# An Algorithm for Optimal Fertilization with Pure Carbon Dioxide in Greenhouses

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**Abstract**

**Pure (bottled or piped) carbon dioxide is commonly supplied to increase productivity of greenhouse crops. As ventilation is necessary for controlling temperature, particularly under sunshine (when a high $CO_2$ concentration would be most desired) there is a need for optimal management of supply, in order to ensure the maximum net return from cost of carbon dioxide supplied and increase in harvest. The optimal concentration depends on many factors: the expected increase of yield thanks to carbon dioxide supply under given climate conditions; the actual ventilation rate; the value of yield and the cost of carbon dioxide. We combined a calculation of the "value" of carbon dioxide supply with an algorithm to calculate the ventilation rate, into a calculation on-line of the optimal supply rate. The algorithm was implemented and tested into a commercial climate control computer.**

## INTRODUCTION

Carbon fertilization –made possible by the direct application of heating fumes– is one of the factors leading to the high productivity of Dutch glasshouse horticulture. Energy saving and application renewable energies ensure that there are less fumes around, a slump gradually made up by piped or bottled $CO_2$. Bottled $CO_2$ is increasingly sold at competitive prices also in the unheated greenhouses of the Mediterranean region. Thanks to the ongoing implementation of the Kyoto protocol into a system for trading emission rights, current world prices of bottled or piped $CO_2$, $P_{CO2}$, are between 0.1 and 0.2 €/kg of carbon dioxide, which is comparable to the cost of producing carbon dioxide by burning gas (as was done in the greenhouses of Northern Europe even in the absence of heating requirement, for instance). Therefore Stanghellini et al. (2009) concluded that, in view of the strong relationship between temperature and production (De Koning, 1994), the most profitable choice for a grower is to ventilate as little as possible (under the constraints of humidity and temperature control) and to supply bottled $CO_2$ up to at least the external concentration. Since in this case there is no outflow of $CO_2$, this level ensures that all $CO_2$ that is supplied is assimilated. A method for $CO_2$ control aimed at maintaining within the greenhouse the same concentration as outside has been described by Kläring et al. (2007).

Maintaining a concentration higher than external would obviously result in a lower efficiency of carbon fertilization, since some $CO_2$ would flow through the ventilators, but it may still make economic sense. This is particularly true in the relatively cold months when ventilation would result in an undesired cooling of the greenhouse and the product prices are high. Therefore an economic management of $CO_2$ fertilisation is badly needed. We developed an optimisation algorithm and tested it in an experimental greenhouse, in the framework of the EU-financed FP7 cooperation project EUPHOROS.

## MATERIALS AND METHODS

The supply of $CO_2$ must balance the assimilation and the loss through ventilation.

$$S = A + V = f\left(I_{sun}, CO_{2,in}\right) + g_V\left(CO_{2,in} - CO_{2,out}\right) \quad \text{mg m}^{-2}\ \text{s}^{-1} \qquad (1)$$

where $g_V$ is the volume exchange by ventilation, per unit surface area of the greenhouse, m$^3$ m$^{-2}$ s$^{-1}$, that is: m s$^{-1}$, and $CO_2$ is the $CO_2$ concentration, mg m$^{-3}$, *in*side and *out*side, respectively. Since $n$ volume changes per hour means replacing in one hour as many cubic meters as the mean height, $h$, of the greenhouse, for each square meter of floor area, $g_V = n \cdot h/3600$.

