Grogra/GroIMP

Light and photosynthesis modelling

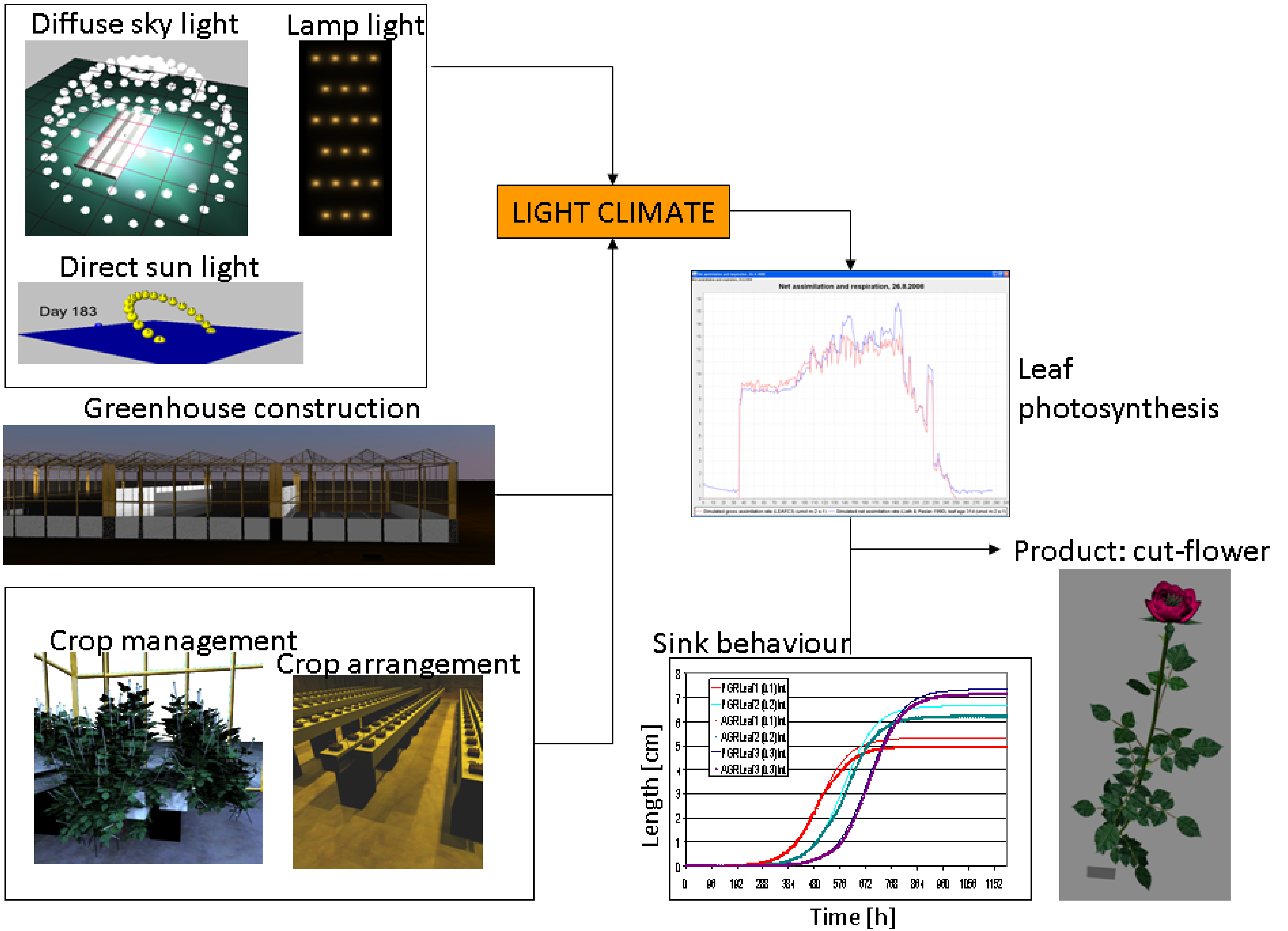
Time : 09:45 - 10:45

Presenter : Gerhard Buck-Sorlin & Michael Henke

Room : CIP III

Summary

- Crop growth can be defined by five physiological determinants:
  - Light Interception, Light use efficiency, dry matter production and loss, duration of growth, and dry matter partitioning.
- Light interception can be modeled based on plant LAI in most cropping situations.
- Light use efficiency is a function of plant species.
- Dry matter production is a function of light interception and light use efficiency summed over the growth cycle of a plant.
- We can influence light interception by our choice of crops, row spacing, and planting geometry.

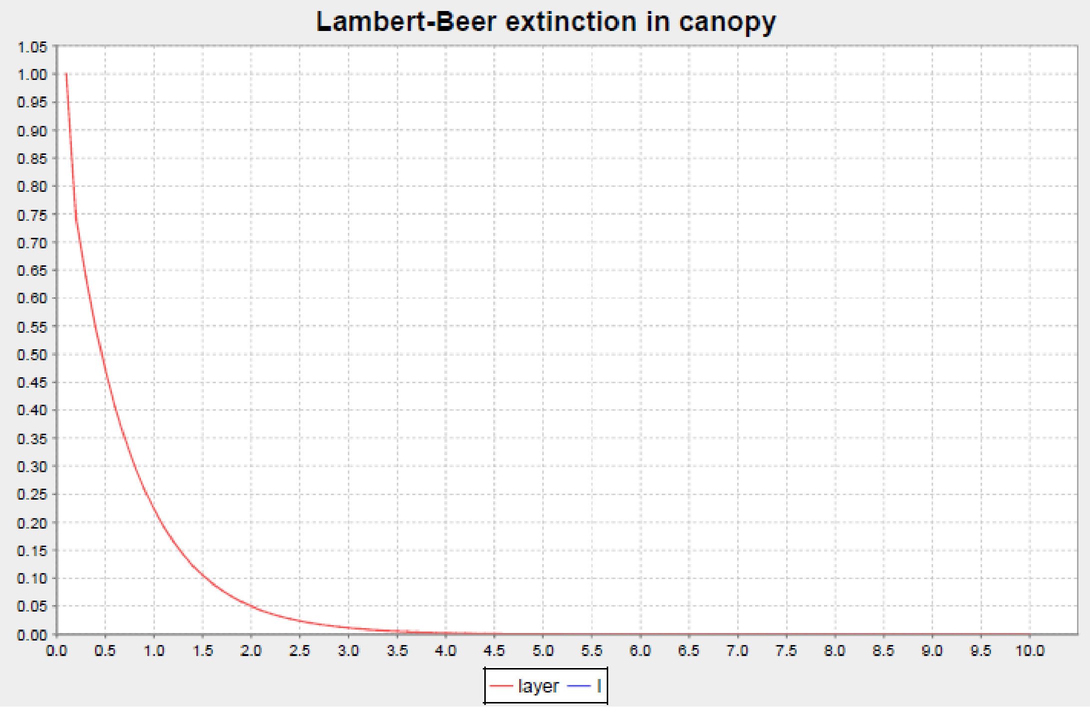


Diffuse sky light
Lamp light
Direct sun light
Day 183
LIGHT CLIMATE
Net assimilation and respiration, 26.8.2008
Leaf photosynthesis
Greenhouse construction
Product: cut-flower
Crop management
Crop arrangement
Sink behaviour
Length [cm]
Time [h]

