ECONOMIC EVALUATION OF CROP PHOTOSYNTHESIS

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Abstract

Crop photosynthesis (P) is a major (fast reacting) yield determining process and therefore it is a suitable criterion to evaluate short term effects of climate control in greenhouses. For optimal climate control the relation between control actions and marginal yields and marginal costs should be settled, within the scope of the established tactical plan. Thus it is essential to evaluate variations in daily P (ΔP) economically.

Taking a full diurnal cycle at time t as the basis for our considerations, it is clear that the dry weight ($W(t+1)$) at the end of that day will change by ΔW, due to ΔP. The economic value of ΔW depends on the crop phase. In the young phase, the phase of crop establishment, ΔW primarily causes variations in time (Δt_p) required to attain the production phase and hence earliness. In the production phase, ΔW will give rise to a change in economic yield (ΔY), or a change in time till harvest (Δt_h). The economic value of Δt_h is difficult to assess in general terms since it depends strongly on the management objectives. A change in earliness Δt_p corresponds to a change in dry weight production in the production phase ΔW equivalent to $\Delta t_p \times GR(t_p)$, assuming that the growth rate at t_p ($GR(t_p)$) will not be changed by Δt_p.

An important problem to be solved is the fraction of dry weight increment that is diverted to the harvestable products (F_{hp}). For crops like pot plants, chrysanthemum or lettuce $F_{hp} \approx 1$. For several other crops F_{hp} appeared to be constant over longer periods of time (months), though appreciable short term fluctuations in F_{hp} occurred. F_{hp} is not necessarily a fixed crop characteristic, but may depend on the growing conditions. Within a given tactical production plan, in our opinion, it may be treated as a constant.

1. Introduction

In horticultural practice, yields and profits may differ appreciably among nurseries (Alleblas, 1987), and, even with the best growers, great differences may be observed in the way the greenhouse climate is controlled. It is therefore quite likely, given also the great complexity of the greenhouse system and the number of possible options with respect to climate control, that relevant improvements in greenhouse climate control could be achieved. Optimal control systems based on models that represent current understanding of crop physiology and greenhouse physics may contribute to achieving such improvements (Challa et al., 1988; Seginer, 1989).

A necessary condition for optimal control is a proper evaluation of marginal profits in relation to control actions (Challa, 1990). Whereas it is relatively easy to predict the cost of various control actions such as heating and CO_2 supply, up till now the assessment of the economic value of the crop response has formed a major obstacle in the development of optimal control systems. The major difficulty is the great discrepancy between the response time of the crop in terms of yield (typically weeks or months) compared to the fast disturbances and response time that play a role in greenhouse climate control (typically minutes). In earlier discussions (Challa and Schapendonk, 1986; Challa and van Straten, 1991; Heuvelink and Challa, 1989) it was shown that crop photosynthesis is the key process that may be used to evaluate short term responses of crop dry matter production to the environment. The economic value of dry matter production, however, was considered only for the case of a stationary situation of an indeterminate growing crop. The purpose of the present paper is to investigate the problem of economic evaluation of crop photosynthesis more generally: for a wider range of crops in different growth stages.

A comprehensive method to evaluate crop photosynthesis economically is to derive an optimal path for the crop state over a complete crop cycle by means of a Hamiltonian function (van Henten and Bontsema, 1991; Seginer, 1992), where the relation between the greenhouse environment and crop performance is evaluated by means of a crop growth model. In this approach the so called co-state variable represents the economic value of a change in crop dry weight as a function of time. This method, however, does not provide insight in the results obtained. In the present study the relation between variations in daily crop photosynthesis and economic yield will be analysed on the basis of crop physiological and horticultural principles.

