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Preliminary Analysis of Plant Response to Environmental Disturbances in Controlled Environments

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Abstract. *The ability to ensure that crop growth and development proceed according to the desired production schedule would be of great advantage for controlled environment plant production systems. One method to accomplish this is to integrate methods for predicting plant responses to changes in the local climate with environmental control algorithms. This requires mathematical crop models that can accurately predict effects of multi-day disturbances on plant growth and development. A growth chamber experiment with lettuce (*Lactuca sativa *L., cv. Waldman's Green) was conducted to generate experimental data on the lettuce yield and daily canopy light absorption in response to a forced light intensity disturbance. A mathematical crop model was fit to a portion of the data and used to generate lettuce yield response curves as a function of simulated disturbances in light intensity that occurred during the production cycle. Comparisons between the model predictions and experimental data show that additional model calibration and experimental treatments are required.*

Keywords: crop modeling, simulations, lettuce, plant growth

Introduction

Environmental control systems in controlled environment plant production facilities (including greenhouses and growth chambers) traditionally focus on maintaining the indoor climate according to pre-defined set points. These set points are typically derived from grower experience or rules-of-thumb for the crop to be grown (Ting and Giacomelli, 1992). The effectiveness of the control system depends on the control logic (usually a form of on/off, proportional, proportional integral, or proportional integral and derivative algorithms), the capabilities of the sensors and actuators, and the physical properties of the controlled environment itself (McCormack and Rummel, 1993). In general, these systems have been developed such that the indoor environment can be maintained relatively independently from outdoor conditions. However, this control approach is not optimal in the sense that information from the plant itself is not utilized in making control decisions.

Recent efforts in control systems design have looked at integrating feedback from the plants with the control algorithm to specify set points on a more dynamic basis. Instead of using environmental set points that are static throughout the production cycle, an understanding of the plant can be incorporated with the control logic so that set points change throughout the season on an hourly or daily basis. One approach is to integrate mathematical predictions of the plant growth and development status with weather and market forecasts to optimize the environmental inputs to the greenhouse on a daily basis. Such an approach can be viewed as feed-forward in that future predictions of the state of the system are used to form the control logic. These efforts are expected to increase controlled environment agriculture profitability through minimization of resource consumption (such as power and / or elevated atmospheric carbon dioxide concentration), maximization of productivity, and potential improvement of crop quality beyond what is achieved under the traditional control approach (see, for example, Both et al., 1998; Challa and van Straten, 1993; Marsh and Albright, 1991; Sigrimis and Rerras, 1996).

Other techniques include the use of off-line controllers or decision support systems that accept current growing conditions as input and output new environmental set points to be enacted by the grower. For example, Fleisher (2001) developed a model-based predictive control algorithm for process control of plant production scheduling in controlled environments. Mathematical crop models were developed that predicted the crop response to daily changes in environmental inputs for light intensity (photosynthetic photon flux, PPF), air temperature, and atmospheric carbon dioxide concentration. At the beginning of the production cycle, the control algorithm used the mathematical crop models to determine the optimum set of daily environmental inputs needed to achieve the desired plant production schedule. During each subsequent day of the production cycle, the algorithm read in values for current environmental conditions, estimated crop growth and development responses, compared these estimated responses with the desired production schedule, and identified new environmental set points to be enacted at the following time-step that would minimize any apparent differences. In this way, the effects of environmental disturbances on the plant production schedule, whether created by the incapability of the control system to obtain the desired environmental input or some external disturbance, can be compensated for. To date, the control algorithm was evaluated only through the input of simulated values and not tested in a controlled environment setting.