Light penetration into a homogeneous canopy, two approaches:
1) Homogeneous turbid medium → Lambert Beer's law

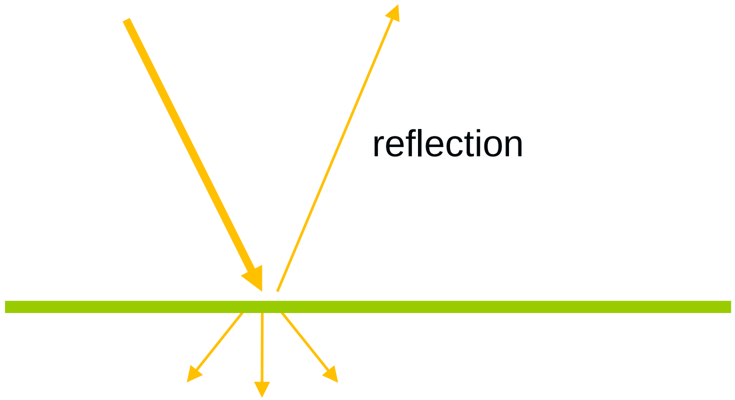
$$I_d = I_0 e^{-kd}$$

I = radiation level at canopy depth d
I_0: incoming radiation (above canopy)
k: extinction coefficient



Demo simple layer model

Light absorption

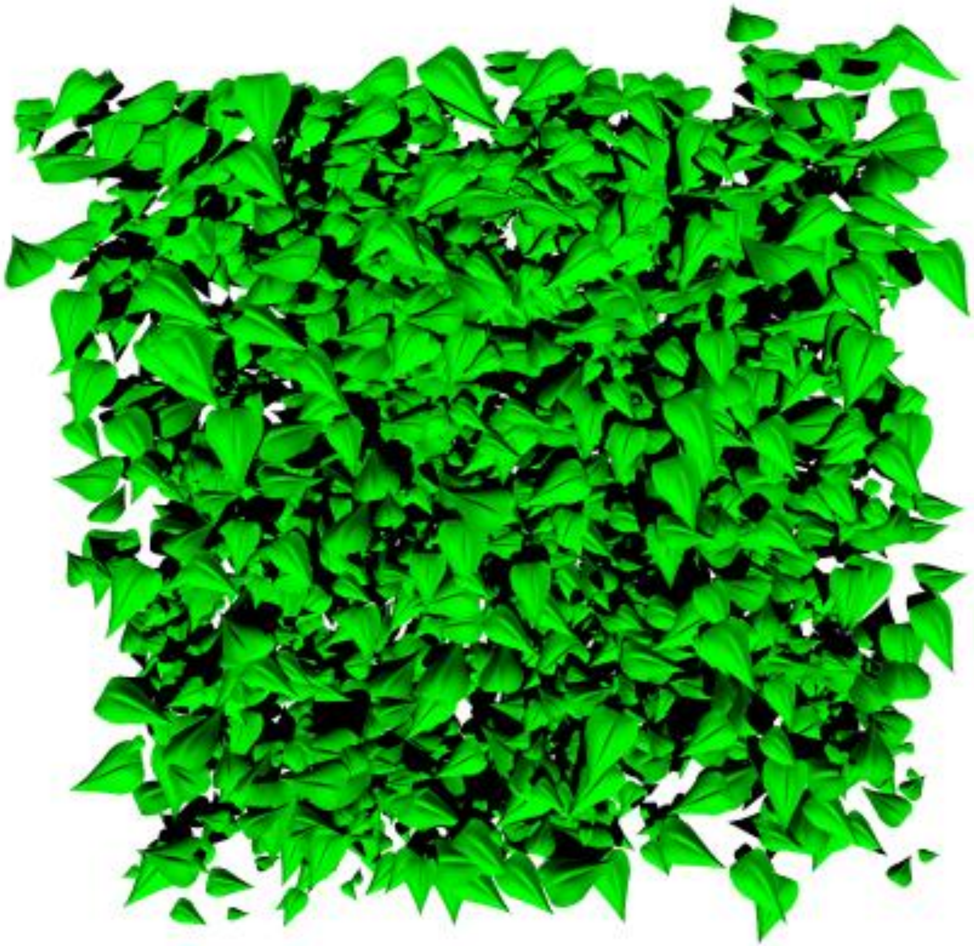


absorbed light = incident – reflected – transmitted light

absorptance + reflectance + transmittance = 1

Light penetration into a homogeneous canopy, two approaches:

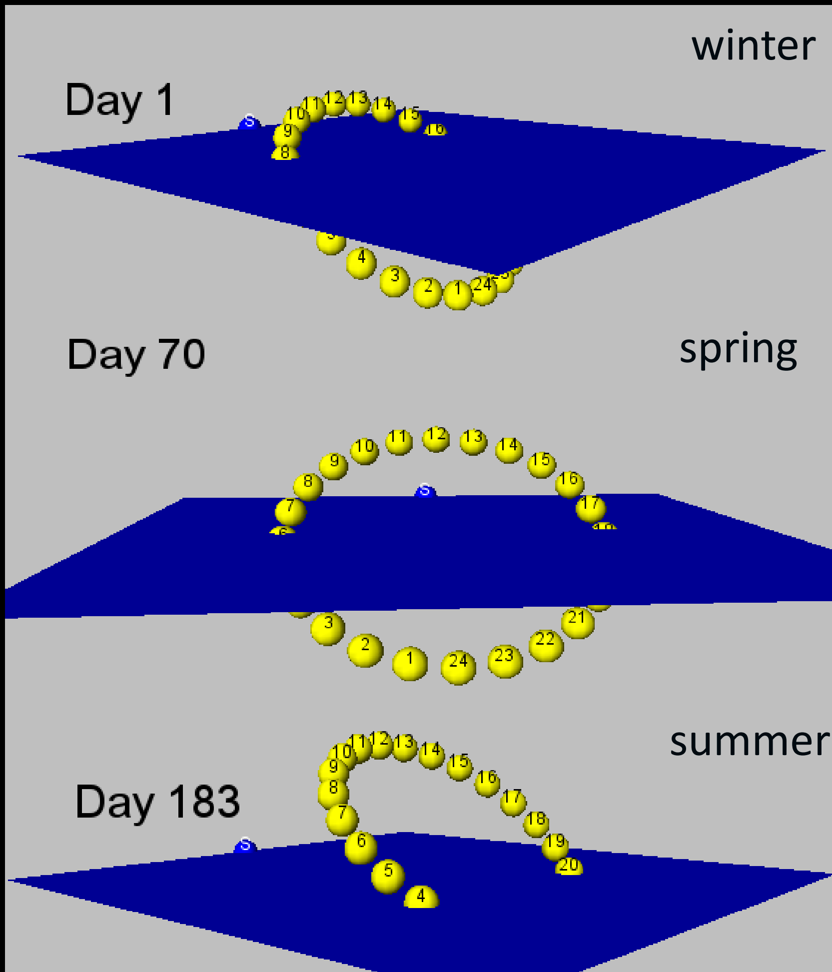
2) SAIL (**S**cattering by **A**rbitrarily **I**nclined **L**eaves) (Bunnik and Verhoef (1984)



Demo SAIL model

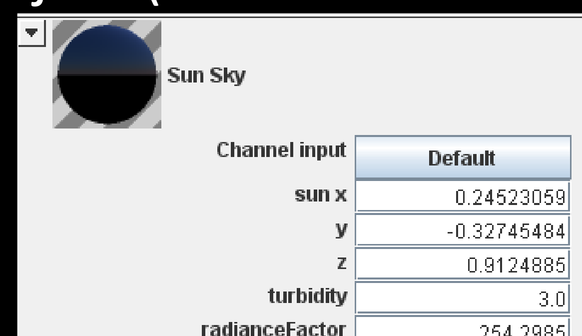
Modelling spatial light distribution: Daylight

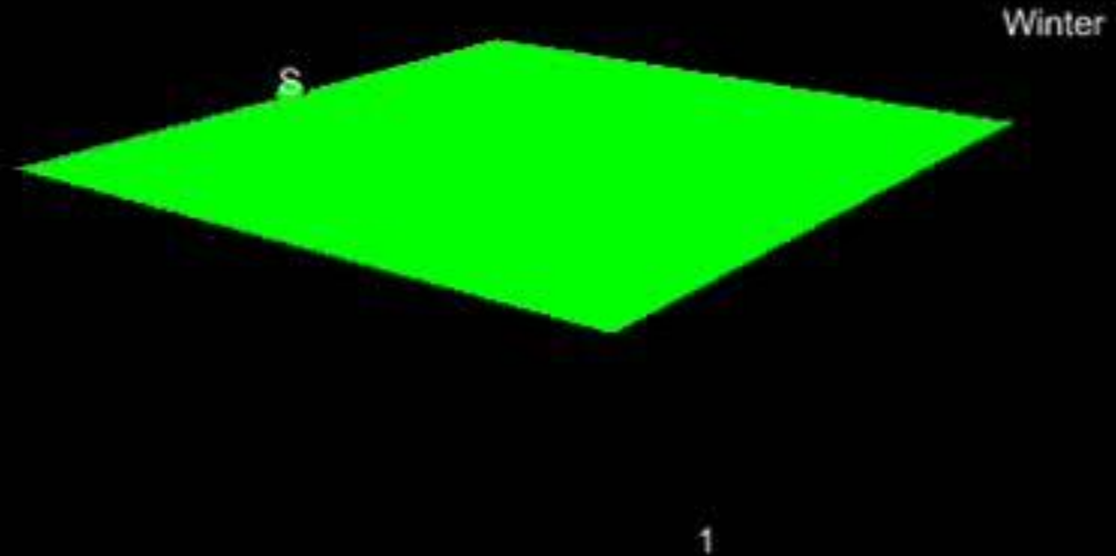
(Goudriaan 1994, modifié)



- input: latitude, day of year, time of day [h]
- simulation of direct sunlight as a directional light source (parallel rays), which changes position, thereby adjusting direction

- simulation of diffuse skylight with sky object (*Preetham et al. 1999*)



