DYNAMIC OPTIMIZATION OF ARTIFICIAL LIGHTING IN GREENHOUSES

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Abstract

A principle for dynamic optimization of artificial lighting in greenhouses is presented, where the optimization criterion is maximization of the term <economic yield minus related costs>. To this purpose it is important to consider the break-even point for artificial lighting, which can be defined as the natural light intensity in a greenhouse at which the costs of using supplementary light equal the additional yield (in economic terms) caused by that supplementary light.

Based on a mechanistic model of crop photosynthesis, break-even points are calculated and their dependency on CO_2 concentration in the greenhouse, product price, leaf area index (LAI), price of electricity and crop conversion efficiency (g fresh weight of harvestable product per g crop gross CO_2 assimilation) is shown.

At given CO_2 concentration and LAI the economic value of 1 g gross CO_2 assimilation and the price of electricity are the 2 major parameters determining the break-even point for artificial lighting. Economic value of 1 g CO_2 assimilated for any specific situation depends on the fraction of dry weight diverted to harvestable products (F_{so}) and percentage dry matter and price of the harvestable product. In the present paper a method to obtain this value for a given situation is worked out and the relation with break-even points for artificial lighting is graphically summarized. The same graph can also be used to get a first impression of the feasibility of the use of artificial light in a specific situation by considering the marginal profit.

According to the present calculations, use of artificial lighting is not profitable for Chinese cabbage in The Netherlands nowadays. Artificial lighting might be feasible with radish (high F_{so}), egg plant and sweet pepper (high auction prices). For cucumber, lettuce and tomato use of artificial lighting is unprofitable during a large part of the year.

1. Introduction

With the recent rapid increase of the area of greenhouses provided with systems for artificial lighting in The Netherlands there is an increasing demand for more insight in the rules for optimal control of these systems. Until 5 years ago, use of artificial lighting in Dutch horticultural industry was limited to the production of young plants (seedlings, cuttings) in winter time and some very special situations e.g. cultivation of Saintpaulia in a 2-layer system or cultivation of lilies. Nowadays, artificial lighting is applied in The Netherlands for greenhouse production of cut flowers (e.g. 200 ha (25%) of roses) and even vegetables (a few hectares of cucumber and tomato).

The decision to install artificial lighting in a greenhouse is a very important strategic one, because the annual investment costs are high. However, once this decision is made, it has to be decided at the operational level, when to switch the lighting system on or off in any specific situation to get optimal performance. The operation of artificial lighting usually follows a fixed scheme e.g. lights on from 4 a.m. till 12 p.m. as long as global radiation outside the greenhouse is less than 40 W m^{-2} (Durieux, pers. comm.). However, it is clear that better decisions are made if not only radiation is taken into account, but also crop characteristics (like leaf area index), CO_2 concentration in the greenhouse, price of electricity and expected product price. The latter can change rapidly, as can CO_2 concentration and even electricity price, if electricity is provided by co-generation of heat and power (total-energy system). In such a situation, electricity will be available at a lower price if there is a heat demand, compared to moments when it is not necessary to heat the greenhouse. Therefore, a dynamic optimization (Bailey, 1985; Challa and Schapendonk, 1986; Seginer, 1980; Steinbuch, 1985), rather than a static one (blue-print), is principally necessary for optimal performance. The optimization criterion is maximization of the term <economic yield minus related costs>. Related costs are only those costs, which are influenced by the operation of artificial lighting, not total costs.

The increased use of computers for climate control (80-90% of horticultural holdings in The Netherlands; Nederhoff, pers. comm.) provides possibilities for dynamic optimization, which are impossible with analogue controllers or control by hand. Nowadays, computers for climate control still basically follow the same principles as analogue controllers and it is still the grower who defines the set points. Computers, however, have much greater potentials. Dynamic optimization of CO_2 concentration control with cucumber, resulted in the same yield as with a fixed concentration of 500 $\mu l\ l^{-1}$, but CO_2 costs were reduced by almost 50% (Nederhoff, 1987). The major problem with dynamic optimization is the difficulty of evaluating plant performance in relation to climatic factors over short intervals of time (Challa and Schapendonk, 1986).

