Using Fluorescence as Control Parameter to Decide Optimal Light Spectrum for Plant Growth

Linnéa Ahlman*, Daniel Bånkestad**, and Torsten Wik*

*Department of Signals and Systems, Chalmers University of Technology, Göteborg, Sweden
**Heliospectra AB, Göteborg Sweden

1 Introduction

Modern greenhouses having lighting systems are large consumers of electricity. In Europe alone, the lighting consumption is estimated to 150 TWh per year. High pressure sodium (HPS) lamps are still dominating and the illumination is in general controlled manually by on/off control. Changing to light emitting diodes (LED) gives the possibility of adapting the spectrum (i.e. changing the power split to diodes of different colours) and to gradually changing the intensity, which implies an energy saving potential. The optimal spectrum might depend on a number of factors, for example plant species, required characteristics and energy use efficiency on the diodes.

Using LEDs with different blue to red (B:R) ratios, as a supplement to sunlight, have been investigated for growing of cucumber seedling [Hernández and Kubota, 2014] and tomato seedling [Hernández and Kubota, 2012]. Their conclusion was that 100% red LED is preferred, indicating that the blue light in the sunlight is sufficient (B:R in sunlight is about 4:3 on $photons/m^2/s$ basis [ASTM, 2012].

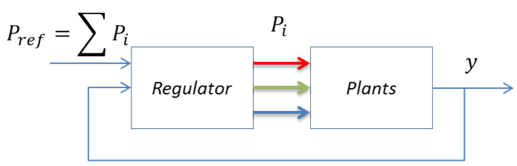

Figure 1: In order to find an optimal spectrum, i.e. how to distribute the power P_{ref} among the different diode groups by feedback control, one needs to find a parameter of plant growth that could be measured remotely and online. In this study we investigate if chlorophyll fluorescence F740 could be a candidate.

The experiments in this study were performed on basil plants in a closed environment with no sunlight. We aim to find a way of changing the spectrum as a function of some growth measure. Figure 1 shows the basic idea; for a given amount input power P_{ref}, how should it be distributed among the different diodes in order

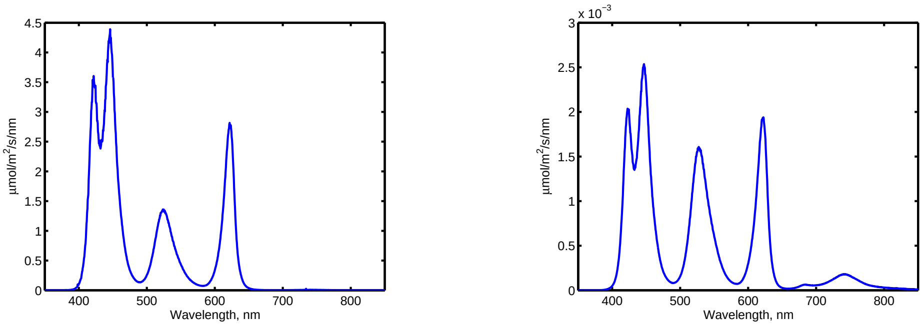

Figure 2: Spectrum when using four diode groups in a LED lamp. Left plot: incident light, i.e. light detected by a spectrometer facing the lamp. Right plot: reflected and fluorescent light, i.e. detected by a spectrometer facing the plants. There are two fluorescent peaks, at 685 and at 740 nm.

to optimize the plant performance, y, such as growth rate, leaf thickness etc. Having a remotely measured plant performance parameter, a self optimizing controller could be sought to find the optimal spectrum. A candidate signal investigated here is steady state chlorophyll fluorescence. The fluorescence signal originates from chlorophyll *a* in photosystem I and II and is an emission of absorbed light energy, with peak wavelengths at 685 and 740 nm. Figure 2 shows a spectrum using four different diode groups. The left plot is the spectrum detected by a spectrometer facing the lamp, i.e. the incident light to the plants. The right plot is the spectrum detected in a spectrometer facing the plants. The same four peaks as for the incident light can be identified, i.e. the reflected light, but also two additional peaks (at 685 and 740 nm) which is the fluorescence. The F740 peak gives the strongest signal, since the F685 is partly reabsorbed by the chlorophyll *a*, and was found to be best suited for our purpose.

The hypothesis in this study was that there is a positive correlation between the amount of absorbed light, the amount of fluorescent light and photosynthetic rate under present conditions (well-irrigated and fertilized crops under normal light conditions). This relation has been observed on both leaf level [Flexas et al., 2002] and canopy level [Guantera et al., 2014], but is dependent on plant health since chlorophyll fluorescence is used to remove excess energy. We want to distribute the total incident light I_{tot} among the available diode groups to reach maximal photosynthetic rate. With our hypothesis this is equal to maximizing the total fluorescence for a given I_{tot}.

Assume we have two diodes, a and b, and assess the changes in fluorescence (with peak at 740 nm, $F740$) when increasing the light by Δa or Δb (where $|\Delta a| = |\Delta b|$). If $\Delta F740(\Delta a) > \Delta F740(\Delta b)$ the conclusion is that increasing the power to diode group a increases the performance more than increasing the power to diode group b. With this argument, the optimal spectrum will be the one where $\Delta F740(\Delta a) = \Delta F740(\Delta b)$. This can, formally, be extended to the case of several diode groups with the result that the optimal spectrum will then be the one where all derivatives are equal.

