ELBESPARELSER I VÆKSTHUS-PRODUKTION MED JUSTERBARE LED LAMPER

AgroTech
Institut for Jordbrugs- og FødevareInnovation

Elbesparelser i væksthusproduktion med justerbare LED lamper

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Report for Elforsk. project PSO 340-040

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Titel Dk. ”Elbesparelser i væksthusproduktion med Justerbare LED lamper”
Titel Eng. “Energysavings in the greenhouse industry with controllable LED displays”

This report on the project consist of 6 parts:

1. **STRATEGIES FOR CONTROLLING ARTIFICIAL LIGHT IN GREENHOUSES**
2. **DESIGN AND DEVELOPMENT OF NEW LED SYSTEM FOR GREENHOUSE EXPERIMENTS**
3. **THE USE OF CHLOROPHYLL *A* FLUORESCENCE FOR ONLINE MONITORING OF PHOTOSYNTHESIS IN PLANT PRODUCTION IN GREENHOUSES**
4. **LEAF PHOTOSYNTHESIS IN STRONGLY FLUCTUATING LIGHT – IMPLICATIONS FOR LAMP CONTROL**
5. **LARGE-SCALE GREENHOUSE TEST OF LED-PROTOTYPE WITH DIFFERENT CONTROL STRATEGIES**
6. **EVALUATION OF STRATEGY AND RESULTS**

Each of the parts above is a milestone in the project plan, except part 4. which was added, when we knew that the chlorophyll fluorscence method was not going to work as a controlling agent for the use of light in plant production.

1. STRATEGIES FOR CONTROLLING ARTIFICIAL LIGHT IN GREENHOUSES

By Anker Kuehn, AgroTech, 18-12-2011

This part of the report summarizes the current strategies for controlling artificial light in the greenhouse industries.

In the 1980's artificial light was installed in most potted plant producing nurseries in Denmark. High-pressure sodium (HPS) lamps are dominating because of a high energy effiency (30%). High-pressure sodium lamps are developed for other purposes than plant production, which means that the spectral distribution is not optimal for plant growth.

Exchanging the high pressure sodium lamps with LED's (Light Emitting Diodes) could give two benefits; the possibility to save energy because the LED in the near future are expected to reach an even higher energy efficiency (over 50%), and a better spectral distribution for plant growth, maybe even optimized for every crop.

In the beginning of the decade, 2000-2010 the energy cost for the Nursery-business was decreasing, which was explaind by a more extensive use of a energy saving, dynamic climate control based on the research project IntelliGrow, at KVL and DJF in collaboration. In the same period of time, however, the energy consumption for electricity increased by 10%. The major part of the electricity is used for artificial light. The use of artificial light cannot be avoided in the winter months, because this will result in bad quality, and because the light gives a better balance between the other growth-factors, especially energy for heating.

The way the artificial light is used has nearly not changed since the 1980's, and there is a need to optimize the use of light. Lately there have been some initiatives on how this could be done. This is a description on different strategies for artificial lighting, either commercial or under development that could have potential for the future.

The purpose is a high photosynthesis, growth and development, which is affected by a complicated interaction between light, CO_2, temperature, humidity, water, and fertilizer. The daily light integral and the temperature integral have likewise effect on the production time and can be a controlling parameter (Moe et al., 2006).

Danish nurseries have HPS lamps giving between 50 and 250 µmol m^{-2} s^{-1}. Different plants have different light demands. Shadow plants, (plants originally growing at the bottom of forests), are saturated by 150-200 µmol m^{-2} s^{-1}, while sun demanding plants can take up to 1500 µmol m^{-2} s^{-1} or more without damage. I Danish nurseries, on a cloudy winter day, the light level will be as low as 50 µmol m^{-2} s^{-1}, while on a sunny day in summer, we have 1000 µmol m^{-2} s^{-1}.

Used today

1. *On/off controlled by global radiance*

The method of turning the lamps off at a certain light level is most commonly used today in Danish nurseries. The growers are confident with this method, but it seems to be inaccurate on certain points. There is need to consider production value and energy consumption.

2. *Daily light integral strategy*

Daily light integral is used in a few nurseries and in certain crops to control the artificial light. When the daily light integral reaches a value determined by the grower, the light is turned off. There are different opinions whether the plant can "remember" and use the natural light from the previous day, so the artificial light can be shut off after a sunny day yesterday (Niu et al., 2001).
Daily light integral is mostly used, in production of dry matter, i.e. tomato or cucumber, but can be used in potted plants and cutflower production. The conclusion was that there is a large difference between plant species and plants having a low light intensity in a long day, grows more than plants having high light intensity in a short day (Jiao et al., 1991).

3. *On/off controlled by global radiance and electricity prices*

Via internet it is possible to see the price of electricity the next 24 hours. Some growers has used this option to select which hours the next day the artificial light should be on, knowing the needs of their crop. This option is operated manually and every day to work.
There are some models, taking in the prices on electricity (Heuvelink and Challa, 1989). In 1997 at KVL a program was developed, which was able to turn on the artificial light, at the cheapest hours of the day, considering the trippletarif-system (a three step prizing system)(Ehler, 1997). This program was tested in nurseries, but was not used afterwards; probably the need for saving energy was not big enough. SDU has developed a program, which takes in the actual electricity prices, this program is not commercially available yet (see pt 5.).

Research/development

4. *On/off controlled by a photosynthesis-model*

Photosynthesis models can be used to estimate the overall growth, by using data of light level, CO_2 and temperature. By modeling tools it was shown that Photosynthesis models could give more energy efficient production (Aaslyng et al. 2006).

5. *On/off controlled by global radiance and electricity-prices, weather forecast and Photosynthesis-model*

In the research project PREDICT, a co-work between research-institutions and VEJR2, the group succeeded incorporating weather forecast in the decision whether to turn on the light. This means that artificial light can be saved, i.e. in the morning on a cloudy day, if the weather forecast predicts sunshine in the afternoon. These ideas are modulated further in a project between AU and SDU. In the program it is calculated when it is economic feasible to turn on the lamps, to increase the light level, to improve the plant growth, considering the electricity price. The concept is based on weather forecast (+/- clouds), electricity prices and integrated photosynthesis from the IntelliGrow photosynthesis model. The program called Dynalight was tested at AU and later on in nurseries. It is currently used in at least one nursery.

6. LED-lamp control

LED's (Light Emiting Diodes) comes in single colors with relatively narrow spectrum. This means the lamps can be designed to plant growth and development, if we know the needs of individual plant species.
Chlorophyll are the energy-harvesting molecule in the leaves, and chlorophyll absorbs light both in the blue and the red region; and reflect most of light in the green region. However, in the leaves there are also orange carotenoids that absorb well in the green region of the spectrum, which also funnel energy into the photosynthetic apparatus. Therefore, when investigating the spectral response of photosynthesis in an intact leaf, the dip in the green part of the spectrum is in the region of 5-30%, depending on the color of the leaf, and not the >95% that is indicated by the light absorption of isolated chlorophyll dissolved in e.g. acetone.This slight dip in the green is why plants appear green to human eyes. However, more light regulated processes are occurring in the plants. Branching is increased by blue light, flowering can be affected by far red (dark red), and the fact that plants actually grows when exposed to yellow light from the high pressure sodium light implies that red and blue is not the only light harvested for growth. The new research LED system described in part 2 is constructed to give the highest degree of freedom with regards to spectral composition, control and dimmability in order to investigate these issues.
It has also been shown that plants can grow in red and red/blue LED light (Aaslyng et al. 2008).
LED's are adjustable in intensity, from zero to full capacity. This means more possibilities in using the light. With this tool it is possible to make the light level more even on the plant by turning up the light, when the natural light decreases i.e. when a cloud covers the sun, and visa versa.

7. Real-time measurement of photosynthesis, to control the lamps

To evaluate the effect of different light strategies, it is necessary to measure height and weight of the plants after a longer period of time. Normally we are using dry weight matter. Today we are able to measure either Photosynthesis directly on the leaf, or chlorophyll fluorescence, which together can give a picture on the plants actual benefit from the current light. Online data are important because the plants' photosynthesis change during the day and the capacity with time of the year (Schapendonk et al., 2006). Research by

Schapendonk et al. (2006) in potted roses shows a god correlation between chlorophyll fluorescence and photosynthesis.

Light startegy related items

Mobile lamps

The purpose was to reduce investments by reducing the number of lamps, but move the lamps in the greenhouse. The results are not promissing (Blom et al., 2006; Marissen et al., 2006).

Diffuse light

To change the light from direct radiation to diffuse is not a part of a light strategy, but can be a part of energy saving solution, while results show that plants grow more from the same amount of radiation when received as diffuse radiation compared to direct radiation (Hemming et al., 2006, Markvart et al. 2010). This work was done with diffuse filters on glass in combination with sunlight and/or HPS lamps as light source.

Interlighting in greenhouse vegetables

In tomato and cucumber plant are grown vertical. Normally, when light is used in the crops, HPS lamps are placed above the crop, but in Finland and northern Norway they started with hanging lamps (Fluorescent bulbs) between the plants, giving the lower leaves more light, with a good result. After LED's are brought on the market LED alternatives are tested in Holland with good results. (Philips).

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2. **Design and development of new LED system for greenhouse experiments**

By Carsten Dam-Hansen, DTU Fotonik, 21-11-2011

This part of the report summarizes the work on the new LED lamps a carried out in the project

The first research LED lamps developed in the PSO project: “Electricity savings in green houses with LED grow light systems” had some shortcomings which were corrected in this project. A new power supply was installed in these lamps for increased light output, resulting in 80 % more blue light. Further the first lamps could only supply blue light at 450 nm and red light at 639 nm. This is not at the absorption peak of chlorophyll and better absorption can be obtained with red light at 660 nm. A number of LED components has come on the market since the first lamps were produced.

Here we have tested two types of 660 nm or deep red LEDs and compared with red LEDs at 639 nm. The total spectral radiant flux has been measured as a function of the operation current. This has been done at a constant operation case temperature of the LED package of 25 °C ± 1 °C. Currents from 100 mA to 700 mA was applied and the voltage was measured. In Figure 1 the measured spectral power distributions is shown for the different operation currents for a 639 nm and a 660 nm rebel LED from Philips Lumileds. The spectra are asymmetric around the peak wavelength and it is seen that the peak wavelength moves towards higher wavelengths as the current increases.

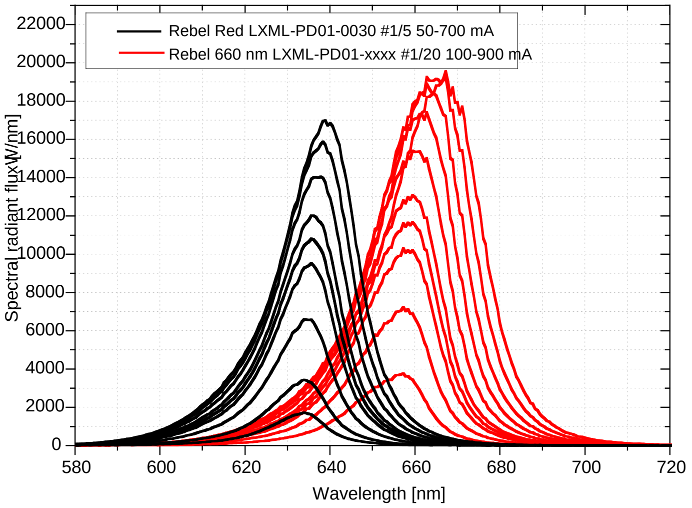

Figure 1 Measured spectral distribution of two types of red rebel LEDs at varying operation currents.

From the total spectral radiant flux measurements the total photosynthetic flux (μmol s^{-1}) has been calculated. It is shown as a function of current in Figure 2 for the two types of Rebel LEDs.

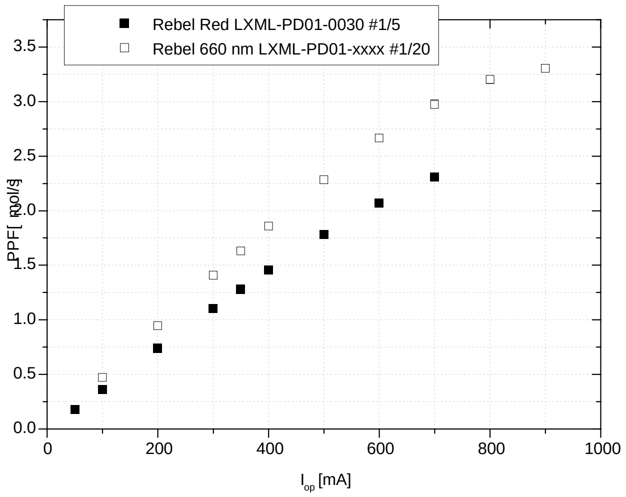

Figure 2 Comparison of measured PPF as a function of operation current.

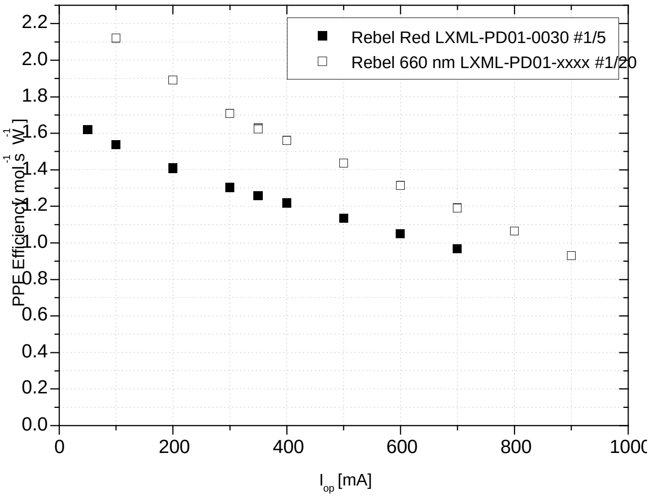

Figure 3 Comparison of measured PPF efficiency as a function of operation current.