In this paper an outline for dynamic optimization of artificial lighting in greenhouses is presented. The basic concepts for dynamic optimization were given by Challa and Schapendonk (1986) and illustrated for CO_2 enrichment. However, a major difference in the case of artificial light is that on/off control is considered, where the main problem is to know the natural light level that is the break-even point for additional lighting. This break-even point is the natural light intensity, where the cost of supplementary light is equal to the additional yield (in economic terms) caused by the supplementary light. Furthermore the problem of economic evaluation of CO_2 assimilation for vegetable crops is worked out into some detail. This evaluation is one of the bases for optimization.

2. Description of the crop photosynthesis model

The crop photosynthesis model used here is a submodel of SUCROS 87 (Spitters et al., 1989), and consists of a leaf photosynthesis model combined with a light distribution model. The photosynthesis-light response of individual leaves is described by the negative exponential function:

$$A_L = A_m \, (1-e^{-\epsilon I_{aL}/A_m}) \qquad (1)$$

in which A_L is the gross assimilation rate, A_m the gross assimilation rate at light saturation, ϵ the initial slope or light use efficiency and I_{aL} the absorbed photosynthetically active radiation (PAR wavelength 400-700 nm). A_m and ϵ depend on CO_2 concentration and leaf temperature (fixed at 20 °C here). At 340 $\mu l \; l^{-1}$ CO_2 values for A_m and ϵ used are 0.7611 mg CO_2 m^{-2} s^{-1} and 0.01310 mg CO_2 J^{-1}, at 1000 $\mu l \; l^{-1}$ CO_2 values are 1.178 and 0.01553 respectively (Gijzen, 1989).

To calculate crop photosynthesis, the distribution of light over different leaves has to be taken into account. Incoming PAR is partly reflected by the canopy. The reflection coefficient (ρ) of the canopy depends on solar elevation, leaf angle distribution, and reflection and transmission characteristics of the leaves. In the present approach the model is simplified by treating all radiation as being diffuse, with uniform distribution. Therefore ρ depends on the reflection and transmission properties of the leaves. Leaf angle distribution was assumed to be spherical. Principally, however, there is no objection to adapt various more specific descriptions instead of the simplified version presented here.

The absorption of diffuse light at a depth L in the canopy decreases approximately exponentially with increasing leaf area within the canopy (Spitters et al., 1989):

$$I_{aL} = k \, (1-\rho) \, I_o \, e^{-kL} \qquad (2)$$

where I_o is the light intensity at the top of the canopy, L the depth within the canopy expressed as the cumulative leaf area index above the leaf layer considered, I_{aL} the absorbed diffuse light at the depth considered and k the canopy extinction coefficient for diffuse light.

Rate of gross CO_2 uptake by the crop is obtained by integration over total leaf area of the crop (Spitters et al., 1989). The calculated response of gross photosynthesis of a crop with a leaf area index of 3 to diffuse light and to ambient CO_2 concentration is given in figure 1. These response curves were assumed to be valid for all vegetables under consideration here. It was also assumed that the response curves are the same for PAR from sunlight (natural light), PAR from artificial light or a combination of sunlight and artificial light.

3. Crop photosynthesis and yield

In order to calculate the economic value of changes in rate of photosynthesis a proportionality is assumed between the rate of gross photosynthesis minus the rate of maintenance respiration and the rate of dry weight production and also between the rate of dry weight production and the economic yield. According to Penning de Vries and van Laar (1982) the relation between growth rate of a crop (G) and rate