The assimilation rate is a function $f$ of sun radiation, $I_{sun}$ and inside carbon dioxide concentration. For the purpose of this work Stanghellini et al. (2008) have selected a simple two-variables model that does reproduce the trend and the level of the more complex model proposed by Nederhoff (1994):

$$A = f\left(I_{sun}, CO_{2,in}\right) = 2.2 \frac{1}{1+\frac{230}{CO_{2,in}}}\left[1-\exp\left(-0.0015 I_{sun}\right)\right] \qquad \text{mg m}^{-2}\,\text{s}^{-1} \qquad (2)$$

where $CO_2$ is the ambient carbon dioxide concentration, here in vpm and $I_{sun}$ is the photon flux density of Photosynthetically Active Radiation (PAR), μmol m$^{-2}$ s$^{-1}$. For sun radiation, $I_{sun}$ can be estimated as twice the value of sun radiation in W m$^{-2}$. If one prefers to use sun radiation in W/m$^2$ then the coefficient is obviously 0.003 instead of 0.0015. Avogadro's law gives the conversion from volume to mass: in the case of $CO_2$, 1 vpm ≅ 2 mg m$^{-3}$. 2.2 mg m$^{-2}$ s$^{-1}$ is the "maximal" assimilation rate of a tomato crop, according to Nederhoff's extensive measurements in commercial farms, which may be reduced by suboptimal values of other factors, such as temperature or water status. Both factors of Eq. (2) are always less than unity.

The optimal supply maximizes profit, that is the value of 1 kg assimilated $CO_2$ (the expected value of yield times a "$CO_2$ fixation efficiency") minus the cost of the supply (the price of 1 kg $CO_2$). The $CO_2$ fixation efficiency can be calculated as follows: the conversion efficiency of $CO_2$ fixation into dry matter is about 70% and the ratio of molecular weights of $CH_2O$ and $CO_2$ is 68%, which means that each kg assimilated $CO_2$ yields about 500 g dry matter (Stanghellini and Heuvelink, 2007). The value of each kg dry matter depends obviously on the crop, its value and harvest index. It will be indicated in the following as $P_{yield}$ and its units are €/kg of dry matter.

The optimal concentration of carbon dioxide is then the one that maximizes profit, that is the value of assimilated $CO_2$ minus the cost of the supply. Indeed, maximising the profit implies that supply should be modulated in order to maintaining the internal carbon dioxide concentration that ensures that the value of $A$ minus the cost of $S$ is maximal:

$$0.5P_{yield}A - P_{CO_2}S = \left(0.5P_{yield} - P_{CO_2}\right) f\left(I_{sun}, CO_{2,in}\right) - P_{CO_2} g_V \left(CO_{2,in} - CO_{2,out}\right) \Rightarrow MAX \quad \text{€ m}^{-2} \quad (3)$$

where obviously if $A$ and $S$ are in mg m$^{-2}$ s$^{-1}$, the prices must be €/mg and $CO_2$ must be in mg m$^{-3}$. Looking for a maximum implies that the derivative of the left hand side of Eq. (3) with respect to the $CO_2$ concentration must be equal to zero. By taking into account that 230 vpm = about 460 mg m$^{-3}$ and defining:

$$F_I = 2.2\left[1-\exp\left(-0.0015 I_{sun}\right)\right] \quad \text{and} \quad 0.5P_{yield} - P_{CO_2} = R\,P_{CO_2}$$

The derivative then can be calculated as:

$$\frac{\partial}{\partial CO_{2,in}} P_{CO_2}\left[R\frac{F_I}{1+\frac{460}{CO_{2,in}}} - g_V\left(CO_{2,in} - CO_{2,out}\right)\right] = 0$$

$$R\,F_I \frac{460}{\left(CO_{2,in}+460\right)^2} - g_V = 0 \quad \Rightarrow \quad CO_{2,in,OPT} = 21.5\sqrt{\frac{R\,F_I}{g_V}} - 460 \qquad \text{mg m}^{-3} \quad (4)$$

