MODELLING THE EFFECT OF SUPPLEMENTARY LIGHTING ON PRODUCTION AND LIGHT UTILIZATION EFFICIENCY OF GREENHOUSE CROPS

Refereed

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Abstract

The effect of supplementary lighting (SL) on dry matter production of greenhouse crops is predictable with ALSIM, a new crop growth model based on SUCROS87. The light utilization efficiency (LUE), defined as daily dry matter production divided by the daily photosynthetic photon flux is a parameter for evaluating the quantitative effect of light on dry matter production. In winter in the Netherlands the LUE is raised by SL, especially by lighting in the natural dark hours. In summer there is hardly influence of SL on the LUE for the simulated growth of a fictitious crop. In winter the leaf area index (LAI) combined with biomass has a great influence on the LUE. Without SL the LUE is already negative at LAI above 2.3, due to a higher respiration than assimilation. SL makes it possible to produce dry matter at higher LAI values. Supplying $C0_2$ in the greenhouse can partially compensate a light shortage. A combination of $C0_2$ and SL can raise the LUE more than the sum of the separate effects. ALSIM is valuable for predicting growth in many situations for many crops if specific crop parameter values are available.

1. Introduction

In the Netherlands supplementary lighting (SL) is frequently used, especially in winter months, to raise the production and quality of the greenhouse product. Only for crops with a high economic value, the application of SL is profitable, because of the high investment costs and the high energy costs during operation. The total area in the Netherlands with SL for ornamental production is 711 ha, where 461 ha is used for cut roses (Griffioen, 1993). Most frequently High Pressure Sodium lighting (HPS) is supplied with a photosynthetic photon flux (PPF) of 25-50 μmol m^{-2} s^{-1} Mostly a minimum dark period of 4-8 hours is maintained to avoid growth disturbances. If the grower does not expect a sufficient positive effect of SL above a certain level of global radiation, the lights are switched off (subjective decision). In summer there is a period that the SL is not operational at all. Heuvelink and Challa (1989) used a simplified crop growth model to calculate break even points for relational costs and profits of SL for different crops at the operational level (immediate response) to support the grower in his decision of using the SL. This approach has to be extended to a daily base. Due to the seasonal changes in the natural photoperiod and irradiance in the Netherlands (latitude 52° N), the contribution of the daily respiration compared to the daily gross assimilation rate is relatively high and therefore has to be taken into account.

A parameter to evaluate light strategies is the light utilization efficiency (LUE) in [g mol^{-1}] defined as daily dry matter production divided by the daily photosynthetic photon flux (Charles-Edwards, 1982). The daily photosynthetic photon flux is the sum of natural and artificial light. The LUE may be used for comparing different strategies within a day or between different days of the year to see short time or seasonal variation.

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Under suboptimal climate or crop conditions the LUE might be negative and might decrease the total crop dry weight, because the daily amount of assimilates required for maintenance respiration might be higher than the daily CO_2 assimilation.

The operation of the SL can be more refined and is expected to result in a higher LUE and dry matter production, when better adjusted to the crop status e.g. Leaf area index (LAI) and biomass, or to climate factors in the greenhouse like temperature and CO_2 concentration. A higher LAI means more biomass with a higher maintenance respiration per unit of ground area, but also a higher gross photosynthesis due to an increased light interception. There is an optimum LAI for net crop growth, having the highest LUE, depending on the season. Increase of LAI and biomass occur at the growth of a young crop and with crops which should reach a certain size for harvesting e.g. pot plants or chrysanthemum. Instead of a given LAI and biomass, for many crops it is possible to regulate these parameters by pruning e.g. rose (Louvenberg and Kool, 1994). This gives the opportunity to create the best crop size for the natural light circumstances in combination with the installed SL. Increasing the CO_2 concentration in the greenhouse enhances the photosynthesis at a broad range of PPF's (Nilsen, 1983; Nederhoff, 1994), but is not always easy available. The temperature fluctuations in heated greenhouses can have great effects on crop development, but the influence on the photosynthesis is rather small for the temperatures maintained in greenhouses (Jiso *et al.*, 1991).

The objective of this study is to quantify the effect of SL strategies on the LUE of a fictitious greenhouse crop in dependence of the crop status (LAI) and CO_2 concentration by means of a crop growth model in order to improve the use of SL for dry matter production on the operational and tactical level. Specific crop aspects such as assimilate partitioning, harvest index, dry matter content and product quality are not taken into account.

