Remote Light Stress Detection for Greenhouse LED Lighting Control

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Abstract: The illumination in greenhouses is in general still controlled manually by on/off control because of the type of lamps (High Pressure Sodium) that are traditionally used. With High Brightness LEDs being introduced on the market today, sufficiently high power for greenhouse grown crops can be achieved, which opens up for advanced lighting control since both light spectrum and intensity can be controlled then. For the growers, maximizing production in order to meet customer demand and economically optimize the production, often imply a high light intensity and a high level of artificial light complementing the natural sunlight. However, a too high intensity causes light stress and a photo inhibition that can significantly reduce the photosynthetic yield and hence, production. A key issue to address is therefore to detect when this level is reached. Here we present new results on how to diagnose the plants remotely based on transient and frequency analysis, system identification and frequency function properties.

1. INTRODUCTION

Industrial scale green houses are enormous consumers of electricity. In Europe alone consumption is estimated to be around 150 TWh per year, which is about the same as the total electricity consumption in Sweden. Clearly, a reduced electricity consumption would have a significant environmental impact.

Greenhouse lamps using High Brightness LEDs are currently being introduced on the market. These lamps have several important advantages compared to the traditionally used High Pressure Sodium (HPS) lamps. The HPS lamps have a significant part of the irradiance in the far red being outside the absorbtion spectrum of the photosynthesis. By combining several different groups of LEDs having different colors the emitted spectrum of a LED lamp can be made to better fit the photosynthesis. Contrary to the HPS lamps, which generally allow only on-off control, LEDs are easily adjustable in power and this opens up for advanced lighting control since both light spectrum and intensity can be controlled then. Such a control applied to planning, spectrum optimization and photo inhibition, as presented in the 17th NPCW Wik et al. (2012), may potentially give both energy savings and increased production (Baker and Rosenqvist, 2004). In this work we focus on one of the mechanisms; photo inhibition. Excess light causes plant stress and the induction of protective mechanisms that lower the yield in tens of percent, even at a level where the human eye cannot detect any change. If too severe, the process is no longer reversible and the plants become damaged with a permanently decreased growth rate.

Plants are fluorescent in that they re-emit absorbed light, of any wavelength, in wavelengths around 685 and 740 nm. The emission of chlorophyll fluorescence (CF) varies depending on photosynthetic yield and plant stress. Chlorophyll fluorescence is therefore widely used as a nondestructive probe of physiology in photosynthetic organisms (Krause and Weis, 1991).

Although the production in greenhouses potentially could benefit a lot from using CF measurements for the control of supplementary lighting, this is rarely done today. During the last decade attempts to introduce CF measurements in commercial greenhouses have been done. However, on-line CF measurements have, to the best of our knowledge, yet not been used for automatic and closed loop control of climate and illumination in greenhouses. One of the most important reason is that it is difficult to get measurement indices that are sufficiently robust. Standard methods, such as PAM (Pulse Amplitude Modulated) techniques, were derived for on-leaf measurements, though equipment is now available for measurements at some distance (Ounis et al., 2001; Moya and Cerovic, 2004). If CF measurements should be used for automatic control, however, the measurement technique must give a representative measurement for the entire area to be controlled and, hence, a remote sensing method is more or less required. Furthermore, the measurement technique must be robust to disturbances, such as variations in incident light. Traditional techniques for stress detection, such as F_v/F_m and corresponding measures, have been tested remotely but near plants (as opposed to on-leaf) but requires dark adapted plants, which excludes them from on-line control in green houses (Takayama et al., 2011).

This research project focuses on developing a remote sensing technique based on CF to be used for the automatic control of illumination in greenhouses. The sensor measures, at a distance of 1-2 meters, the CF from the whole region of the plant canopy illuminated by the lamp, thus giving an aggregated measure. The method is based on that the dynamics of the induced fluorescence signal

reveals information on photosynthetic yield as well as stress mechanisms in the plants. The dynamics of the photosynthesis and the heat dissipation processes induced by stress, is studied as an input output relation, where the input is emitted light from the lamp and the output is re-emitted fluorescence. Here we present a first approach in studying this input output relation, using frequency and transient analysis.