2. Crop growth

In general, the time course of the dry weight (W; g m^{-2}) of crops during their life cycle can be characterised by a sigmoid growth pattern (Kropff and Spitters, 1987). If, for the following global description, variations in radiation are ignored, this growth pattern may be readily explained on the basis of present knowledge on leaf area development and crop photosynthesis (Kropff and Spitters, 1987). After emergence or planting, crop growth is primarily limited by the ability to intercept light. With increasing dry weight the Leaf Area Index (LAI) increases, and hence the interception of radiation is increasing more or less in proportion to LAI and as a result growth is approximately exponential. With increasing LAI, however, self shading and mutual shading of plants within the crop reduce the efficiency of light interception per unit of leaf area. Beyond a LAI of 2 - 2.5, depending also on the leaf angle distribution (de Wit, 1965), light interception approaches its maximum (figure 1) and is relatively insensitive to variations in LAI. As a consequence crop growth at this stage proceeds approximately linearly with time (under constant average conditions). With many crops, growth levels off in the final stage. This is due to a decrease of photosynthetic efficiency of an increasing fraction of the leaves, a phenomenon often accompanied by maturation of the reproductive and/or storage organs of the crop and associated break-down of essential leaf components. This final stage of crop senescence will be disregarded in this global overview.

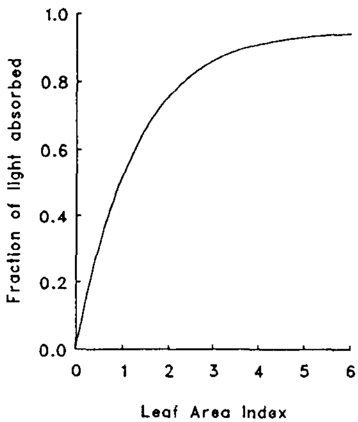

Figure 1 - Relation between leaf area index (LAI) and the fraction of light absorbed (L_a) by a crop according to: $L_a = (1-\rho)(1-e^{-k \times LAI})$ with ρ = crop reflection coefficient (0.05) and k = leaf extinction coefficient (0.8) (Goudriaan, 1982).

In order to evaluate crop photosynthesis over a range of different crops and cultivation systems in greenhouses, it is necessary to schematise strongly: a young and a production (closed canopy) phase are distinguished and a linear relation between the dry weight of the harvestable product (W_{hp}) and W is assumed. These schematisations will be discussed later.

2.1. The young phase

The young phase can be characterised as the phase of crop establishment. The main objective of the grower in this crop phase, therefore, is to increase the LAI, and investments in harvestable organs (where this may play a role) are usually curbed (e.g. cucumber, sweet pepper).
In order to evaluate the crop photosynthesis rate (P; g CO_2 m^{-2} day^{-1}, greenhouse area basis) in this stage, it has to be linked in some way to the primary objective, the establishment of a closed canopy. With this objective, the initial strategy is to achieve a target LAI value for the crop, or, given the density of crop plants, a target value for the leaf area per plant (A; m^2). A relevant parameter is the leaf area ratio (LAR; m^2 g^{-1}), the ratio of A to dry weight per plant, or the ratio of LAI to the crop dry weight per unit area (W; g m^{-2}). It is reasonable to assume that, at time t_p , the time of transition from the young to the production phase, LAR will not vary much, partly because growers, to a certain extend, will control crop growth according to an "ideal" plant quality. Hence the objective of a closed canopy is equivalent to the attainment of a target crop weight W_{ref}. The value of a change in P, ΔP, therefore should be evaluated in terms of the change in time Δt_p, required to attain W_{ref}.