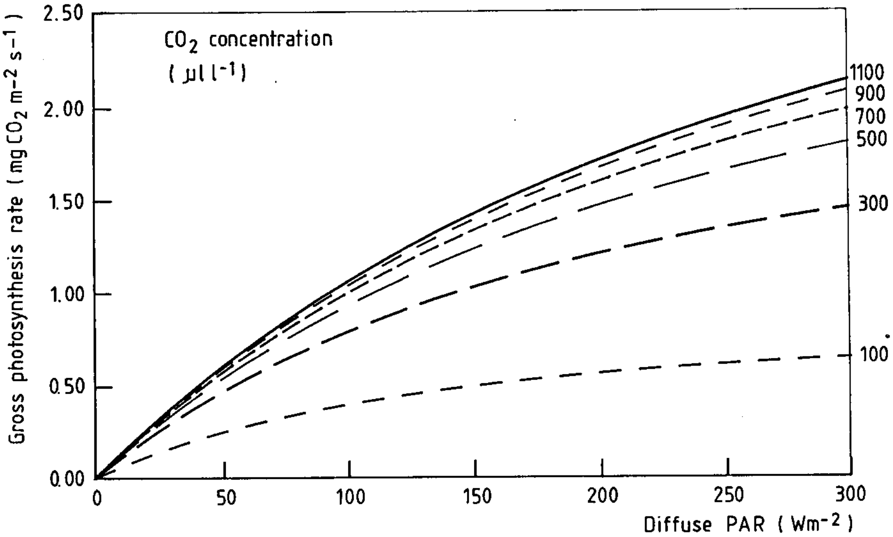

Figure 1 - Gross photosynthesis rate of a whole crop with a leaf area index of 3, as a function of diffuse photosynthetically active radiation (PAR), at different CO_2 concentrations in the greenhouse.

of gross photosynthesis (P) may be described by:

$$G = 0.68\ Y\ (P-R_m) \qquad (3)$$

where 0.68 is a conversion factor to convert units of g CO_2 to g glucose, Y is the carbon conversion yield (g of structural dry weight formed per g of glucose consumed) and R_m represents the rate of maintenance respiration. For optimization it is relevant to consider differences in growth rates, rather than absolute values. From equation 3 it follows that:

$$\Delta G = 0.68\ Y\ \Delta P \qquad (4)$$

where maintenance respiration is eliminated mathematically, under the reasonable assumption that R_m is not affected by different radiation levels.

A good average estimate for Y is 0.7 (Penning de Vries and van Laar, 1982). This means (equation 4) that each g variation in gross CO_2 assimilation results in 0.48 g variation in dry weight production. In order to evaluate gross CO_2 assimilation economically, as a next step the fraction of dry weight diverted to harvestable products (F_{so}) has to be known. For important greenhouse crops like tomato, cucumber and sweet pepper values for F_{so} in the order of 0.7 to 0.8 are reported in literature (table 1). Consequently, approximately 0.35 g dry weight is diverted to harvestable products for every g CO_2 increase in gross CO_2 assimilation.

To obtain the equivalent fresh weight, dry weight content of the harvestable product has to be known. Values for some greenhouse crops are given in table 1. For cucumber 1 g increase in gross rate of CO_2 assimilation gives rise to approximately 0.33 g increase in dry weight of harvestable products with a dry matter content of 3.5%. Thus the overall figure is that for each additional 9.5 g fresh weight of cucumber fruits 1 g gross CO_2 assimilation is required.

The economic value of variations in gross photosynthesis can be estimated from a prediction of the product price at harvesting time. For cucumber fruits harvested in January the average Dutch auction price in the years 1985-1987 was 0.32 ct g^{-1} fresh weight (table 2). Hence, based on this average, 1 g increase in gross CO_2 assimilation yields 3 ct (1 ct = Dfl 0.01).

4. Survey of break-even points for artificial lighting

In the case of artificial lighting only two conditions exist: lights on or lights off. The principle of dynamic optimization is that both situations are compared and the most economic choice for that moment is realized. The natural light intensity in the greenhouse at which both possibilities give rise to equal net rate of financial output is called the break-even point. Below this break-even point lights should be on and vice versa. This break-even point is the natural light intensity in the greenhouse at which the marginal (related) costs of supplementary light equal the marginal production.

