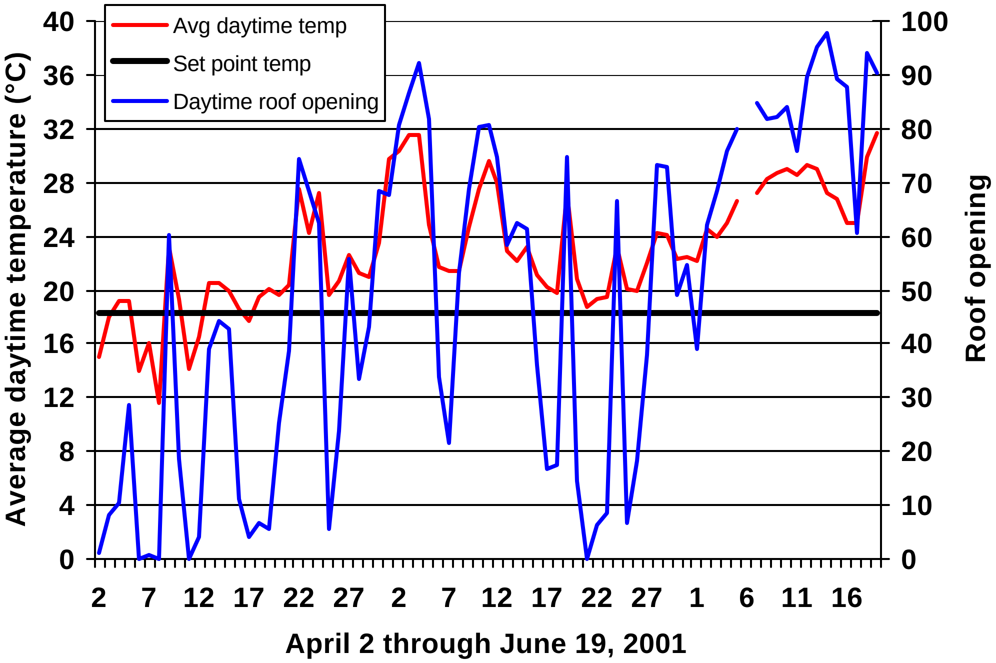

Figure 6. Average daytime temperature, temperature set point and roof opening for a 2.5-month period.

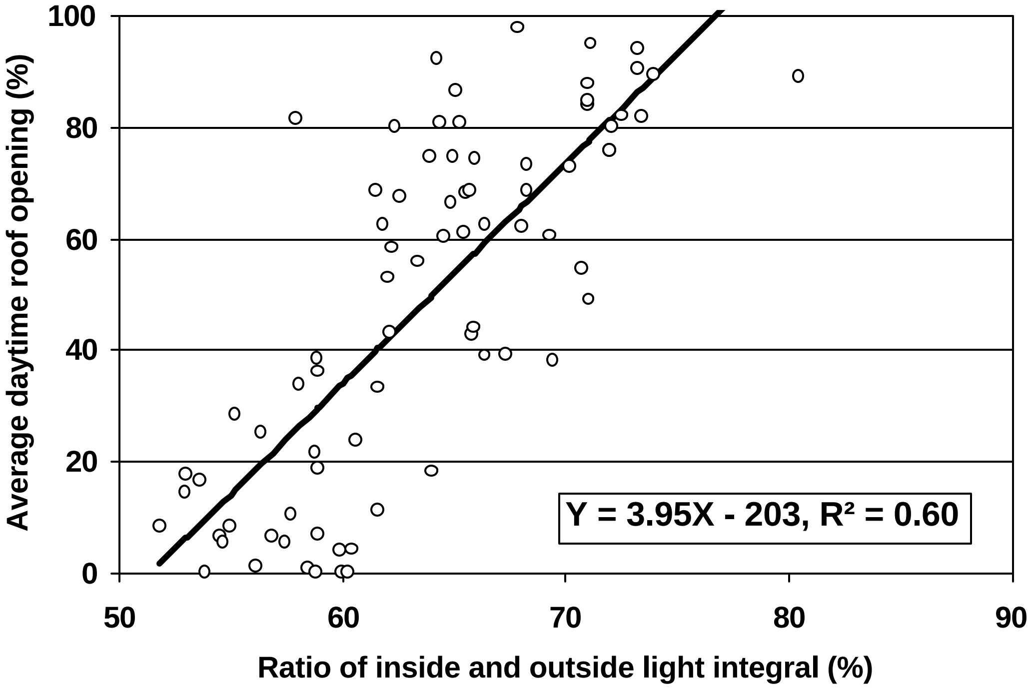

Figure 7. Correlation between the ratios of inside and outside light integrals and the average daytime roof opening.

