Simulating Seasonal Patterns of Increased Greenhouse Crop Production by Conversion of Direct Radiation into Diffuse Radiation

R.E.E. Jongschaap, T.A. Dueck,
S. Hemming and L.F.M. Marcelis
Plant Research International
P.O. Box 16, NL-6700AA Wageningen
The Netherlands

N. Marissen
Applied Plant Research
Division Glasshouse Horticulture
Linnaeuslaan 2a, NL-1431JV Aalsmeer
The Netherlands

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Abstract

The conversion of direct solar photosynthetically active radiation (PARDir) into diffuse radiation (PARDif) and its effects on greenhouse crop production were analyzed with simulation models. PARDir can be converted into PARDif by increasing the haze of greenhouse covers with a minimal loss of radiation transmission. At specific sun incidence angles, PARDif penetrates more deeply into the canopy than PARDir, thereby decreasing saturation effects in upper, and increasing photosynthesis rates at deeper layers. Increased profits can be realized if the crop is intercepting more incoming radiation at more efficient parts of the canopy. A dynamic crop growth model was used to quantify the yearly production of tomato, cucumber and sweet pepper, calculated on a daily basis. For different degrees of haze, six virtual leaf compartments were simulated in the canopy. These layers were analyzed for PAR availability, PAR absorption and photosynthesis rates.

Model results showed that the conversion of direct to diffuse radiation shifted the vertical distribution of PAR to deeper canopy layers. Total photosynthesis in the top layer of the canopy was reduced by 0.5%, but photosynthesis per MJ absorbed PAR increased. Deeper canopy layers received and absorbed more PAR, thereby increasing total canopy photosynthesis. If all incoming PARDir was converted to PARDif, cucumber photosynthesis increased by 1.5% (winter), 4.0% (summer) and 3.4% (fall). For sweet pepper it was 1.5% (winter), 4.3% (summer) and 4.2% (fall) and for tomato it was 1.4% (winter), 3.5% (summer) and 2.6% (fall). Different reactions between crop types were related to differences in leaf area index evolution in the course of the growing season. About 55% of all benefits were obtained in summer months (May-June-July), when the amount of PARDir is the greatest and leaf area index (LAI) is sufficiently high.

INTRODUCTION

The quality and quantity of solar PAR used for greenhouse crop production is determined by the daily and seasonal variability in solar radiation of a specific location, in combination with greenhouse cover characteristics. Total PAR and fraction PARDir is lower in winter than in the summer months. Transmission through a greenhouse cover (τ_C) is generally higher for PARDir than for PARDif, as diffuse radiation (on average) has lower incidence angles leading to lower τ_C. Greenhouse covers vary in τ_C and PARDir conversion capacity.

The vertical PAR profile in the canopy is often inefficiently distributed because the upper parts of the crop intercept the largest amount of radiation (Dueck et al., 2006), where the light use efficiency is low due to radiation saturation effects. Canopy temperatures are more likely to rise in the canopy where radiation is absorbed. Except for a few hours in summer during high sun elevations, PARDif in the Netherlands (52°N) penetrates more deeply into the canopy than PARDir. As a result of the vertical radiation profile, part of the Rubisco in older plant parts that are situated in deeper and darker canopy layers disintegrates and is consecutively transported to the growing plant parts that are exposed to higher radiation intensities (Ono et al., 1996). In these growing parts it can be used again for the photosynthesis process. Additional consequences of shifts in vertical radiation profiles can be expected in changing canopy temperatures and transpiration rates, as demonstrated in arable crops (Greenwald et al., 2006). In the horizontal plane, diffuse radiation is more homogenously distributed; this in contrast to direct radiation where self-shading and greenhouse construction parts may cause additional shading of the canopy. If the horizontal distribution of radiation would be more homogeneous as a result of making it diffuse, crop photosynthesis would be higher.