In practice, the majority of these control approaches do not achieve the predicted production and management results primarily because (1) there is a knowledge gap on quantifying the dynamic relationship between plant responses and climate (Van Pee and Berckmans, 1998), and (2) real-time indication of the plant status is not integrated with the model predictions during the production cycle. This paper focuses on validating mathematical modeling efforts in order to improve prediction of plant growth and developmental responses to off-nominal environmental disturbances that occur during the production cycle. A mathematical crop model, previously used for daily predictions of crop canopy gas exchange, is used to develop lettuce yield response curves as a function of various forced disturbances in the daily light integral during the production cycle. A series of growth chamber experiments are planned to generate data on the response of lettuce yield to various forced disturbances in the daily light integral during the production cycle. An initial trial run was completed, the results of which are compared with the mathematical crop model predictions.

Methods

Growth Chamber Experiments

A series of leaf lettuce (*Lactuca sativa* L., cv. Waldman's Green) experiments are planned at the New Jersey Agricultural Experiment Station Greenhouses at Rutgers University inside two walk-in EGC growth chambers. An initial trial experiment has been completed and is described in this section. Lettuce seeds were sown by hand into 120 19 mm (¾") rockwool cubes (Grodan, Inc.) at a density of one seed per cube. After seeding, the cubes were watered from above using tap water and placed in an ebb and flood production tray within one of the walk-in growth chambers. The cubes were covered with translucent PVC film for the first forty-eight hours after sowing to increase humidity around the seeds. Cubes were bottom irrigated six times per day for four minutes with tap water. After germination was observed (two days after seeding, DAS), a diluted nutrient solution (electroconductivity of 0.6 mS cm^{-1}) consisting of solution grade $CaNO_3$ (Hydro-Gardens, Inc., 15.5-0-0) and Peter's Professional Hydro-sol formula (The Scott's Company, 5-11-26) was used. Daily average environmental conditions for the first thirteen days after seeding were 297 ±3μmol m^{-2} s^{-1}, 22.8 ±1.2°C day / 22.3 ±0.2°C night temperature cycle, 78 ±1 % RH, and a 16 hour photoperiod.

At DAS 13, eighty plants were selected for uniformity and transplanted into 76 mm (3") rockwool cubes (Grodan, Inc.). These cubes were placed into one of four acrylic photosynthesis boxes (PS Box) located within the production area of the second EGC walk-in growth chamber. Each PS Box consists of four sides with a detachable top lid, all made of transparent acrylic. Each PS Box measures 0.95 (L) by 0.66 (W) by 0.76 (H) m, for a total growing area of 0.64 m^2 and a volume of 0.48 m^3 each. They each rest on a watertight rectangular interface tray to allow the nutrient solution to be delivered using an ebb and flow irrigation system. A perforated PVC plate supports the rockwool cubes for each plant at a specified height at a planting density of 20 plants per PS Box. Perlite is spread on this support plate in order to prevent excessive moisture from evaporating into the aerial environment inside the PS Boxes, and to allow air movement through the root zone. The perlite also prevented algae growth by blocking light from entering the root zone. For further information on the system design and operation, see Giacomelli et al. (2001).

Air temperature, relative humidity, and light intensity were controlled in this chamber by manually programming the control unit of the walk-in growth chamber. An external system for carbon dioxide monitoring and control was used to obtain elevated atmospheric carbon dioxide concentration. Six thermocouples were used in each PS Box to measure the air temperature at canopy height, below and above the canopy, at the root zone, inside the air plenum, and the temperature in the rockwool cubes. Infrared sensors are also used to measure the canopy temperature after canopy closure. A relative humidity sensor was included in one of the four PS Boxes. Other sensors include an EC and pH meter for automatic monitoring of the nutrient solution. Nutrient solution was delivered automatically to the bottom of each PS box every four hours during the life cycle for a period of three minutes. Solution electroconductivity was 1.2 +/- 0.2 mS cm^{-1}. Nutrient solution was dumped from the reservoir tank and replaced every week.