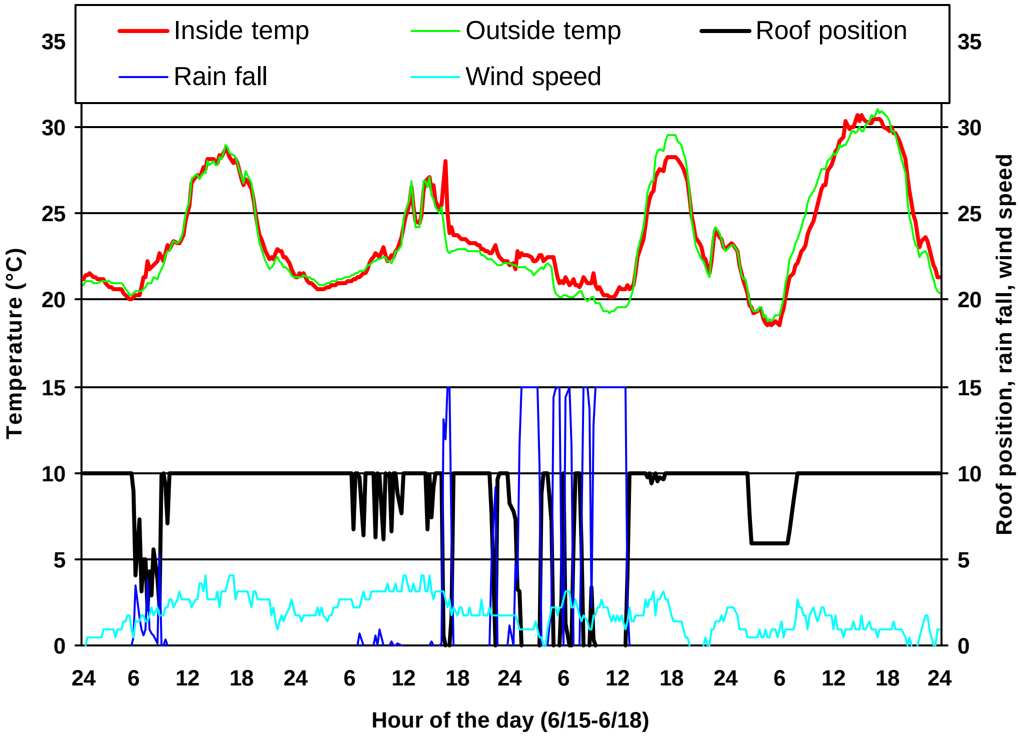

Figure 8. Greenhouse inside and outside environment conditions for a 4-day measuring period.