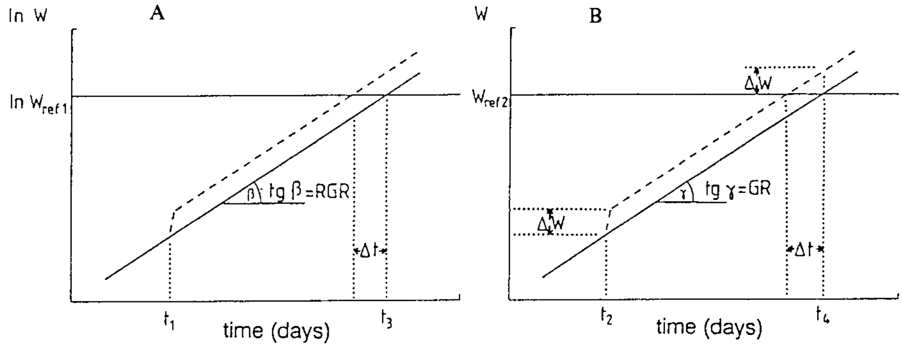

Figure 2 - Effect of a change in daily crop photosynthesis (ΔP) during the young crop phase (A, log scale) and during the production phase (B, linear scale). t_1 and t_2: start of day with P (—) or P+ΔP (- - -). Evaluation at resp. t_3 and t_4. GR = Growth Rate; RGR = Relative Growth Rate; t = time; W = dry weight; W_{ref} = reference weight.

The relation between ΔP and Δt_p can now be quantified following the principles of standard growth analysis theory (Hunt, 1982). A change in crop photosynthesis ΔP at day t causing a change in dry weight ΔW at the end of day t will give rise to a change in time Δt_p, required to attain W_{ref} (figure 2A):

$$\Delta t_p = \Delta \ln[W(t)]/RGR(t) = (\ln[W(t) + \Delta W] - \ln[W(t)])/RGR(t) \quad (1)$$

where RGR(t) = Relative Growth Rate at time t.
According to Challa and Schapendonk (1986)

$$\Delta W = 0.68\alpha\Delta P \quad (2)$$

where α = conversion efficiency of CH_2O to structural dry weight and 0.68 = conversion factor for CO_2 to CH_2O units. Hence, equation (1) now can be written as:

$$\Delta t_p = \ln[1+0.68\alpha\Delta P/W(t)]/ RGR(t) \quad (3)$$

The value of this Δt_p will be discussed in the next section on the production phase, where its consequence becomes evident. From equation (3) follows that the value of ΔP depends on the relative growth rate and on the weight of the crop: at a high RGR, a ΔW resulting from ΔP will result in a small Δt_p because the crop needs little time at this high RGR to attain W + ΔW; at low W, LAI is small and hence the contribution of the same ΔP to RGR is much greater than at high W with a high LAI. When RGR(t) is constant with time, growth is purely exponential, but this is not a necessary condition for the validity of equation (3).

2.2. The production phase

In contrast to the young phase, the production phase is characterised by a relatively low sensitivity of the rate of growth (GR = dW/dt; g m^{-2} day^{-1}, greenhouse area basis) to LAI. The assumption, that the ratio between ΔW and ΔW_{hp}, F_{hp} (but not necessarily that of W and W_{hp}) is constant, will be further examined in the next section. The question is then how the effects from the Δt_p, which occurred during the young phase, and from the changes in crop photosynthesis (ΔP) during the production phase, can be evaluated.

Comparable to the young phase, a change in crop photosynthesis, ΔP, in the production phase will give rise to a change in dry weight ΔW (equation 2; figure 2B). However, a Δt_p arisen in the young phase will cause a change in dry weight in the production phase due to a change in the start (t_p) of the production phase:

$$\Delta W = \Delta t_p \times GR(t_p) \quad (4)$$

with $GR(t_p)$ = growth rate of the crop at the onset of the production phase t_p.

Because the fraction of dry weight increment diverted to harvestable product, F_{hp}, is assumed to be constant, this change in dry weight in turn will cause a change in dry weight of the harvestable product ΔW_{hp}:

$$\Delta W_{hp} = \Delta W \times F_{hp} \quad (5)$$

The economic value of ΔW_{hp} depends strongly on the type of crop and the way the culture is managed. A first distinction can be made between products sold by weight or by piece. For products that are sold by weight ΔW_{hp} will give rise to a change in economic yield ΔY (NLG m^{-2}; NLG = Dutch guilders):

$$\Delta Y = \Delta W \times F_{hp} \times \text{price}(t_h)/DMC \quad (6)$$

where price(t_h) = expected price per unit fresh weight at harvest time t_h (NLG g^{-1}) and DMC = dry matter content (g g^{-1}) of the harvestable product. An additional assumption is that ΔW_{hp} does not affect price(t_h) and/or DMC, an assumption based on the principle that quality and other crop properties are kept in accordance with the tactical plan of the culture and hence remain unaffected.