2. Materials and methods

2.1. Model description

The crop growth model made is called ALSIM (Artificial Light SIMulator). It is an explanatory model with a modular structure similar to the greenhouse crop model of Gijzen (1992) based on SUCROS87 (Spitters *et al.*, 1989). In a greenhouse under defined crop and climate conditions, i.e. irradiance, temperature and CO_2 concentration, the potential dry matter production can be simulated. Gijzen *et al.* (1990) and Bertin and Heuvelink (1993) validated large parts of the model for different greenhouse crops receiving only solar radiation.

In ALSIM it is assumed that for photosynthetic active radiation (PAR, 400 - 700 nm), either from solar radiation or from an artificial light source, there is no difference in the photosynthetic response. In ALSIM it is possible to choose between: solar radiation, artificial lighting or a combination of both. In the last case artificial lighting is called supplementary lighting (SL). In case of SL, assumed to be 100% diffuse, the photosynthetic photon flux (PPF) of artificial light is added to the diffuse fraction of the natural PPF in the greenhouse. Photoperiodic effects are not included, so in ALSIM a photoperiod of 24 h is possible with a constant effectiveness, while in practice there might be negative effects on growth and development (Vézina *et al.*, 1991) and a diurnal pattern of effectiveness (Challa, 1976). In this study the maximum photoperiod is limited to 18 h d^{-1}. With ALSIM it is possible to give a value for solar radiation in W m^{-2} outside the greenhouse for switching the SL. Above that level the lighting is not operational. This method is often used in Dutch horticultural practice. If the lamps are switched on or off a lag-time of 30 minutes is taken, because frequently switching is harmful for the economic life of the lamps.

With ALSIM the light utilization efficiency was calculated on a daily base. The simulations with ALSIM were done with a fictitious crop having every day of the year a fixed same size with the same maintenance respiration. As input for solar radiation a reference year for the Netherlands was taken, selected from the long-term weather records (Breuer and Van de Braak, 1989). The light transmission for an average Venlotype greenhouse for direct and diffuse radiation was calculated with the model of Bot (1983). The crop was assumed to use the whole greenhouse area and to have a spherical leaf angle distribution. Other important parameters of ALSIM for the standard situation are given in table 1.

2.2. Simulations

In the different simulations done with ALSIM the following parameters were varied: with or without SL; level for solar radiation for switching the lights on below 1 W m^{-2} (only in the natural dark period) to lighting at solar radiation below 200 W m^{-2}; LAI values from 1 to 8, with as a consequence that the biomass also changed according to formula 1; $C0_2$ concentrations from 100 to 1200 µl l^{-1}.

$$\mathbf{TDW = LAI * 1/SLA * 1/LWR} \qquad (1)$$

where: TDW = Total Dry Weight (g m^{-2})
LAI = Leaf Area Index
SLA = Specific Leaf Area (m^2 g^{-1})
LWR = Leaf Weight Ratio

Although the simulations were made for every day of the year, in the comparisons of the LUE the monthly average of the most extreme situations of the year, December and June were taken.

3. Results

The simulated production of the fictitious crop under ambient light and $C0_2$ conditions in the Netherlands in a greenhouse is very low during winter and even negative in December (figure 1) due to a higher respiration than $C0_2$ assimilation. With SL (37.5 µmol m^{-2} s^{-1}) a minimum production is guaranteed throughout the year. Switching off the SL above given levels of solar radiation restricts the number of operational hours and decreases the production rate (table 2). The relative differences in production rate with 18 h d^{-1} SL taken as the potential production (100 %), are in December up to 126% for the treatment without SL. In June this difference is only 10%. In December the LUE decreases with a declining switching level. The promotive effect of SL on the LUE is more than proportional in this situation with the greatest influence at low switching levels. In June there is no influence of SL on the LUE, regardless the way of using it.

The LAI has great influence on the LUE (figure 2). In December with only sun light the LUE is positive below a LAI of 2.3. At a higher LAI the increase in respiration due to a higher biomass is higher than the increase in $C0_2$ assimilation by a higher light interception. With SL the maintenance respiration is compensated for, which makes the LUE positive up to a LAI of 5.3 with an optimum at a LAI of approximately 2. In June the LUE is positive for the calculated range of LAI from 1 to 8 with an optimum LAI of 3-5. The LAI effect in June is smaller than in December. In June SL has very little influence on the LUE at different LAI's.