It is seen that the photosynthetic photon flux is noticeable higher for the red Rebel at 660 nm. In order to evaluate the applicability we need to consider the photon flux efficiency. In Figure 3 the efficiency of the LEDs with regard to PPF, which is the ratio of the calculated PPF and the measured consumed power. The PPF efficiency is observed to be over 1.5 μmol/sW at 100 mA and falls to about 1.0 μmol/sW at 700 mA for the Red Rebel LED. It is noticeable higher with over 2.1 μmol/sW at 100 mA and about 1.2 μmol/sW at 700 mA for the Rebel LED at 660 nm. High-pressure sodium lamps which is normally used for greenhouse illumination has an efficiency of around 1.9 μmol/sW. For the Rebel LED at 660 nm the PPF is over 1.9 μmol/sW for operation currents under 250 mA. Since a higher efficiency is obtained with the 660 nm red LEDs and a better corespondance with the absorption peak of chlorophyll is was decided to implement 660 nm LEDs in the new lamps.

Color rendering

For workers in the greenhouse environment it will be difficult to assess the quality of plants in red and blue light only. The color rendering of green leaves will be very poor and they will tend to look very dark and redish. Therefore there is a necessity to provide white light with high color rendering properties in the greenhouse environment when people work there. Most LEDs for general lighting is white LEDs, which are blue LEDs with a phosphor that absorbs some of the blue light and emits green and red light. In this way white light LED can be produced with different spectral distributions characterized by the correlated color temperature. In order to the photon flux distribution of different types of white LEDs has been analyzed. In Figure 4 the different spectral power distributions of white LEDs is shown as a function of wavelength.

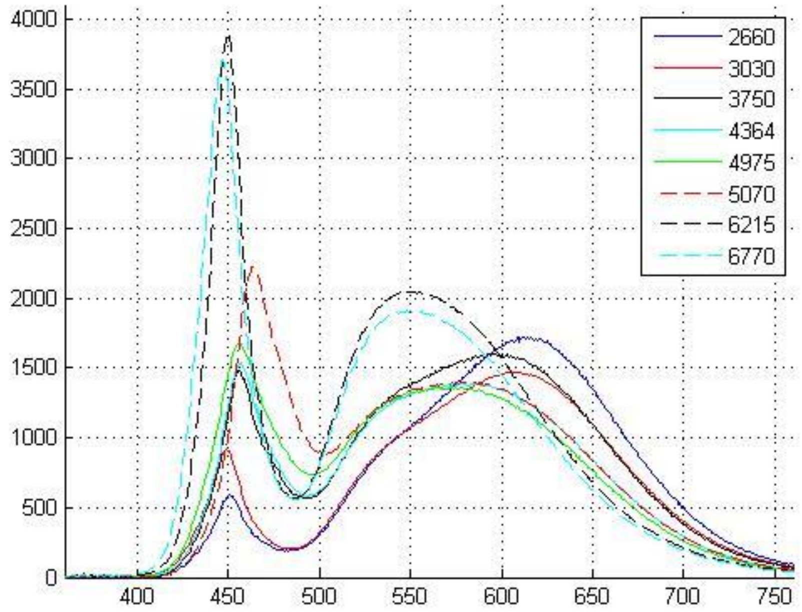

Figure 4 Measured spectral radiant power distribution of differnt white LEDs with correlated color temperatures from 2660 K to 6770 K.

It can be seen that there is a large difference in the relative distribution of blue, green and red light for the different types of white LEDs. Cold white LEDs with correlated color temperatures above 5000 K is seen to have a distinct blue peak at around 450 nm. In order to make a better analysis of the spectral composition a calculation of the photon flux in the blue, green and red spectral regions is performed. The blue region is defined as 400-500 nm, green as 500-620 nm and the red region as 620-700 nm. The result of this calculation is shown in Table 1.

Table 1 Calculation of spectral properties of white LEDs for different correlated color temperature, CCT, radiant flux, luminous flux, photosynthetic photon flux values and ratios in the blue (400-500 nm), green(500-620 nm) and red (620-700 nm) spectral region.

LED @ 350 mA	CCT	RF	LF	PF	PF blue	PF green	PF red	Blue/PPF	Green/PPF	Red/PPF
	[K]	[mW]	[lm]	[µmol/s]	[µmol/s]	[µmol/s]	[µmol/s]	[%]	[%]	[%]
White_2660K_350mA.txt	2660	271,5	82,68	1,257	0,088	0,672	0,497	7,0	53,5	39,6
White_3030k_350mA.txt	3030*	1013	309,7	4,634	0,504	2,506	1,624	10,9	54,1	35,0
White_3750K_350mA.txt	3750	307,7	95,46	1,396	0,230	0,760	0,406	16,5	54,4	29,1
White_4364K_350mA.txt	4364	277,1	86,95	1,246	0,245	0,688	0,313	19,7	55,2	25,1
White_4975K_350mA.txt	4975	284,9	87,18	1,269	0,299	0,684	0,285	23,6	53,9	22,5
White_5070K_350mA.txt	5070	306,6	91,5	1,366	0,344	0,709	0,313	25,2	51,9	22,9
White_6215K_350mA.txt	6215	380,3	121,6	1,671	0,452	0,960	0,260	27,0	57,5	15,6
White_6770K_350mA.txt	6770	369,2	113,5	1,610	0,476	0,895	0,239	29,6	55,6	14,8

It is observed that for all the white LEDs around 50 % of the photon flux is in the green region. Depending on the correlated color temperature the blue photon flux ranges from 7 – 30 %, while the red photon flux ranges from 40 – 15 %.
The new lamps where designed to be able to provide both colored light, blue at 450 nm and red at 660 nm as well as white light for improved color rendering. It was chosen to supplement the blue and red LEDs, with both white and green LEDs. From the calculations shown in Table 1, it was decided to choose a neutral

white LED at a correlated color temperature of 4500 K that has a color-rendering index of 79 and a blue photon flux ratio of 21 %. The green LEDs were implemented in order to be able to keep a high photon flux in the blue and red spectral region, but still achieving white light. Furthermore the lamps where equipped with far-red LEDs at 735 nm, however these do not alter the visual performance and is not considered here. Oslon LEDs[1] from OSRAM where chosen for this application. These are produced with viewing angles of 80 or 150 deg and the 80 deg. LED is used here. The characteristics of the LEDs were measured in the laboratorium under control of operation temperature. In Figure 5 the measured forward voltage as a function of operation current for the four different LEDs is shown.

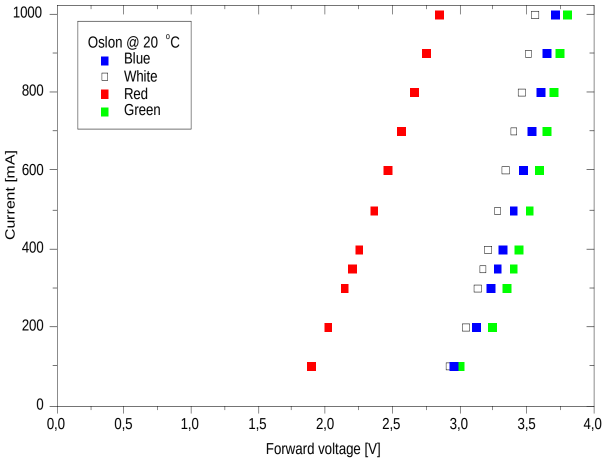

Figure 5 Measured forward voltage as a function of operation current for the four different LEDs.

From the characterization measurements the print layout for the light source was designed. It consists of 42 hyper red, 12 blue, 24 green and 18 white LEDs. They can be run at an operation current of 1000 mA and will emit approx. 290 µmol/s at full power. In Table 2 the measured and calculated spectral properties of new LED lamps is shown. The spectral radiant flux (W/nm) and the spectral photosynthetic photon flux (µmol s^{-1} nm^{-1}) are shown in the first two columns. In the last column chromaticity of the light is shown in the (u',v') chromaticity diagram with a green cross. The red line indicates the chromaticity of a temperature emitter, e.g. a black body radiator. The position along the line varies with the color temperature. Five different operation states are shown. First a red and blue state where the chromaticity is far from the white light area (red line), second for the green light only to show the chromaticity of this light that can be used to compensate the chromaticity of the red/blue light. The third is the white LED state showing the chromaticity on the red line at 4500 K. The forth states shows the spectral composition of the light when white and green LEDs are used to compensate for the red/blue light in order to achieve white light. In the fifth state all LEDs are operated at full power.

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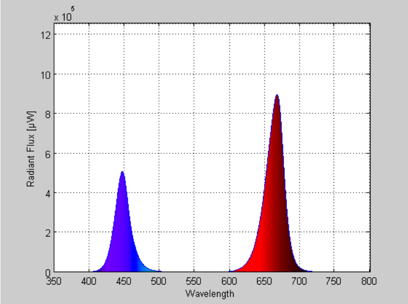
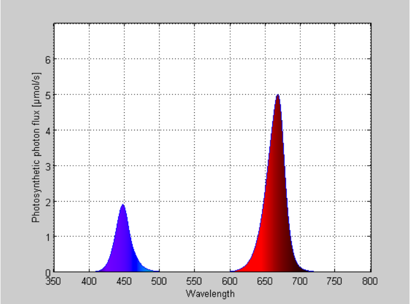
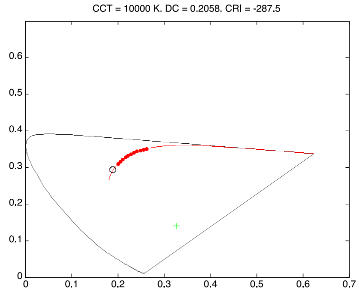
[1] *http://www.osram-os.com/osram_os/EN/Products/Product_Promotions/OSLON_SSL_80_and_150/OSLON_SSL_80/index.html*

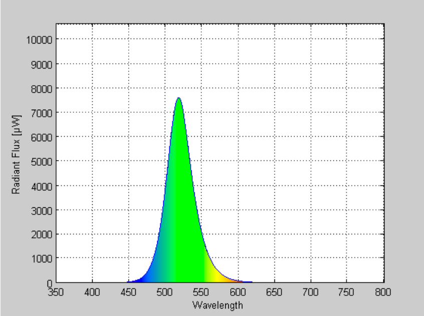
Table 2 Measured and calculated spectral properties of new LED lamps, showing the spectral radiant flux (W/nm) and the spectral photosynthetic photon flux (µmol s^{-1} nm^{-1}). In the column to the right the chomaticity of the light is shown in the (u',v') chromaticity diagram marked with a green cross. Here the red line indicates the color of white light from a black body radiator.

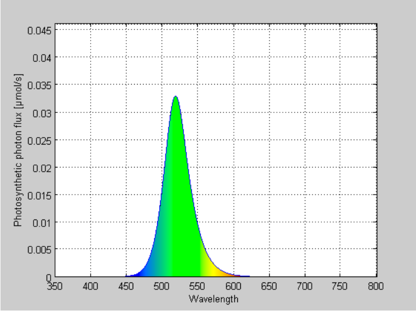
Spectral radiant flux: ***Spectral photosynthetic photon flux*** ***(u',v') chromaticity diagram***