The photosynthetic response of the canopy to the conversion of PARDir into PARDif is expected to differ gradually, as the amount and fraction of PARDir in relation to global solar radiation is seasonally dependent. Furthermore, the PAR intercepting capacity of crops may be diverse, as differences in crop development and crop management result in a different evolution of leaf area index in the course of the growing season. Leaf picking in tomato and sweet pepper e.g., is motivated by increased radiation use efficiency (Dueck et al., 2006), or by increased fruit ripening if solar radiation is able to reach the fruits and increase fruit temperatures (Slack, 1986; Adams and Valdés, 2002). Additionally, the dissimilarity between crops in allocating assimilates to fruits may result in differences between crop yields. In order to quantify different crop responses to diffuse PAR availability, a crop growth simulation model should be used that is able to mimic these differences. Hemming et al. (2006) already analyzed the effects of diffuse greenhouse covers on vegetable production on a yearly basis (cucumber: +4.2%; sweet pepper: +4.1%; tomato: +2.9%).

The objective of this study was to quantify and analyze the seasonal effects on greenhouse crop production for increased conversion of direct into diffuse radiation, ranging between 0.0 (reference: no conversion) and 1.0 (100% conversion), using simulation models. The analyses were performed for climate conditions in the Netherlands and comprised the simulation of standard production systems of cucumber (*Cucumis sativus* L.), sweet pepper (*Capsicum annuum* L.) and tomato (*Lycopersicon esculentum* L.) in a conventional Dutch Venlo-type glasshouse.

MATERIALS AND METHODS

A greenhouse climate model (KASPRO; de Zwart, 1996) used representative climate data for the Netherlands (Breuer and van de Braak, 1989) to calculate climate conditions in a conventional Dutch Venlo-type glasshouse (Hemming et al., 2006). A dynamic crop growth model (INTKAM; Gijzen et al., 1998; Marcelis et al., 2000) was used to simulate standard management practices for a full production year of cucumber, sweet pepper and tomato on a daily basis (Table 1). Row patterns, leaf physiological ageing and sub-optimal nutrient supply were not taken into consideration. As the growth cycle of cucumber is relatively short, 3 growth cycles were simulated for cucumber (winter, summer and fall, in agreement with Dutch practice) to achieve a full production year. To investigate the seasonal effects of PARDir conversion, production in winter (until 30 April), summer (1 May-31 July) and fall (from 1 August onwards) were analyzed.

INTKAM calculates photosynthesis rates in hourly time-steps, based on detailed biochemical equations (Farquhar et al., 1980) which are affected by intercepted radiation, (canopy) temperatures and CO_2-concentrations in the greenhouse. Other climate factors influencing photosynthesis rates are radiation and vapour pressure deficit. The PAR fraction that can be intercepted by the canopy depends on leaf area index ($m^2\ m^{-2}$) and radiation extinction coefficients, according to Lambert-Beer's law (Eq. 1; Monsi and Saeki, 1953). Radiation extinction coefficients (k) depend on radiation transmission (τ_L) through the canopy (Eq. 2).

$$fAPAR = 1 - e^{-k \cdot LAI} \tag{1}$$

$$k = \left(\frac{-\ln(\tau_L)}{LAI} \right) \tag{2}$$

with $fAPAR$ = fraction intercepted PAR (-), k = radiation extinction coefficient (-), τ_L = radiation transmission fraction through the canopy (-). For the simulation experiment, a homogeneous leaf angle distribution was assumed, with k_{DIF}=0.78 as the extinction coefficient for PARDif. The extinction coefficient for PARDir (k_{DIR}) is variable, as it depends on clustering and scattering of individual leaves and varies with sun incidence angle (and thus with daily and seasonal patterns). Gaussian integration (Hildebrand, 1956) over 3 leaf angles was used to upscale PAR interception from individual leaves to canopy interception. In this approach, the fractions leaf reflection (0.15) and reflection from the surface below the canopy (0.40) were integrated.

The original simulation model was adapted to calculate photosynthesis rates in six (arbitrarily set) 'leaf compartments'. These leaf compartments were virtually organized from top to bottom of the canopy, containing 10% (in the top layer 1), 20% (in each layer 2, 3, 4 and 5) and 10% (in the bottom layer 6) of the total leaf area index. For each leaf compartment, the simulation model calculated available PAR, absorbed PAR and photosynthesis rates for a number of scenarios. Results were integrated for all leaf compartments, for 3 seasons and for a full production year.

