

A Simulation Study on the Interactive Effects of Radiation and Plant Density on Growth of Cut Chrysanthemum

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Abstract

In the present study, we used a photosynthesis-driven crop growth model to determine acceptable plant densities for cut chrysanthemum throughout the year at different intensities of supplementary light. Dry matter partitioning between leaves, stems, and flowers was simulated as a function of crop developmental stage. Leaf area index was simulated as leaf dry mass multiplied by specific leaf area, the latter being a function of season. Climatic data (hourly global radiation, greenhouse temperature, and CO₂ concentration) and initial organ dry mass were model inputs. Assimilation lights were switched on and off based on time and ambient global radiation intensity. Simulated plant fresh mass with supplementary light (49 $\mu\text{mol m}^{-2} \text{s}^{-1}$) for 52 cultivations (weekly plantings, reference plant densities, and length of the long and short day period) was used as reference plant fresh mass. For four other supplementary light intensities (31, 67, 85, and 104 $\mu\text{mol m}^{-2} \text{s}^{-1}$), dry matter production was simulated with the reference plant density and length of the long and short day period for each planting week and plant fresh mass was calculated. The acceptable plant density was then calculated as the ratio between plant fresh mass and reference plant fresh mass multiplied by the reference density.

Under low natural light intensities, plant density could be increased substantially (>30%) at increased supplementary light intensities, while maintaining the desired plant mass. Simulated light use efficiency (g additional dry mass • MJ⁻¹ additional supplementary light) was higher in winter (4.7) than in summer (3.5), whereas it hardly differed between the supplementary light intensities. This type of simulations can be used to support decisions on the acceptable level of plant density at different intensities of supplementary lighting or lighting strategies and on optimum supplementary light intensities.

INTRODUCTION

Year-round production of greenhouse cut chrysanthemum, a short-day plant, is possible by controlling photoperiod by means of black-out screens and supplementary light. Throughout the year, growers aim at a constant quality (e.g. plant mass) by varying plant density and duration of the long-day period, and, more recently, by using supplementary assimilation light during periods of poor natural light conditions. In 1997, about 25% of Dutch cut chrysanthemum growers used supplementary assimilation light (Vernooij and Ploeger, 1999). Supplementary assimilation light results in an increased production, an improved quality, and a decreased production time in chrysanthemum (Eng et al., 1985; Andersson, 1990; Vernooij and Ploeger, 1999). Important practical questions, however, are: (1) what is the economic optimal intensity for supplementary light and (2) what are acceptable plant densities throughout the year at different levels of supplementary light intensity. Many factors influence the answer to these questions. Investigating them, merely by doing experiments, seems infinite, because of the large

number of possible combinations (planting week, combined with assimilation light intensity and plant density). Crop simulation models are valuable tools in these situations as a valid model allows for accurate crop growth predictions for a large range of input combinations in a very short time. These predictions are needed for answering the before-mentioned questions. However, the economically optimal plant density and intensity of supplementary lighting depends, besides the response of the crop, also on other factors such as electricity price and the market prices for different qualities of cut chrysanthemum.

In the present study, we used a photosynthesis-driven crop growth model for cut chrysanthemum, derived from the tomato model TOMSIM (Heuvelink, 1995) to investigate acceptable plant densities throughout the year at different supplementary assimilation light intensities.

MATERIALS AND METHODS

General Model Description

A photosynthesis-driven crop growth model for cut chrysanthemum, CHRYSIM1.0 has been derived from the tomato model TOMSIM (Heuvelink, 1995). Dry mass production in CHRYSIM1.0 is modeled in the same way as in TOMSIM. Daily crop growth rate (g m^{-2}) is computed from daily crop gross assimilation rate (P_{gd} , $\text{g CH}_2\text{O m}^{-2} \text{d}^{-1}$) minus maintenance respiration (R_m , $\text{g CH}_2\text{O m}^{-2} \text{d}^{-1}$), multiplied by a conversion efficiency from assimilation to dry matter. P_{gd} depends on crop leaf area and radiation and R_m is a function of temperature, organ biomass, and simulated relative crop growth rate (Heuvelink, 1995). In CHRYSIM1.0, the maximum endogenous photosynthetic capacity of a leaf was assumed to be $1 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, whereas in TOMSIM a standard value of $2 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ is assumed. This reduction is based on preliminary validation experiments showing over-estimations of predicted biomass under high light conditions. However, it needs further investigation.