It can be shown, that the evaluation of ΔP in the young phase is consistent with that in the production phase. At t_p, the time of the transition between the two phases, according to equation (3) and (4), and keeping in mind that GR(t) = RGR(t) × W(t):

$$\Delta W = \ln[1+0.68\alpha\Delta P/W(t_p)] \times W(t_p) \quad (7)$$

whereas, at t_p, according to equation (2):

$$\Delta W = 0.68\alpha\Delta P \qquad (8)$$

Since ΔY is directly proportional to ΔW (equation 6) it is sufficient to show that the right terms of equation (7) and (8) are equal, at least for small $\Delta P/W(t_p)$:

$$0.68\alpha\Delta P = \ln[1 + 0.68\alpha\Delta P/W(t_p)] \times W(t_p) \qquad (9)$$

If both sides of equation (9) are divided by $W(t_p)$ it is easy to see that for the limit transition of $0.68\alpha\Delta P/W(t_p) \rightarrow 0$:

$$0.68\alpha\Delta P/W(t_p) = \ln[1 + 0.68\alpha\Delta P/W(t_p)] \qquad (10)$$

This is also demonstrated in the example of figure 5, where the transition between the young and the production phase does not show a discontinuity.

In the case of indeterminate crop growth, a situation dealt with previously (Challa and Schapendonk, 1986; Heuvelink and Challa, 1989), ΔW_{hp} will be distributed among the growing harvestable organs. These organs will be harvested after a certain lag-time which depends on their age. The average lag-time, which depends on the age-distribution of the organs and the distribution of dry matter over different age classes, may be estimated by half the time required from initiation till harvest.

If products are sold by piece (e.g. cucumber, cut flowers) equation (6) may still be used if the average dry weight per piece is not affected, because ΔW will give rise to a corresponding change in the number produced. Otherwise the relation between the weight and the price per piece has to be established.

Determinate growing crops like kohlrabi, radish and pot plants are harvested at the end of the production phase and the evaluation of ΔW is then determined by the planning of the moment of harvest. Basically there are two choices, either t_h is fixed and then equation (6) and the related discussion still holds, or the size (weight) of the harvestable crop parts is fixed and then ΔW will cause a change in the moment of harvest Δt_h:

$$\Delta t_h = \Delta W / GR(t_h) \qquad (11)$$

where $GR(t_h)$ = expected growth rate of the crop at t_h. The value of Δt_h is difficult to assess in general terms, because it is related closely to the overall management of the nursery. The value of Δt_h should then be considered within the framework of the tactical plan. The price per unit product might change due to the change in the date of marketing. Furthermore, a reallocation of the available resources (e.g. labour, greenhouse area) in the tactical plan may affect the costs. In the most simple case, where the next culture starts as soon as the previous is harvested, Δt_h may be evaluated by equation (4), applied for the next culture.

3. Fraction of W increment diverted to harvestable product (F_{hp})

As shown in the previous section, F_{hp} plays an important role in the economic evaluation of crop photosynthesis. The assumption that F_{hp} is constant, will be examined now.

If (almost) the complete crop is harvested, F_{hp} = 1 and hence constant. Examples are pot plants, chrysanthemum and lettuce. In many crops, the harvest index (harvested dry weight/total plant dry weight) is not constant, neither in time, nor under different conditions. However, for tomato plantings with largely differing growth patterns (figure 3A), F_{hp} appeared to be the same and constant over longer periods of time (months; figure 3B). In fact, once the growth of the harvestable product has started, for several crops (and even at different plant densities in the case of radish), a linear relation was found between plant dry weight and dry weight of the harvestable product, the intercept giving an estimate of the dry weight per plant at the start of the production phase (figure 4).