Four line quantum sensors were used to measure the incident photosynthetically active radiation (PAR) above the canopy, transmitted PAR through the canopy, and PAR reflected from the canopy and substrate to provide a non-destructive indication of canopy development over time. PAR reflected from the substrate was estimated by multiplying the albedo of the PS Box substrate (0.35) times the measurement of PAR transmitted through the canopy. Canopy absorption of photosynthetically active radiation (APAR) was then determined from the following (Gallo and Daughtry, 1986), where PAR was measured in terms of photosynthetic photon flux (PPF):

$$\mathrm{APAR} = [(C_{ppf} + R_{ppfs}) - (T_{ppf} + R_{ppfc})] / C_{ppf} \quad (1)$$

where:

C_{ppf} -incident PAR above the canopy, µmol m^{-2} s^{-1}
T_{ppf} -transmitted PAR through canopy, µmol m^{-2} s^{-1}
R_{ppfc} -PAR reflected from the canopy and substrate, µmol m^{-2} s^{-1}
R_{ppfs} -PAR reflected from the substrate, µmol m^{-2} s^{-1}

At DAS 26, five pieces of fiberglass screening material were used to shade two of the four PS Boxes to reduce the incident photosynthetic photon flux (PPF) above the canopy to 50% compared to that of the non-shaded boxes. The screening was removed on DAS 33, at which point two of the boxes, one shaded and one un-shaded, were harvested and measured for shoot dry mass. On DAS 40, the lettuce plants in the final two PS boxes were harvested and measured for shoot dry mass. Target environmental conditions for the growth chamber were 300 µmol m^{-2} s^{-1} (reduced to 150 µmol m^{-2} s^{-1} for days 26 through 33 for two of the four PS boxes), 23 / 23°C day night temperature cycle, elevated carbon dioxide concentration of 1200 µmol mol^{-1}, and 70% relative humidity. A 16 hour photoperiod was maintained.

Mathematical Model

A version of the 'energy-cascade' model (EC) (Volk et al., 1995) was used for simulations of lettuce growth and development. The model was developed for use in estimating life cycle canopy gas exchange rates (mol CO_2 m^{-2} d^{-1}) for various crops that were to be grown in controlled environment production facilities with hydroponic nutrient delivery systems for NASA's (National Aeronautics and Space Administration) Advanced Life Support research program. In the model, plant growth is described by three steps: (1) the absorption of photosynthetic photon flux (PPF) by the plant canopy within the defined growing area, (2) the conversion, during photosynthesis, of absorbed light energy into nonstructural carbohydrate, termed canopy quantum yield (CQY), and (3) the conversion of nonstructural carbohydrate into structural biomass, termed carbon use efficiency (CUE). The model uses the following assumptions: (A) a linear increase in canopy light absorption between seedling emergence and canopy closure, (B) a constant value for light absorption from canopy closure through the onset of senescence, (C) a constant CQY from emergence through the onset of senescence, (D) a linearly decreasing CQY from the onset of senescence through crop maturity, and (E) a constant CUE throughout the crop life cycle. Given values for the CQY and CUE parameters and user inputs for daily light intensity, photoperiod and dates for canopy closure (t_A), onset of senescence (t_Q), and maturity (t_M), the EC model output values for daily crop growth rate (mol C m^{-2} d^{-1}) and dry mass (g CHO m^{-2}). Note that because the model was originally intended for hydroponic nutrient delivery systems, the assumption of non-limiting nutrients and water was used in its development.

A modified version of the EC model (MEC) developed by Cavazzoni (1999) was used in this research. The modifications provide the user with the ability to simulate the effects of daily environmental conditions on plant growth rate. This version added growth and developmental components so that t_A, t_Q, and t_M were computed from environmental inputs, including day and night air temperature. In order to accomplish this, a subroutine for computing daily leaf growth mass and leaf area index of the plant canopy was added. Additional parameters, specific for particular crops, were added to the model such as specific leaf area (SLA), a ratio of leaf area per unit leaf dry mass.