Divide by 2 to transform in vpm. The optimal supply (that is, the injection rate that warrants the maximum profit) can be calculated as well:

$$S_{OPT} = A_{CO_2,in.OPT} + V_{CO_2,in,OPT} = F_I \frac{CO_{2,in,OPT}}{CO_{2,in,OPT} + 460} + g_V \left( CO_{2,in,OPT} - CO_{2,out} \right) =$$

mg m$^{-2}$ s$^{-1}$ (5)

$$= F_I - g_v \left( 460 + CO_{2,out} \right) + 21.5 \left( F_I \, g_v \right)^{\frac{1}{2}} \left( R^{\frac{1}{2}} - R^{-\frac{1}{2}} \right)$$

with the outside $CO_2$ concentration in mg m$^{-3}$, $g_v$ in m$^3$ m$^{-2}$ s$^{-1}$ and the prices in € mg$^{-1}$. Multiply by 36 to get kg$_{CO2}$ ha$^{-1}$ h$^{-1}$. The optimal supply will during implementation need to be limited to be >=0 and the coefficient 2.2 mg m$^{-2}$ s$^{-1}$ of the assimilation rate may be made crop dependent.

Eq. (5) shows that the optimal $CO_2$ supply rate only depends on the ratio $R$ between value and price of $CO_2$ and not on the two singularly. Figure 1 shows that – under given conditions (of radiation and $R$ = value/price ratio) – the optimal supply rate rapidly increases with ventilation rate and then decreases to the level that replaces crop assimilation.

Most methods to calculate the ventilation rate through pressure distribution and thermodynamics models require knowledge of a daunting number of parameters of the greenhouse and ventilators geometry, in addition to the measurement of wind speed, direction and opening angle of the ventilators. Therefore we chose for a simpler approach, that is to determine the ventilation rate through measured climate variables inside and outside the greenhouse (Bontsema et al., 2007). This was done by determining $g_v$ as the solution of the combined steady-state enthalpy and vapour balance equations of the greenhouse. Although in principle the ventilation rate could be determined by the sensible heat balance alone, the solution becomes very unstable with small temperature differences between inside and outside. Therefore we have applied the following procedure that is more robust. In particular, the enthalpy balance is written as:

$$I_{rad}\tau + c_{pipe}\left(T_{pipe} - T_{in}\right) + c_{soil}\left(T_{soil} - T_{in}\right) - c_{cover}\frac{A_{cover}}{A_{soil}}\left(T_{in} - T_{out}\right) - g_v \rho c_p \left(T_{in} - T_{out}\right) - L\left(E - C\right) = 0 \qquad \text{W m}^{-2} \quad (6)$$

where $I_{rad}$ indicates sun radiation (W m$^{-2}$); $\tau$ the transmissivity of the greenhouse cover; $c$ the heat transfer coefficient, respectively of the heating *pipe*s, the *soil* and the *cover* (W m$^{-2}$ K$^{-1}$); $T$ the temperature, respectively of the heating *pipe*s, the *soil* and the air *in*side and *out*side (°C); $A$ is the surface of the *cover* and the *soil* of the greenhouse (m$^2$); $\rho c_p$ is the volumetric heat capacity of air (J m$^{-3}$ k$^{-1}$); $L$ is the latent heat of evaporation (J g$^{-1}$); $E$ and $C$ are the evapotranspiration and condensation flux densities (g m$_{soil}^{-2}$ s$^{-1}$).

And the vapour balance is:

$$E - C - g_v\left(\chi_{in} - \chi_{out}\right) = 0 \qquad \text{g m}^{-2}\ \text{s}^{-1} \quad (7)$$

with $\chi$ indicating the vapour concentration (g m$^{-3}$). The two equations can be combined in matrix form:

$$\begin{bmatrix} L & \rho c_p\left(T_{in} - T_{out}\right) \\ 1 & -\left(\chi_{in} - \chi_{out}\right) \end{bmatrix} \times \begin{bmatrix} E - C \\ g_v \end{bmatrix} = \begin{bmatrix} I_{rad}\tau + c_{pipe}\left(T_{pipe} - T_{in}\right) + c_{soil}\left(T_{soil} - T_{in}\right) - c_{cover}\frac{A_{cover}}{A_{soil}}\left(T_{in} - T_{out}\right) \\ 0 \end{bmatrix} \quad (8)$$

and inversion yields the two unknowns $g_v$ (the ventilation rate) and the difference between evapotranspiration and condensation, although the second is not required here.