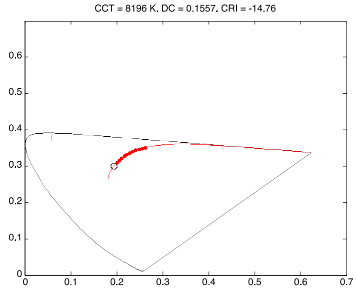


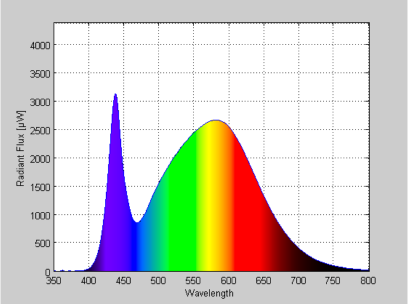


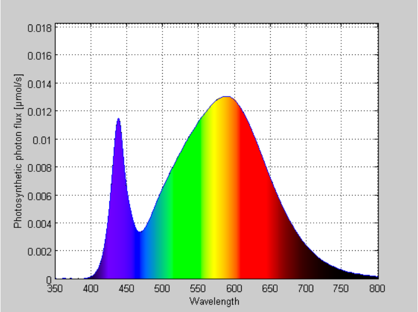


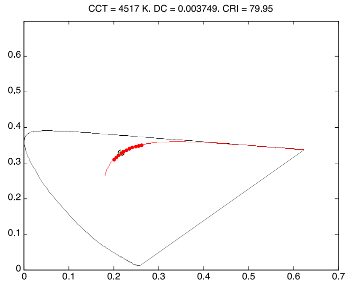


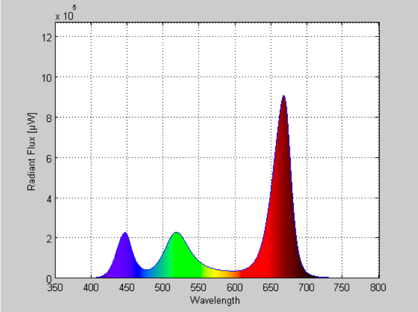


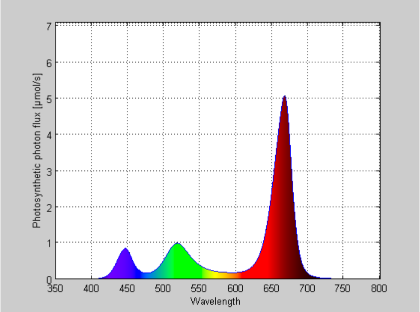


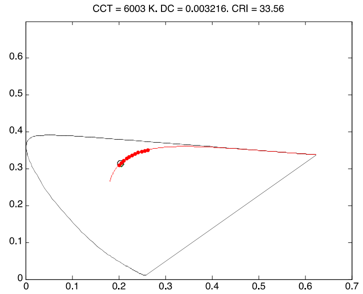


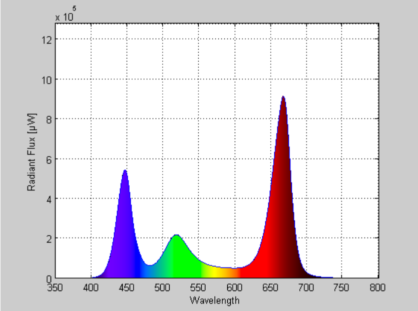


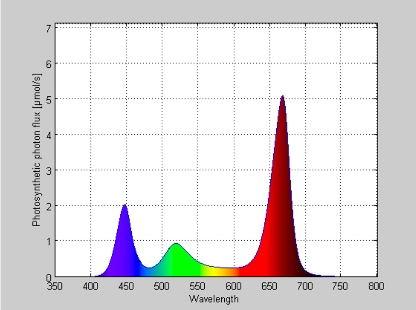


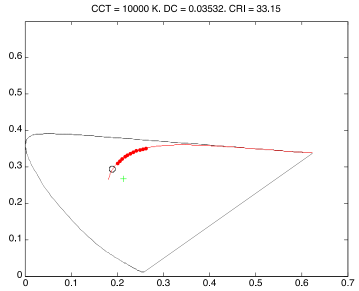












In Table 3 the spectral properties of the light from the new lamps is given with regards to white light and color rendering, and for the photon flux distribution in the blue, green and red spectral regions.

Table 3 Spectral characteristics of the different operation states of the new lamps, correlated color temperature, chromatic distance, color rendering index, total photon flux, total and relative photon flux in the blue (400-500 nm), green(500-620 nm) and red (620-700 nm) spectral region.

state	CCT [K]	DC 10^-3	CRI	PF [µmol/s]	PF blue [µmol/s]	PF green [µmol/s]	PF red [µmol/s]	Blue/PPF [%]	Green/PPF [%]	Red/PPF [%]
1 Red/blue	NA	NA	NA	211	52	2,1	157	24,5	1,0	74,5
2 Green	NA	NA	NA	36	5	31	0,09	13,2	86,6	0,2
3 neutral white LED	4517	3,7	80	41	9	24	9	21,4	57,3	21,4
4 white light	6003	3,2	34	248	32	53	163	12,9	21,4	65,7
5 full power	10000	35	33	288	65	57	166	22,6	19,8	57,6

It can be seen that it is possible to run the new lamps in different states. For optimum efficiency when color rendering has no influence, i.e. when no workers are present in the greenhouse, the lamps can be run in state 1 with only red and blue light. When white light is needed it is possible to run the lamps in different states. State 4 yields white light at a high color temperature of 6003 K and a low color rendering index of 34, combined with a high total photon flux and a blue and red photon flux ratio that corresponds to the values used in the greenhouse experiments.

3. THE USE OF CHLOROPHYLL *A* FLUORESCENCE FOR ONLINE MONITORING OF PHOTOSYNTHESIS IN PLANT PRODUCTION IN GREENHOUSES

By Eva Rosenqvist,KU-Life, 12-12-2011

Modulated chlorophyll *a* fluorescence is a non-destructive method to monitor the photosynthetic performance of plants. Here I will summarize the main conclusions.

Chlorophyll fluorescence is emitted from photosystem II (PSII) in the light reaction of the photosynthetic apparatus. It can be used to monitor both the energy balance between photochemistry and non-photochemical processes (heat dissipation). If you measure the operation efficiency of PSII at different light levels and multiply the value with the light that has been absorbed by PSII, you also get a measure of the electron transport through PSII (ETR). The climate parameters that affect this site directly are *light* and *temperature* i.e. any change in these parameters show directly in the quantum yield of PSII (the efficiency, by which the light energy is converted to chemical energy by PSII, to be used for CO_2 fixation and other metabolic processes). That means that the effect of lamp control in principle could be monitored by fluorescence measurements.

However, the carbon gain of the plant is also affected by the CO_2 concentration inside the leaf, which is affected both by the external CO_2 concentration in the surrounding air and the stomatal conductance. Under ambient CO_2 conditions the plant does not only perform photosynthesis (CO_2 fixation), but there is also a competing fixation of oxygen (O_2) through photorespiration. The latter process release CO_2, i.e. it is the opposite process to photosynthesis. Photosynthesis and photorespiration is performed by the same enzyme (Rubisco) and how much activity that is directed to the two processes, depends on the ratio between CO_2 and O_2 in the cells.

From a production point of view photorespiration should be minimized. From the plant’s point of view, photorespiration is an emergency process that allows it to maintain a high metabolic activity if the CO_2 supply is limited through stomatal closure caused by e.g. water stress. If the energy from the light reaction (PSII) can’t be used, there is a serious risk of damages caused by over-excitation by excess light. Because both photosynthesis and photorespiration function as sinks for energy from PSII, we can only detect the *total* Rubisco activity as reflected in the fluorescence from PSII, *not the two separate* enzyme activities.

Therefore the extra photosynthesis that is created by elevated CO_2, where both the increased amount of substrate (CO_2) and suppression of photorespiration due to increased CO_2/O_2 ratio, is not fully detected when the electron transport through PSII is measured. However, it seems as changes in photosynthesis caused by stomata closure is detected because the lack of CO_2 becomes so severe, that photorespiration can’t compensate for the loss of photosynthesis.

Light response of photosynthesis in naturally fluctuating light

LIST OF ABBREVIATIONS (primarily used in the figures)

ETR	Index of the electron transport rate of the photosynthetic light reaction, linked to the light harvest and energy supply for CO_2 fixation by photosynthesis
Leaf Temp	Leaf temperature
PAR	Photosynthetic Active Radiation (μmol m^{-2} s^{-1}), i.e. light in the wavelength range 400-700 nm that drives photosynthesis

In natural light photosynthesis follows the light level unless the light shifts are so large and quick to create a temporary imbalance in the photosynthetic apparatus. An example of a precise light response curve in natural light is shown in Fig. 1, which very closely follows a perfect theoretical curve. The measurement was done in the afternoon of a day with only few clouds i.e. the light changes gently.

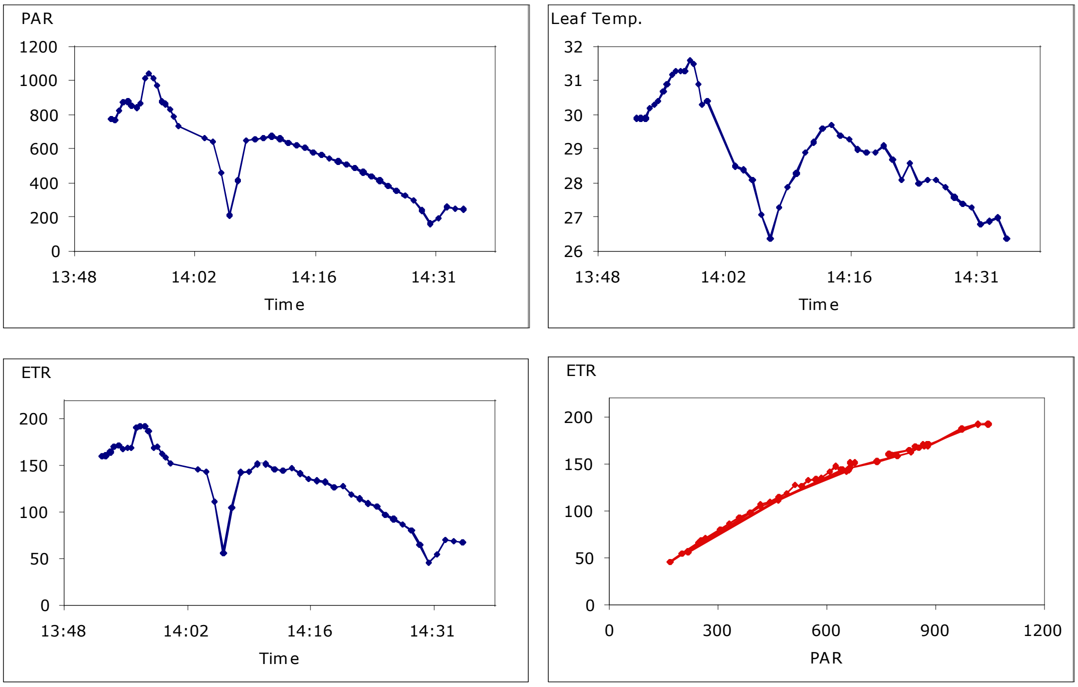


Figure 1. *Time course of light level (PAR, μmol m^{-2} s^{-1}), leaf temperature (°C) and electron transport (ETR) in a Chrysanthemum leaf in the natural light of a greenhouse in clear weather. The last graph (red) is the light response of electron transport when the light level shows gentle changes.*

When the light is more fluctuating the light response of electron transport is not as smooth (Fig. 2). However, also photosynthesis measured as CO_2 fixation is affected in a similar way by fluctuating light, i.e. these scattered data reflects the reality. When the light fluctuates photosynthesis will not operate in steady-state condition but in a constant transition state between different light levels. The same pattern was seen for pot roses.

The plant has a very advanced system that regulates the light harvest in the chlorophyll antennae, increasing the energy efficiency in low light and lowering it in high light, to balance the energy input and utilization. At the same time the plant regulates the CO_2 supply into the leaves by adjusting the stomatal conductance, through which CO_2 enters the leaves. All these things together operate to balance photosynthesis in an unstable environment. However, a complete balance is impossible and therefore we see these scattered data, because this is how photosynthesis operates in the real life of a plant.

Also temperature effects are directly reflected in ETR, since temperature acts directly on PSII.

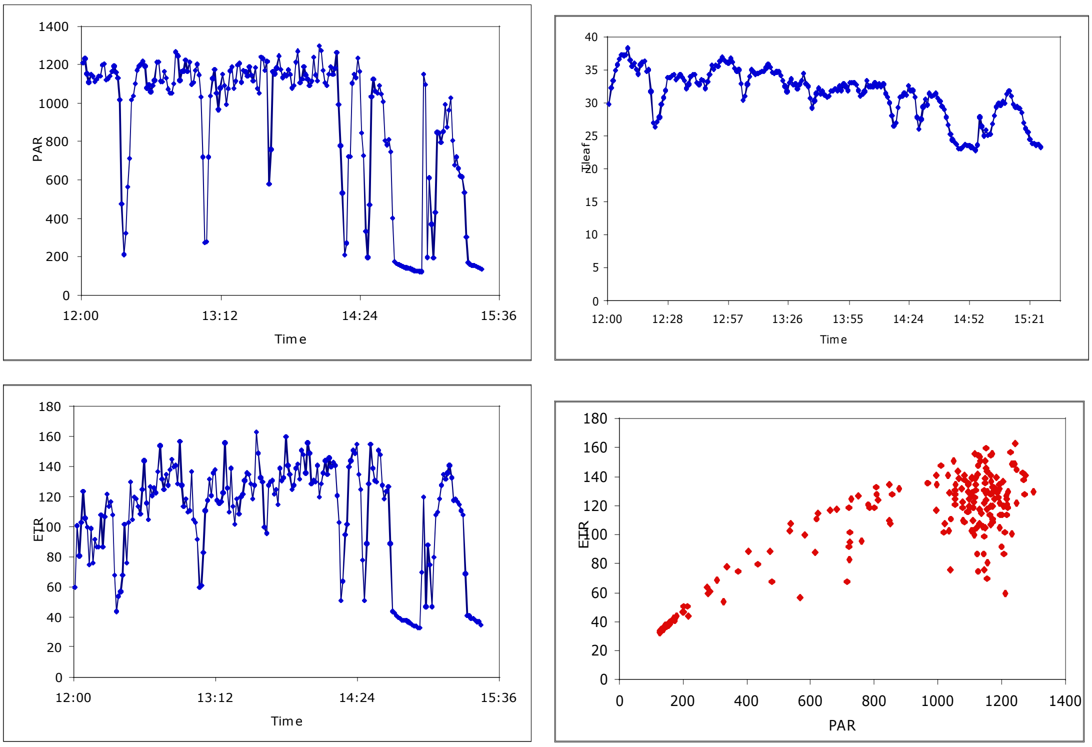


Figure 2. *Time course of light level (PAR, µmol m*$^{-2}$ *s*$^{-1}$*), leaf temperature (°C) and electron transport (ETR) in a Chrysanthemum leaf in the natural light of a greenhouse in cloudy/sunny weather. The last graph (red) is the light response of electron transport when the light level shows drastic changes.*

Even though the scattered data may look confusing it should be noticed that the most severe scattering is found at high light, where sun and shade from moving clouds create the light environment. Under those weather conditions supplemental light is rarely used. The lamps are *primarily* used at light levels of PAR < ca. 500 µmol m^{-2} s^{-1}, where the changes doesn’t create such severe scattering of data.