A non-linear mathematical expression for CQY as a function of atmospheric carbon dioxide and irradiance was developed. Thus, CQY is no longer a constant value, but a function of the current environmental conditions in the environment. The model can be used for estimating the direction and magnitude of changes in crop canopy gas exchange (and thus crop growth rate), harvest index, and production scheduling due of off-nominal conditions. The general simulation works on a 24-hour time increment with Equation 2 as the driving equation in the model:

$$DCG = 0.0036 \cdot H \cdot CUE \cdot A \cdot CQY \cdot PPF \quad (2)$$

where:

DCG	–	daily carbon gain (mol C m^{-2} d^{-1})
0.0036	–	conversion factor
H	–	photoperiod (hr)
CUE	–	carbon use efficiency (mol C mol^{-1} C)
A	–	light absorption (fraction of incident PPF)
CQY	–	canopy quantum yield (mol C mol^{-1} photon absorbed)
PPF	–	photosynthetic photon flux (µmol m^{-2} s^{-1})

At each time increment, A is computed based on leaf area of the canopy and CQY is calculated as a function of PPF and the atmospheric carbon dioxide concentration. Following the calculation with Equation 2, a fraction of DCG is converted to new leaf mass based on a temperature growth function specific to the crop being simulated. The MEC was calibrated for lettuce by Cavazzoni (1999) by adapting parameters for CUE, CQY, and SLA, among others, from a single data source with average environmental conditions of 22°C day / night temperature cycle, 278 µmol m^{-2} s^{-1} PPF, 16 hour photoperiod, 1000 µmol mol^{-1} CO_2 concentration with a planting density of 19.2 plants m^{-2}. The model was written in Mathematica (Wolfram Research, Inc.). Results from model simulations were exported to Microsoft Excel (Microsoft, Inc.) for further analysis.

Results

Averaged daily environmental conditions and yield mass at harvest for each PS Box are shown in Table 1. An initial comparison between the MEC predicted canopy light absorption and measured values showed that the MEC model required calibration in order to be applied to the current dataset (Figure 1). Experimental data for canopy light absorption and dry mass at harvest for PS Boxes 1 and 2 were used to calibrate the MEC model for the conditions in the Rutgers growth chambers, with data from PS Box 2 used to make calibration changes, and PS Box 1 used as an independent dataset to check the calibration. Measured and predicted values for canopy light absorption are shown in Figure 1. Model predicted values for APAR (absorbed photosynthetically active radiation) show a canopy development rate much greater than what was measured in PS Box 2. Canopy closure (defined here as the point at which 90% of incident PPF above the canopy is absorbed by the crop canopy) occurred at DAS 24 in the model and DAS 36 in the experiment. In addition, the average model predicted value for CQY was 0.076 mol C mol^{-1} absorbed photons. A value of 0.035 mol C mol^{-1} absorbed photons was measured from the experiment. As a result, the model over-predicted values for plant dry mass by 165% compared to the experimental value of 166 g dry mass m^{-2} for PS Box 2.

Table 1: Experimental results, including averaged daily environmental values and their standard deviations, for each PS Box*.

	PS Box 1	PS Box 2	PS Box 3	PS Box 4
Treatment	No Shade DAS 33 harvest	No Shade DAS 40 harvest	Shade DAS 33 harvest	Shade DAS 40 harvest
Yield mass (g m^{-2})	76.5 ± 12.1	165.9 ± 27.1	49.9 ± 8.3	76.2 ± 6.4
PPF (µmol m^{-2} s^{-1})	314 ± 5.6	306 ± 7	284 ± 67**	287 ± 66**
Canopy T_{day} (°C)	23.0 ± 0.4	22.5 ± 0.7	22.9 ± 0.6	23.4 ± 0.5
Canopy T_{night} (°C)	23.0 ± 0.3	22.7 ± 0.5	23.1 ± 0.3	22.9 ± 0.2
Relative Humidity (%)	-	-	-	71 ± 7

*Average atmospheric carbon dioxide concentration was 1211 +/- 116 µmol mol^{-1}.