The related costs for supplementary lighting are mainly electricity costs. In addition, the costs related to depreciation of the lamps should be taken into account. As the guaranteed economic life of the

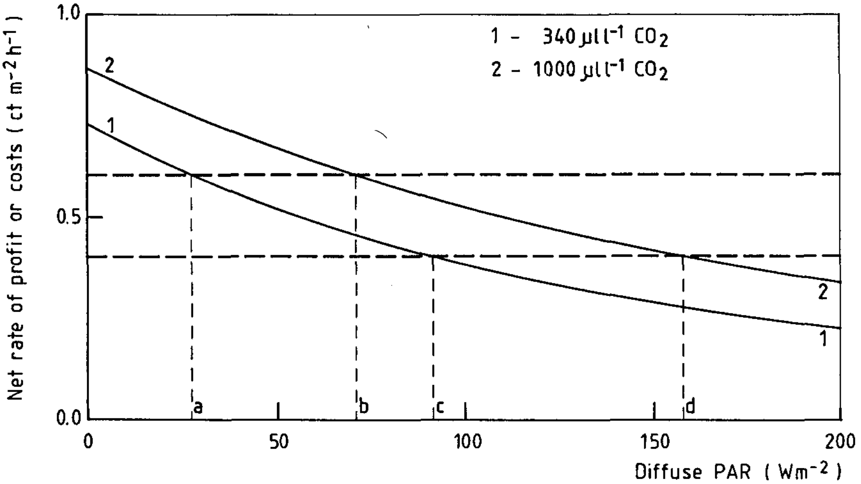

Figure 2 - Calculation of break-even point (a,b,c,d) for artificial lighting as related to natural light level inside the greenhouse. Economic yield of supplementary lighting (7.36 W m^{-2}) at 2 CO_2 concentrations in the greenhouse. Electricity costs of supplementary lighting at an electricity price of 10 and 15 ct kWh^{-1}. Standard values used were respectively: leaf area index (3 m^2 leaf m^{-2} soil), leaf temperature (20 °C), crop conversion efficiency (10 g fresh g^{-1} CO_2) and product price (0.25 ct g^{-1} fresh). 1 ct = Dfl 0.01

usual lamp types is at least 10,000 hrs, these costs are of minor importance, and therefore neglected here.

The light intensity for supplementary lighting used in the present calculations is based on Dutch horticultural practice. It is assumed that 1 high pressure sodium lamp (Philips SON-T 400W) is installed on every 10 m^2 of greenhouse. When the efficiency of the lamp (0.23 W W^{-1}) and of the luminaire (approximately 0.8) are taken into account, this installation gives rise to a supplementary light intensity of 7.36 W m^{-2} (Nederhoff, 1988). However, preliminary calculations showed that break-even points are little influenced by supplementary light intensity (2 - 20 W m^{-2}).

Values used to illustrate the optimization principle (figure 2) are a leaf area index of 3, a conversion efficiency of 10 g fresh weight of harvestable product per g gross CO_2 assimilation and an expected auction price of Dfl 2.50 per kg fresh weight of harvestable product. Economic yield of supplementary lighting is given for 340 and 1000 μl l^{-1} CO_2 inside the greenhouse. The costs are based on an electricity price of 0.10 resp. 0.15 ct kWh^{-1}. Break-even points are situated at the intersection of economic yield and related cost curves.