Dry matter partitioning between leaves, stems, and flowers was simulated as a function of crop developmental stage. Stage 0 is planting date, Stage 1 is start of short day, and Stage 2 is harvest stage. Between these stages, developmental stage increased linearly with time. For example, if a certain cultivation long day period ends 15 days after planting, 10 days after planting the developmental stage is 0.67. Leaf area index was simulated as leaf dry mass multiplied by specific leaf area.

Modules for controlling day length and additional light from assimilation lamps (switch on/off depends on outside radiation intensity) were added. Actual crop photosynthetic rates are calculated for each half-hour step and integrated to a daily value (P_{gd}). Supplementary assimilation light was assumed to be 100% diffuse.

Model Input

Values for daily global radiation outside were taken from Breuer and Van de Braak (1989), representing average data for De Bilt (52°N , The Netherlands), but with natural variation (Fig. 1). Temperature and CO_2 concentration were assumed to be constant during 24 h. Average 24 h greenhouse temperature ranged from 19°C in winter to 21°C in summer and CO_2 concentration (Fig. 1) ranged from $400 \mu\text{mol mol}^{-1}$ in summer to $1000 \mu\text{mol mol}^{-1}$ in winter. The strategy for assimilation lamps usage was dependent on global radiation (switch on at 200 W m^{-2} and off at 300 W m^{-2}). Crop management information, i.e. plant densities ($43\text{-}65 \text{ plants m}^{-2}$), duration of the long day period (10-20 days), and total cultivation period (64-82 days) for weekly plantings at an assimilation light level of $49 \mu\text{mol m}^{-2} \text{ s}^{-1}$ was obtained from DLV consultancy group (De LandbouwVoorlichting adviesgroep, Wageningen, The Netherlands; Fig. 2). Day length was 20 h for the long day and 11.5 h for short day.

Initial organ dry weight per plant was input into the model: 0.16 g for leaves, 0.09 g for stems, and 0.03 g for roots. The functions describing the above-ground dry matter partitioning in relation to crop developmental stage were based on destructive

measurements in several experiments (Fig. 3). Based on experiments with plants grown in expanded clay grit, it was assumed that a constant fraction (0.1) of total crop growth was partitioned to the roots. Specific leaf area (SLA) is a function of day of the year (Fig. 4), however, different than the one used in TOMSIM. Greenhouse transmissivity for diffuse radiation was assumed to be 70%.

Approach

Total dry mass production at reference plant densities and length of the long and short day period (Fig. 2) under the reference assimilation light intensity of $49 \mu\text{mol m}^{-2} \text{s}^{-1}$ was simulated for each planting week. These total dry mass productions were converted into plant fresh mass by dividing by plant density (Fig. 2) and dry matter content (0.11-0.14 based on harvesting time through the year). Simulated plant fresh mass at $49 \mu\text{mol m}^{-2} \text{s}^{-1}$ was used as reference plant fresh mass. For four other assimilation light intensities (31, 67, 85, and $104 \mu\text{mol m}^{-2} \text{s}^{-1}$) dry matter production was simulated with the same reference plant density and length of the long and short day period (Fig. 2) and plant fresh mass was calculated. The acceptable plant density was then calculated as the ratio between plant fresh mass and reference plant fresh mass multiplied by the reference density. This final step was based on the observation of Langton et al. (1999) that changes in space per plant gave near proportional changes in weight per plant.

RESULTS

Simulated total dry mass and plant fresh mass at the reference supplementary light intensity of $49 \mu\text{mol m}^{-2} \text{s}^{-1}$ showed a seasonal pattern (Fig. 5 and 6). Simulated plant fresh mass was almost twice as high in summer than in winter (Fig. 5). Increased supplementary light intensities strongly increased dry mass production in winter, whereas in summer, almost no effect was observed (Fig. 6). In summer (planting week 22), supplementary light represented less than 6% of the integral of natural light incident on the crop for all five supplementary light intensities. However, in winter (planting week 40), this was 76% and 22%, for 104 and $31 \mu\text{mol m}^{-2} \text{s}^{-1}$, respectively.

Increased assimilation light intensity substantially increased acceptable plant densities in winter, whereas in summer the effect was only small (Fig. 7). For example, when planted in week 40, a crop grown at 39 plants m^{-2} with $31 \mu\text{mol m}^{-2} \text{s}^{-1}$ supplementary light resulted in a plant fresh mass of 82 g, just as a crop grown at 61 plants m^{-2} with $104 \mu\text{mol m}^{-2} \text{s}^{-1}$. Yearly production obtained at an assimilation light intensity of 31, 49, 67, 85, and $104 \mu\text{mol m}^{-2} \text{s}^{-1}$, was 233, 248, 263, 278, and 292 $\text{plants m}^{-2} \text{year}^{-1}$, respectively.