The experiments and more analysis and results will be available in (Carstensen et al., Manuscript).

2. MATERIALS AND METHODS

In order to investigate how the dynamics is affected, plants acclimated to different conditions were exposed to light ranging from low intensity to increasing inhibiting intensity, and then low intensities again for the plants to recover. The plants used in the experiments were sweet basil Nufar (*Ocimum Basilicum*) grown in growth chambers in four different growth conditions:

(1) LED light, 80 μE intensity
(2) LED light, 500 μE intensity
(3) HPS light, 80 μE intensity
(4) HPS light, 500 μE intensity

where the notation μE is μmol of photons per m^2 and s.

The light in each experiment consisted of two parts; an excitation light signal (sinusoid or step) and a background light going through four phases:

(1) 110 μE for 2.5 h
(2) 530 μE for 1 h
(3) 1750 μE for 2 h
(4) 110 μE for 3-6 h

Analysis of fluorescence from plants, using fluorescence indices such as F_v/F_m, is a well established method for detecting plant stress. However, such standard methods require on-leaf measures and a completely controlled environment. As already mentioned, to be used in practice for automatic control, the stress has to be sensed remotely. As an indication of light stress level, the maximum efficiency of PSII photochemistry can be used, through the ratio Fv/Fm. How Fv/Fm evolved during the experiments is shown in Fig. 1.

The curves in Fig. 1 also illustrates the difficulty of getting robust measures without remote sensing, though the expected trends during the four phases can be identified. Decreasing levels during Phase 2 and 3 illustrates an increasing level of stress, and the measurements during Phase 4 displays a recovery phase. It is also evident that the behaviour is different depending on the light the plants have been acclimated to. The lower the acclimation light the more stressed the plants are. Also, it appears clear that acclimation to HPS spectrum makes the plants more susceptible to light stress than acclimation to the LED spectrum. They also appear to have a slower recovery during the last phase.

Two different excitation signals were employed: (1) light varying between two levels, forming step increases and step decreases and (2) sinusoidal varying light. The step length was chosen to be 300s, since that was the time it took for

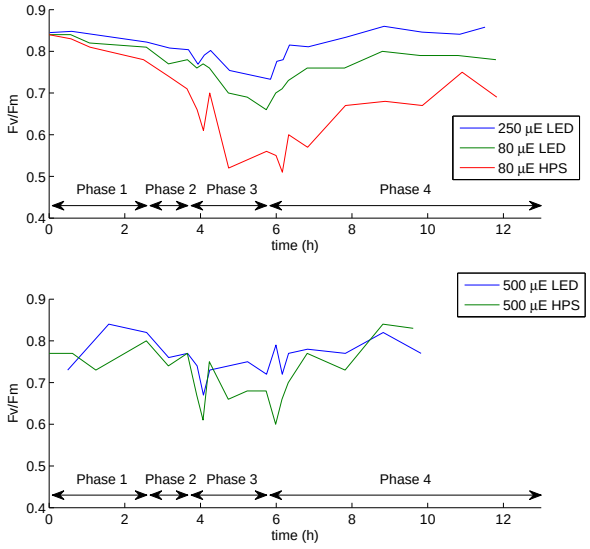

Fig. 1. Fv/Fm measured during experiments with sinusoids as excitation signal. Fv/Fm measured on plant material acclimated to different light intensities and spectrum as indicated in the graph. The figure shows the mean value of four leaves.

the transient fluorescence response to settle, and the slow kinetics of the fluorescence has been reported to contain specific information on stress (Strasser 2004). The sinusoid period was selected because this frequency ($\omega \approx 0.1$ rad/s) has been reported to reveal interesting dynamical features in plants by Nedbal (2003), and was also believed to catch dynamic features observed in previous experiments (Wik et al., 2012). Both a resonance peak and strong upper harmonic oscillations are reported to occur, not only in fluorescence but also in CO_2 capture, upon harmonically modulated light at this frequency.