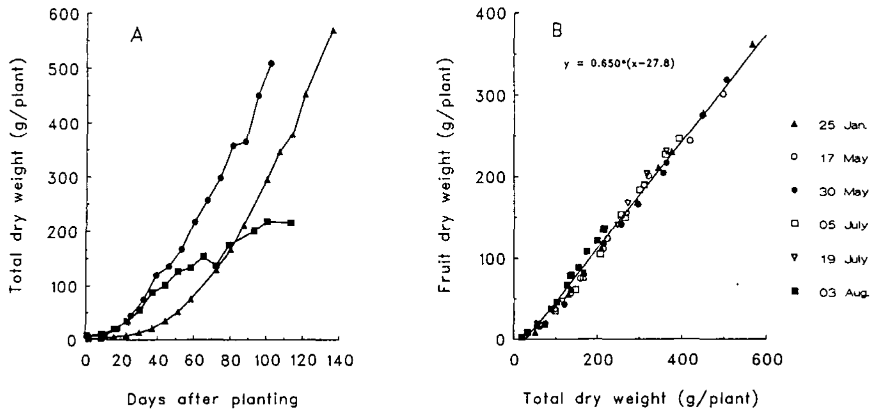

Figure 3 - (A) Growth pattern of tomato crops planted in January, May or August, and (B) the relation between total plant dry weight and fruit dry weight (6 planting dates). All dry weights include harvested plant parts (Heuvelink, unpubl.).

In contrast to tomato (figure 3), the relation between plant dry weight and dry weight of the harvestable product differed, for different kohlrabi plantings (figure 4E). Also for tomato (figure 4A) this relation, determined in horticultural practice by de Koning (1991), differed from that determined in our experiments (figure 3B). The slope of the line relating plant dry weight to dry weight in the harvestable product (F_{hp}), thus may depend on the growing conditions (e.g. influence on fruit set).

It should be mentioned here that, for kohlrabi, the harvestable product does not consist of tuber only, but usually the product consists of some leaves as well. For radish, in the case of mechanical harvest, the harvested product is the tuber, otherwise the whole plant is harvested (F_{hp} = 1).

It is clear (Figs. 3 and 4) that, while on the long run a linear relation may exist between W and W_{hp}, large short term fluctuations in F_{hp} may occur (e.g. figure 4B). Such fluctuations occur in many indeterminate growing crops, e.g. sweet pepper (Hall, 1977), cucumber (Liebig, 1978; Marcelis, 1992) and tomato (de Koning, 1989). How these short-term fluctuations in F_{hp} have to be taken into account in the economic evaluation of crop photosynthesis will be discussed later.

4. An example: the tomato crop

For a tomato crop planted on May 17 (data in figure 3), the value of ΔP over a period of 100 days was calculated (figure 5). By the functional approach (Hunt, 1982), a second order polynomial was fitted for the relation between the natural logarithm of W (lnW) and time. Data from destructive measurements for the first 25 days were used: t_p = 28 days (figure 3B), F_{hp} = 0.72 (figure 4A); values of α, product price and DMC (0.7 g dry matter g^{-1} CH_2O, 0.2 NLG g^{-1} fresh and 0.06 g g^{-1} respectively) according to Heuvelink and Challa (1989).

As expected, the value of ΔP is high shortly after planting, but drops quite fast to a constant level (production phase). In other words: to realise the same ΔP, higher marginal costs will be acceptable in the young crop phase than in the production phase. Because of the low LAI, however, higher inputs will be required under the same conditions to obtain the same ΔP.

Figure 5 shows the same pattern as the co-state variable P_l for leaf area (Seginer, 1992, figure 1), but van Henten (personal communication) showed that if only one co-state variable for weight is considered, the value of it increases slightly with time in the production phase. This rise may be attributed to the effect of maintenance respiration: it is advantageous to postpone the formation of dry weight to a certain extend once a closed leaf canopy is formed, because all