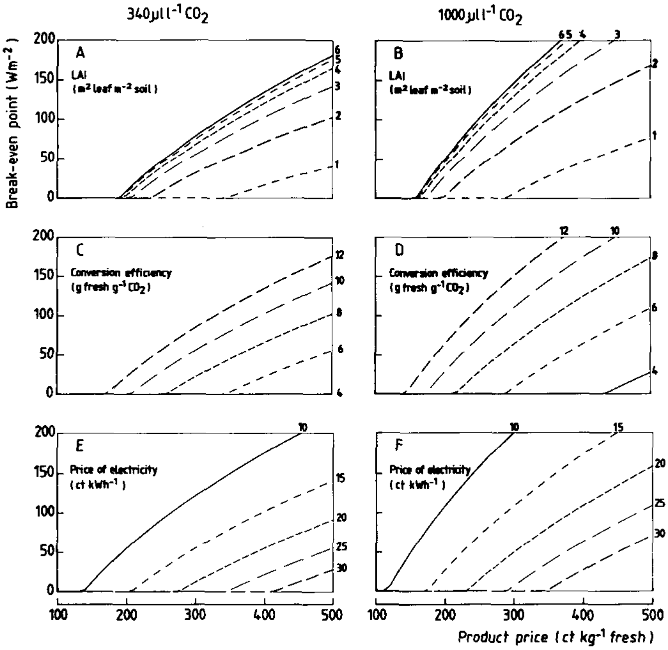

Figure 3 - Calculated break-even points (W m^{-2} PAR in the greenhouse) for artificial lighting (7.36 W m^{-2}) as a function of product price. Parameters varied were leaf area index (LAI) of the crop (a,b), conversion efficiency from CO_2 assimilated to fresh weight of the harvestable product (c,d) and electricity price (e,f) at a concentration of 340 μl l^{-1} CO_2 (a,c,e) and 1000 μl l^{-1} CO_2 in the greenhouse (b,d,f). Standard values used were the same as in figure 2 at an electricity price of 15 ct kWh^{-1}. 1 ct = Dfl 0.01

5. Results

Figure 3 shows the effect of CO_2 concentration, product price, leaf area index (LAI), conversion efficiency and price of electricity on the break-even point for artificial lighting. As one might expect a higher CO_2 concentration, product price, leaf area index and crop conversion efficiency result in a higher break-even point, whereas a higher electricity price gives rise to a lower break-even point. Above a value of LAI=3 the influence of LAI is small compared to the other parameters. This is caused by the high percentage of light intercepted by the canopy at a leaf area index of 3. In contrast to LAI, CO_2 concentration, product price, crop conversion efficiency and price of electricity have a large effect on the break-even point. The influence of temperature is not shown, because in the range 15 - 25 °C temperature hardly influences the rate of gross crop photosynthesis (Challa, 1989). Product price, which has a large influence on the break-even point, is not known exactly in advance, therefore reliable estimates are of utmost importance. It is clear, that the break-even point for artificial lighting is certainly not a fixed value, as usually assumed in horticultural practice.

At given CO_2 concentration and LAI the economic value of 1 g gross CO_2 assimilation and the price of electricity are the 2 major parameters determining the break-even point for artificial lighting. In order to generalize these calculations on artificial lighting for different conditions and crops, the influence of these major parameters on the break-even point is shown in figure 4. At an electricity price higher than or equal to 15 ct kWh^{-1} artificial lighting can not be

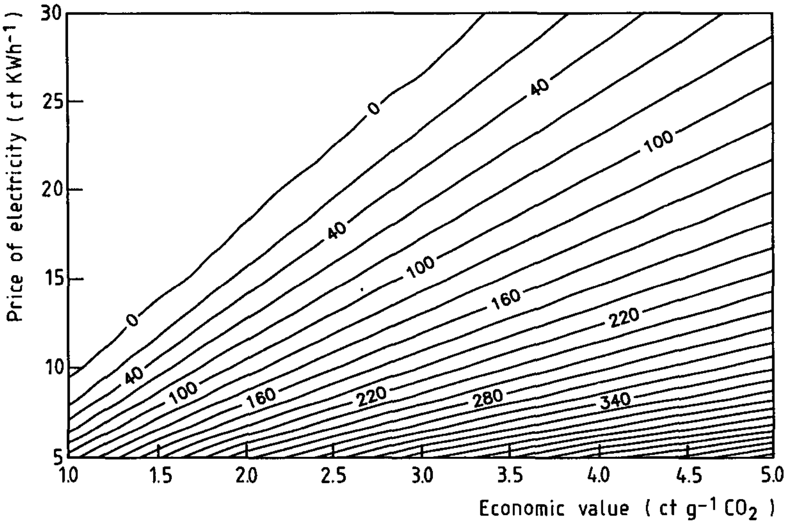

Figure 4 - Break-even points (figures in contour map) for artificial lighting (at an intensity of 7.36 W m^{-2}) as a function of economic value of gross CO_2 assimilation and electricity price. Standard values used were respectively: leaf area index (3 m^2 leaf m^{-2} soil), leaf temperature (20 °C) and CO_2 concentration (1000 μl l^{-1}).

profitable (break-even point less than 0 W m^{-2}) if the economic value of 1 g gross CO_2 assimilation is less than 1.7 ct g^{-1} CO_2. This means that even when annual investment costs are neglected, the use of artificial light is not profitable under these conditions.