A range of simulation scenarios were defined, affecting PAR availability and PAR composition above the canopy. Furthermore, 3 different greenhouse glass transmission factors for direct global radiation (τ_C) were considered, representing 'dark' (τ_C=0.85), 'conventional' (τ_C=0.90) and 'light' (τ_C=0.95) greenhouse cover characteristics. Available PARDir was converted to PARDif by multiplication with a haze factor of 0.0 (reference), 0.3, 0.6, 0.8 and 1.0, representing the capability of greenhouse materials to convert direct radiation into diffuse radiation. It was assumed that haze did not affect light transmission through the greenhouse cover and that other climate variables remained stable (Hemming et al., 2006).

RESULTS AND DISCUSSION

The crop growth simulation model INTKAM produced distinct leaf area index growth curves for cucumber, sweet pepper and tomato (Fig. 1). Differences in leaf area index evolution can be related to the number of crop cycles (3 for cucumber; 1 for sweet pepper and tomato), maximum leaf area index, leaf picking in tomato management and a senescent phase of sweet pepper leaf area at the end of the production period. These patterns are in agreement with observations in conventional Dutch greenhouse management.

In general, $k_{DIF} < k_{DIR}$ in the Netherlands (52°N), except for a few hours at mid-day for a couple of days in the summer when high sun incident angles result in $k_{DIF} > k_{DIR}$. At lower latitudes (i.e. closer to the equator), sun incident angles are higher on average, resulting in a reduction of the potentials for the conversion of direct into diffuse radiation.

By increasing haze from 0.0 (no conversion) to 1.0 (fully diffuse radiation) in a conventional greenhouse (with τ_C=0.90), the vertical light distribution in the canopy changed considerably and was different per crop type (Table 2). For all τ_C values (0.85, 0.90 and 0.95), more diffuse radiation led to a shift in PAR availability from top canopy layers to deeper canopy layers. Crops with a higher LAI (sweet pepper > tomato > cucumber), on average were more capable of absorbing extra PAR in deeper canopy layers (Table 3), thereby increasing photosynthesis rates (Table 4). At the start of the growth cycle (3 times per year for cucumber), more diffuse radiation fell through the canopy on the ground and was lost for production. With conventional greenhouse covers (τ_C=0.90) at maximum haze, yearly photosynthesis increased by 3.2% for cucumber, 3.6% for sweet pepper and 2.7% for tomato. About 55% of all benefits were obtained in summer months (May-June-July), when the amount of PARDir is the greatest and leaf area index (LAI) is sufficiently high (Table 4). For crop production (dry matter allocated to fruits), these effects were even more pronounced, as yearly crop production increased by 4.2% for cucumber, 4.1% for sweet pepper and 2.9% for tomato.

The effect of haze increase on crop photosynthesis follows the 'law of diminishing returns' (Fig. 2). At 60% of the maximum haze, ca. 85% of the positive effects were realized. Higher τ_C resulted in larger benefits from more diffuse radiation. With modern production techniques (such as special greenhouse cover coatings), it is possible to increase haze and maintain high transmission coefficients (τ_C) at the same time (Hemming et al., 2006). The phenomena of increased photosynthesis rates by conversion of direct into diffuse radiation at medium latitudes, has also been documented for arable cropping systems (Cohan et al., 2002). The aerosols (clouds of solid or liquid particles in the atmosphere) responsible for this conversion have negative effects on PAR transmission (Greenwald et al., 2006). As a result, photosynthesis rates are only increased with moderately thick aerosol loadings on cloudless days with high solar radiation, whereas on overcast days, photosynthesis rates are reduced. The special coatings available for greenhouse covers do not have the disadvantage of losing too much PAR.

The results of this glasshouse simulation study showed that by introducing haze, PAR absorption in top canopy layers of different greenhouse crops could be reduced and transferred to deeper canopy layers. The reduction in crop photosynthesis was relatively small in top canopy layers, where saturation of the photosynthesis process was the cause for inefficient radiation use. The extra PAR availability absorbed in deeper canopy layers was more efficiently used, and resulted in an overall photosynthesis increase, leading to increased fruit production. Relatively small haze values have a positive effect on crop production and at haze=0.60, already 85% of the benefits are realized. Simulation results showed that low LAIs, such as at the beginning of the growth period due to crop genetic resources or due to leaf picking, the introduction of haze may lead to radiation loss, as it falls through the canopy. If possible, these losses should be avoided as it reduces the potential increase in crop production. The seasonal contribution to the yearly increase in greenhouse crop photosynthesis is about 12% in wintertime, 56% in summertime and 32% in fall.