## RESULTS AND DISCUSSION

As both assimilation and ventilation requirement vary with the conditions, the optimal supply Eq. (5) has to be calculated on-line by the climate control computer, $g_v$ being determined through Eq. (8). We implemented this algorithm as a DLL into the commercial climate control system (HortiMaX Optima) of one of the greenhouses of the Experimental Station of the Fundación Cajamar, Almeria, Spain. Figure 2 shows the results for one sunny spring day in two compartments: one very well ventilated and one allowed to become warmer. The crop was tomato, expected to be valued at 1 €/kg (value of 1 kg assimilated $CO_2 \approx 5.5$ €) and the price of bottled $CO_2$ was 0.2 €/kg, both of which the grower had to enter beforehand. As it could be guessed also by Figure 1, the optimal supply strategy, under these financial conditions, drops very soon to maintaining inside the external concentration, that is to supply exactly the amount absorbed by the canopy. It is therefore worthwhile ventilating as little as possible, allowing higher temperatures in the greenhouse which can be helpful in taking advantage of a high $CO_2$ concentration (Dieleman et al., 2005).

We have not considered capital costs in this analysis, since fixed costs obviously do not affect the optimal strategy, but only the net profit to be attained. Incrocci et al. (2008) have analyzed the overall profitability of carbon fertilization in market conditions where installations are relatively expensive because of the dearth of demand, such as in Italy. They observed that, even then, capital costs are a significant fraction of the overall costs only for dedicated installations in greenhouses smaller than 1 ha.

## CONCLUSIONS

Whenever carbon dioxide is not available simply as the rest product of heating, it must be supplied in the most economical fashion. This ensures the best possible return for the grower and prevents unnecessary emissions. The optimal $CO_2$ supply rate has to be determined on line, in view of the actual ventilation rate and of the potential assimilation, which vary continuously with the weather conditions. We have shown that a simple assimilation model and a routine to determine ventilation on-line can be combined into an optimisation algorithm that can be implemented in a climate computer, to calculate in real time the economically optimal $CO_2$ concentration and the corresponding $CO_2$ injection rate.

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### Literature Cited

Bontsema, J., Hemming, J., Stanghellini, C., Visser, P.H.B. de., Henten, E.J. van., Budding, J., Rieswijk, T. and Nieboer, S. 2007. On-line monitoring van transpiratie en fotosyntheseactiviteit. Wageningen: Wageningen UR Greenhouse Horticulture, Wageningen, Nota 451.

De Koning, A.N.M. 1994. Development and dry matter distribution in glasshouse tomato: a quantitative approach. PhD dissertation Wageningen Agricultural University, Wageningen, 240p.

Dieleman, J.A., Meinen, E., Marcelis, L.F.M., de Zwart, H.F. and van Henten, E.J. 2005. Optimisation of $CO_2$ and temperature in terms of crop growth and energy use. Acta Hort. 691:149-154.

Incrocci, L., Stanghellini, C., Dimauro, B. and Pardossi, A. 2008. La concimazione carbonica in serra nella realtà italiana: aspetti produttivi ed economici. Il Floricultore. 45(5):35-40.

Kläring, H.-P., Hauschild, C., Heißner, A. and Bar-Yosef, B. 2007. Model-based control of $CO_2$ concentration in greenhouses at ambient levels increases cucumber yield. Agricultural and Forest Meteorology 143:208-216.
Nederhoff, E.M. 1994. Effects of $CO_2$ concentration on photosynthesis, transpiration and production of greenhouse fruit vegetable crops. PhD dissertation, Wageningen University, Wageningen 213p.
Stanghellini, C. and Heuvelink, E. 2007. Coltura e clima: effetto microclimatico dell'ambiente serra. Italus Hortus. 14(1):37-49.
Stanghellini, C., Incrocci, L., Gázquez, J.C. and Dimauro, B. 2008. Carbon dioxide concentration in Mediterranean greenhouses: how much lost production? Acta Hort. 801:1541-1549.
Stanghellini, C., Kempkes, F.L.K. and Incrocci, L. 2009. Carbon dioxide fertilization in Mediterranean greenhouses: When and how is it economical? Acta Hort. 807:135-142.