Without SL in December the LUE becomes positive above a $C0_2$ concentration of 900 µl l^{-1} at a LAI of 3 (figure 3). With SL the LUE is positive at $C0_2$ concentrations higher than 135 µl l^{-1}. $C0_2$ enrichment at low concentrations has a stronger increasing effect on the LUE than at higher $C0_2$ concentrations. In June the LUE is always positive for the simulated $C0_2$ concentrations with also a more pronounced effect of $C0_2$ enrichment at low concentrations. In this case SL does not change the LUE, the lines in figure 3 are identical

4. Discussion

According to the light response curves of photosynthesis the photosynthetic light use efficiency is highest at low PPF and decreases with increasing PPF (e.g. Björkman, 1981). The best method for improving the LUE with SL is using the lighting system as much as possible during periods with low or no solar irradiance. An economic advantage is that often the electricity price in the off-peak hours during night time is lower. Nevertheless, growth disturbances due to the extended photoperiod could occur (Vézina, 1991), and a critical photoperiod for flowering of some crops can be a limitation for using SL at night. Operating SL during high solar irradiance gives only a slight improvement of the LUE.

The LAI is important for LUE and production during the whole year. According to the simulations, the optimum LAI for dry matter production in summer is higher than 3. In winter the optimum LAI is lower than 3. Plants make their own morphological adaptations, which have their consequences on assimilation rates (Björkman, 1981). In winter due to low solar irradiance the leaf weight ratio and the specific leaf area can be higher than they are in summer, e.g. for rose crops (results not published). This means that the leaves are thinner with a more extended surface to intercept the light better and with a lower maintenance respiration expressed per unit of leaf area (Brouwer, 1983). In summer, when the maintenance respiration does not play an important role compared to the assimilation rate, the leaves are thicker and a higher fraction of assimilates is transported to other parts (storage organs) of the plant, which results in a lower leaf weight ratio than in winter. Therefore actual differences between summer and winter in the LUE may slightly differ from the simulations with fixed leaf properties of the crop during the whole year.

With SL there is a higher optimum LAI for the LUE in winter with a higher production, but SL has no effect on the LUE during summertime. To have the ideal crop appearance (LAI and biomass) for producing marketable products, one can change the appearance by pruning or removing leaves etc. Desirable is that the decrease in assimilation due to a lower light interception will be not as big as the decreased respiration.

With ALSIM and from literature (e.g. Nilsen *et al.*, 1983) it is concluded that light can be partially compensated for by higher levels of $C0_2$. In the Netherlands using the exhaust $C0_2$ from a natural gas burned boiler is a cheap way to maintain high levels of $C0_2$ in the greenhouse during winter when the windows are closed. Supplementary lighting has a much greater influence on LUE than increased $C0_2$, but a combined use of SL with $C0_2$ enrichment gives the highest LUE

Besides light and $C0_2$ a third climatic factor to regulate the production of a crop is the temperature. According to the used model it is better to lower the temperature during periods with no photosynthesis to decrease the maintenance respiration. Maintenance respiration is more sensitive to temperature than photosynthesis. SL during the natural dark period shortens the period a lower temperature can be kept, especially in winter. Due to this, a part of the positive effect of SL on photosynthesis can be flattened by the unwanted higher maintenance respiration. The balance between these two, to obtain the optimum day and night temperature, should be optimized with the model.

This paper gives some possibilities of how to reach the highest LUE with the help of the crop growth model ALSIM. This general approach with a fictitious crop should be applied on specific crops with their own parameters to predict their production rate. The related costs to create optimal environmental conditions (SL, $C0_2$, temperature and labour) should be compared with the predicted increased yield. With financial analysis the best production strategy can be found considering the different regulating factors for crop and climate.