The chlorophyll fluorescence is emitted with two peaks; one centered around 685 nm and one around 740 nm. The former one is within the absorption spectrum of the photosynthesis and is therefore to a large extent reabsorbed. Absolute irradiance, measured with a spectrometer facing the plants and integrated over the interval 700-780nm, thus representing the fluorescence signal with maximum at 740nm, was therefore used as system output in the analysis.

The intensity of the excitation signal (blue LEDs) at each time instance was also calculated as the integrated absolute irradiance (μE) in the wavelength interval 380-480nm, based on data collected with a spectrometer facing the lamp.

In the analysis of the sinusoid experiments, sinus signals (for the known frequency) were first fitted to the measured input and output by least square fitting of amplitude, phase and mean level. The fit of the sinusoids were all over high to both the excitation signal and the fluorescence signal, which motivated a linear analysis in terms of gain and phase shifts. The *fluorescence gain* was then simply determined as the ratio of the output and input

amplitudes, and the phase shift as the difference between the estimated phases.

The step responses were different for step increases and step decreases, implying that the system is actually nonlinear. This motivated a separate estimation of models to step increases and step decreases, while keeping the modelling linear. Hence, prior to the modeling, data was cut into step increases and step decreases, with 60s of data included before each change in level. The dynamics of the responses to the step increases exhibited stronger dynamic features than those for step decreases. Therefore, we choose to focus only on the step increases in this work.

The linear modeling was performed by estimation of one model to each step to let the model parameters, within one selected model structure and order, adapt as the dynamics in the photosynthesis are changed due to altered physiology. Hence, the first part in the identification procedure was to find a model structure and model order applicable to all the four different phases in the experiment. Since the step responses under low light intensity, during Phase 1 and 4 of the experiment, exhibited the most complex transients, the model structure and order was selected based on its suitability for modeling step responses for these experimental phases. After standard testing of ARX, ARMAX, Output Error (OE) and Box Jenkins (BJ) models (Ljung, 2007), it was found that OE models with 3 poles and 4 zeros gave the best results in simulation on both estimation data and validation data, independently of the prefiltering of the data.

3. RESULTS

Fuorescence gain The fluorescence gains for the five set of plants grown under different light treatments are shown together with the Fv/Fm in Figure 2. Within each phase of the experiment the fluorescence gain exhibits slow continuous changes, whereas in the transition between the phases the gains respond instantly to the changed background light intensity. The slow continuous changes in the fluorescence gain clearly agree with the changes in the Fv/Fm and are therefore interpreted as changes in photoinhibition and heat dissipation processes. The instant changes in the fluorescence gain upon changes in the background light intensity have no counterpart in the Fv/Fm and are likely related to changes in the photosynthetic yield or to saturation effects.

Phase shifts Figure 3 shows how the phase shifts vary during the experiment. The relation between the phase shifts and the Fv/Fm apparently depends on both acclimation and background light intensity in an intricate way, which will be explained and discussed in relation to the results of the step responses. However, some observations can be made here.

Whether the phase shifts are positive or negative is determined by the background light intensity in relation to what light intensity the plants are acclimated to. Negative phase shifts were only observed for plants facing a lower light intensity than they were grown under. For plants facing the light intensity they were grown under, or higher intensities, the phase shifts were positive. Furthermore, a decrease in the absolute value of the phase shifts was related to a decrease in Fv/Fm, whereas an increase in the absolute value of the phase shifts was related to an increase in the Fv/Fm.

It should be noted that, as a stress indicator, the phase shift has an important advantage over the fluorescence gain since it is basically independent of the amplitude and, thus, robust with respect to changes in leaf area, morphology and distance for example.

Results with step excitation In Figure 4 step respones from the four phases are shown. As can be seen, the fluorescence transients differ between different phases of the experiments and also between plants acclimated to different light intensities.

The original hypothesis of the approach in this work was that changes in model parameter values could be used to track stress levels in plants. It turned out though that both light intensity and stress level not only affected the parameter values but also the complexity of the dynamics. For plants under low light a model order with 3 poles and 4 zeros was motivated, whereas under higher light intensity this model order gave rise to cancellations between poles and zeros, implying that a lower model order was more suitable. The loss of complexity due to stress or increased light intensity made it inconvenient to track plant stress through these values. This is not only because the loss of complexity gave rise to jumps in these values but also because their uncertainties increased.