** Large standard deviation due to shading treatment.

Two parameters within the MEC model were further calibrated. The expression for CQY was reduced by a factor of two based on differences between CQY determined from experimental data and CQY calcualted by the model. The second parameter that was calibrated was the specific leaf area, which defines the amount of leaf area per gram of leaf dry mass. This value was increased from 225 $cm^2\ g^{-1}$ to 285 $cm^2\ g^{-1}$ in order to match canopy development observed during the experiment. The difference between experimental dry mass and calibrated MEC model predicted dry mass at harvest was 1.01% for PS Box 2 following these modifications. The calibrated MEC model over-predicted the dry mass in PS Box 1, harvested at DAS 33, by 22%.

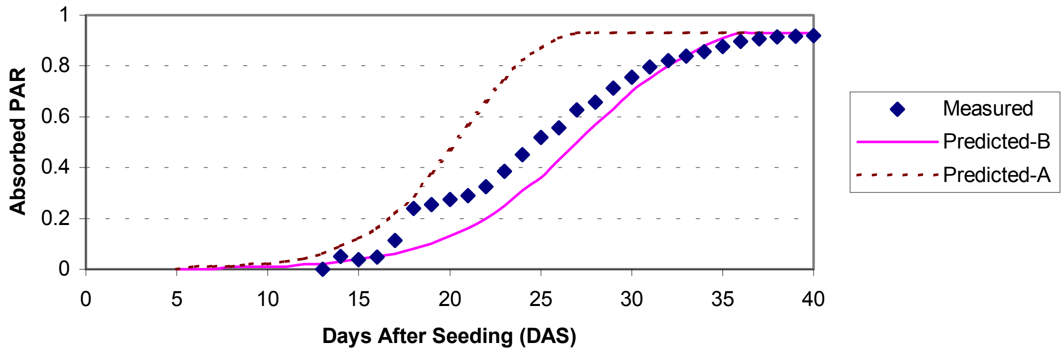

Figure 1: Comparison between experimental values (Measured) and model predicted values for APAR, expressed as a fraction of the incident PAR above the canopy. Legend: Measured – experimental data, Predicted-A – uncalibrated model data, Predicted-B – calibrated data.

The calibrated MEC model was used to generate a series of response curves in order to quantify the effect of light intensity disturbances during the lettuce growth cycle on yield. A nominal run was conducted to establish baseline yield information. Nominal was defined as an average daily light intensity of 300 µmol $m^{-2}\ s^{-1}$, a day / night temperature cycle of 23°C, atmospheric carbon dioxide concentration of 1200 µmol mol^{-1}, 70% relative humidity, a photoperiod of 16 hours, and a planting density of 31.2 plants m^{-2}, as utilized in the experiment. Three factors were varied in the model simulations, (1) the time during the growth cycle at which the disturbance in irradiance was initiated (timing), (2) the duration, in days, of the disturbance (duration), and (3) the magnitude of the disturbance in terms of percent reduction of the nominal light intensity value (magnitude). The output, or response, for each simulation was the yield at DAS 40 expressed as a percentage reduction of the yield simulated with the nominal conditions. Three yield response curves are shown in Figure 2.

The top curve shows the effect of magnitude versus timing on the lettuce yield. In this figure, the duration of the disturbance was held fixed to eight days. For example, a disturbance starting at DAS 10 (on the x-axis) was coupled with a reduction of 25% light intensity from the nominal value of 300 µmol $m^{-2}\ s^{-1}$ (on the y-axis). Because the duration was fixed to eight days, this means the simulation effectively reduced light intensity to 25% of the nominal value for DAS 10 through 17. This treatment resulted in a simulated 10-20% reduction in yield at harvest (DAS 40) (marked as '1' in Figure 2). As another example, timing at DAS 5 versus a magnitude of 38% shows a yield loss of about 20% (marked as '2' in Figure 2). As the timing of the disturbance increases from left to right along the x-axis, it can be observed that the yield response does not change for a given magnitude. This suggests that timing does not affect lettuce yield, but the magnitude of the light intensity reduction does.