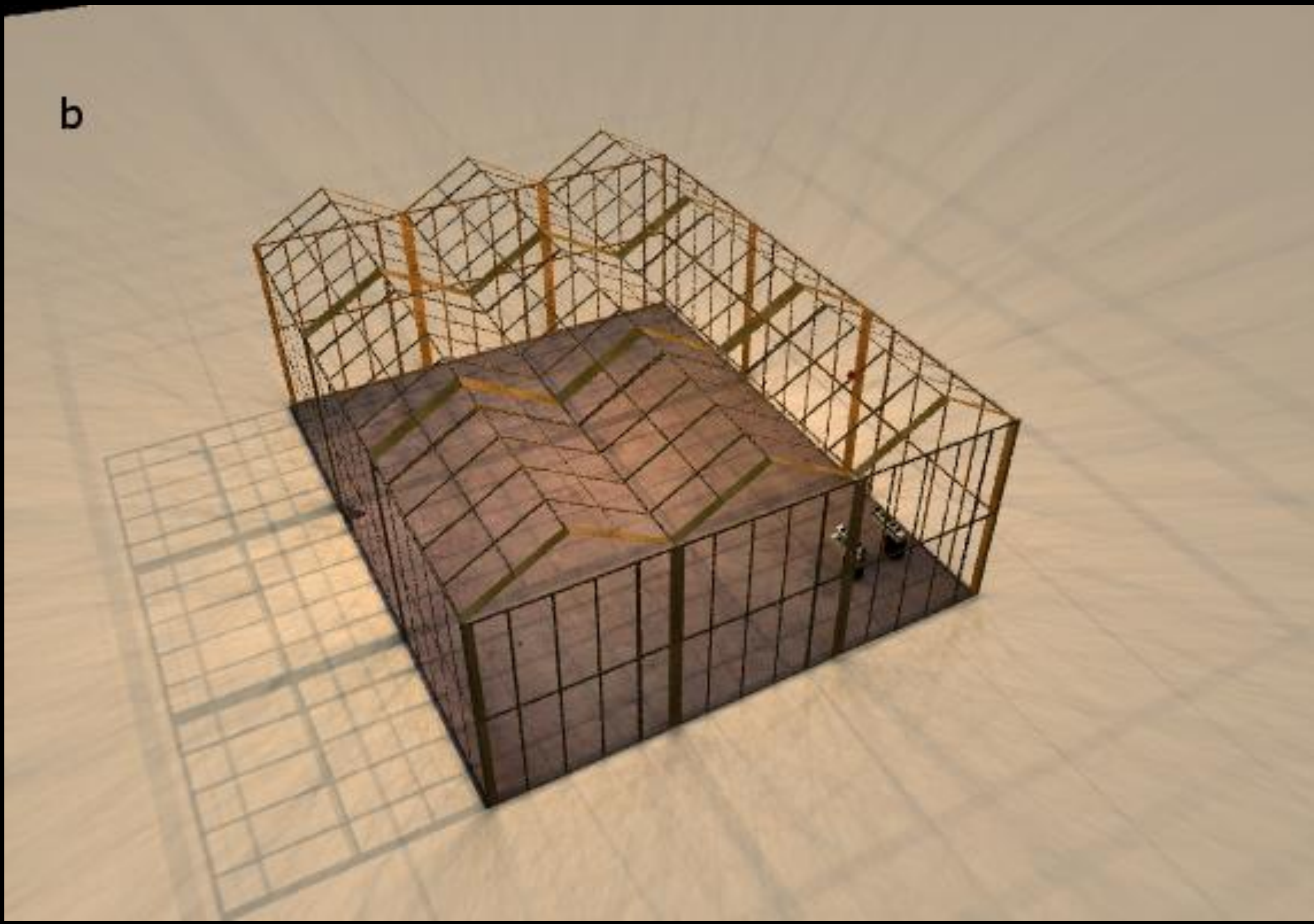

Winter
S
1

https://www.youtube.com/watch?v=FwZHEhz4hNM

Light distribution: Virtual greenhouse

View onto a virtual greenhouse simulated with the GroIMP platform

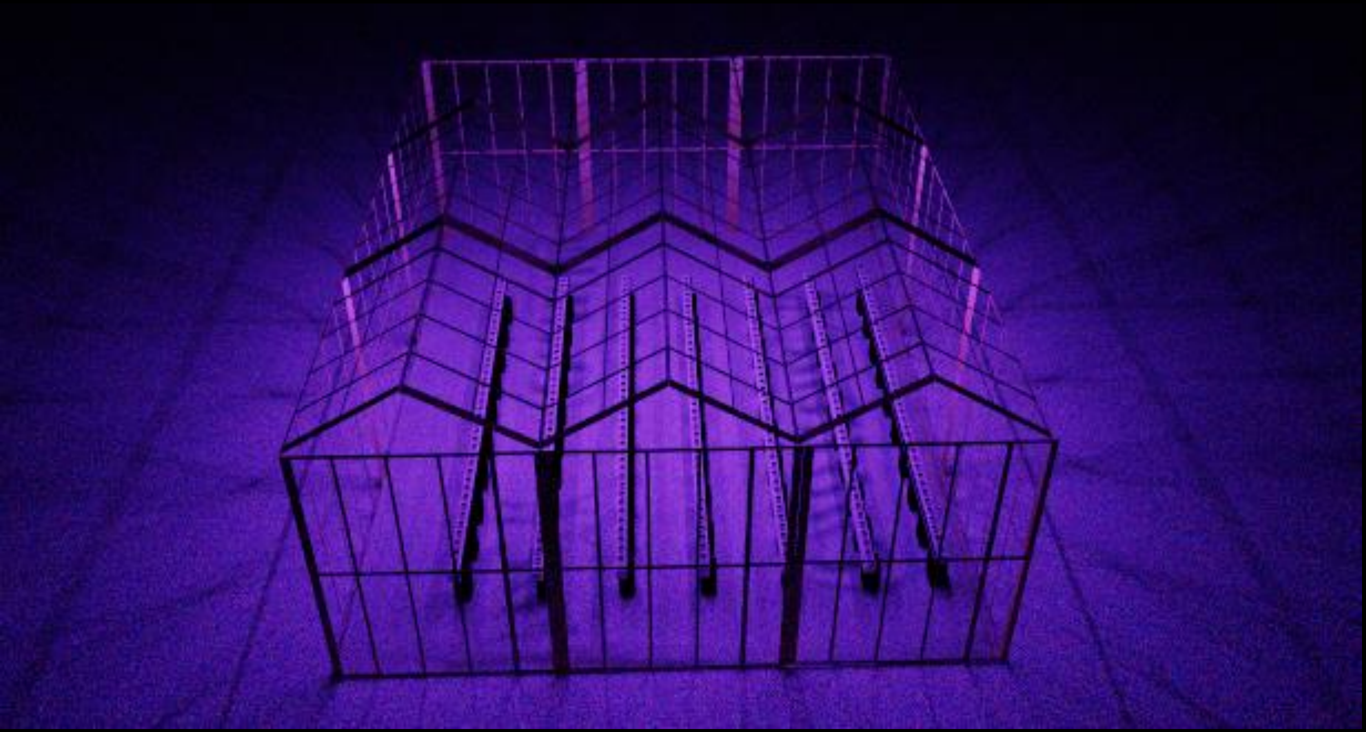
Lighting is simulated using 24 equally spaced SON-T assimilation lamps