Instead of tracking parameters or combinations thereof a better approach appears to be to base the analysis on information in the frequency plane. In fact, the identified frequency functions proved to converge with increasing model order. A study of the fluorescence transients in the frequency domain revealed three main features relating to acclimation, light intensity and stress respectively.

Acclimation to different light intensities affected how fast the dynamics of the fluorescence response was. The step responses from plants acclimated to $80\mu E$ and $500\mu E$ were similar in shape, but the step responses from plants grown under $80\mu E$ were faster. In the frequency domain the faster dynamics exhibited by the low light acclimated plants corresponds to a shift of the frequency function towards higher frequencies (see Fig. 5). Light intensity also affected the fluorescence dynamics such that it became faster when the intensity was increased, shifting the frequency function towards higher frequencies as shown in Figure 5. Furthermore increased light intensity led to more trivial dynamics as already discussed.

Decreased Fv/Fm made the dynamics less complex in the frequency range studied here. Figure 6 shows how the frequency function was changed during recovery of Fv/Fm under $80\mu E$. During recovery the complexity of the dynamics was successively increased, which could be seen through an increased resonance peak and increased phase shifts. The increased complexity of the dynamics gained during recovery of Fv/Fm could also be seen through the pole-zero placements of the modeled step responses. During recovery, poles and zeros lying close to each other were moved further away from each other.

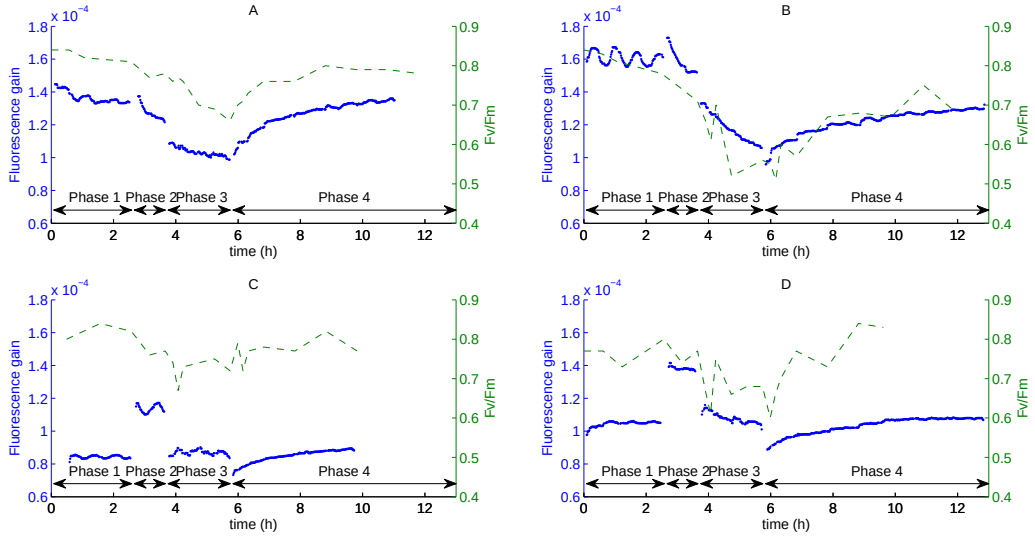

Fig. 2. Fluorescence gain and Fv/Fm from plants acclimated to $80\mu E$ and the LED spectrum (A), $80\mu E$ and the HPS spectrum (B), $500\mu E$ and the LED spectrum (C) and $500\mu E$ and the HPS spectrum (D). The oscillations in the fluorescence gain are due to temperature variations in the lab.