## Figures

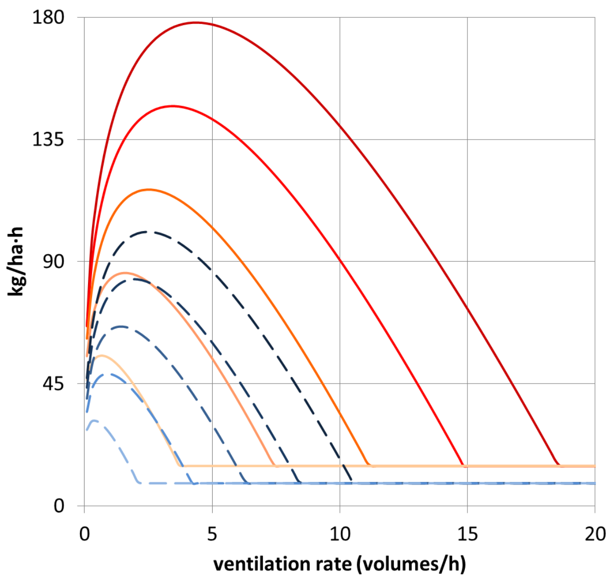


Fig. 1. Optimal carbon dioxide supply (kg ha$^{-1}$ h$^{-1}$) as function of the ventilation rate (h$^{-1}$) of a greenhouse 4.5 m high. The two groups of lines are calculated respectively for a sun radiation of 600 W m$^{-2}$ (drawn lines) and 300 W m$^{-2}$ (dashed lines). Within each group, the darker the line, the highest the ratio between the value of assimilated $CO_2$ and its price. The horizontal value is the value that maintains concentration inside equal to outside, in both cases.

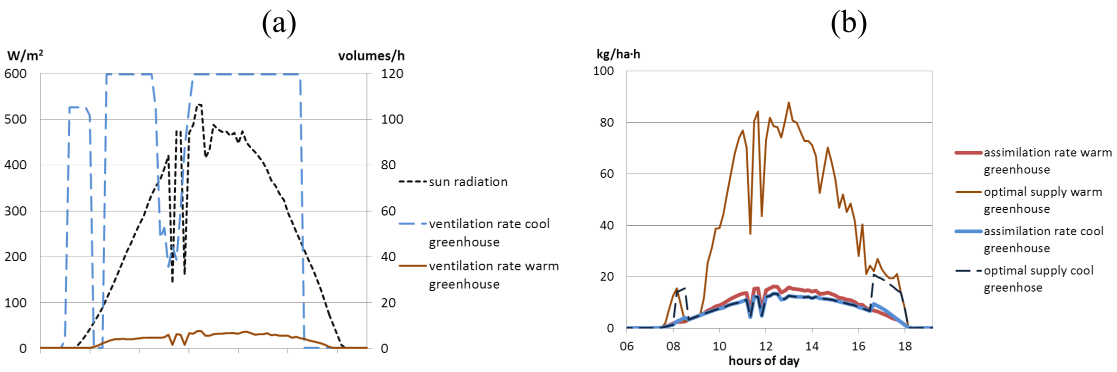


Fig. 2. (a) sun radiation during a spring day (W $m^{-2}$, left axis) and ventilation rate ($h^{-1}$, right axis) determined by Eq (8), for two compartments managed very differently (one was allowed to become much warmer than the other). (b) the calculated values of optimal carbon dioxide supply in each compartment, and corresponding assimilation rate (both kg $ha^{-1}$ $h^{-1}$) for the same day. The optimal supply in the much ventilated compartment was only the replacement of assimilated carbon dioxide, except in the early morning and late afternoon, when there was less ventilation (see top).