Conclusion

Chlorophyll fluorescence can be used to monitor online performance of photosynthesis and its dependence on the greenhouse climate. In this project the fluorescence has been measured on single leaves at the time, since the equipment available only allows measurements of one sample at the time. If fluorescence is going to be used to monitor plant performance during production it will be necessary to have multiple measuring heads connected to several leaves, since the variation in individual leaves can hide overall patterns because of the heterogeneity of the light environment in a greenhouse.

Light and temperature are directly reflected in the ETR measurements, while factors involving elevated CO_2 are not equally visible in the data. Therefore, to monitor the effect of the 'total climate', a trained eye has to be involved in the evaluation of the data. The possible practical applications for chlorophyll fluorescence has been summarized by Baker and Rosenqvist (2004).

References

Baker NR, Rosenqvist E. 2004. Application of chlorophyll fluorescence can improve crop production strategies: an examination fo future possibilities. J. Exp. Bot. 55: 1607-1621.

4. LEAF PHOTOSYNTHESIS IN STRONGLY FLUCTUATING LIGHT – IMPLICATIONS FOR LAMP CONTROL

By Eva Rosenqvist, KU-Life, 12-12-2011

LIST OF ABBREVIATIONS (primarily used in the figures)

C_i	Intracellular CO_2 concentration (ppm), i.e. the CO_2 concentration inside the leaf
g_s	Stomatal conductance (mmol m^{-2} s^{-1}), i.e. a measure of how open the stomata are
PAR	Photosynthetic Active Radiation (µmol m^{-2} s^{-1}), i.e. light in the wavelength range 400-700 nm that drives photosynthesis
P_n	Net photosynthesis (µmol m^{-2} s^{-1})

Supplementary light is an absolute necessity for greenhouse production of most ornamental crops in Denmark in the period autumn – spring. One key question for the control of supplementary light is, at which light level to turn off the light. The light requirements differ greatly between species. The currently used SON-T lamps cannot be turned on/off frequently but needs e.g. 15 minutes cooling after turning off, before they can be turned on again. If turned on/off more frequently, the life time of the bulbs decreases. LED lamps can both be frequently turned on/off and dimmed, if supplied with a dimmer.

With the possibility of turning on LED lamps more often a new question arises: will it pay off to let the lamps fill in the “gaps” in the light, when the light level fluctuates due to clouds. The natural light is the most unstable of all the climate parameter that plants are exposed to (Fig. 1).

In the example shown in Fig. 1 it could be an obvious option to turn on the lamps around 12:00 and just after 13:00, when the light level is low due to clouds. The question is if the lamps should be used to fill in the “gaps” of light in the time intervals around 10:00 and 11:00.

The rate of photosynthesis is determined by the combination of light (energy source), CO_2 (substrate) and temperature (determines the activity of all enzymes). In darkness several of the photosynthetic enzymes are deactivated. For photosynthesis to run optimally the enzymes need to be activated to a level that is appropriate for the present light level.

Also contributing to this is the stomatal conductance that ensures the CO_2 supply into the leaves. It is regulated by a combination of light, CO_2 and water balance, where the balance between CO_2 supply and water loss ensures an – for the total plant – optimal CO_2 supply, while minimizing water losses when needed.

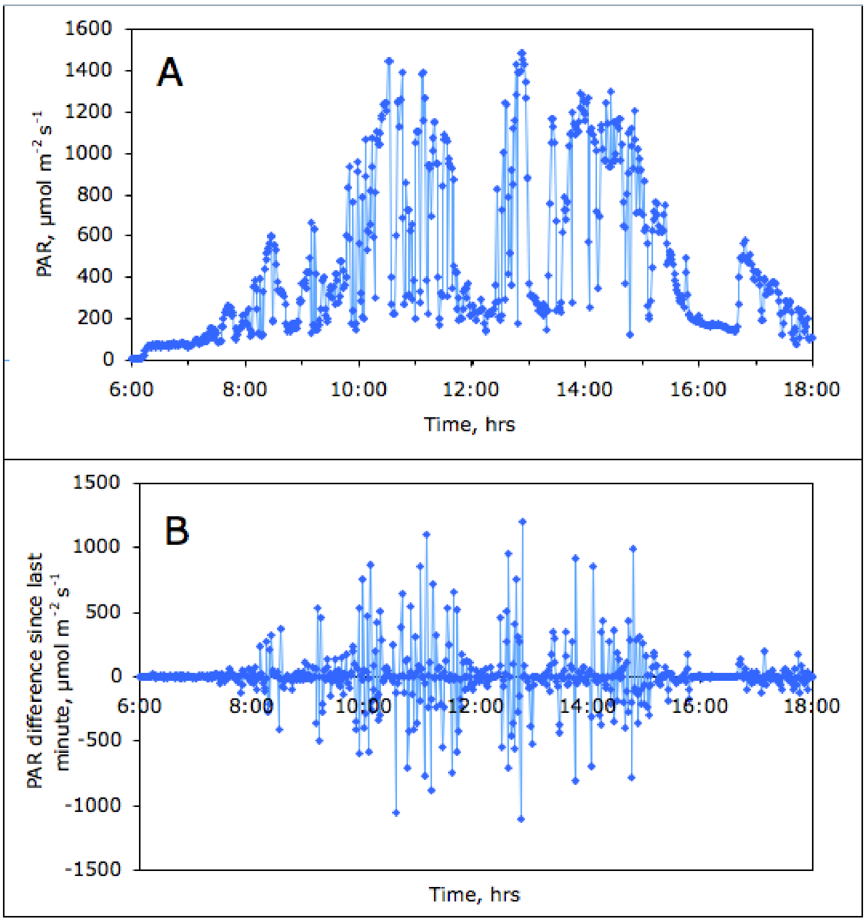


Figure 1:* *A. *The natural light in a greenhouse in April measured every minute.* ***B.*** *The light shift calculated as the difference in light level since last minute measurement.*

Plants and measurements

To investigate how the stomata conductance and the activation of photosynthetic enzymes are affected by quick fluctuations in the light level we have made measurments on *Chrysanthemum* (45 series) and *Rosa* (15 series) and a few supplements on *Euphorbia millii* (Crown of Thorns), which is a species that is renown for its sensitive stomata (closes the stomata if subjected to irregular air humidity).

Photosynthesis has been measured by a CIRAS-2 photosynthesis system, which allows us to measure the gas exchange of CO_2 and water vapour in a leaf in a leaf chamber, while it is still attached to the plant. The light level was determined by a lamp (LED with the combination of white and red diods).

The combinations of timing and light levels have been 1, 2, 5 and 8 min intervals with light combinations 50/250, 50/500 and 50/1000 µmol m^{-2} s^{-1} (cf. Fig. 2B).

Since the stomatal conductance at the start of the measurments will influence the results, most of the measurements have been done on plants that has been moved from the greenhouse to the dim light of the laboratory already in the morning, before the greenhouse climate has induced stomatal serious opening, thus enable us to study the combination of enzyme activation and stomatal opening. A few examples will be shown here.

Results and Discussion

When the light is shifting between 50 and 1000 µmol m^{-2} s^{-1} in a *Chrysanthemum* leaf with an initial high stomatal conductance (Fig. 2) there is almost no remaining effect of the light "gap", when the light again changes to high light: also with only 1 minute of high light the rate of photosynthesis is capable to come back to its original level. This plant has been taken directly from the greenhouse in light, i.e. the enzymes were well activated and stomata conductance high already in the beginning of the measurment. The light control of stomata is clearly shown in the time response of g_s, where it increases in the high light pulses and decreases in the low light periods.

To judge the contribution of stomatal conductance and enzyme activation to the overall rate of photosynthesis a plot is made between photosynthesis and intracellular CO_2 concentration (high light = low C_i due the the consumption of CO_2 throught photosynthesis, low light = high C_i dure to low rates of photosynthesis). In Fig. 1 all shifts between low and high C_i takes place with the same steep slope, which tells us that the stomata conductance does not limit photosynthesis at high light in this example.

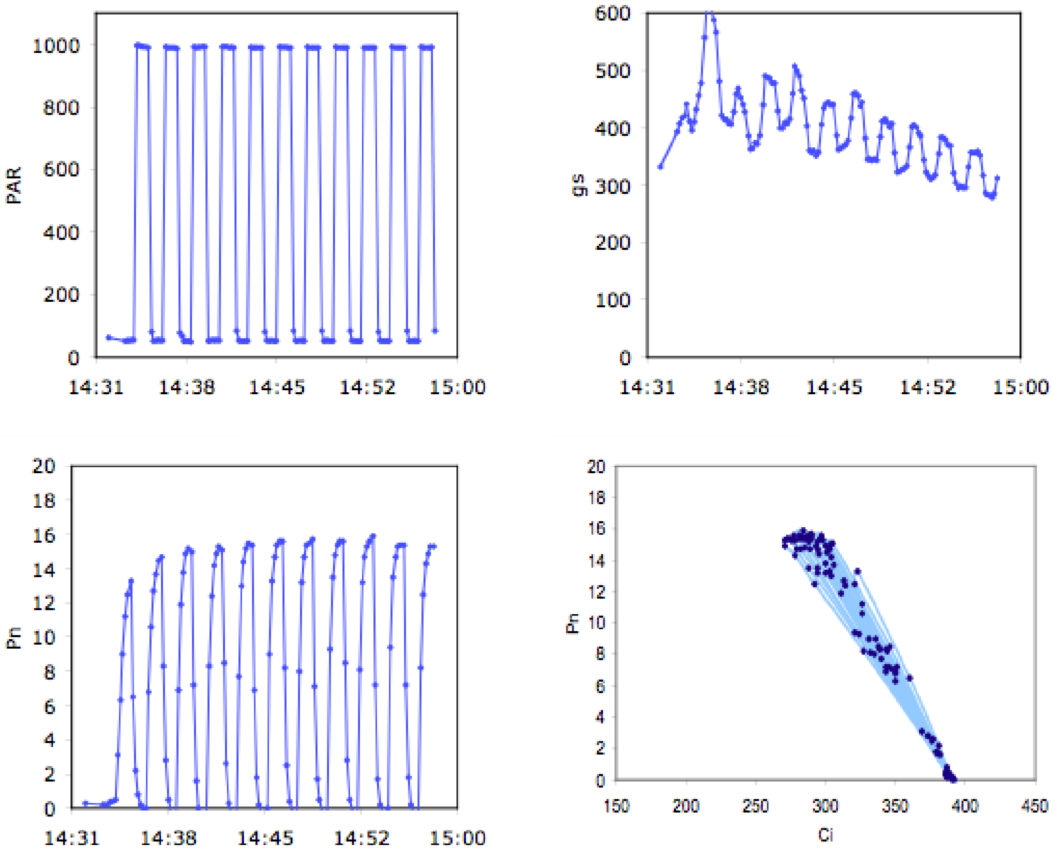


Figure 2: *The time course of photosynthesis (P_n, µmol m^{-2} s^{-1}) of Chrysanthemum with 1 min shifts between 50 and 1000 µmol m^{-2} s^{-1} with an initial* ***high*** *stomatal conductance (g_s, mmol m^{-2} s^{-1}) and* ***activated*** *enzymes (the plant taken directly from the greenhouse in light). The last figure shows ther relationship between photosynthesis and the intracellular CO_2 concentration (C_i, ppm).*

When the *Chrysanthemum* has been taken from the greenhouse in the early morning, before the stomatal conductance has increased, the shift between 50 and 500 µmol m^{-2} s^{-1} show a different pattern (Fig. 3). The rate of photosynthesis increases gradually for each period of high light, accomanied by gradually increasing stomatal conductance.

Most pronounced is the different pattern shown in the Pn vs C_i. The first light shift is indicated by the red arrow and for each high light pulse the slope of the line between the low P_n/high C_i values (caused by low light) and the high P_n/low C_i values (caused by high light) becomes steeper. The slope is correlated to the stomatal conductance. After the last light pulse the drop down to high C_i has the slope is steeper, indicated by the orange arrow. This slope in Fig. 3 is still slightly lower than in Fig. 2, because the final stomatal conductance is still lower than in Fig. 2 (partly caused by a lower light level).