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Table 1. Main standard parameters used in ALSIM

Characteristics fictitious crop	
* Total Dry Weight (TDW)	375 g m^{-2}
* Leaf Weight Ratio (LWR)	0.4
* Leaf Area Index (LAI)	3.0
* Specific Leaf Area (SLA)	0.020 m^2 g^{-1}
* Assimilate requirement (ASRQ) (= growth respiration)	1.43 g CH_20 g^{-1} dry matter
* Maintenance Respiration (Rm) at 20°C	10.6 mg CH^20 g^{-1} dry matter.d^{-1}
Climate	
* Temperature	20 °cC
* $C0_2$	340 µl l^{-1}
* Solar Radiation	Selected reference year for the Netherlands (Breuer and Van de Braak, 1989)
Supplementary lighting (SL)	
* Photosynthetic photon flux (PPF)	37.5 µmol m^{-2} s^{-1}
* Dark period	6 h d^{-1}
* SL operational at solar radiation lower than	100 W m^{-2}

Table 2 -Average dry matter (DM) production and light utilization efficiency (LUE) of a fictitious crop (table 1) in relation to hours of supplementary lighting (SL max. 18 h d^{-1}) operational below the different levels of solar radiation (SL switching level) in December and June

	December			June		
SL switching level [W m^{-2}]	SL [h d^{-1}]	production rate [gDM $m^{-2}d^{-1}$]	LUE [g DM mol^{-1}l	SL [hd^{-1}]	production rate [gDM $m^{-2}d^{-1}$]	LUE [gDM mol^{-1}]
without SL	0	-0.49	-0.22	0	16.80	0.72
1	10.5	0.92	0.26	1.6	17.02	0.72
25	12.7	1.23	0.31	2.7	17.17	0.72
100	16.1	1.66	0.38	5.4	17.51	0.72
200	17.7	1.85	0.40	8.6	17.88	0.73
continuously	18.0	1.88	0.41	18.0	18.71	0.72

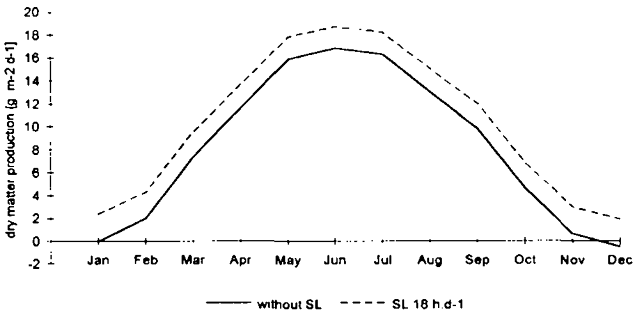

Figure 1 Average dry matter production of a fictitious crop (table 1) during the year with or without supplementary lighting (18 h d^{-1}, 37.5 μmol m^{-2} s^{-1})

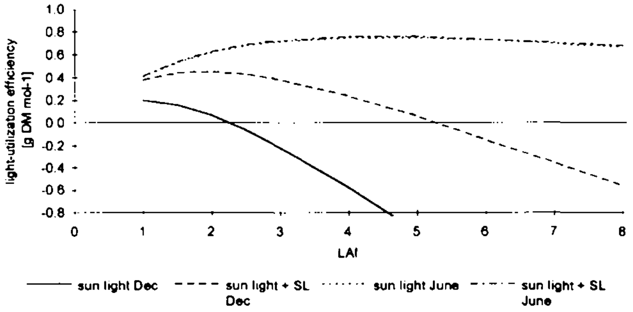

Figure 2 Average light utilization efficiency of a fictitious crop (table 1) in relation to supplementary lighting(18 h d^{-1}, 37.5 μmol m^{-2} s^{-1}) and leaf area index (LAI) in December and June

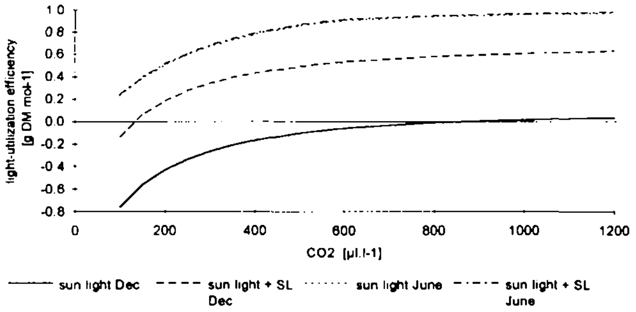

Figure 3 Average light utilization efficiency of a fictitious crop (table 1) in relation to supplementary lighting(18 h d^{-1}, 37.5 μmol m^{-2} s^{-1}) and CO_2 concentration in December and June