2 Experiments and preliminary results

Experiments were performed on basil plants in a closed environment. Two Heliospectra LED lamps were placed 0.9 m above the plants. Two spectrometers were used to detect the light, one detecting the incident light and one detecting the reflected and fluorescent light. In addition, an infrared gas analyzer (IRGA) was used for measuring photosynthetic rate based on carbon dioxide uptake on a single leaf.

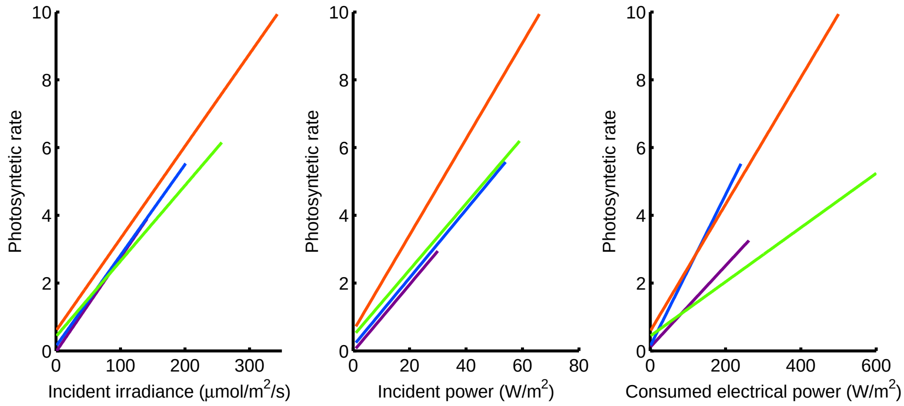

Figure 3: Photosynthetic rate (PN) versus (a) incident irradiance, (b) incident power, (c) consumed electrical power. Four diode groups are tested, one at a time, corresponding to the four lines in each subplot.

2.1 One diode group lighting at a time

In the first setup only one diode group was used at a time. The results showed that there is a high correlation ($R^2 = 0.95$) between photosynthetic rate (PN) and fluorescence F740 at low light intensity and they increase linearly with light intensity (Figure 3). PN as a function of photon irradiance (Figure 3a) indicates slightly higher PN using red diodes, possibly due to nonlinearities at light intensities close to zero. The derivatives slightly change if PN is investigated with respect to incident power (Figure 3b); relatively higher derivatives for long wavelength light (red) and relatively lower derivatives for short wavelength light (purple), since light energy is inversely proportional to wavelength. The derivatives for all lines are almost equal, except for the red group clearly having higher derivatives. Taking the efficiency of the different diodes into consideration (Figure 3c) further changes the derivative. The highest derivative, corresponding to the most efficient use of energy, is then the blue group.

2.2 Background light

In the second setup different background lights were tested; one regime with blue to red (B:R) ratio 3:1 and with B:R ratio 1:3. Four different light intensity levels were tested for each regime. For a given background light one diode group was changed at a time, in order to measure the fluorescence changes as a function of incident light ($dF740/dI$), at the given operating point. Figure 4 shows the results for dominating blue background light (B:R 3:1) and Figure 5 shows the same information for dominating red background light (B:R 1:3).

The results are similar to those presented in Section 2.1. To reach the optimal spectrum (based on photon irradiance, not energy) the amount of red light should increase and the amount of green light should decrease; no matter if the B:R ratio is 1:3 or 3:1.

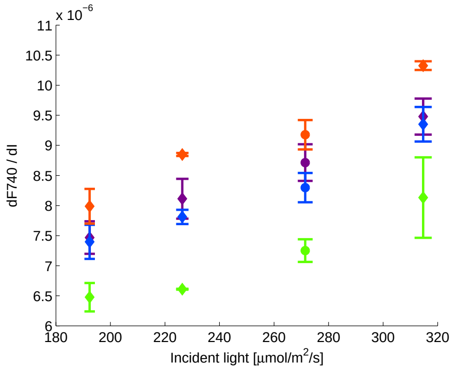

Figure 4: Derivative $F740$ vs incident light at four operating points with dominating blue background light (B:R 3:1).

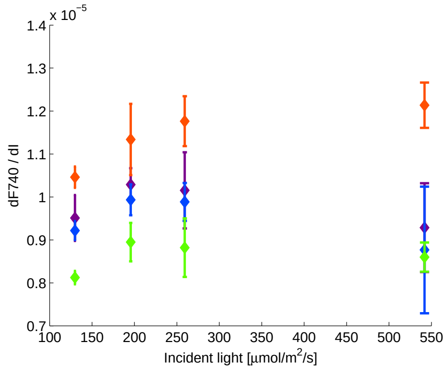

Figure 5: Derivative $F740$ vs incident light at four operating points with dominating red background light (B:R 1:3).

3 Final conclusions

Under present conditions photosynthetic rate and fluorescence 740 correlates well, and therefore, it seems reasonable to use F740 as a control parameter to find optimal spectrum for plant growth. The results indicate that the optimal spectrum with respect to short term photosynthetic growth (not taking efficiency of diodes into consideration) has less blue light than B:R 1:3. If using the control strategy suggested here, it is likely that some boundary conditions are needed (for example maximum and minimum B:R ratio) to ensure long term healthy plants.

References

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