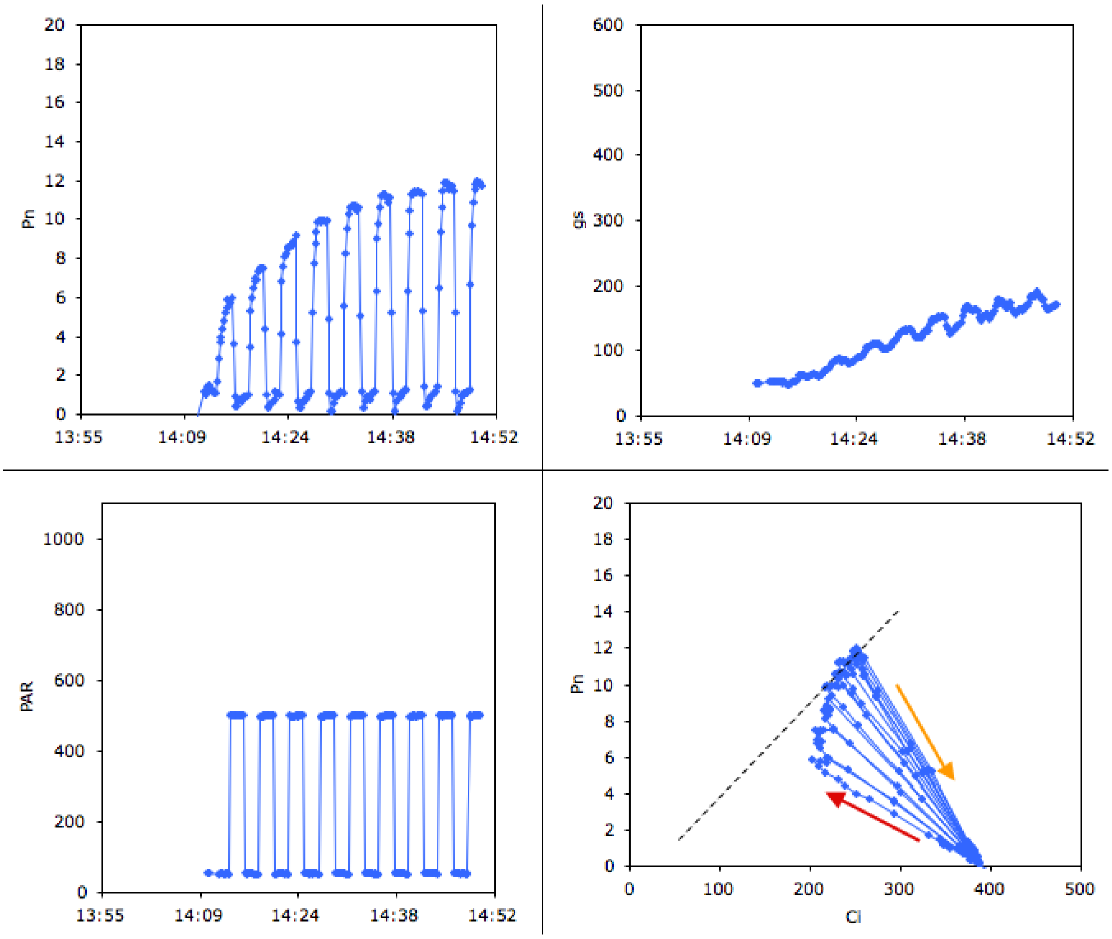


Figure 3: *The time course of photosynthesis (Pn, µmol* m^{-2} s^{-1}*) of Chrysanthemum with 2 min shifts between 50 and 500 µmol* m^{-2} s^{-1} *with an initial* ***low*** *stomatal conductance (*g_s*, mmol* m^{-2} s^{-1}*) and* ***inactivated*** *enzymes. The last figure shows ther relationship between photosynthesis and the intracellular* CO_2 *concentration (*C_i*, ppm).*

If the stomatal conductance is disturbed by e.g. decreasing air humidity, this can trigger stomatal closure. This is shown in Fig. 4, where the starting point was high g_s and activated enzymes. The photosynthesis and stomata conductance decreases gradually and in the P_n vs C_i graph the development in the three light pulses follows the black arrow.

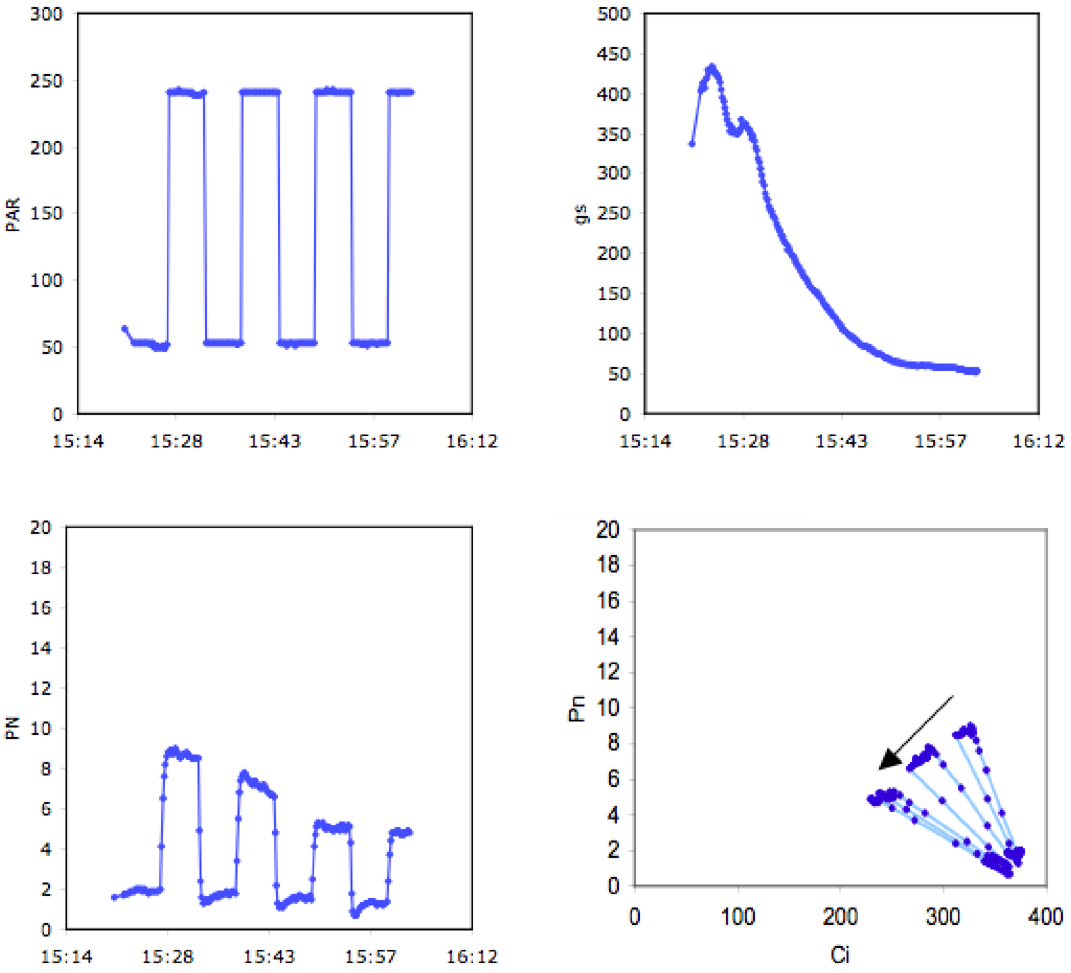


Figure 4: *The time course of Chrysanthemum at 5 min shifts between 50 and 250 µmol m*$^{-2}$ *s*$^{-1}$*, starting at high* g_s *and activated enzymes.*

If the stomatal conductance is kept increasing during 5 min light pulses between 50 and 500 µmol m^{-2} s^{-1} light, 5 min interruption of the high light is not enough to deactivate the enzymes or substantially close the stomata.

The pot roses show similar pattern as *Chrysanthemum*.

We think that the relationships shown here between light levels, stomatal condutance and degree of activation of the enzymes of the photosynthetic apparatus, are quite universal between species, based on our own measurments and what are found in the literature. However, we have focused on high light species in this investigation, since they are the most energy demanding for supplemental light.

Concluding remarks

Plants respond very fast to changes in light level and the enzyme activity and stomatal conductance are regulated simultaneously to optimize photosynthesis under any given climate condition. The light is the climate parameter that shows the strongest fluctuations in short time. However, these responses are also influenced by other climate factors such as air humidity and water availability in the pot, though the latter not often a problem in pot plant production.

The question is if it would be beneficial for plant production to fine-tune the light level when using LED lamps, or if they should be turned on/off like the traditional SON-T lamps. If the photosynthetic apparatus loses activation and stomata conductance during a short period of low light, it would be beneficial to fill this “gap” by LED light, not to lose the potential to fully use the next period of high light. If, however, the activation state and stomatal conductance remains high one only have to consider, how much the supplemental light during that short time period contributes to the total light integral (light sum) of that day.

Our results indicate that if the humidity conditions are optimal (not triggering stomatal closure) photosynthesis can remain activated up to five minutes if high light is interrupted by a passing cloud. That means that clouds of a duration up to five minutes does not need to be compensated by LED light, just to ensure a high activation state of the photosynthetic apparatus before the next period of high light.

To decide whether to turn on the lamps or not, one should consider a combination of the following:

What is the weather forecast: can we expect sun later in the day, or will the day be overcast?

How much should the lamps contribute on daily basis to the total light integral, before they are turned off?

How much will the light from the lamps contribute to the total light integral that day, if turned on to fill “gaps” in the light?

What is the present electricity price – does it pay off economically vs. plant production to turn on the light?

There is a pronounced difference in the need of supplemental light between overcast and sunny days. The light example show in Fig. 1 is from a sunny day with scattered clouds. On an overcast day the maximum light level will not be higher than what is seen around noon in Fig. 1. So in conclusion, these considerations are as much economical and related to weather forecasts, as plant physiological.

5. LARGE-SCALE GREENHOUSE TEST OF LED-PROTOTYPE WITH DIFFERENT CONTROL STRATEGIES

By Eva Rosenqvist, KU-Life, Carsten Dam-Hansen, DTU Fotonik and Anker Kuehn, AgroTech 20-12-2011

LIST OF ABBREVIATIONS (primarily used in the figures)

C_i	Intracellular CO_2 concentration (ppm), i.e. the CO_2 concentration inside the leaf
ETR	Index of the electron transport rate of the photosynthetic light reaction, linked to the light harvest and energy supply for CO_2 fixation by photosynthesis
g_s	Stomatal conductance (mmol m^{-2} s^{-1}), i.e. a measure of how open the stomata are
PAR	Photosynthetic Active Radiation (µmol m^{-2} s^{-1}), i.e. light in the wavelength range 400-700 nm that drives photosynthesis
PPF	Photosynthetic photon flux (µmol s^{-1})
PPFD	Photosynthetic photon flux density (µmol m^{-2} s^{-1})
P_n	Net photosynthesis (µmol m^{-2} s^{-1})

LARGE-SCALE GREENHOUSE TEST OF LED-PROTOTYPE WITH DIFFERENT CONTROL STRATEGIES

In the project two large-scale greenhouse experiments have been made. The winter 2009/2010 the four lamps constructed in the first LED project from PSO was used. In the winter 2010/2011 a larger experiment was designed that included four old and four new lamps. In both experiments pot roses (Rosa x hybrid 'Ingrid Madigan', Figure 1, which is a light demanding crop, was used.

Figure 1 An experimental LED lamp over pot roses 'Ingrid Madigan' in the greenhouse at the time of final plant harvest.

The aim of the experiments was to compare LED light with conventional SON-T lamps that are currently used in Danish nurseries. The first year the light treatments were SON-T, 100% red LED and 20% blue/80% red LED. To more thoroughly investigate the effect that the change to LED can have on the overall plant performance, when the heat radiation from the lamps disappear, the second year's experiment was extended to also include radiation heat as a treatment on its own. We also made two lamp control strategies, to investigate the possibility of reducing the burning time of the supplementary light in a light demanding crop like pot roses.

Treatments and climate measurements

The treatments can be divided into two categories: the spectral radiation and lamp control (burning time).

Spectral radiation

- SON-T lamp
- LED 100% red
- LED 20% blue in red
- IR radiation (no light) by terrass heaters
- Control, no supplementary light or heat radiation

Burning time

- 20 hours light/4 hours dark, called constant light in the figures
- Lamps/IR controlled by an energy model

That gives in all 10 treatments.

The following climate parameters were measured in each treatment: PAR, global radiation, air temperature and leaf temperature by thermocouples inserted into the leaves. The light sensors were placed just above the canopy and adjusted twice a week as the plants grew.

Plants and harvest parameters

In commercial production pot roses are cut back twice to promote branching. Plants of pot roses (Rosa x hybrida 'Ingrid Madigan') arrived after second cut in two batches, one week apart, to have two true replicates of the experiment.

When the plants reached flowering they were harvested to characterize the size and flowering of the plants. For each treatment and replicate 12 plants were harvested and divided into plant height for each of four cuttings per pot, number of buds and flowers, and dry weight of leaves, buds+flowers and stems. With 10 treatments and two replicates 240 plants were harvested.

Characterization of the light environments

Eight LED research lamps were used in the experiment. The four old lamps were upgraded with a new and larger power supply so that the K2 red and blue LEDs can be run at full power. This has resulted in the possibility of providing more light in the experiments.

The four new research LED lamps was designed and developed to supplement the old lamps in providing red and blue light in larger scale experiments. A better spectral distribution of the light is implemented in the new lamps in shifting the red from 639 nm to 660 nm, for better overlap with chlorophyll absorption. Furthermore the new lamps are developed to be able to produce far red, green, and neutral white light.

The eight research LED lamps was set up in four areas where pairs of two lamps provided the illumination for an area of approx. 1 m². To ensure even light distribution within the treatments this was measured over an area of 0.8 m x 1.6 m in a 10 by 10 cm grid. The measurement was during dark hours in the evening to ensure only to measure light from the selected lamps. A spectroradiometer was used in order to measure both the spectral composition and the photosynthetic photon flux density, PPFD, (µmol m^{-2} s^{-1}) as a function of position on the tables. The measurements were performed at 20 cm above the tables and showed negligible light contributions from the neighbouring tables.

In Figure the measured light distribution is shown for the two pairs of lamps running at 100 % red. In Figure 3 and Figure 4 the measured light distribution is shown for the two pairs of lamps running at 20 % blue and 80 % red. The measured blue ratio is also shown as a function of position for these setups.