Buck-Sorlin et al. 2009

Productschap Tuinbouw

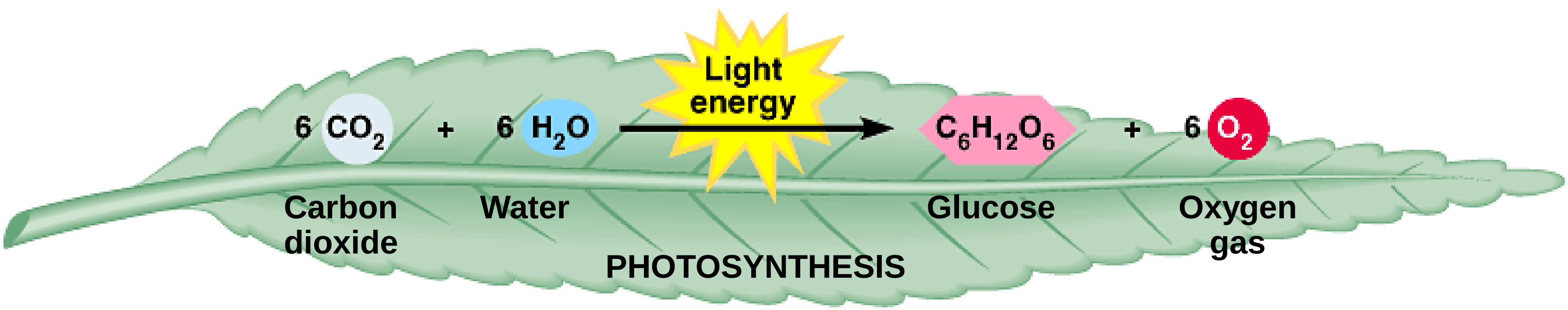
Virtual Plant Network
WAGENINGEN UR



Modelling of photosynthesis

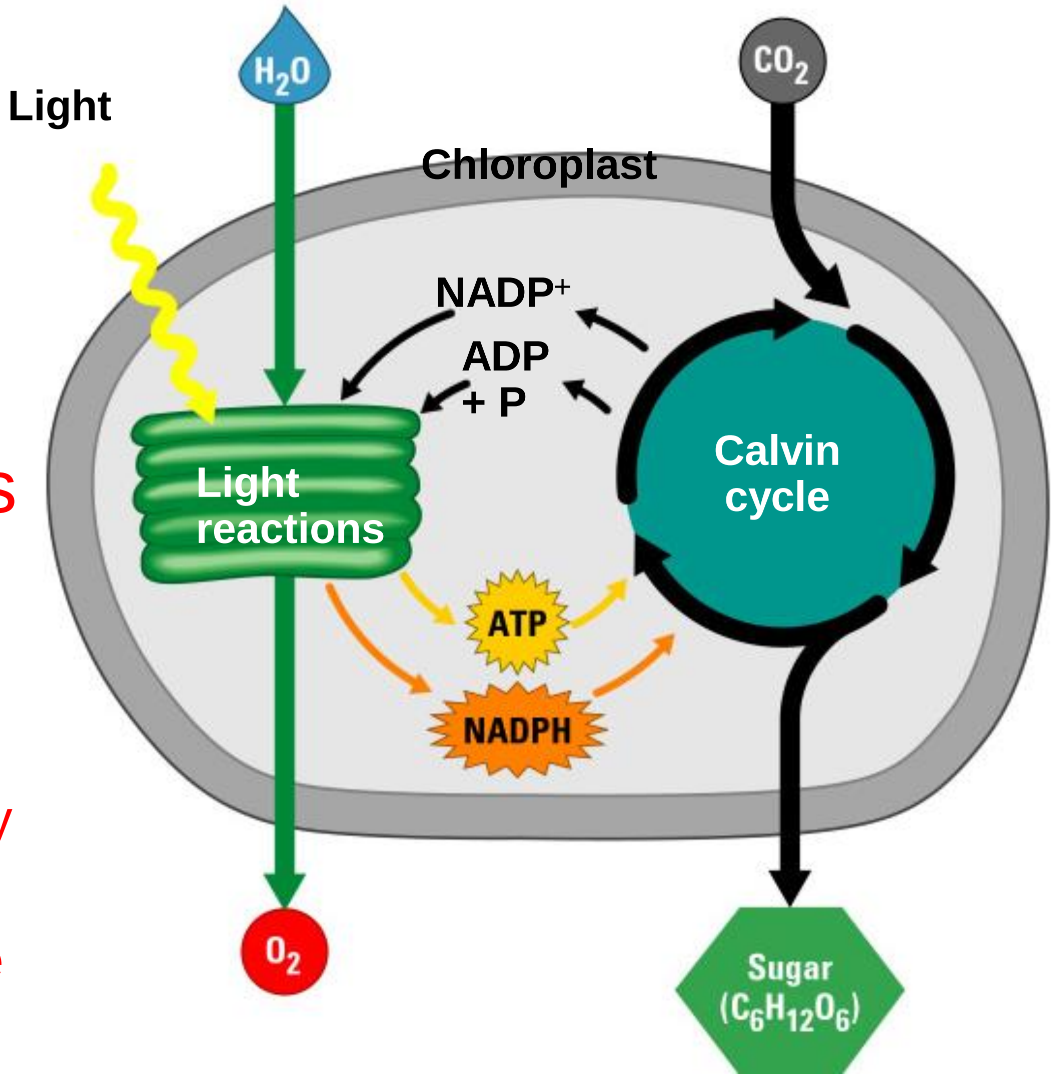
AN OVERVIEW OF PHOTOSYNTHESIS

- Photosynthesis is the process by which autotrophic organisms use light energy to make sugar and oxygen gas from carbon dioxide and water



AN OVERVIEW OF PHOTOSYNTHESIS

- The light reactions convert solar energy to chemical energy
  - Produce ATP & NADPH
- The Calvin cycle makes sugar from carbon dioxide
  - ATP generated by the light reactions provides the energy for sugar synthesis
  - The NADPH produced by the light reactions provides the electrons for the reduction of carbon dioxide to glucose



A first model of photosynthesis

- Blackman 1905: "*When a process is conditioned as to its rapidity by a number of separate factors, the rate of the process is limited by the pace of the "slowest" factor*".
- Five factors controlling assimilation recognized, of which three are easily measurable:
  - amount of CO_2 available,
  - amount of H_2O available,
  - intensity of available radiant energy,
  - amount of chlorophyll present,
  - temperature in the chloroplast.
- Blackman's model describes a response of photosynthesis which increases linearly with irradiance (light-limited) until the available supply of CO_2 prevents further increase in the rate of photosynthesis with irradiance (CO_2-limited)