Crop characteristics needed for an evaluation of the feasibility of artificial lighting under Dutch conditions are given for some crops (table 1 and 2). The price of electricity is 18.5 ct kWh^{-1}, whereas off-peak price is 15.1 ct kWh^{-1}. These values are average values for the Westland (main glasshouse area in The Netherlands) in 1987. However, electricity price fluctuates between 9 and 20 ct kWh^{-1} (Vermeulen, pers.comm.), depending on delivery conditions. By co-generation of heat and power growers can produce electricity at a price of 8-10 ct kWh^{-1}. For Chinese cabbage artificial lighting cannot be profitable under Dutch conditions at an electricity price greater or equal to 15 ct kWh^{-1} (table 2 and figure 4). For cucumber, lettuce and tomato the use of artificial lighting is unprofitable during a large part of the year. The best potentials are obtained with radish (high F_{so}), egg plant and sweet pepper (high auction prices).

6. Discussion

In order to estimate the profit of dynamic optimization of artificial lighting for radish, a comparison was made with the usual control strategy. In January (3.3 ct g^{-1} CO_2) the break-even point is 130 W m^{-2} at an electricity price of 15 ct kWh^{-1} (figure 4). This means that e.g. for the average Dutch natural light conditions of 15 January the lights are on during the whole day. The value of the crop produced on this day (4 a.m. till 8 p.m.) is 44.04 ct m^{-2} for the optimized light regime at a CO_2 concentration of 1000 $\mu l\ l^{-1}$, if a maintenance respiration of 10% of gross crop photosynthesis is assumed. Electricity costs were 9.66 ct m^{-2} in this case. If the lights are switched off when the outside global radiation (greenhouse transmitivity was calculated according to Gijzen (1989)) is greater than 40 W m^{-2} (usual control strategy), these values are resp. 38.39 ct m^{-2} and 5.76 ct m^{-2}. Hence on this specific day the term <economic yield minus related costs> is increased by 1.75 ct m^{-2} through dynamic optimization of artificial lighting, compared to the usual control strategy. This is a very conservative estimate of the benefit of optimization, because influence of light in the early stages (faster development of leaf area; increase in earliness) is not taken into account. Further calculations are necessary to estimate the profit of dynamic optimization of artificial lighting compared to the usual control strategy. However, it is clear that increase in economic crop yield through dynamic optimization may be of practical interest, the more because the cost of dynamic optimization is negligible.

For the reliability of calculated break-even points the validity of the crop growth model and of the predicted product prices is of great importance. Cucumber photosynthesis measurements were compared with predictions of the present model by Nederhoff et al. (1988; 1989). The model was validated for production of cucumber by Nederhoff and Schapendonk (1985). On average, accuracy of model predictions was within 10% (crop photosynthesis) to 15% (crop production). For good predictions of product prices the experience of the grower is of great importance, but it is likely that where product price depends on the market this aspect is of greater importance than inaccuracies in the prediction of production.

It should be emphasized that the calculations in the present contribution are not aimed for the decision, whether or not to install lighting systems. To that purpose a long-term cost-benefit analysis should be made (e.g. Vermeulen, 1988). However, it should be noticed that the running costs, mainly electricity, often contribute to more than 50% of the total costs of lighting (Vermeulen, 1988). The assumption, that electricity costs are the only marginal costs, does not influence the present approach. In figures 2, 3 and 4 electricity costs can be read as marginal costs.

In practice of course there should be a certain lag-time (15-30 minutes) after switching the lamps before they are switched again, because too frequent switching is harmful to the economic life of the lamps.

It should be kept in mind that, besides the influence of light on crop performance through photosynthesis, also photoperiodic effects can be important. For example, it is well known that continuous illumination causes leaf injury symptoms in tomato (Bradley and Janes, 1985). This makes a minimum dark period of about 6 h necessary with tomato and with some other crops as well. Another phenomenon which is not taken into account in the present approach is photomorphogenesis. For example, with lettuce a higher light intensity can give a better crop quality due to a lower length/width ratio of individual leaves (Bensink, 1971). A good quality usually will result in higher prices. Another example is radish, where it is well known that daylength plays an important role in the induction of tuber formation (Craker et al., 1983).