Light use efficiency (LUE) at different assimilation light intensities was calculated as additional total dry mass divided by additional intercepted photosynthetic active radiation (PAR) integral over the entire growing period, relative to the cultivation at the lowest level of supplementary light ($31 \mu\text{mol m}^{-2} \text{s}^{-1}$). LUE varied with season (3.5-4.7 g MJ^{-1}) and slightly decreased with increasing assimilation light intensities (Fig. 8).

DISCUSSION

Despite the use of supplementary light at $49 \mu\text{mol m}^{-2} \text{s}^{-1}$, no constant plant mass throughout the year was obtained (Fig. 5). However, the seasonal adjustments in plant density, length of the long day and short day period (Fig. 2), and the use of supplementary light resulted in a much more uniform plant mass than one would expect based on the natural light pattern throughout the year (Fig. 1). A variation in daily natural light integral by a factor of 10, resulted in a variation in plant mass by only a factor of 2.

For winter crops, a substantial increase in plant density is possible under higher supplementary light intensities without affecting plant fresh mass. Whereas in summer, acceptable plant densities are hardly affected by supplementary light intensities (Fig. 7). This resulted from the fact that in winter crops, supplementary light substantially contributed to the total light integral and increased crop photosynthesis and biomass production (Fig. 6), which has also been observed by Eng et al. (1985) and Heuvelink et

al. (2001). In summer crops, supplementary light hardly contributed to the total light integral, as the natural light integral was already very high and the number of hours the lamps were on was low (twice as long a natural day length and five times higher average natural light intensities as in winter). It seems unexpected that $104 \mu\text{mol m}^{-2} \text{s}^{-1}$ supplementary light in a winter crop results in acceptable plant densities which are even higher than in summer. However, it should not be forgotten that the reference plant mass was much lower in winter than in summer (Fig. 5).

According to our simulations, yearly chrysanthemum production increases substantially with supplementary light intensity. This agrees with observations in practice, when comparing yields of greenhouses with or without supplementary light (Vernooij and Ploeger, 1999). These authors even reported that in the Netherlands, greenhouses with supplementary light, despite a higher energy use per square meter, showed a 9-18% more efficient energy use (expressed in m^3 of gas per financial value of sold flowers) than greenhouses without supplementary light.

LUE showed a seasonal pattern, being about 35% higher in winter than in summer (Fig. 8). Such an effect is to be expected, as in summer during the long day period, the supplementary light is applied together with natural light, whereas in winter, part of the supplementary light is given during natural darkness. Besides, more long days are given to a winter-grown crop and also, then, a larger proportion of the supplementary light is given during natural darkness compared to a summer crop. As the light-photosynthesis response curve shows saturation at high light intensities for leaves, and to a much lesser extent also for a crop canopy, the efficiency of supplementary light supplied during darkness will be higher than for light added to natural light. In addition, LUE in summer was lower because of a lower CO_2 concentration in the greenhouse compared to winter (Fig. 1). Lower CO_2 concentration explained about 30% of the seasonal pattern in LUE.

It should be noted that the effect of different supplementary light intensities has been simulated using a fixed scheme for each planting week. However, Andersson (1990) reported that the application of supplementary light during short day conditions reduced production time in pot chrysanthemum. Furthermore, it seems likely that higher supplementary light intensities make it possible to shorten the number of long days. On the other hand, it is expected that the acceptable plant density in the case of a reduced cultivation period is lower than presented in Fig. 7. Basically, there is to some extent, a trade-off between length of the long day period and acceptable plant density. Furthermore, increasing plant density is associated with progressively slower flowering, especially in autumn and winter (Langton et al., 1999).

This paper illustrates how a photosynthesis-driven model, CHRYSIM1.0, can be used to support decisions on acceptable plant densities at different intensities of supplementary lighting. The development and use of such models for ornamental crops is still very limited (Marcelis et al., 1998), whereas the possibilities for applying such models are, especially in greenhouse production, large (Challa, 1985). For example, the results of the present simulation can also be used in economic calculations on optimum supplementary assimilation light intensity, as has been shown by Roelofs et al. (2001).