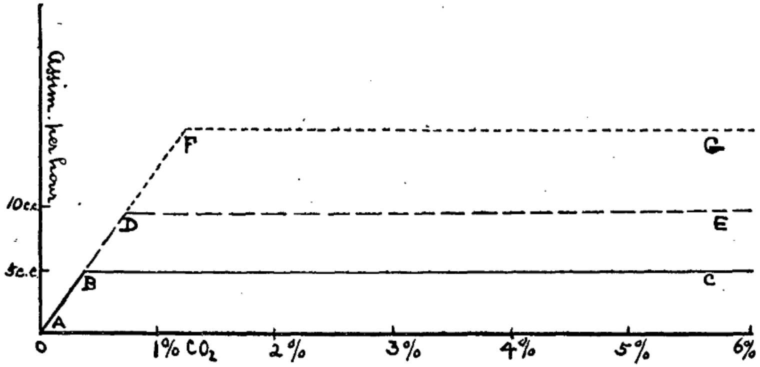
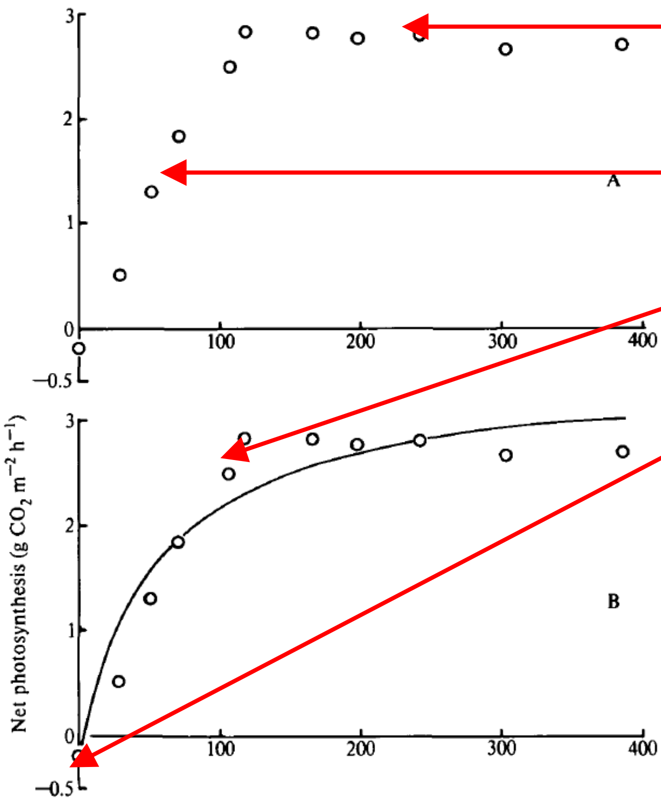


Fig. 6. Diagram II.

$$P = \begin{cases} \alpha I, & I \le P_m/\alpha, \\ P_m, & I > P_m/\alpha. \end{cases}$$

A first model of photosynthesis

- Rabinovitch (1951) proposed a number of alternative models, which were based on the *biochemical reactions* within the chloroplasts and used various simplifying assumptions to describe these complex reactions.
- The model proposed by Rabinowitch (1951) described the relationship between photosynthesis and irradiance in terms of a <u>*rectangular hyperbola*</u>



- Above 100 W no increase in the net CO_2 exchange → saturation of the photosynthetic system by light.
- Below 100 W m^{-2} linear relationship between P_n and irradiance.
- only relatively small intermediate section of curvature → the 'shoulder'.
- Point at zero irradiance measure of rate of dark respiration, R_d.

Rectangular Hyperbola

Thornley, 1976: A modification, appropriate for photosynthesis, of the model proposed by Michaelis and Menten for a simple enzyme-substrate reaction has been derived:

$$P_g = \frac{\alpha I \cdot (C_f / r_x)}{\alpha I + (C_f / r_x)}$$

where

P_g = rate of gross photosynthesis

α = photochemical efficiency

I = irradiance

C_f = CO_2 concentration at the site of fixation

r_x = chemical or carboxylation resistance.

Nonrectangular hyperbola

$$P_n = \frac{\alpha PAR + P_{g_{max}} - \theta R_d - \sqrt{\left(-(\alpha PAR + P_{g_{max}} - \theta R_d)\right)^2 - 4\theta\left(\alpha PAR\left(P_{g_{max}} - (1-\theta)R_d\right) - R_d P_{g_{max}}\right)}}{2\theta}$$

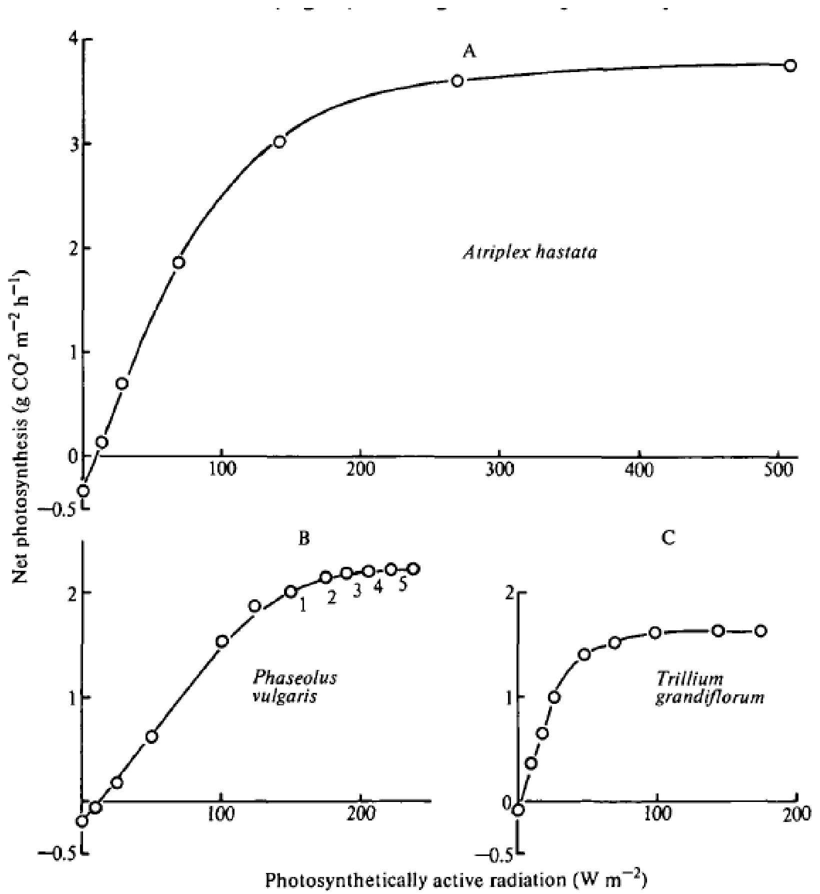


FIG. 3. Published curves for leaf net photosynthesis of C_3 plants in response to irradiance: (A) Bjorkman, 1975; (B) Chartier *et al.* (1970); (C) Taylor and Pearcy, 1976. The fitted curves were obtained from the photosynthesis–light response model.

where *a* = initial slope at zero irradiance and

θ = ratio of physical to total resistance: describes the degree of curvature at the shoulder of the PLR.

Assuming that α, θ, P_{max}, and R_d are independent of irradiance, this equation describes the PLR as a *non-rectangular hyperbola*.