Symbols and units

Symbol	Unit	Meaning
A_L	mg CO_2 m^{-2} leaf s^{-1}	Gross assimilation rate
A_m	mg CO_2 m^{-2} leaf s^{-1}	Gross assimilation rate at light saturation
ϵ	mg CO_2 J^{-1}	Light use efficiency
F_{so}		Fraction of dry weight diverted to harvestable products
G	mg m^{-2} soil	Growth rate of the crop per unit ground area
I_o	W m^{-2}	Light flux density at the top of the canopy
I_{aL}	W m^{-2}	Absorbed PAR
k		Extinction coefficient for diffuse radiation in the canopy
L	m^2 leaf m^{-2} soil	Cumulative leaf area index: leaf area per unit ground area (counted from the top of the canopy)
LAI	m^2 leaf m^{-2} soil	Leaf area index; total crop leaf area per unit ground area
P	mg CO_2 m^{-2} soil s^{-1}	Rate of crop gross CO_2 assimilation per unit ground area

PAR	$W\ m^{-2}$	Photosynthetically active radiation (400 - 700 nm)
ρ		Canopy reflection coefficient for diffuse light
R_m	mg CO_2 m^{-2} soil s^{-1}	Rate of maintenance respiration per unit ground area
Y		Carbon conversion yield: structural dry weight formed per weight of glucose consumed

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Table 1 - Fraction of dry weight diverted to harvestable products (F_{so}), dry weight content of harvestable product and overall efficiency for conversion of gross CO_2 assimilation to fresh weight of harvestable product for some greenhouse vegetable crops.

Crop	F_{so}	Dry weight content [1] (%)	Conversion efficiency (g fresh g^{-1} CO_2)	References for F_{so}
Chinese cabbage	0.8[2]	4.5	8.5	-
Cucumber	0.7	3.5	9.5	Gijzen (pers.comm.)
Egg plant	0.8	7.0	5.4	Srinivasa Rao(1984)
Lettuce	0.85[2]	5.0	8.1	-
Radish	0.9	5.0	8.6	Suzuki (1978)
Sweet pepper[3]	0.8	8.5	4.5	Hall (1977)
Tomato	0.7	6.0	5.6	Khan & Sagar (1969) Hurd et al. (1979)

[1] After Anonymous (1971-)
[2] Estimated value
[3] Harvested as ripe (red) fruits

Table 2 - Economic value of 1 g gross CO_2 assimilation for some greenhouse vegetable crops in different seasons in The Netherlands.

Crop	Conversion efficiency[1] (g fresh g^{-1} CO_2)	Month	Average auction price[2] (1985-87) (ct g^{-1} fresh)	Economic value (ct g^{-1} CO_2)
Chinese cabbage	8.5	Jan	0.11	0.9
		Apr	0.18	1.5
		Aug	0.06	0.5
		Oct	0.03	0.3
Cucumber	9.5	Jan	0.29	2.8
		Apr	0.18	1.7
		Aug	0.09	0.9
		Oct	0.15	1.4
Egg plant	5.4	Jan	0.82	4.4
		Apr	0.37	2.0
		Aug	0.17	0.9
		Oct	0.33	1.8
Lettuce[3]	8.1	Jan	0.29	2.3
		Apr	0.23	1.9
		Aug	0.16	1.3
		Oct	0.14	1.1
Radish[4]	8.6	Jan	0.39	3.3
		Apr	0.35	3.0
		Aug	0.21	1.8
		Oct	0.18	1.5
Sweet pepper[5]	4.5	Jan	0.54	2.4
		Apr	0.68	3.1
		Aug	0.29	1.3
		Oct	0.28	1.3
Tomato	5.6	Jan	0.07	0.4
		Apr	0.35	2.0
		Aug	0.09	0.5
		Oct	0.14	0.8

[1] Calculations in table 1

[2] After Anonymous (1988); 1 ct = Dfl 0.01

[3] It was assumed that a lettuce head weights 200 g fresh

[4] It was assumed that a bunch of radish weights 200 g fresh

[5] Harvested as ripe (red) fruits