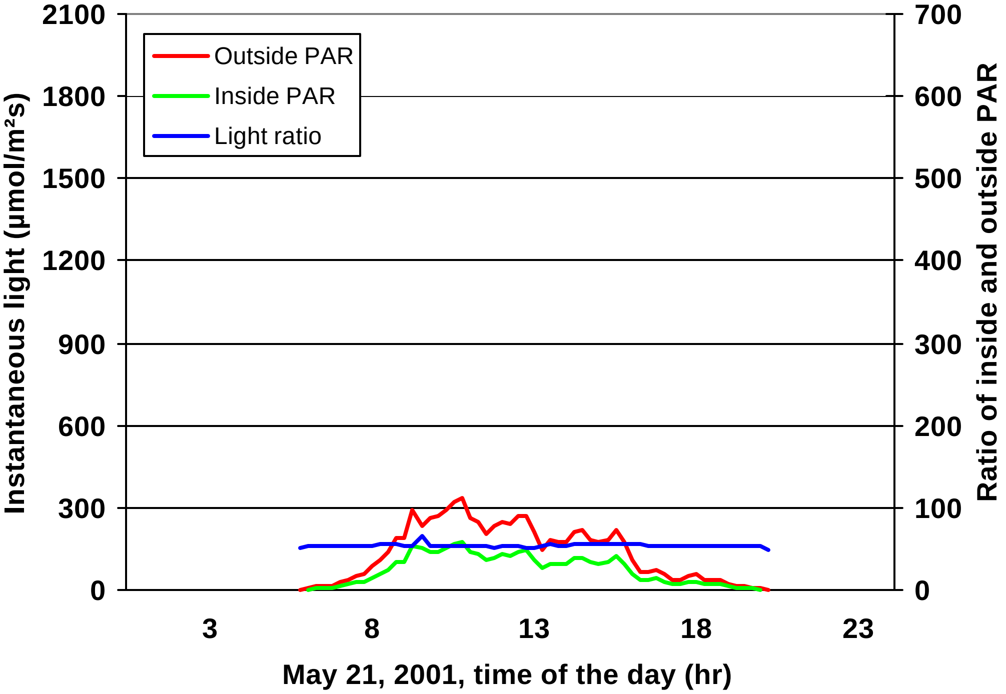

Figure 9. Instantaneous (15-minute averages) inside and outside light conditions and their ratios for May 21, 2001 (very cloudy day).

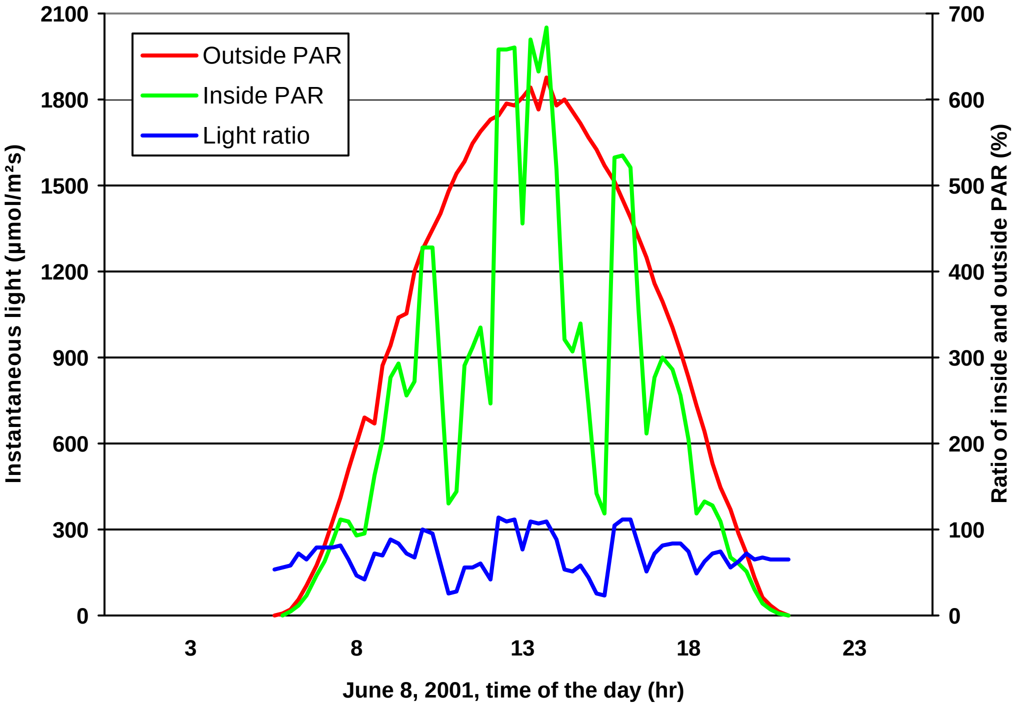

Figure 10. Instantaneous (15-minute averages) inside and outside light conditions and their ratios for June 8, 2001 (very sunny day).