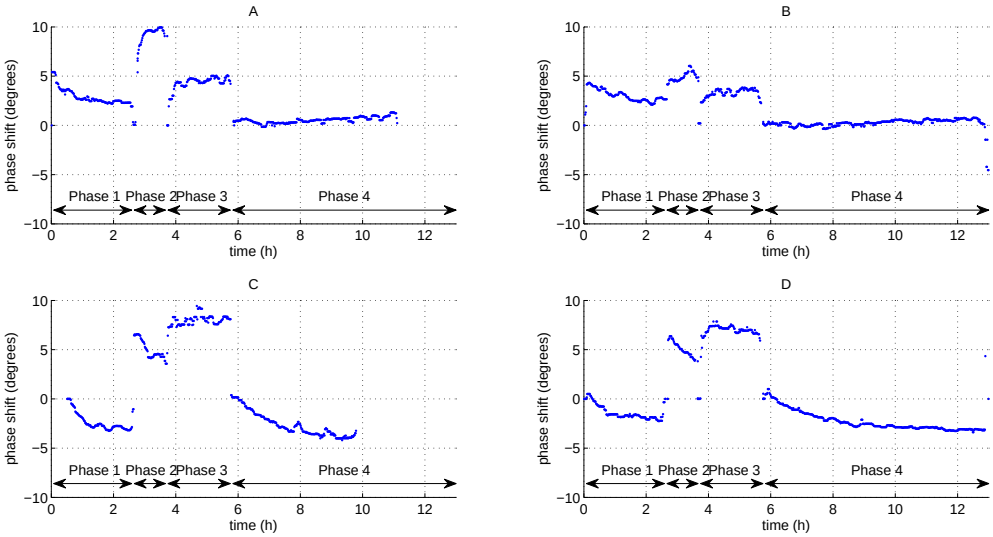

Fig. 3. Phase shifts in the fluorescence signal for plants acclimated to $80\mu E$ and the LED spectrum (A), 80 μE and the HPS spectrum (B), $500\mu E$ and the LED spectrum (C) and $500\mu E$ and the HPS spectrum (D).

The observed behaviour, where the light flux (energy) in relation to the capacity of utilising energy (due to acclimation) determines how fast the system responds to an input signal, is coherent with a system of flows and buffers. For such systems, the response to an input change is faster the smaller the buffer volume, and the higher the flow is. Furthermore, as the capacity of a buffer is reached the system will lose a dynamic state, which corresponds to a loss in complexity and system order. This is also the phenomena observed here, when pole-zero cancellations occurred as the light intensity became too high compared to the plants capacity. Although a buffer-flow system alone would not give rise to any resonance, this can be caused by feedback mechanisms in the system.

Comparing step and sinusoid excitation results The results from the experiments with sinusoidal varying light alone were somehow hard to interpret. Especially the phase shifts appeared complex. Fortunately, the frequency domain results from the step responses provides an explanation. The frequency functions presented in Figure 5 showed that the background light intensity in relation to the light intensity the plants are acclimated to determined the position of the frequency function. This clearly explains why the phase shift and the amplification of an input signal of a fixed angular frequency ($\omega = 0.1\ rad/s$) could vary significantly depending on the plant material and background light intensity. According to the Bode plots for the plants acclimated to $500\mu E$ and Phase 1 of the experiment (see Figure 5), an input signal of frequency