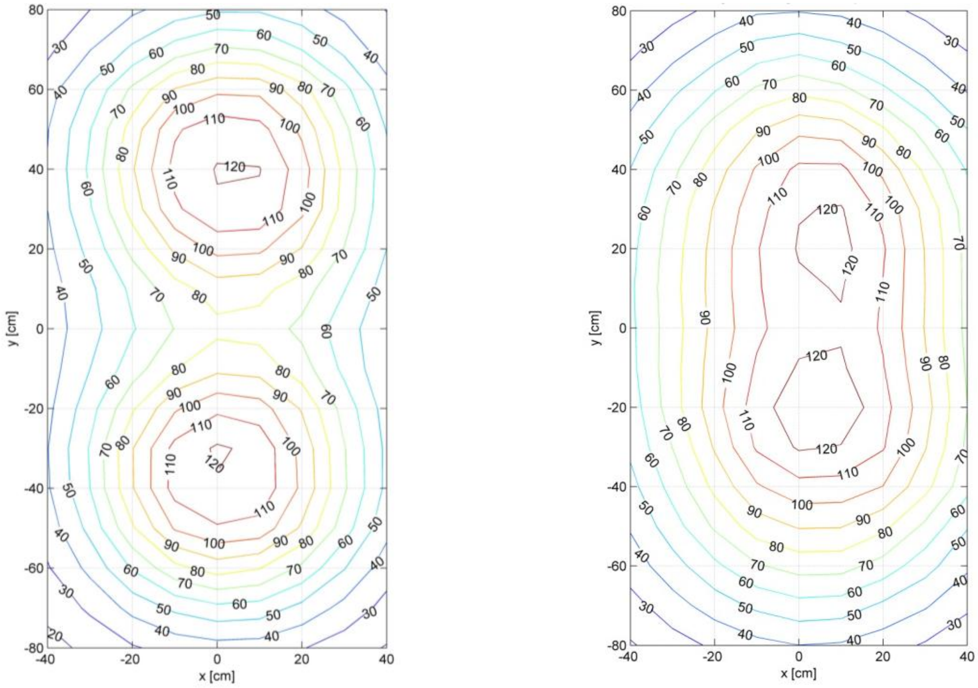


Figure 2 Contour plots showing the measured photosynthetic photon flux density (µmol m^{-2} s^{-1}) as a function of position for the two pair of lamps running at 100 % red. left: old lamps no. 1 and 2, right: new lamps no. 5 and 6.

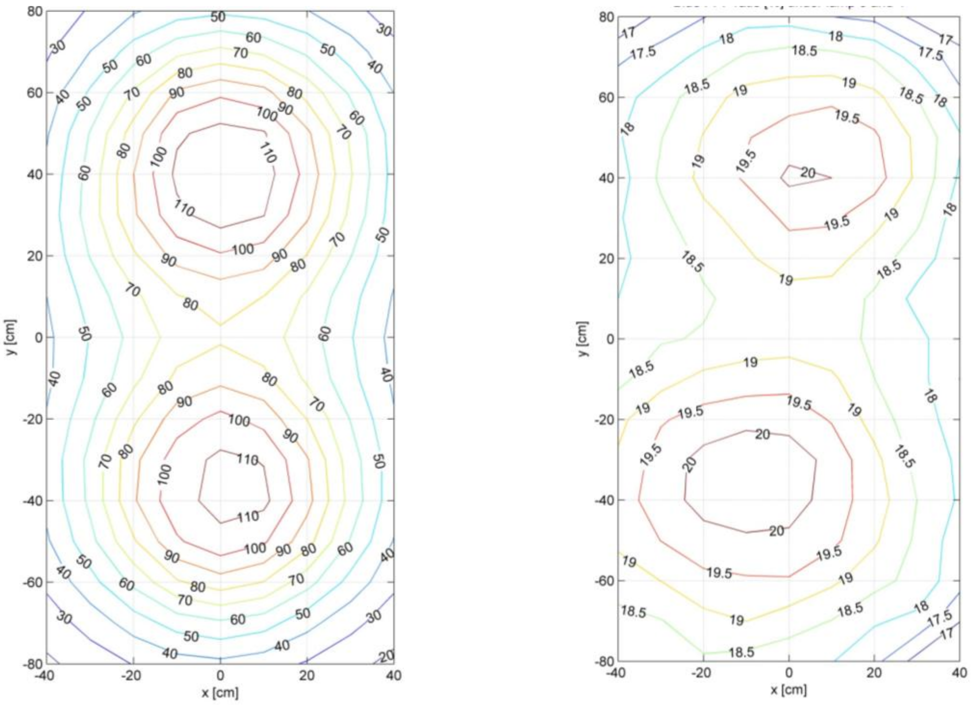


Figure 3 Contour plots showing the measured photosynthetic photon flux density (µmol m^{-2} s^{-1}) (left) and measured blue ratio (%)(right) as a function of position for old lamps no. 3 and 4 running at 20 % blue light.

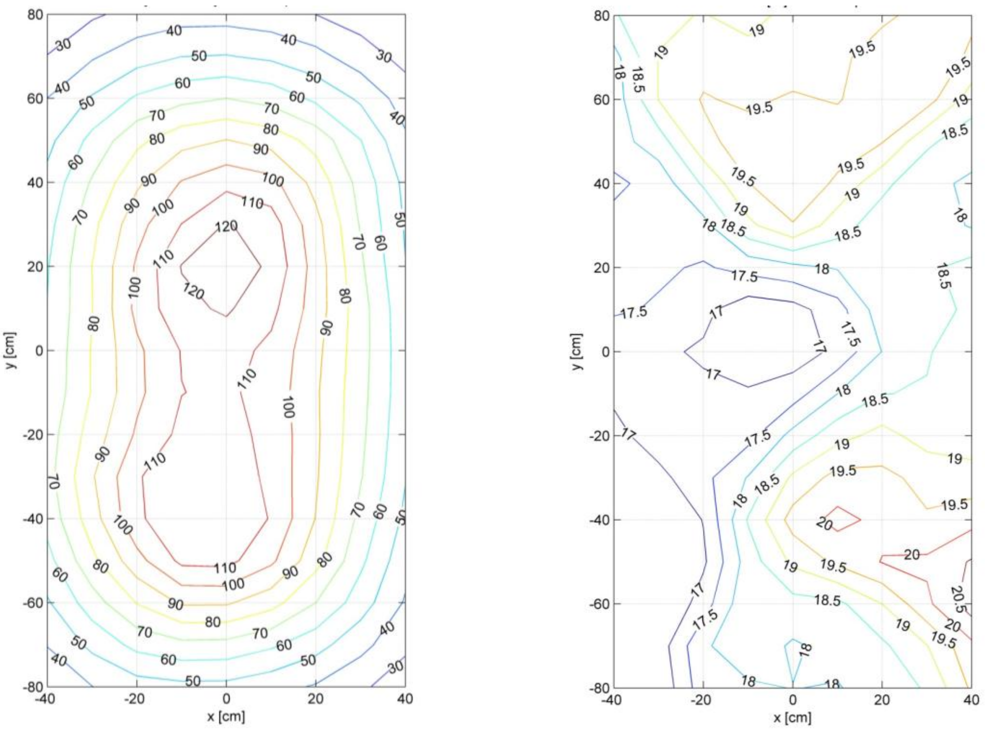


Figure 4 Contour plots showing the measured photosynthetic photon flux density (µmol m-2 s-1) (left) and measured blue ratio (%) (right) as a function of position for new lamps no. 7 and 8 running at 20 % blue light.

The measurements show an even photosynthetic photon flux density in the central part of 0.5 m by 1.2 m of the investigated area. The distribution measurements have been used to set the mean value of the photosynthetic photon flux density over the plant area to 100 µmol m^{-2} s^{-1} for all treatments.

A small difference in the light distribution under the new and old lamps is noticeable. The old lamps produce a light distribution with two peaks areas while the new lamps produce a single more elongated area with high intensity. This is due to the fact that the new lamps are designed with a type of LEDs with a viewing angle of 80 deg, while the old lamps are designed with LEDs having a viewing angle of 140 deg.

The measurements on the right of Figure and Figure , show an even relative distribution of red and blue light with a measured blue ratio that varies from 17 to 20 % over the whole measured area.

The LED lamps are water cooled in order to ensure a stable and reproducible irradiation. The LED lamps has been programmed to enable

- a fixed day/night cyclus for lamp no. 5, 6, 7 and 8
- control of lamp no. 1, 2, 3 and 4 from the climate computer via an on/off relay .

The spectral power distribution of the light from the LED lamps is shown in Figure . It is shown as the total radiant flux in W/nm.

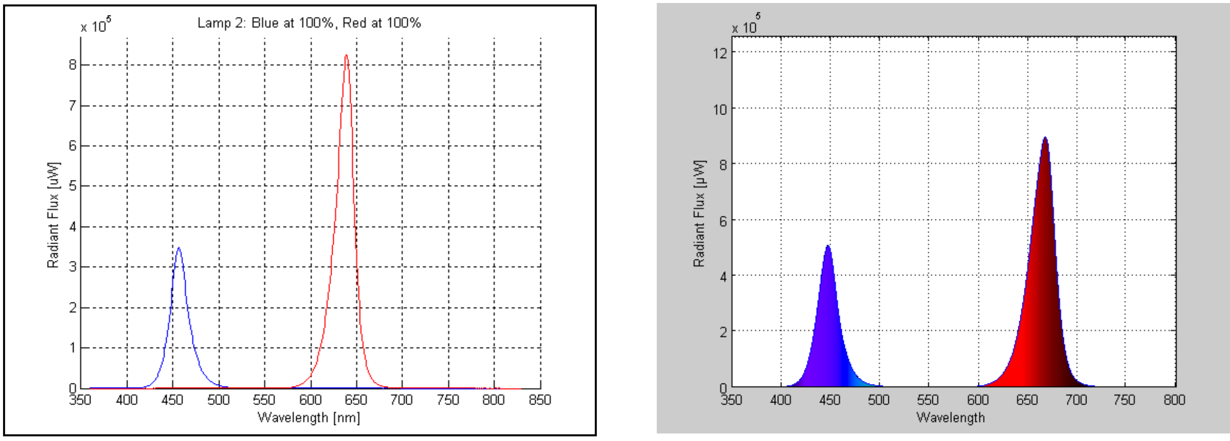


Figure 5 Measured power distribution of the light from the old lamps, no. 1-4 (left) and from the new lamps, no. 5-8 (right), only running with red and blue light.

It is seen that the peak wavelength for the red light is shifted from 639 nm in the old lamps to 660 nm in the new lamps. The peak wavelength for the blue light is almost the same around 450-455 nm. The measured composition of red and blue light for the new lamps (Right in Figure) corresponds to a blue light photon flux ratio to the total photon flux of 24 %. That is slightly higher than for the 20 % in the greenhouse experiments.

Results and discussion, climate parameters

The daily sum of light during the experiment followed the burning time of the lamps in each treatment (Figure) i.e. it follows three patterns; 20 hours, energy model and no supplemental light. The first batch of plants arrived 26 January and the second one week later. During the first week it was clear that the SON-T lamp that was turned on for 20 hours gave too little light and was thus lowered, to ensure equal amount of light compared to the LED treatments.

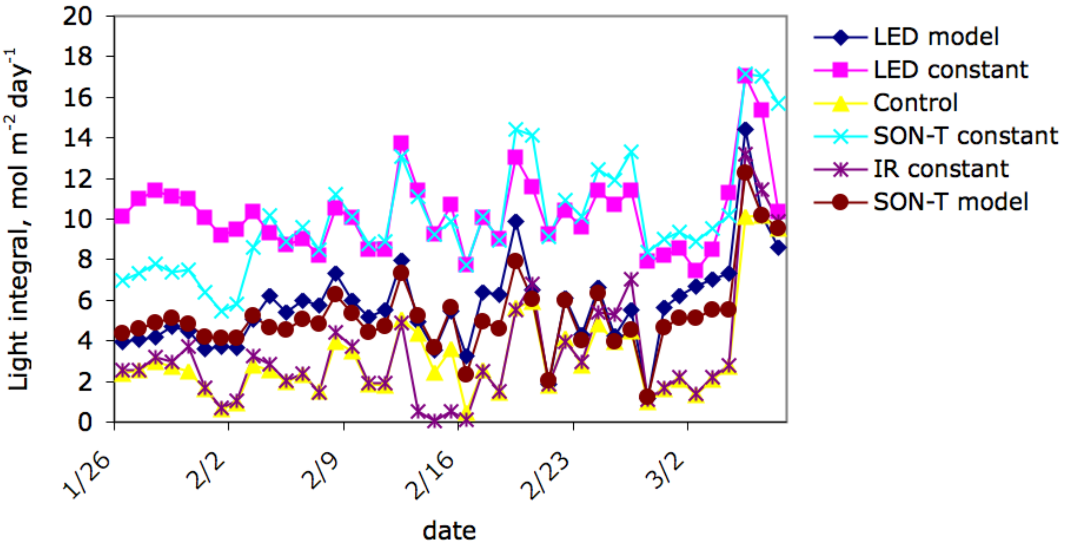


Figure 6. The development of the light integral (light sum) during the experiment. The LED data covers both color combinations. (The date format is American, with the month before the day.)