The middle figure in Figure 2 shows the yield response for duration versus magnitude. In this case, the disturbance was held constant at DAS 26. For example, a duration of 5 days versus a 25% magnitude shows between 0 to 10% reduction in lettuce yield (marked as a '3'). Moving slightly to the right along the x-axis, an 8 day duration versus a 25% magnitude shows between a 10 to 20% reduction in lettuce yield (marked as a '4'). The results confirmed that the stronger the magnitude of the disturbance, the less the duration required before an equal effect on plant yield was observed. Even with a 50% reduction in light intensity, a minimum of three days was needed before a significant effect (defined here as greater than 10%) was shown on the lettuce yield.

The bottom graph in Figure 2 shows effects of duration versus timing. The magnitude of the disturbance was kept to a 25% reduction in light intensity. In general, as one moves in the direction of increasing timing along the y-axis, the same lettuce yield response is observed for a fixed duration. As was the case in the top figure, timing had a very small effect on the yield, while duration showed the strongest effect with increasing duration resulting in an increase in disturbance effect on yield.

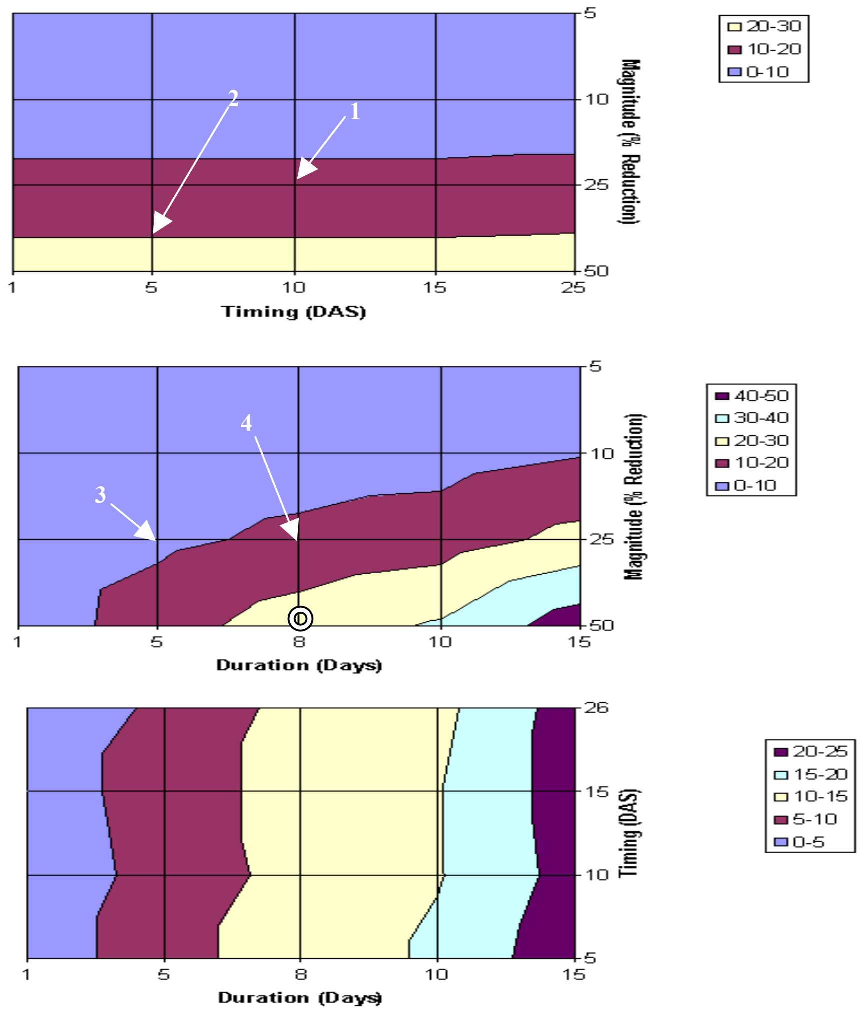

Figure 2: Yield response curves for timing versus magnitude (top), duration versus magnitude (middle), and duration versus timing (bottom). Disturbance effects are expressed in terms of the percentage of lost yield as compared to a nominal case without disturbances. Lettuce yield was predicted at DAS 40 in all cases. Symbols: '1', '2', '3', '4' refer to examples defined in the text. The 'O' identifies the disturbance used in the experiment.