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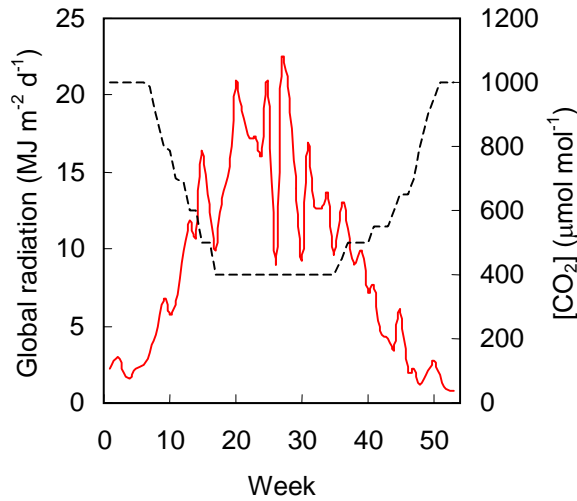


Fig.1. Average global radiation (solid line) and CO₂ concentration (dashed line) used in the simulations.

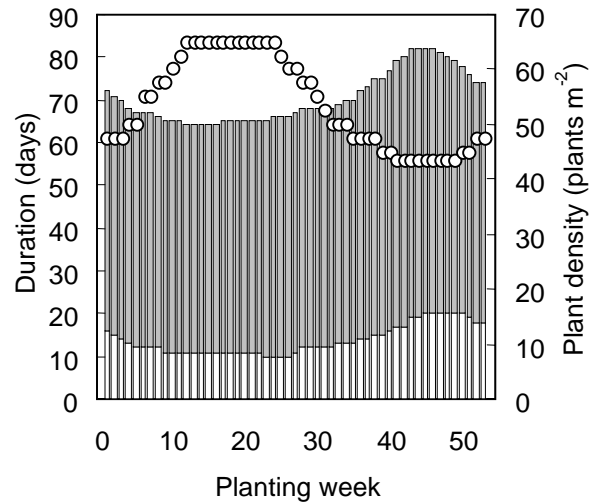


Fig.2 Reference duration of long day (open bars) and short day (grey bars) and plant densities (○) for weekly plantings.

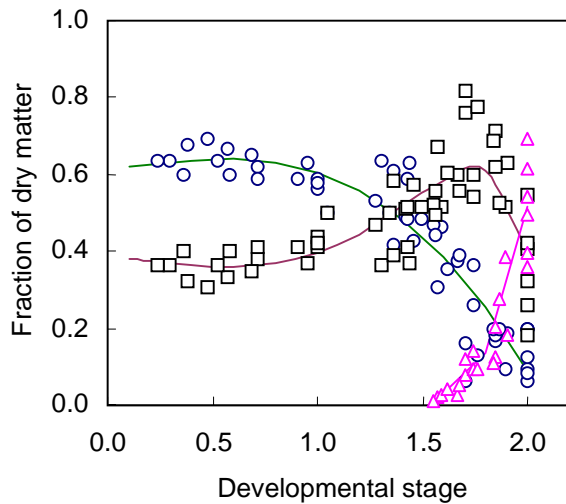


Fig.3. dy matter partitioning to leaves (○), stems (□) and flowers (△) as a function of developmental stage (0=planting date, 1=start of short day period, 2= harvest ripe). Destructive measurements from several greenhouse experiments (symbols). Third order polynomial functions were fitted for leaves and flowers through experimental data and used in the simulation model.

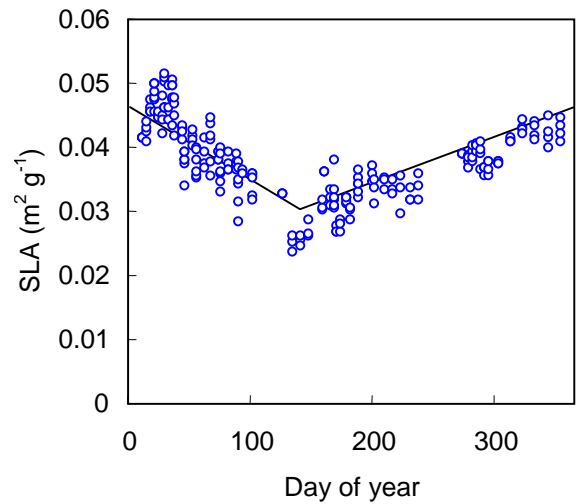


Fig.4. Specific leaf area (SLA) as function of day of year. Destructive measurements from several greenhouse experiments (○). Linear regression lines were used in the simulation model.