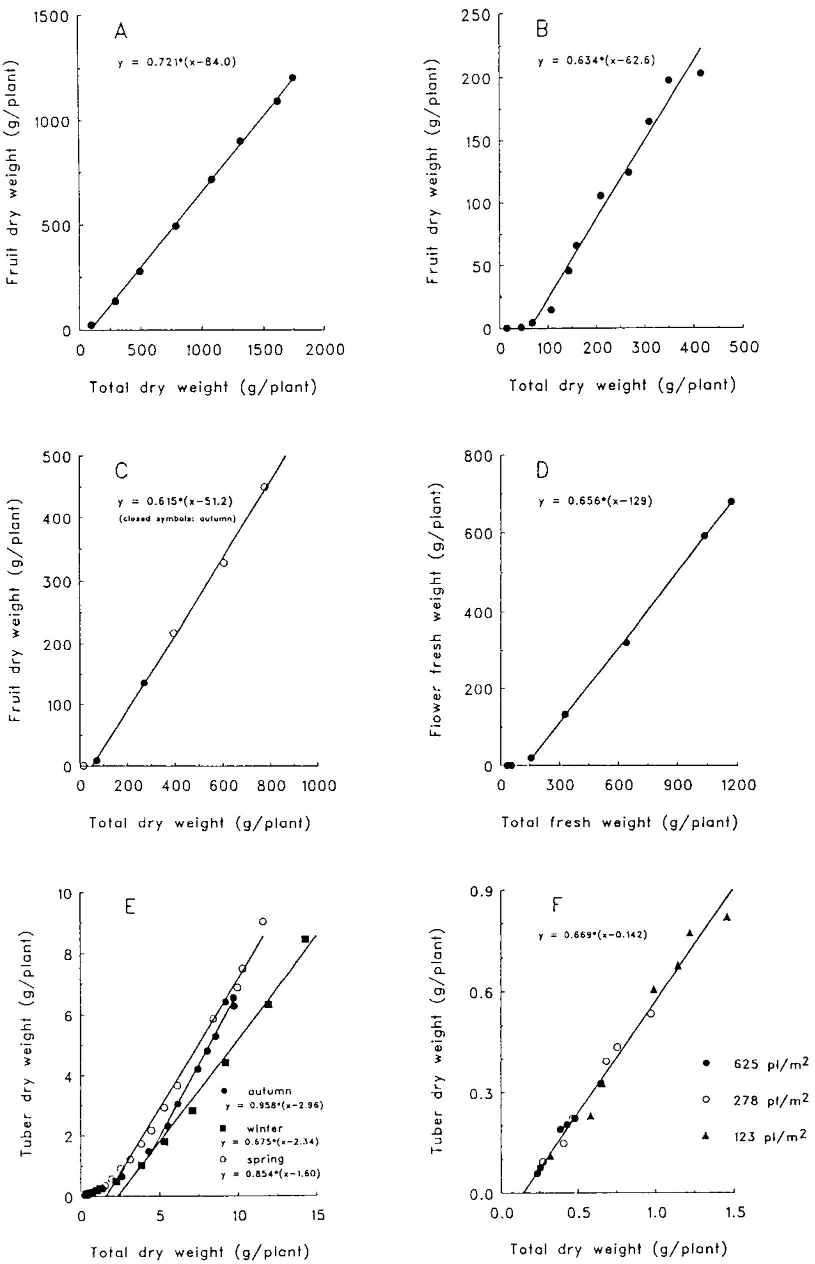

Figure 4 - Relation between total plant dry weight and dry weight in the harvestable product for six crop species. All dry weights include harvested plant parts. (A) tomato (de Koning, 1991), (B) cucumber (Liebig, 1978), (C) sweet pepper (Vegter, 1989), (D) rose (de Vried and Dubois, 1992), (E) kohlrabi (Liebig, unpubl.), (F) radish (Heuvelink, unpubl.).

dry weight has to be maintained until the end of the cultivation. This aspect was ignored in our approach.