- Marshall and Biscoe, 1980

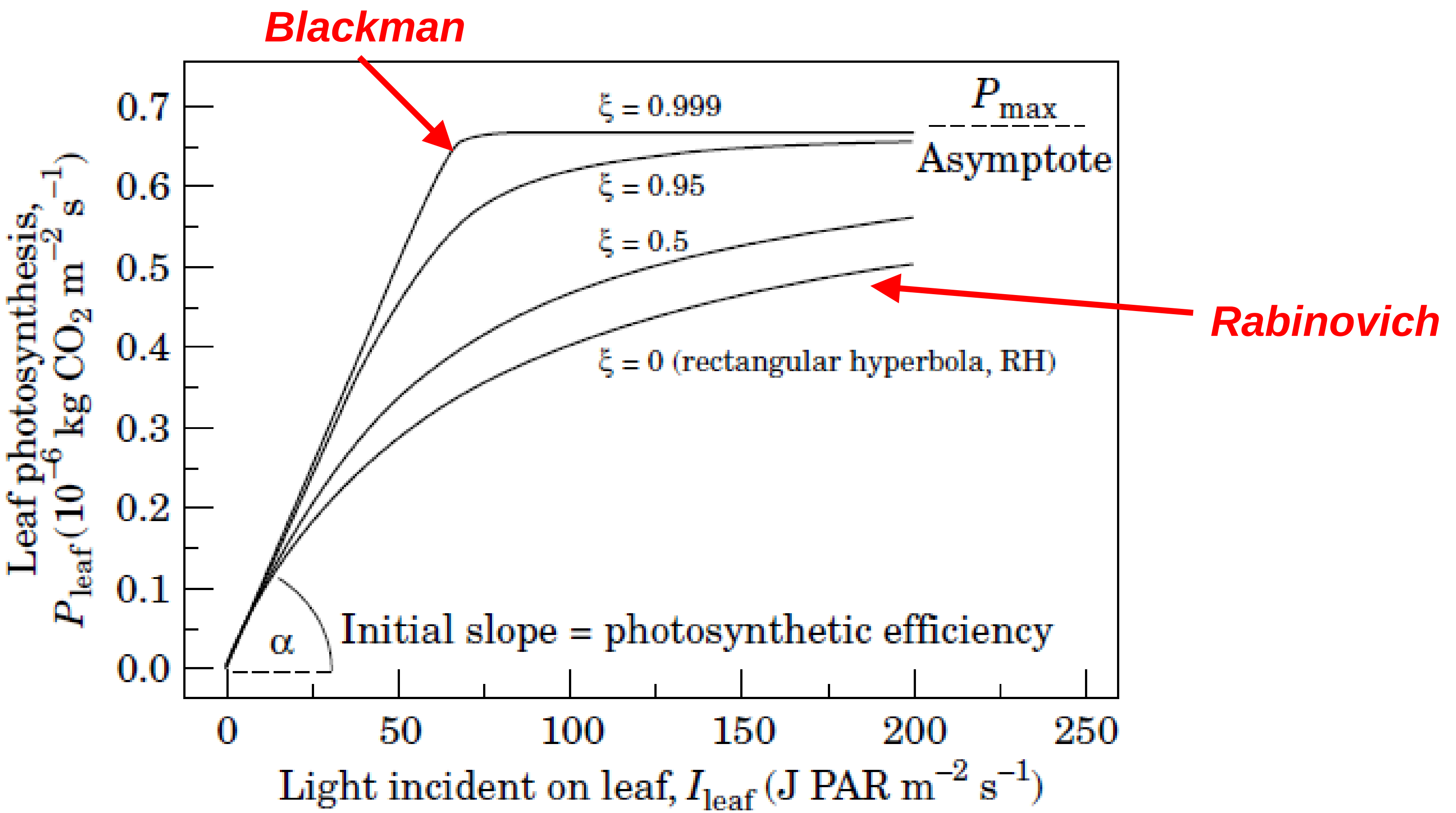


FIG. 1. Non-rectangular hyperbola for leaf photosynthesis. Equation (1) is plotted for $\alpha = 1 \times 10^{-8}$ kg CO_2 J^{-1} [0·0494 μmol CO_2 (mol PAR)$^{-1}$], $P_{max} = 0{\cdot}667 \times 10^{-6}$ kg CO_2 m^{-2} s^{-1} (15 μmol CO_2 m^{-2} s^{-1}). Four different values of the 'sharpness' parameter ξ are shown, with $\xi = 0$ corresponding to the rectangular hyperbola. 10^{-6} kg CO_2 = 23 μmol CO_2. 1 J PAR = 4·6 μmol PAR.

Thornley (1998)

A biochemical photosynthesis model

$$W_c = V_{\mathrm{m}} \frac{C_{\mathrm{i}} - \Gamma}{C_{\mathrm{i}} + K}$$

$$W_j = J \frac{C_{\mathrm{i}} - \Gamma}{4.5 C_{\mathrm{i}} + 10.5 \Gamma}$$

W_c: Rubisco-limited gross photosynthesis rate [mmol m^{-2} s^{-1}]
W_j: light-limited gross photosynthesis rate [mmol m^{-2} s^{-1}]
V_m: maximum carboxylation rate [mmol m^{-2} s^{-1}]
J: electron transport rate [mmol m^{-2} s^{-1}]
C_{i}: intercellular CO_2 concentration [ppm or Pa]
Γ: CO_2 compensation point without dark respiration
K: function of enzyme kinetics

Net CO_2 assimilation rate:

$$A = \min(W_c, W_j) - R_\mathrm{d}$$

R_d = daytime leaf dark respiration

Stomatal conductance

Ball et al. (1987) and Ball (1988) proposed a semi-empirical equilibrium model of stomatal conductance based on a number of gas exchange experiments with C3 and C4 plants, i.e.

$$g_{sv} = mA_n \frac{h_b}{c_b} + b_{sv}$$

With $\boldsymbol{m}$ = composite sensitivity of $\boldsymbol{g_{sv}}$ to net CO_2 assimilation ($\boldsymbol{A_n}$) (species-specific, non-dimensional) and relative humidity ($\boldsymbol{h_b}$) and CO_2 concentration ($\boldsymbol{c_b}$) at the leaf surface, i.e. within the leaf boundary layer ($\boldsymbol{h_b}$ is a decimal fraction, and $\boldsymbol{c_b}$ is a mole fraction). For C3 plants, m varies between 8 and 16 (Ball, 1988).
$\boldsymbol{b_{sv}}$ = stomatal conductance that remains unaffected by the atmospheric environment or leaf biochemistry.