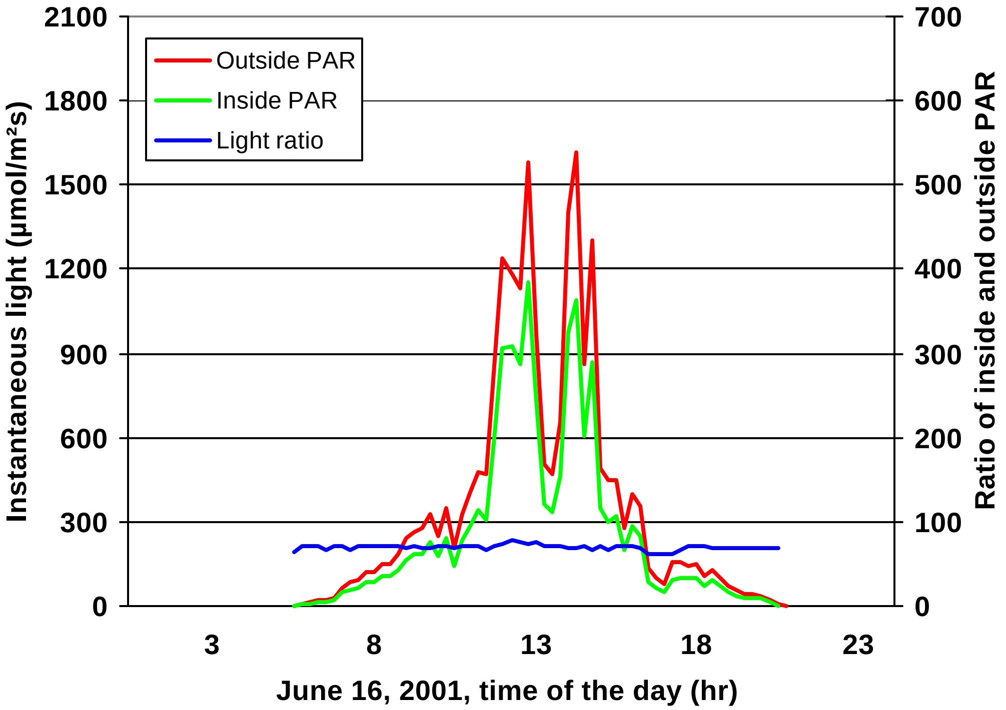

Figure 11. Instantaneous (15-minute averages) inside and outside light conditions and their ratios for June 16, 2001 (variable cloudy day).

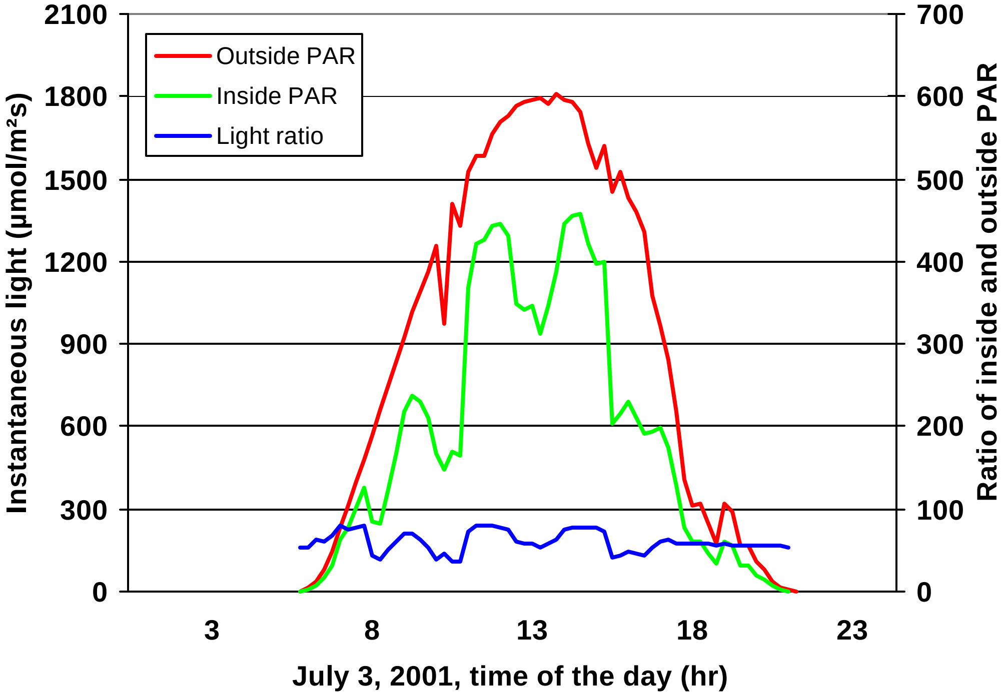

Figure 12. Instantaneous (15-minute averages) inside and outside light conditions and their ratios for June 16, 2001 (sunny day, with the roof closed on purpose).