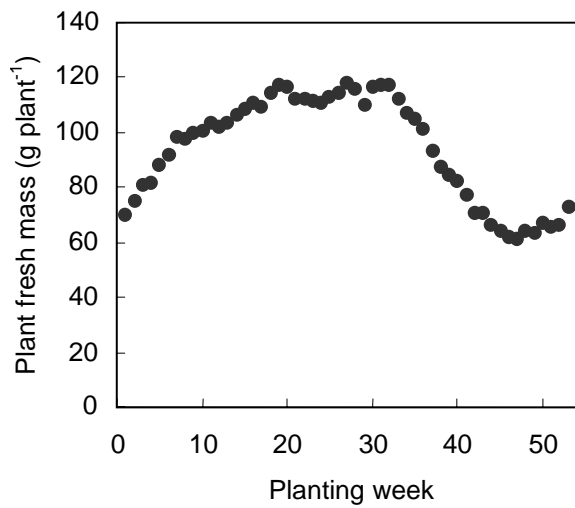


Fig.5. Simulated plant fresh mass at reference plant density and at $49 \mu\text{mol m}^{-2} \text{s}^{-1}$ supplementary light.

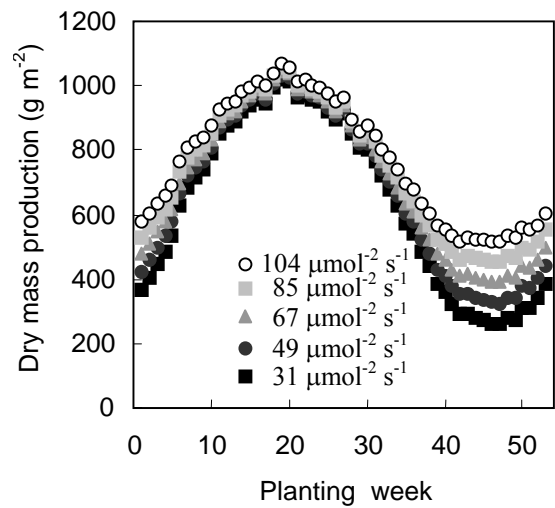


Fig.6. Simulated total dry mass production at different assimilation light intensities.

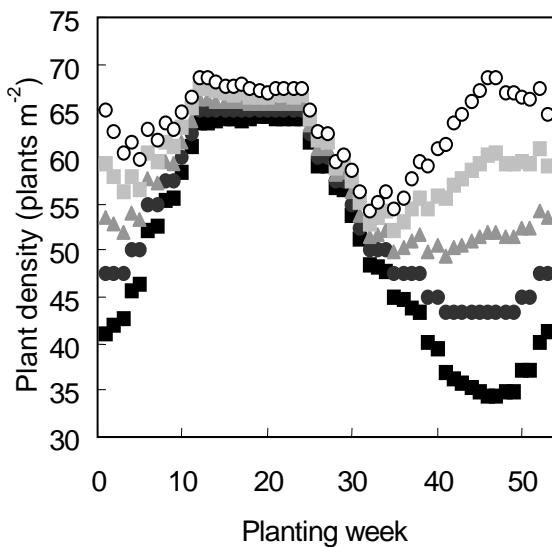


Fig.7. Acceptable plant densities calculated for different assimilation light intensities (legend in Fig. 6) and reference plant densities (\bullet) for $49 \mu\text{mol m}^{-2} \text{s}^{-1}$.

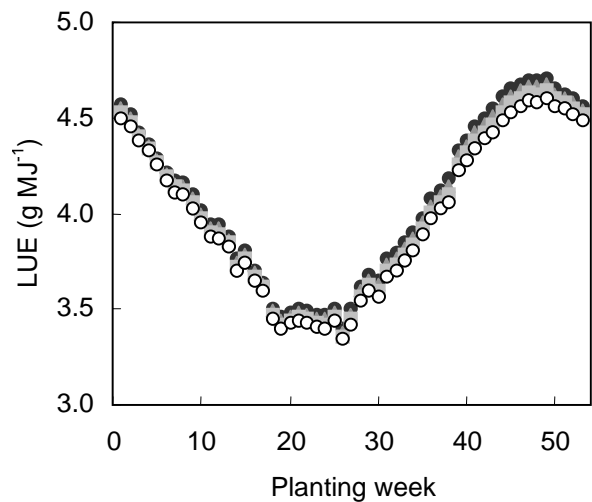


Fig.8. Light use efficiency (LUE) at different assimilation light intensities (legend in Fig. 6). LUE calculated as additional total dry mass divided by additional intercepted PAR integral relative to $31 \mu\text{mol m}^{-2} \text{s}^{-1}$.