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A Coupled Model of Photosynthesis, Stomatal Conductance and Transpiration for a Rose Leaf (*Rosa hybrida* L.)

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The following three models were combined to predict simultaneously photosynthesis, stomatal conductance, transpiration and leaf temperature of a rose leaf: the biochemical model of photosynthesis of Farquhar, von Caemmerer and Berry (1980, *Planta* **149**: 78–90), the stomatal conductance model of Ball, Woodrow and Berry (In: Biggens J, ed. *Progress in photosynthesis research*. The Netherlands: Martinus Nijhoff Publishers), and an energy balance model. The photosynthetic parameters: maximum carboxylation rate, potential rate of electron transport and rate of triose phosphate utilization, and their temperature dependence were determined using gas exchange data of fully expanded, young, sunlit leaves. The stomatal conductance model was calibrated independently. Prediction of net photosynthesis by the coupled model agreed well with the validation data, but the model tended to underestimate rates of stomatal conductance and transpiration. The coupled model developed in this study can be used to assist growers making environmental control decisions in glasshouse production.

Key words: *Rosa hybrida* L., photosynthesis, stomatal conductance, transpiration, coupled model, cut-flower, crop simulation, calibration, validation.

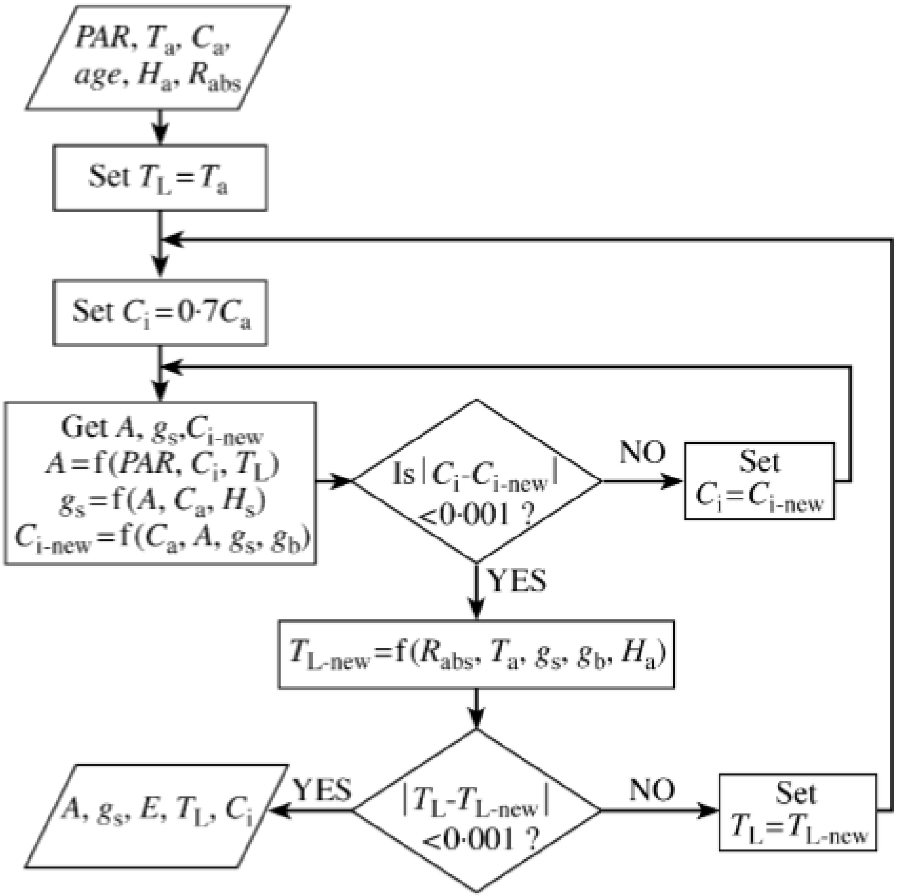

FIG. 1. Schematic diagram of the model flow.

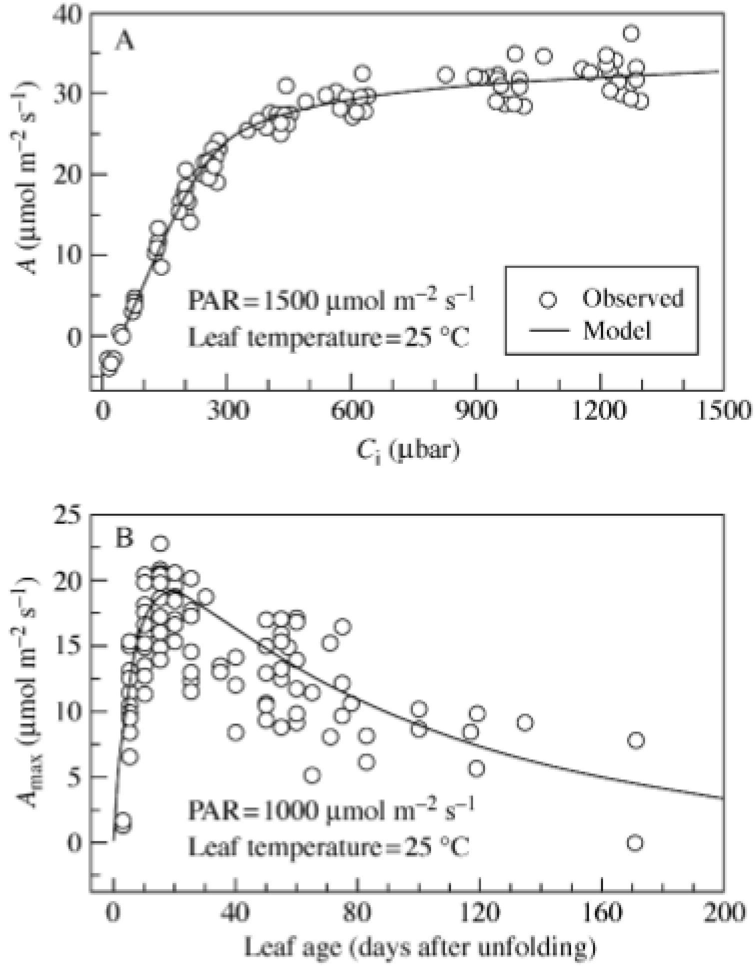

FIG. 2. Photosynthesis sub-model calibration. A, A/C_i response. Solid line represents the prediction of photosynthesis sub-model using measured C_i. B, Leaf age response of A_{max}. Solid line represents the prediction of leaf age function.