Carbon Dioxide Fertilization in Mediterranean Greenhouses: When and How is it Economical?

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Abstract

In a greenhouse without carbon fertilization, the CO_2 absorbed in the process of photosynthesis must ultimately come from the external ambient through the ventilation openings. The ventilation of the greenhouse implies a trade-off between ensuring inflow of carbon dioxide and maintaining an adequate temperature within the house, particularly during sunny but chilly days. Crop production is known to increase both with carbon dioxide concentration and with [average] temperature. Therefore, the management of ventilation in such conditions is looking for "the lesser of two evils". After recalling the conclusion of a previous paper that carbon fertilization up to at least external concentration is the surest and cheapest way to increase productivity in such conditions, we deal with the question of optimal fertilisation in presence of natural ventilation. Allowing for a higher than external concentration obviously reduces the efficiency of the supply, but it does not necessarily reduce profit. By applying some economics to a simple assimilation model, we show that in many conditions–particularly with relatively high radiation–maintaining higher than external concentrations does make economic sense, certainly up to ventilation rates of 10 per hour.

We conclude that the optimal management of carbon fertilisation should aim at concentrations well above 1000 vpm in the absence of ventilation, and gradually decrease to maintaining the external value at ventilation rates well in excess of 10 per hour. Market conditions (value of produce v price of CO_2) should determine the trend between these two extremes, that is, how fast or gradually should a grower limit fertilisation to only maintaining the external concentration.

INTRODUCTION

In a previous paper (Stanghellini et al., 2008) we have discussed the effect of carbon dioxide depletion on productivity of "mild winter" greenhouses. We have shown that in greenhouses without CO_2 injection the management of ventilation is a trade-off between allowing inflow of carbon dioxide and the management of temperature. We have shown this by comparing data of two growers (in Almeria, Spain and Ragusa, Italy) who–in spite of the very similar climate conditions in the two places during the month of November 2006–realised quite different conditions inside their greenhouses, thanks to the different management of ventilation (Table 1).

Our conclusion was 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.

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

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prices are high. This simple problem of economic optimisation is the subject of the present paper.

MATERIALS AND METHODS

The flow of supplied CO_2, *S*, must balance the CO_2 that is assimilated, *A*, and the CO_2 that is lost to the external ambient, *V*:

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

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 we have selected a simple two-variables model that does reproduce the trend and the level of the more complex model proposed by Nederhoff (1994):

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

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), $\mu mol\ m^{-2}\ s^{-1}$. For sun radiation, I_{sun} can be estimated as twice the value of sun radiation in $W\ m^{-2}$, whereas Avogadro's law gives the conversion from volume to mass: in the case of CO_2, 1 vpm $\cong$ 2 $mg\ m^{-3}$. 2.2 $mg\ m^{-2}\ s^{-1}$ is the "maximal" assimilation rate of a tomato crop, according to Nederhooff's extensive measurements in commercial farms, which may be reduced by suboptimal values of radiation and/or carbon dioxide. Both factors of eq(2) are always less than unity.

The worth of 1 kg assimilated CO_2 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). With a harvest index of 65% and a dry matter content of the produce of 6% (for instance tomato), this is a fresh weight of tomatoes of about 5 kg. To assign it a value, for instance, the producers' price of tomato, P_{tom} in Almeria in the month of November of the years 2003 through 2006 has been between 0.55 and 1.15 € kg^{-1} (Fundación Cajamar, 2006 and 2007). Altogether the value of 1 kg assimilated CO_2 would have then been between 2.75 and 5.90 €.

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^{-1}, which is comparable to the cost of producing carbon dioxide by burning gas (as done in the heated greenhouses of Northern Europe, for instance).

The net profit of supplying carbon dioxide with a fixed capacity is shown in Fig.1, for a number of combinations of sun radiation at the top of the crop, and ventilation requirement of the greenhouse. Obviously not all combinations are possible in a naturally ventilated greenhouse, since usually a high sun radiation implies a high ventilation requirement. Therefore, the naturally occurring combinations will tend to crowd along the lower-left to upper right diagonal. Nevertheless, Fig. 1 makes clear that there is scope for an intelligent management of carbon fertilization. The optimal supply 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, maximizing 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:

$$5P_{tom}\,A - P_{CO_2}S = \left(5P_{tom} - P_{CO_2}\right)f\left(I_{sun}, CO_{2,in}\right) - P_{CO_2}g_V\left(CO_{2,in} - CO_{2,out}\right) \Rightarrow MAX \quad € \text{ m}^{-2} \; (3)$$

RESULTS AND DISCUSSION

We have calculated the “optimal” CO_2 concentration for a number of conditions. The results are displayed in Fig. 2, which makes clear that there are quite a number of conditions in which it does make sense maintaining a higher than external concentration in the house, in spite of its ventilation. “Optimal” management of carbon fertilization should therefore aim at maintaining relatively high concentrations in the absence of ventilation, and gradually falling back to the “minimal” management–that is matching inside the carbon dioxide concentration outside–only at relatively large ventilation rates and/or expensive CO_2. Fig. 2 shows that both the level to be maintained in the absence of ventilation and the steepness of the trend at intermediate ventilation rates depend on intensity of radiation and on the economics, that is the value of yield vs the cost of CO_2.