The question remains if photosynthetic characteristics of leaves in deeper and older canopy layers are similar to those in top and younger canopy layers. Therefore, the meaning of physiological age in terms of photosynthesis efficiency should be investigated, and if it is affected by increased radiation levels (e.g. due to diffuse radiation that penetrates more deeply into the canopy). In the summer of 2006, Plant Research International conducted cucumber experiments with diffuse and clear greenhouse coatings in order to find answers to the questions above.

ACKNOWLEDGEMENTS

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Tables

Table 1. Dutch management settings and length of the growth cycles (d) for cucumber, sweet pepper and tomato. Values in parentheses indicate Julian day number.

	Cucumber			Sweet pepper	Tomato
	Winter	Summer	Fall		
Start	16-Dec (350)	1-May (121)	1-Aug (213)	21-Nov (325)	12-Dec (346)
End	30-Apr (120)	31-Jul (212)	5-Nov (309)	6-Nov (310)	20-Nov (324)
Cycle	136	92	97	341	344

Table 2. PAR availability (MJ m^{-2}) with reference[1] (τ_C=0.90; haze=0.0) per season[2], with contribution per leaf layer (L) if fully diffuse conversion (haze=1.0) is applied. Indicated is the increase per leaf layer in comparison to reference conditions.

	PAR availability (MJ m^{-2})											
	Cucumber				Sweet pepper				Tomato			
	Win	Sum	Fall	Σ	Win	Sum	Fall	Σ	Win	Sum	Fall	Σ
L	*281*	*614*	*363*	***1257***	*294*	*614*	*364*	***1272***	*282*	*614*	*377*	***1273***
1	0	0	0	**0**	0	0	0	**0**	0	0	0	**0**
2	3	3	5	**11**	4	4	5	**13**	3	3	4	**10**
3	3	3	5	**12**	5	2	3	**9**	4	3	5	**12**
4	3	2	4	**9**	4	1	1	**5**	3	3	4	**10**
5	2	2	2	**6**	3	0	0	**3**	2	2	3	**7**
6	1	1	2	**4**	2	0	-1	**1**	2	1	2	**5**

[1] Reference values in italic

[2] Win = winter (ending 30 April), Sum = summer (1 May-31 Jul) and Fall (beginning 1 Aug)

Table 3. PAR absorption (MJ m^{-2}) with reference[1] (τ_C=0.90; haze=0.0) per season[2], with contribution per leaf layer (L) if fully diffuse conversion (haze=1.0) is applied. Positive/negative values indicate increase/decrease in comparison to reference conditions.

	PAR absorption (MJ m^{-2})											
	Cucumber				Sweet pepper				Tomato			
	Win	Sum	Fall	Σ	Win	Sum	Fall	Σ	Win	Sum	Fall	Σ
L	*250*	*524*	*292*	***1066***	*261*	*585*	*347*	***1194***	*253*	*554*	*327*	***1133***
1	-3	-3	-4	**-11**	-3	-4	-5	**-12**	-3	-3	-4	**-10**
2	-1	0	0	**-1**	-1	2	3	**4**	-1	0	-1	**-2**
3	1	1	1	**3**	1	1	2	**4**	1	1	1	**2**
4	1	1	1	**2**	1	1	1	**2**	1	1	1	**3**
5	1	0	1	**2**	1	0	1	**2**	1	1	1	**2**
6	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**
Σ	-1	-1	-1	**-4**	-1	0	1	**0**	-1	-1	-2	**-4**

[1] Reference values in italic

[2] Win = winter (ending 30 April), Sum = summer (1 May-31 Jul) and Fall (beginning 1 Aug)

Table 4. Photosynthesis (g CO_2 m^{-2}) reference values[1] (τ_C=0.90; haze=0.0) per season[2], with contribution per leaf layer (L) if fully diffuse conversion (haze=1.0) is applied. Positive/negative values indicate increase/decrease in comparison to reference conditions.