Figure 8 shows a “snapshot” of some of the greenhouse conditions (15-minute averages) during a 4-day period (June 15-June 18). The indoor (1.2 m or 4 ft above the floor) and outdoor (at the weather station) temperatures closely follow each other in the range from approximately 18 to 31ºC (65-88ºF). In addition, Figure 8 shows the roof position (0 is fully closed and 10 is fully opened), rainfall (in minutes per 15-minute time interval), and wind speed (in m $s^{-1}$). Significant time periods with rain were recorded during June 16 and 17, resulting in complete closure of the roof, and simultaneous opening of the side vents (data not shown). High wind speeds during the morning hours of June 16 also resulted in (some) roof closure. Cooler temperatures during the very early hours of June 18 caused the roof to be closed from a fully open position to approximately 60% open.

Figures 9, 10, 11, and 12 show 15-minute averages of inside and outside instantaneous light intensities (PAR) and their ratio. May 21 (Figure 9) was a very cloudy day with a low light integral (only 3.8 mol $m^{-2}$ $d^{-1}$ inside the greenhouse). The heavy cloud cover resulted in mostly diffuse radiation and a constant instantaneous PAR ratio of approximately 54%. June 8 (Figure 10) was a sunny day with few clouds. The large amount of direct radiation caused clear shadow patterns (from the greenhouse structure, e.g., the gutters) inside the greenhouse and resulted in large fluctuations of the inside instantaneous light intensity. Interestingly, the light intensity inside the greenhouse, during several time periods, was higher than the outside intensities. This is caused by light reflection off the fully opened roof segments. For the entire day, the result was that the ratio of inside and outside light intensity (PAR) fluctuated significantly (the average ratio was 71% with an inside light integral of 41.3 mol $m^{-2}$ $d^{-1}$). On June 16 (Figure 11) the weather conditions were windy and cloudy, and the solar radiation was mostly diffuse. The light integral was 14.3 mol $m^{-2}$ $d^{-1}$, with a particular dark period around solar noon (13:00 hr), and (partial) roof closing before and after solar noon due to high wind speeds and/or rain (Figure 8).

Additional data were collected on July 3 (Figure 12), a day during which the roof was kept closed on purpose. Ventilation occurred by opening the side vents only. The light integral was 32.1 mol $m^{-2}$ $d^{-1}$. Comparing Figures 8 and 12 shows the different greenhouse light conditions for a sunny day (with mostly direct radiation) when the roof is fully opened (June 8) and when the roof is fully closed (July 3). On July 3, the average ratio of inside and outside light intensity (PAR) was 60% and it fluctuated significantly until later in the day, when cloud cover resulted in mostly diffuse solar radiation.

## Discussion and Conclusions

All results presented in this paper were collected from an empty greenhouse (without a crop). In addition, no greenhouse heating was required during any of the measurements conducted.

Although the data collected over the 2.5 month period are preliminary, they show that, on average, the greenhouse structure blocks a significant amount of light from reaching the crop despite the crop receiving several hours of unobstructed sunlight when the roof is opened. However, under (high) light conditions, the instantaneous light intensity can be higher inside the greenhouse compared to outside due to light reflection off the opened roof segments. Whether this additional light is useful for crop photosynthesis is questionable, especially when the crop already experiences light saturation conditions.

In order to evaluate the greenhouse light environment, the ratios of inside and outside light integral and instantaneous PAR intensity were calculated. The amount of roof opening was determined by the computer control system from the indoor temperature deviation from the set point (18.3ºC or 65ºF) and/or by rainfall or wind speed), and to a lesser extend determined by the outside temperature and solar radiation. On warm(er) and cloudy days, the greenhouse roof can be fully opened, while the solar radiation is mostly diffuse with a lower intensity (and integral). On such days, the PAR ratio is constant during the day, while on sunny days (with lots of direct solar radiation), the PAR ratio fluctuates considerably due to the shadow patterns created by the greenhouse structure. These different responses due to different light conditions make it more challenging to evaluate the light environment in an open-roof greenhouse. Ideally, these light data should be simultaneously collected in a conventional greenhouse design in order for a more meaningful comparison.

Future research will continue to investigate the benefits and potential drawbacks of open-roof greenhouses as well as floor heating systems in combination with ebb and flood floor irrigation.

## Acknowledgments

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