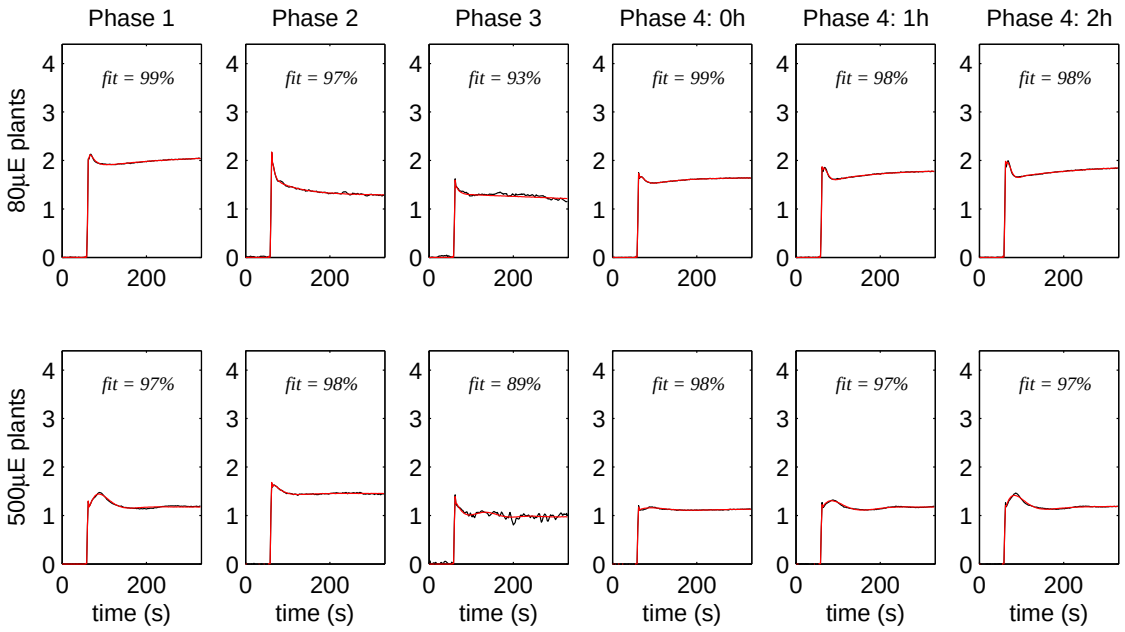

Fig. 4. Fluorescence responses to step increases; from left to right one step from each of Phase 1, Phase 2 and Phase 3, and 3 steps from Phase 4: first step during recovery, after 1h of recovery and after 2 hours of recovery. Filtered raw data (black) and simulated data (red) in the same graph.

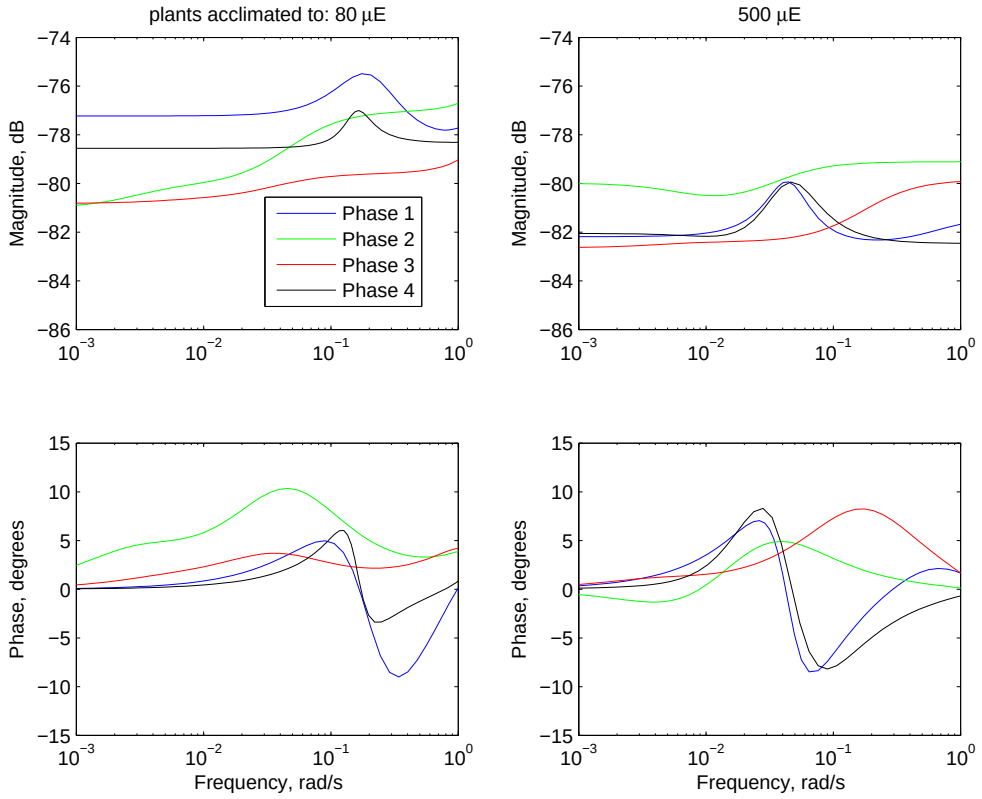

Fig. 5. Bode diagrams showing the mean value of the frequency functions from the different phases (Phase 1, blue, Phase 2 green, Phase 3, red and Phase 4, black) of the experiments. From left to right, plants acclimated to $80\mu E$ and $500\mu E$.