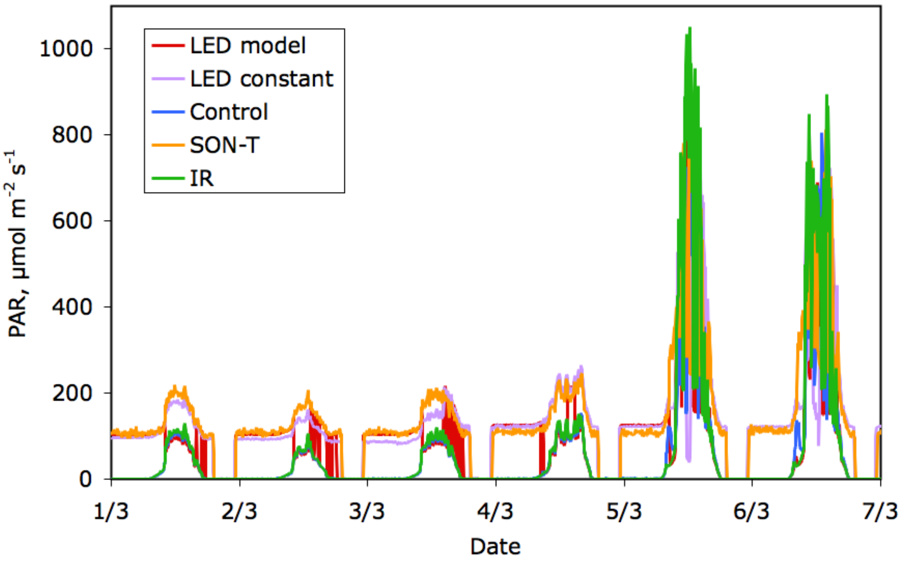


Figure 7 Examples of the diurnal light pattern in the treatments during six days in the end of the experiment with four overcast and two sunny days.

The light environment varied drastically between days (Figure). During the morning hours the different light treatments received the same light levels but the burning time differed between the 20 h and the energy model treatment.

The energy model

The energy model is based on dry matter gain per day. The dry matter for the end product was estimated to 3.4 g pr. plant, and 35 plants m^{-2} makes 119 g m^{-2}. The roses will be ready in 45 days, which means 2.64 g m^{-2} of dry matter should be gained every day. This 2.64 g $m^{-2}day^{-1}$ is the target value. If every single days gain corresponds with the target value, the plant will have the decided dry weight in the end.

Every day the dry matter gain from the natural light was calculated, and if this was not enough compared to the target value, it was calculated how many hours of light was needed with the lamps turned on to reach the target value. And the calculated hours was added when electricity was cheapest during the following dark period.

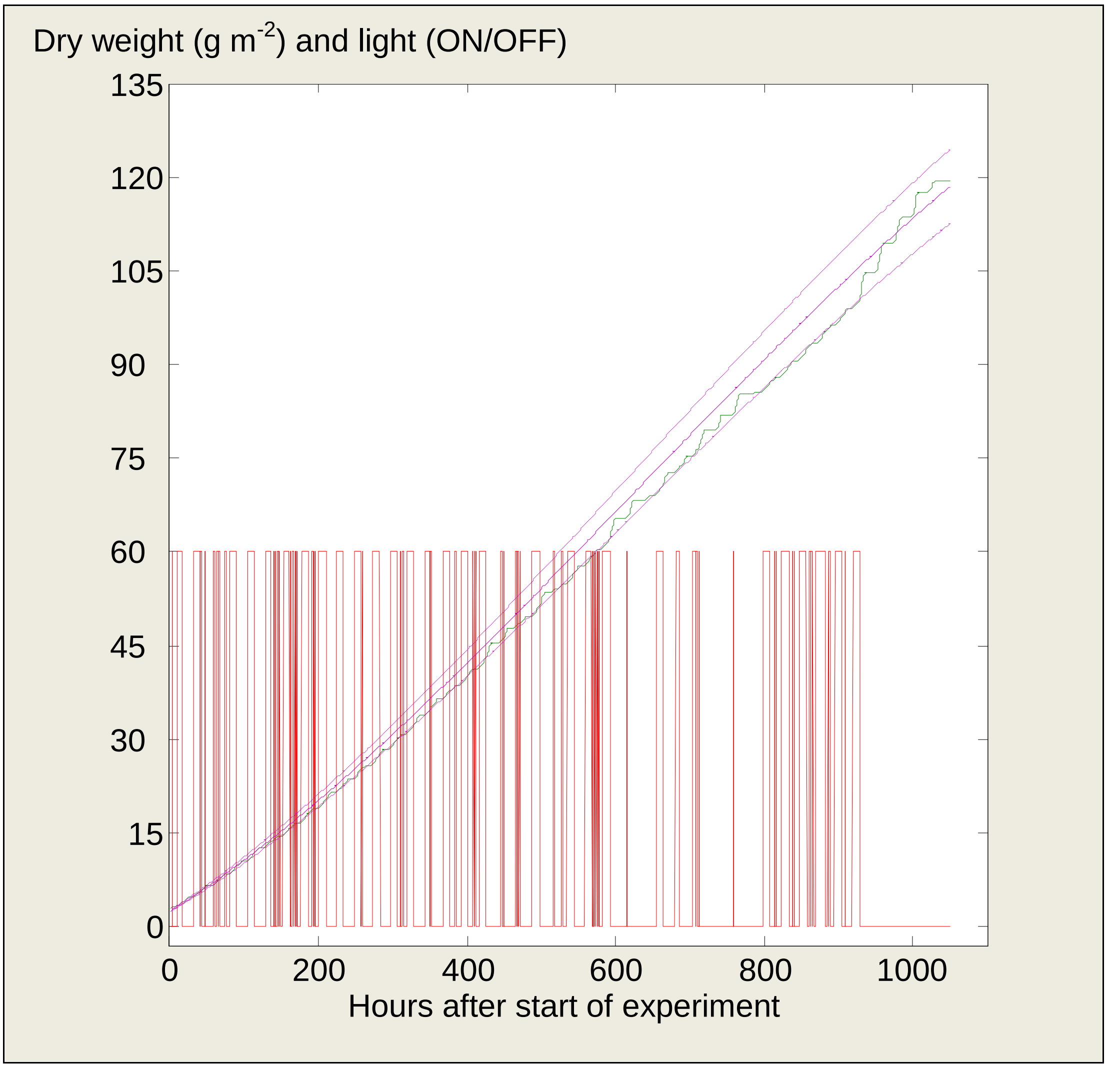


Figure 8 Burning time of the model based lamp control. The solid line is the target value and the dotted are 95 % fractals. The green line is the calculated actual dry weight, and the red shows whether light is on/off.

A 5% tolerance was included in the model, leaving space for natural fluctuations in daylight and saving energy (Figure 8).

The 20 hour light treatment had 875 hours of light and the model turned the light on in 327 hours, saving 548 t or 62% compared to 20 hour light. The model was able to keep the growth within the 95% fractal all through the experiment. In the last part of the experiment, the natural light was actually more than sufficient, so despite the model did not turn on the light, still the calculated actual dry weight, went from below to above the target-line.

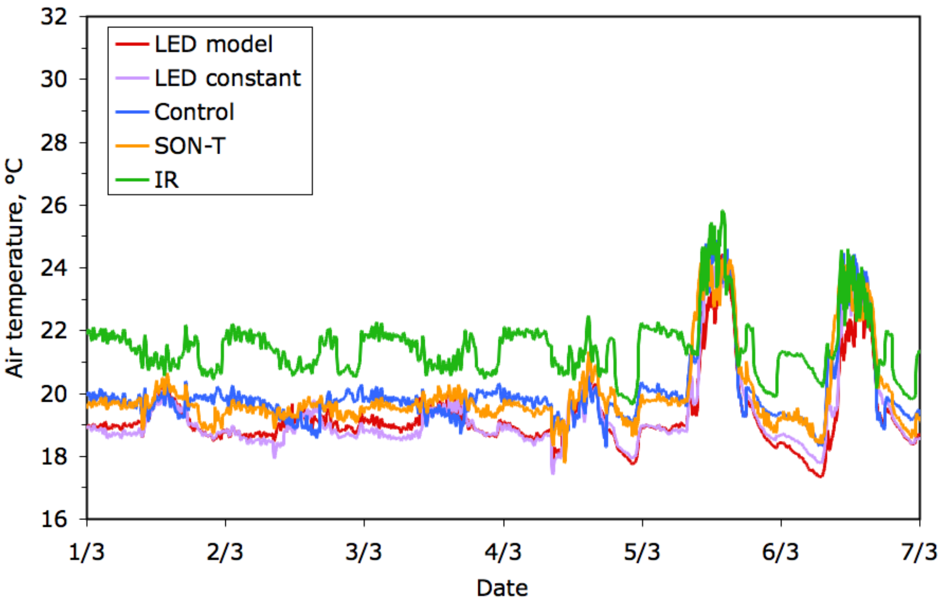


Figure 6 The air temperature in the different treatments.

The air temperature showed minor variations within ca 1°C between the control, LED and SON-T treatments, while air temperature of the IR treatment in general was 2°C higher that the highest of the other treatments (Figure 6). This indicates that under our experimental circumstances the SON-T lamps does not contribute to any great extent to the air temperature. However, it should be kept in mind that the circumstances are very different compared to commercial greenhouses. Our experiment took place in a greenhouse with room for ca 18 large benches, where we used five for the experiment. In this large greenhouse only two SON-T lamps were turned on, which explains why we do not see any effect by the SON-T lamps on the air temperature. In commercial greenhouses the heat radiation from the lamps will contribute more to the air temperature through the heating of all surfaces hit by the radiation.

The mean leaf temperature was primarily affected by the IR radiators (Figure 7). The SON-T treatment showed a gradual increase of leaf temperature, which may be explained by the growth of the plants, which moved the upper leaves closer to the lamps each week. The leaf temperature that did not receive any heat radiation from SON-T lamps or IR radiators followed each other closely throughout the experiment.

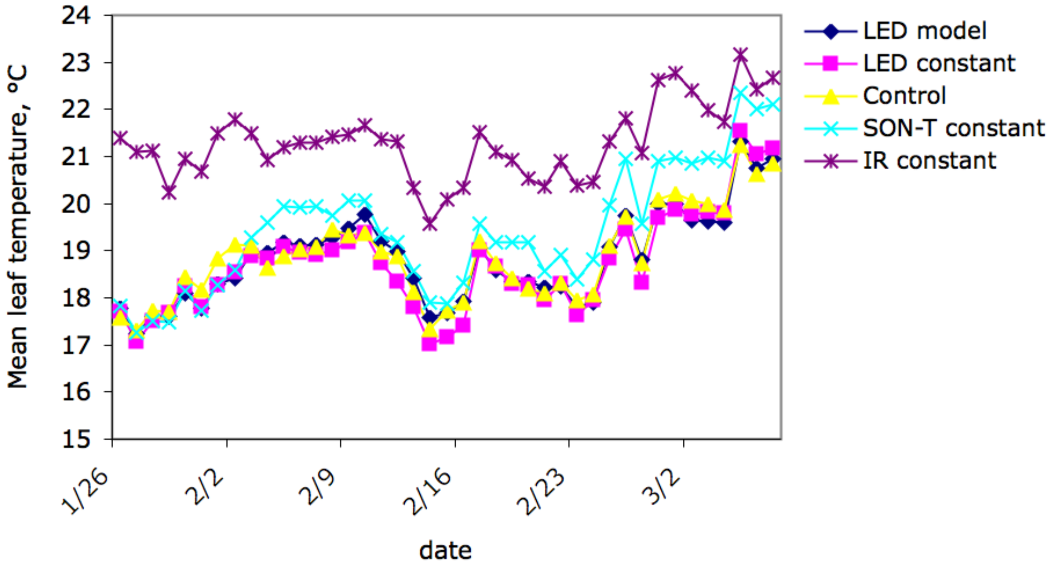


*Figure **7** The mean leaf temperature for each 24 h period.*

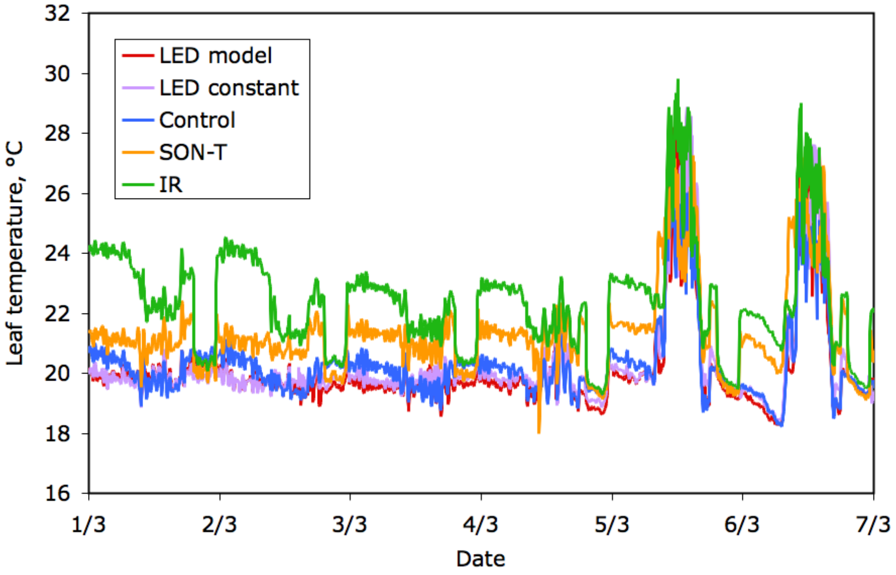


Figure 8 The daily patterns of the leaf temperature during the transition from overcast to sunny weather in the end of the experiment.

The leaf temperature was more affected by the SON-T lamps that the air temperature (Figure 8, cf. Figure 6). This is explained by the physical laws, where radiation heat does not heat air (which is a very thin medium) easily, but heats solid materials (in this case leaves). The leaf temperature under the SON-T lamps is consequently ca 1°C higher than under the LED lamps that does not radiate IR radiation, or in the control. This indicates that even with only 1-2 SON-T lamps turned on, they have a significant effect on the leaf temperature. In our case the difference was only 1°C but when discussing with commercial growers, the often estimate the effect from the SON-T lamps to be 3-4°C. Substituting the SON-T lamps with LED lamps in those nurseries will require a change in the use of the heating system to obtain the desired air temperature for optimal production. These energy aspects have to be taken into account when discussing the energy aspects for changing from SON-T to LED light.