Next, the MEC model was used to simulate the effects caused by the shading treatments from the lettuce experiments. Daily inputs for PPF were input into the model based on measurements from the treatment harvested at DAS 40 (PS Box 4). As shown in Figure 3, model predictions followed measured values for light absorption until about DAS 26. Shading started on DAS 26. From this point, it is evident that the model predictions for canopy light absorption do not follow the experimental measurements. The final dry mass reported by the model at DAS 40 over-predicted the experimental value of 76 g m^{-2} by 83%. When compared with the harvest data from PS Box 3, the dry mass was over-predicted by 64%.

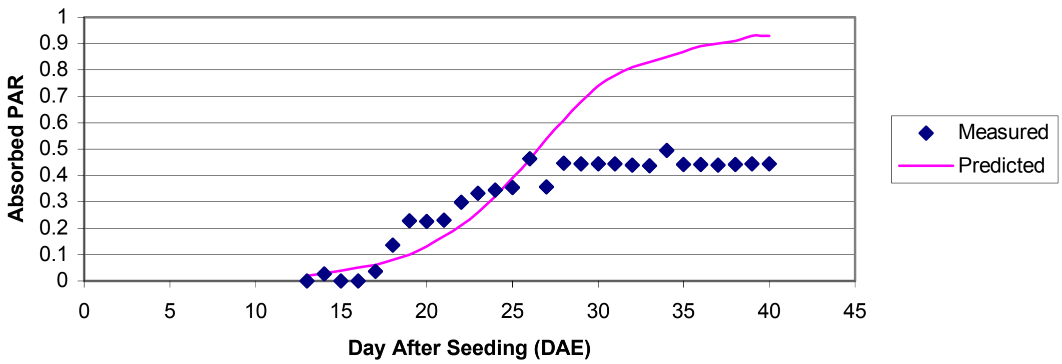

Figure 3: Comparison of model prediction values (Predicted) and experimental measurements for absorbed photosynthetically active radiation for the shaded PS Box 4 treatment.

Discussion

Environmental conditions measured in each of the PS Boxes were similar throughout the course of the production cycle (Table 1). Note that the large standard deviation in average PPF value for PS Boxes 3 and 4 is due to the light shading treatment imposed from DAS 26 through 33. Differences in lettuce yield at harvest between shaded and un-shaded treatments were 185% for the 40 DAS harvest (PS Boxes 2 and 4) and 294% for the 33 DAS harvest (PS Boxes 1 and 3). These differences were initially attributed to the effect of the shading treatment.

The fact that model calibration was necessary was not surprising as the MEC model reported in Cavazzoni (1999) was validated using only one data set. However, the relative low yields obtained in this experiment, as compared to results in other papers (e.g., Wheeler et al., 1994) were of concern, and resulted in the reduction of CQY by a factor of 2. Subsequently, the SLA value was increased to match the canopy development as indicated by Figure 1. This modification to SLA needs to be verified by measuring leaf expansion in future experiments with lettuce.

The shading treatments in the experiment were designed to produce information regarding plant response to changes in light intensity that occurred in the middle of the production cycle. As such, they were intended to be useful for verifying the MEC model predictions. In Figure 2, the middle graph is labeled with an 'O' to show the measured yield data from this experiment on the yield response curve (at a duration of 8 days on the x-axis, and 50% magnitude reduction on the y-axis). At this point along the curve, the model predicts a decrease in lettuce yield of 20 to 30% from the nominal value if harvested at DAS 40. However, the shaded experimental data at DAS 40 (PS Box 4) showed a 185% decrease in yield as compared to the unshaded data from PS Box 2. Moreover, when the actual yield values are compared to MEC predicted values, the yield is over-predicted by 83% at DAS 40 (using PS Box 4 data) and 64% at DAS 33 (PS Box 3 data).