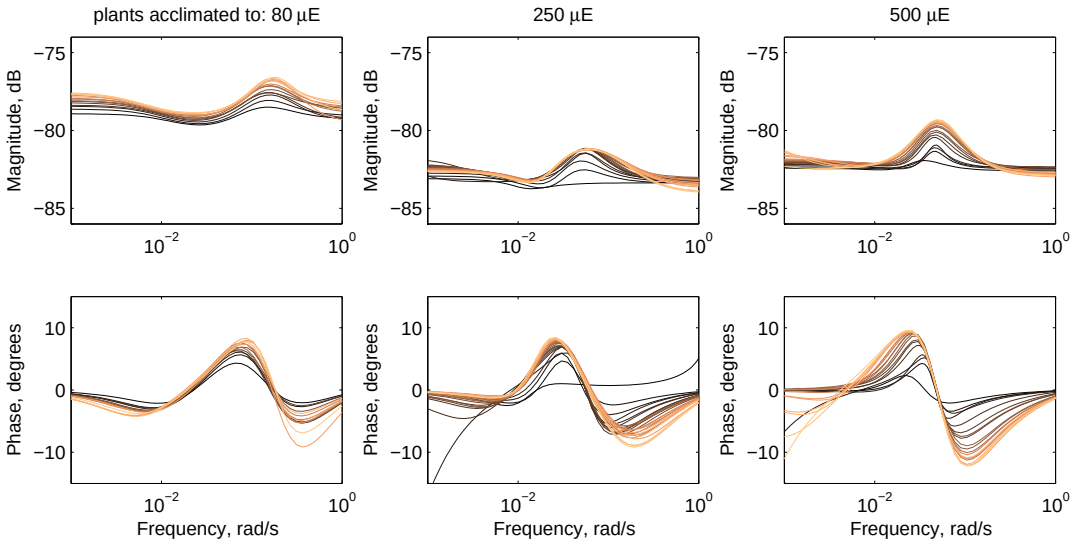

Fig. 6. Bode diagrams showing recovery from stress under $80\mu E$ in Phase 4 of the experiments. From left to right plants acclimated to $80\mu E$, $250\mu E$ and $500\mu E$. The color-scale goes from black to yellow with black indicating the beginning of Phase 4 and yellow the end.

$\omega = 0.1\ rad/s$ will get a negative phase shift. However, the corresponding Bode plot for the plants acclimated to $80\mu E$ is shifted towards higher frequencies, resulting in a positive phase shift for an input signal of $\omega = 0.1\ rad/s$. This is in agreement with the phase shifts presented in Figure 3. When the light intensity is increased, also the Bode plots for the plants acclimated to $500\mu E$ moved towards higher frequencies and consequently, the sinusoid of frequency $\omega = 0.1\ rad/s$ becomes positively phase shifted. Moreover, the discontinuities in the fluorescence gain upon changed background light intensity (see Figure 2) could to some extent be explained by movements of the position of the resonance peak in the Bode diagrams.

4. CONCLUSIONS

The dynamics of plant chlorophyll fluorescence was studied through frequency- and transient- analysis in experiments where plants acclimated to different light intensities and spectra were exposed to low light, high light and excess light. One of the key findings was that the background light intensity in relation to the light intensity that the plants were acclimated to determined how fast the plants responded to a light excitation. Hence, light intensity shifted the plants dynamic behaviour in the frequency domain. Perhaps even more interesting was that the complexity of the dynamics was decreased upon increased light intensity above the light intensity of acclimation. The complexity of the dynamics was also affected by light induced stress. The mechanisms behind these observations have the character of a flow-system with buffer volumes and feedback, where the buffers likely are metabolite pools. These results were obtained from the analysis of black-box models of step responses. Interestingly, these results were also in agreement with the gain and phase shifts obtained with sinusoid excitation.

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