Results and discussion, plant growth

The plant height was primarily affected by the presence or not presence of supplemental light. The control and IR treatments were considerably shorter than the others, both with respect to maximum shoot height (Figure 9) and mean shoot height (Figure 10). The plant that had not received supplementary light had also less uniform plant height. The highest shoot was ca 55% taller than the mean shoot height in the control and IR treatments, but only ca 35% taller in the treatments receiving supplementary light. This indicates that light deficiency in pot roses hits extremely hard on the plant quality during the winter production.

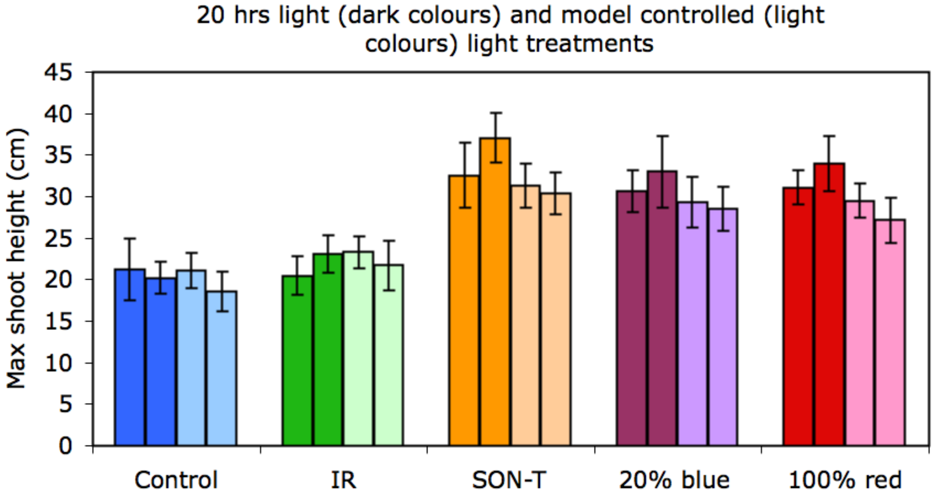


Figure 9 Maximum shoot height (out of four cuttings) per pot. The pair of bars with the same color represents the two replicates within each treatment.

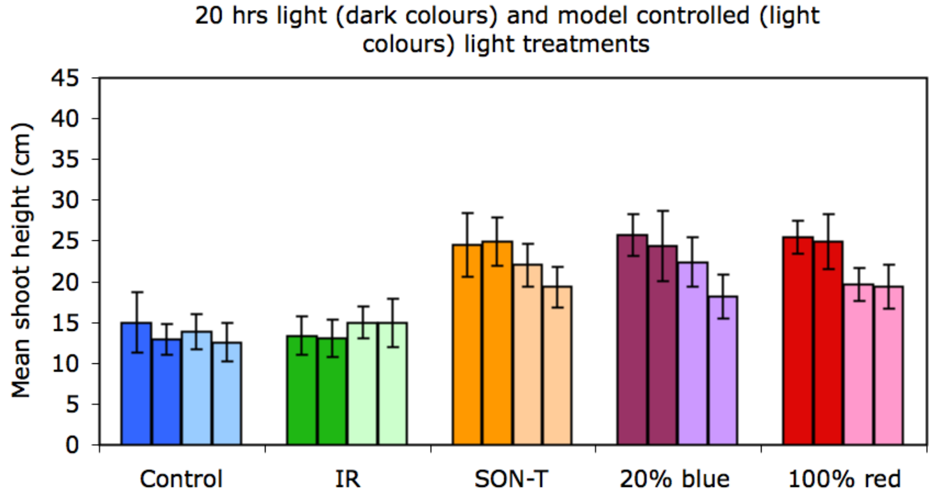


Figure 10 Mean shoot height per pot. The pair of bars with the same color represent the two replicates within each treatment.

The supplemental light had a more nuanced effect on the dry matter production of the plants (Figure 11). The control and IR treatments showed extremely constant dry weight for the two treatments without supplemental light, and replicates. For all the light treatments there was a difference between the two lamp control treatments, where the control by the energy model resulted in smaller plants.

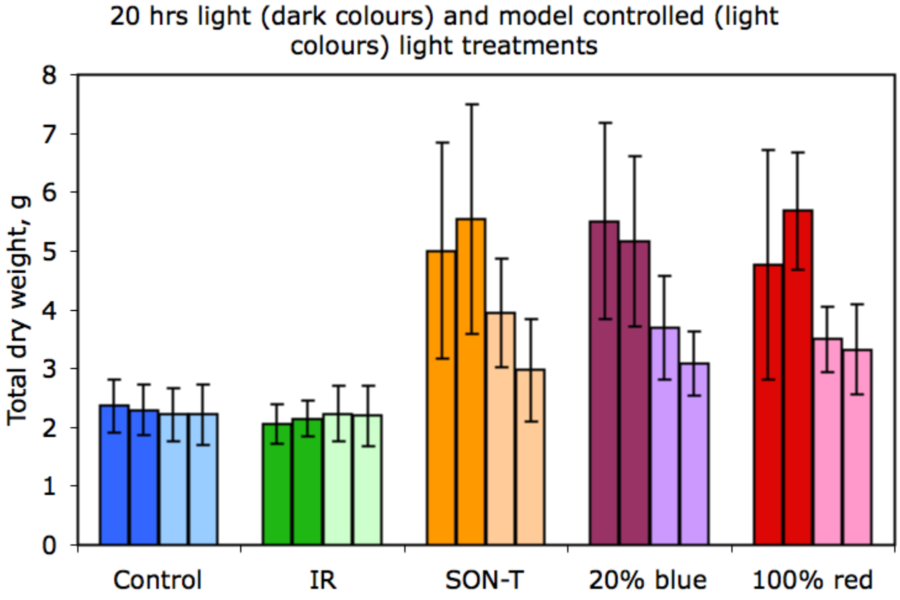


Figure 11 The total dry weight of the plants. The pair of bars with the same color represent the two replicates within each treatment.

The number of flowers was even more dependent on the light treatment, where the model based lamp control had fewer buds and flowers than where the lamps were turned on for 20 hours per day (Figure 12).

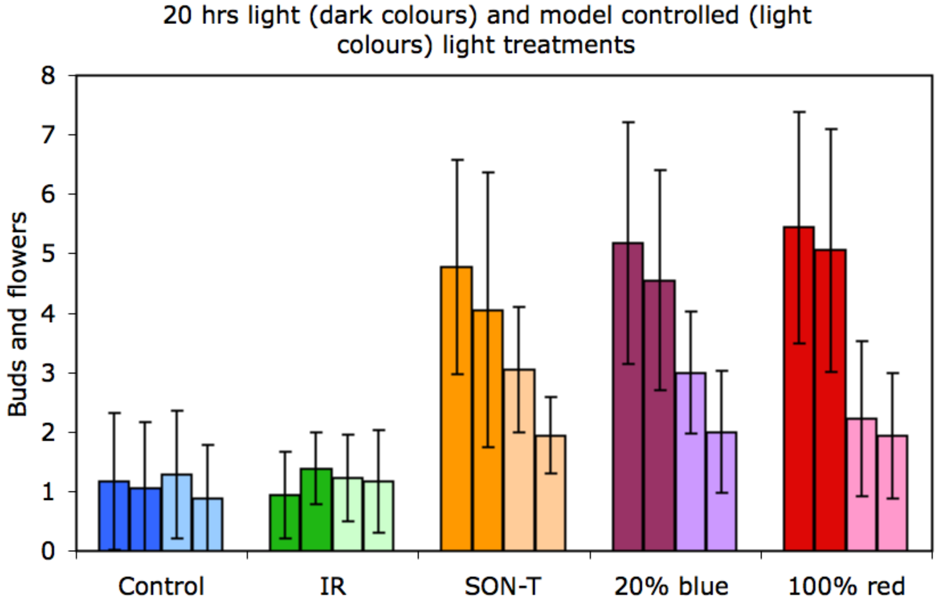


Figure 12 Number of flowers and buds. The pair of bars with the same color represent the two replicates within each treatment.

The biomass production was linearly correlated to the total light integral during the experiment and the same was true for the number of flowers and buds. This was explained by a tight linear correlation between the plant size and how many buds and flowers the plant could carry. The fact that this relationship is linear in its whole range indicating, that the supplemental light could not saturate the need of the crop. The appearance of the plants are exemplified by a comparison of plants grown with SON-T lamps and the two lamp control strategies (Figure) and all the types of radiation treatment with 20 hours control (Figure).

Figure 16 The effect of lamp control strategy on the final plant appearance. The two plants to the left are SON-T lamps controlled by the energy model, while the two plants to the right are SON-T lamps turned on for 20 hours per day.

The results shows, that the energy model treatment did not produce plants with sufficient quality and size, while the natural background light in January-March was too low to save electricity for artificial light. The target value (dry matter/day) was chosen too low, but the fact that the calculated actual dry weight was kept within the 95% fractal, shows that the model do work. The target value should instead be selected to the value of the 20 hour light treatment (approximately 5.3 g pr plant). In this experiment, this would lead to similar plant size and dry weight, and no saving electricity for light.

Figure 17 The effect of the different treatments with 20 hours duration on plant appearance, from the left: control, IR, SON-T, 20% blue in red and 100% red.

To ensure that we are able to investigate the effect of supplemental light on plant production on a ‘difficult’ crop, we chose pot roses. They are known as a light demanding species. Indeed, our results showed that even 20 hours supplemental light of ca 100 µmol m^{-2} s^{-1} was not enough to saturate the need with respect to dry matter production and flowering in pot roses in January – March, when the natural background light is very low. The control background of light was also very low until the last week of production but this pattern is not at all unusual under Danish conditions.

When the effect of the spectral composition of lamps for plant production is investigated the environmental circumstances are very important for the results. We have made our experiments in a greenhouse with natural light as background. That means that specific effects of the spectral distribution of different lamps are mitigated by the background radiation, since that light to a great extent is white, i.e. any ratios between spectral ranges of the lamps will be softened by the white background light. Under these circumstances we were not able to find any difference in the efficiency of the different lamp with different spectral composition in the region of Photosynthetic Active Radiation that drives all photosynthesis in the plants. For pot roses this indicates, that the more energy efficient red light, is enough and the more energy expensive blue light is not needed, as long as produced with natural daylight as background.

There is a trend in Danish nurseries at the moment, to invest in insolation screens that are not transparent to light. It is not clear from our results, how a rose crop will react in this kind of production system. There are several days where the natural total light integral is so low (control and IR in Figure) that the insulation screens can be expected to have been closed the whole day in a commercial nursery, to save energy for heating.

Conclusion

The spectral composition of the artificial light are without importance when light are supplementary to daylight even in winter

SON-T lamps do increase the temperature of the leaves, due to IR-radiation along with the PAR-radiation. In this experiment leaf temperature was increased by 1°C, where only two lamps were installed, but in nurseries with more lamps 3-4°C increase are reported.

LED’s can provide the light for growth, but do not increase leaf temperature the same way SON-T do. This is in some cases beneficial, when high light intensities are wanted, together with low leaf temperature.
Roses are a light demanding culture, and 100 µmol m^{-2} s^{-1} in 20 hours in Jan-Mar 2011 was not saturating for the plants.

6. EVALUATION OF STRATEGY AND RESULTS

By Eva Rosenqvist, KU-Life, Carsten Dam-Hansen, DTU Fotonik and Anker Kuehn, AgroTech 20-12-2011

Chlorofylfluorscense can maybe be used for on-line control of the lamps in the darkest time of the year when the maximum natural PAR < 500 µmol m^{-2} s^{-1}. In the spring – autumn season it is more doubtful due to the high natural light levels that cause extreme light fluctuations and thereby unstable photosynthesis, which is directly reflected in the fluorescence measurments.

Fluctuations under 5 minutes (even big ones) does not trigger deactivation of the plant metabolism or serious stomatal closure. It is therefore not necessary to “fill holes” of short duration in the light by turning on the light for only few minutes. If this pays off or not, will be determined more by how big part of the total daily light integral that comes from the supplemental light.

The Greenhouse LED, SON-T, and terrass heater experiment showed that SON-T and LED can be used for growth, but SON-T provide higher leaf temperature. This will be an important issue for all species that require growth temperature above ca 20°C. A change to LED light will require a different climate control strategy via the heating system, to keep the required leaf temperature. To produce a certain amount of plant biomass will always require a certain amount of resources in terms of light, water/nutrients, CO_2 and temperature, regardless of the source. The trick is to balance the different resources, so no one is in excess that can not be fully utilized.

In our greenhouse experiment it is obvious “a photon is a photon”, i.e. the actual colour of the supplemental light has no direct influence on the growth of the roses. However, this is because of the natural background daylight in the greenhouse. It is well known from the literature that different monochromatic light in growth rooms can cause severe problems with plant development and morphology, like leaf shape and branching. With increasing use of energy saving non-transparent, white insulation screens that block out the natural daylight in commercial greenhouses, this is an issue that has to be addressed further.

The energy saving model can probably save electricity in spring and autumn but the target for final plant size must be chosen with care and the higher target the smaller energy saving. However, to create a dynamic light control that saves energy while still ensuring an appropriate plant production one will have to include both energy prices and weather forecasts, as well as photosynthesis models, as has been done in the Dynalight project that has run as a collaboration between AU and SDU.

Energysaving in the greenhouse industry will today depend on energy saving models and hopefully in the near future on more effective LED’s.