These results suggest that the MEC model does not accurately predict the effects of disturbances in light intensity on lettuce. However, since the data presented in this paper is preliminary, additional experiments are currently being conducted to confirm the observed results. Based on the experimental measurements for canopy light interception, there appear to be some additional factors besides the light intensity treatment. For example, in Figure 3, it appears that canopy development stops after DAS 28. A similar pattern of canopy growth was observed in PS Boxes 1 and 3 (data not shown) that suggests other factors are influencing plant growth. Visual observations made during the experiment confirmed that the lettuce canopies in PS Boxes 1,3, and 4 never closed prior to harvest. Possible factors include unequal air flow rates within each PS Box, unequal depth of the nutrient solution within each PS Box during irrigation, and the use of older, possibly less vigorous seeds causing lower yields. These problems may also explain the discrepancy between lettuce yield from this experiment and other published sources and are being investigated during the next set of experiments.

Despite the uncertainty in the validity of the MEC model predictions, there are some tentative conclusions that can be made from the response curve simulations (Figure 2). First, the timing of the disturbance had no effect on yield with respect to changes in the magnitude of the light intensity disturbance (top graph). It appears that there is a slight effect on yield when timing is varied with respect to disturbance duration (bottom graph), but this is probably not significant. If this result proves true with further testing, this implies that lowering the light intensity at the beginning of the life cycle has the same effect as lowering it at the middle or end. This information is useful for incorporating plant response into future environmental control strategies. It was also apparent that the combination of both the magnitude of the disturbance and the duration had the greatest effects on yield loss. For example, at least three days were required before an effect larger than a 10% reduction in lettuce yield becomes evident, even if a 50% magnitude reduction in light intensity is used. As the duration increases, even a 10% reduction in light intensity eventually has an effect on lowering lettuce yield, implying that the cumulative daily light integral has a strong effect on determining lettuce yield at harvest. Note, however, that a 5% reduction in light intensity had less than 10% yield reduction regardless of duration. This provides information for understanding the plant's tolerance to such disturbances. This result also supports other efforts that have been done in developing environmental control systems for lettuce. For example, Albright et al. (2000) demonstrated the ability to achieve consistent lettuce yields year-round in a greenhouse by controlling the daily light integral with supplemental lighting.

The model predictions on lettuce response after environmental disturbances could be useful in many ways. The procedure developed to calibrate the predicted crop responses can be utilized for other important greenhouse crops. The response curves can also be used to direct research efforts by focusing the experimental design. For example, future experiments will be designed to evaluate the result that timing of the disturbance has, by itself, no effect on yield. The predicted response curves also indicate what combinations of treatment factors (such as magnitude of the disturbance and duration) should be further evaluated through experimentation.

Conclusion

The development of more optimal environmental control systems for controlled environment plant production facilities would benefit from the ability to incorporate plant responses to changes (disturbances) of the environmental conditions into the control logic. One method to accomplish this is the development of mathematical crop models that can predict effects of environmental disturbances on plant growth and development throughout the production cycle. With this in mind, a mathematical crop model was evaluated for the ability to accurately predict lettuce growth responses when environmental disturbances in light intensity are introduced during the production cycle. An initial growth chamber experiment with lettuce (*Lactuca sativa* L., cv. Waldman's Green) was conducted in which the incident light intensity above two lettuce stands was reduced by half. The model was calibrated for the growth chamber conditions and used to generate yield response curves as a function of the timing of the disturbance, the duration of the disturbance, and the magnitude (in terms of percent reduction from the nominal light intensity value). This information will be used to design future experimental treatments needed for verifying the model predictions and to increase the understanding of crop responses to off-nominal environmental disturbances.

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