	Photosynthesis rate (g CO_2 m^{-2})											
	Cucumber				Sweet pepper				Tomato			
L	Win	Sum	Fall	**Σ**	Win	Sum	Fall	**Σ**	Win	Sum	Fall	**Σ**
	3314	*5387*	*3395*	***12095***	*3454*	*6059*	*3992*	***13505***	*3406*	*5736*	*3758*	***12900***
1	-20	-17	-23	**-61**	-23	2	-11	**-33**	-24	-20	-24	**-67**
2	6	61	31	**98**	9	139	98	**245**	9	36	11	**56**
3	21	76	43	**140**	24	77	50	**151**	24	64	32	**120**
4	20	54	34	**108**	20	29	20	**69**	20	60	35	**115**
5	15	34	23	**72**	15	11	9	**35**	14	46	31	**91**
6	6	11	8	**26**	6	4	3	**13**	5	17	13	**35**
Σ	49	218	116	**383**	51	262	169	**481**	49	202	99	**350**

[1] Reference values in italic

[2] Win = winter (ending 30 April), Sum = summer (1 May-31 Jul) and Fall (beginning 1 Aug)

Figures

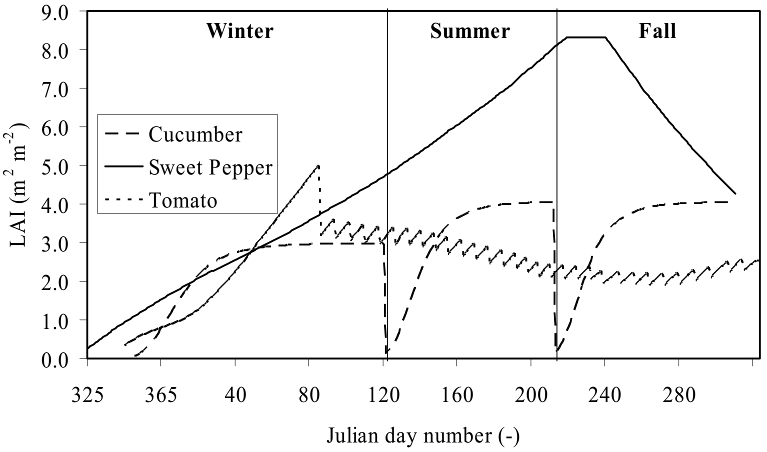

Fig. 1. Leaf area index (m^2 m^{-2}) simulations for cucumber, sweet pepper and tomato in winter, summer and fall. PAR conversion is most beneficial in the summer period (May-July).

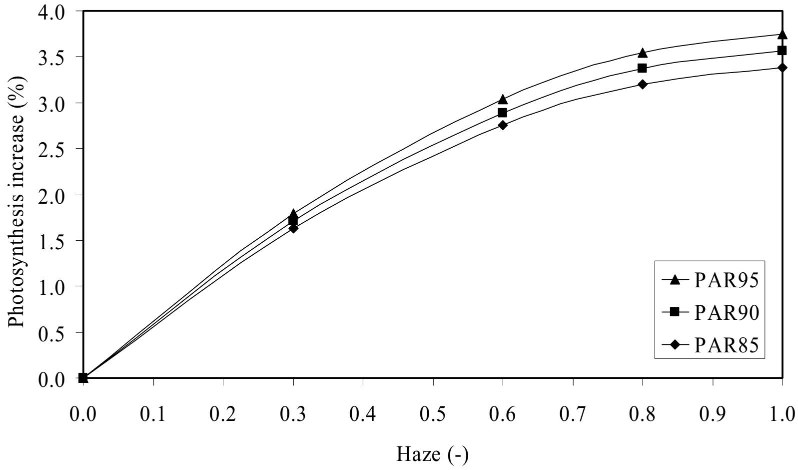

Fig. 2. Simulated effect of haze (i.e. fraction PARDir that is converted into PARDif) on yearly photosynthesis increase (%) of sweet pepper for different greenhouse cover transmission factors τ_C (0.85, 0.90 and 0.95), in comparison with reference (haze=0.0).