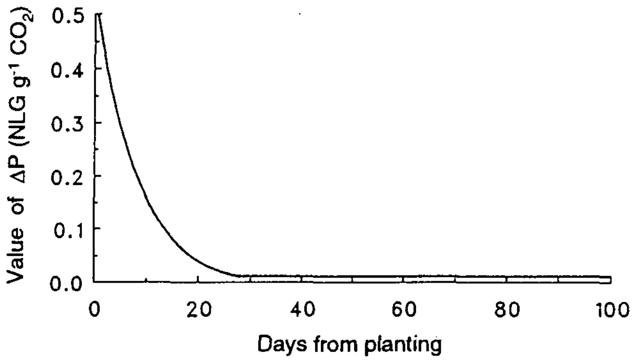

Figure 5 - Economic value of ΔP for a tomato crop (planted 17 May 1988). $\ln W = 0.00188t^2 + 0.0436t + 2.27$, with $t_p = 28$, $F_{hp} = 0.72$, price = 0.2 NLG g^{-1} fresh, $\alpha = 0.7$ g dry matter g^{-1} CH_2O and DMC = 0.06 g g^{-1}.

5. Discussion and conclusions

In this study a distinction has been made between the young phase and the production phase. The transition between both phases has been defined by W_{ref}, the reference weight, attained at t_p. A clear definition of this transition has not been given, but since it was shown that for small $\Delta P/W(t_p)$ the economic evaluation of ΔP at t_p is consistent in either phase the choice of W_{ref} is not critical and may be related to the crop concerned. If $F_{hp} \approx 1$ t_p may be chosen such that light interception approaches its maximum (LAI $\approx$ 2.5), whereas if $F_{hp} < 1$ a suitable criterion for W_{ref} is the weight obtained by extrapolation of the linear relation between plant dry weight and dry weight of the harvestable product to the ordinate (figure 4).

For several crops F_{hp} was constant over longer periods of time (months), though appreciable short term fluctuations in F_{hp} occurred. However, within a given tactical plan, in our opinion, F_{hp} may be treated as a constant. Fluctuations in F_{hp} during the production phase are usually caused by variations in the age distribution of the harvestable organs (e.g. Marcelis, 1992). If the constant average value of F_{hp} reflects a causal relation, these fluctuations may be ignored in the economic evaluation of ΔP, except for the effects on the average time till harvest and associated price of the product. In case the constant average value of F_{hp} does not reflect a causal relation, more knowledge on the effect of greenhouse climate in the different crop stages (flushes) is needed before an economic evaluation of crop photosynthesis is possible for this situation.

In this paper some emphasis has been put on F_{hp}, but it is clear from equation (6) that product price and DMC are equally important in evaluating ΔP. It is assumed that climate optimisation does neither influence product price, nor DMC: both are treated as exogenous variables. The problem of price prediction is clearly beyond the scope of this paper. However, ΔP might influence product price, as has been discussed in a previous section.

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Symbols and units

Symbol	Unit	Meaning
α	-	carbon conversion factor: g structural dry matter formed per g carbohydrate
A	m^2	leaf area per plant
DMC	-	dry matter content in the fresh harvestable product
F_{hp}	-	fraction of dry weight increase that is diverted to harvestable product
GR	g m^{-2} day^{-1}	crop growth rate per unit greenhouse area
k	-	extinction coefficient for diffuse radiation in the canopy
L_a	-	fraction of radiation absorbed by the canopy
LAI	-	leaf area index: crop leaf area per unit greenhouse area
LAR	m^2 g^{-1}	leaf area ratio (LAI/W)
NLG		Dutch Guilders
P	g m^2 day^{-1}	rate of gross CO_2 assimilation per unit greenhouse area
price	NLG g^{-1}	price of harvestable product per unit fresh weight
ρ	-	reflection coefficient for diffuse radiation of the canopy
RGR	day^{-1}	relative growth rate
t	day	time
t_h	day	harvest time
t_p	day	time of the transition between the young and the production phase, when the reference weight W_{ref} is attained
W	g m^{-2}	total crop dry weight per unit greenhouse area
W_{hp}	g m^{-2}	dry weight of harvestable product per unit greenhouse area
W_{ref}	g m^{-2}	reference weight defining the transition between the young and the production phase
Y	NLG m^{-2}	economic yield per unit greenhouse area

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