What this means in terms of required injection capacity and potential profit can be seen in Fig. 3 which demonstrates that, in the measure that the expected value of produce increases, it is worthwhile supplying significant amounts of CO_2 even at relatively high ventilation rates, certainly under a good sunshine. With high-value crops this implies injection capacities well exceeding the 180 kg/h·ha = 5 mg m^{-2} s^{-1} typical of Dutch glasshouses (see bottom panel). Obviously the largest profits are to be reaped under high sunshine and low ventilation rates, which does lend some support to the Dutch fashion of the “semi-closed greenhouse”, that is a greenhouse where priority is given to other means of temperature management (such as energy storage and/or evaporative cooling) before ventilation: for instance Van Leeuwen, (2006) and Heuvelink et al., (2008).

What is clear is that the best management of carbon fertilization should count on relatively high capacity (how high depends on the value of the product and on the cost of CO_2), and should be able to control supply according to light intensity and ventilation rate, even though this may increase the cost of the installation with respect to simple systems with constant flow.

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

It is quite likely that most growers could expect a good return on the investment of an installation for CO_2 fertilization, certainly with farms exceeding about 1 ha. The system should have a maximal injection capacity even in excess of the 180 kg/h·ha typical of Dutch installations, and the ability to regulate the flow accounting for current sun radiation and ventilators’ opening. If such an installation were available, a good management strategy would be to ventilate as little as possible (that is, as little as the control of humidity and temperature would allow) and control the CO_2 concentration gradually within the house, from a high level (higher than 1000 vpm) in the absence of ventilation, down to the level outside, at ventilation rates well exceeding 10 per hour.

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Tables

Table 1. Mean daytime values of carbon dioxide concentration; daily total of sun radiation and temperature difference between inside and outside, in the two greenhouses, November 2006.

	Almeria	Ragusa
CO_2 (vpm)	321	373
I_{sun} (MJ $m^{-2}\cdot d^{-1}$)	8.5	8.4
ΔT (in – out)	2.6	0.6

Figures

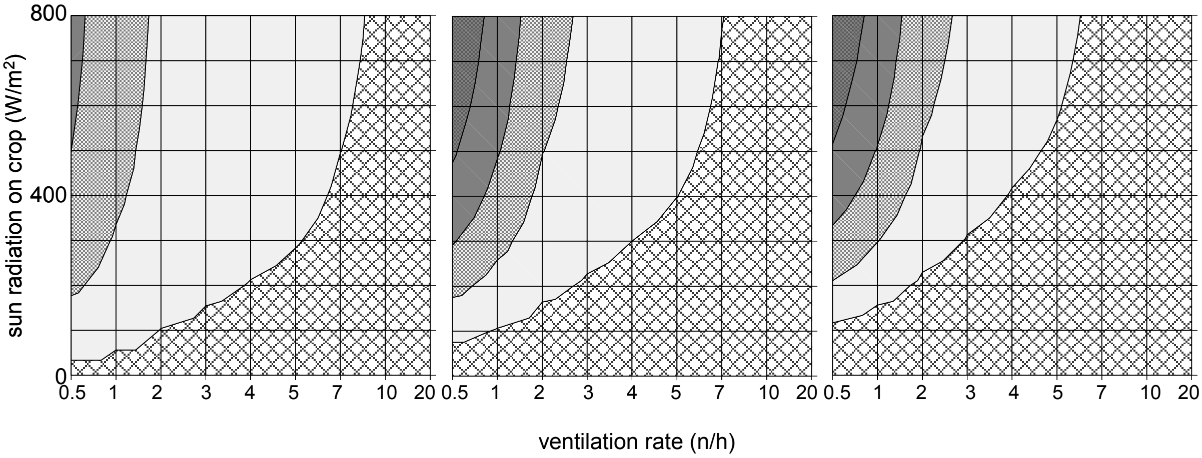

Fig. 1. Net return of a fixed carbon dioxide supply rate (from left to right: 36, 108 and 180 kg/h·ha), depending on sun radiation at the top of the crop, and the air exchange rate in a greenhouse of 4 m mean height, for a price of bottled CO_2 of 0.20 €/kg and of the tomato of 0.55 € kg^{-1}. The increasing darkness of the areas represents profits between 0 and 30; 30 and 60; 60 and 90; 90 and 120 €/h·ha, respectively. The hatched area represents a net loss, in all cases contained between 0 and 30 €/h·ha. 180 kg/h·ha is the standard capacity of supply systems in Dutch glasshouses.

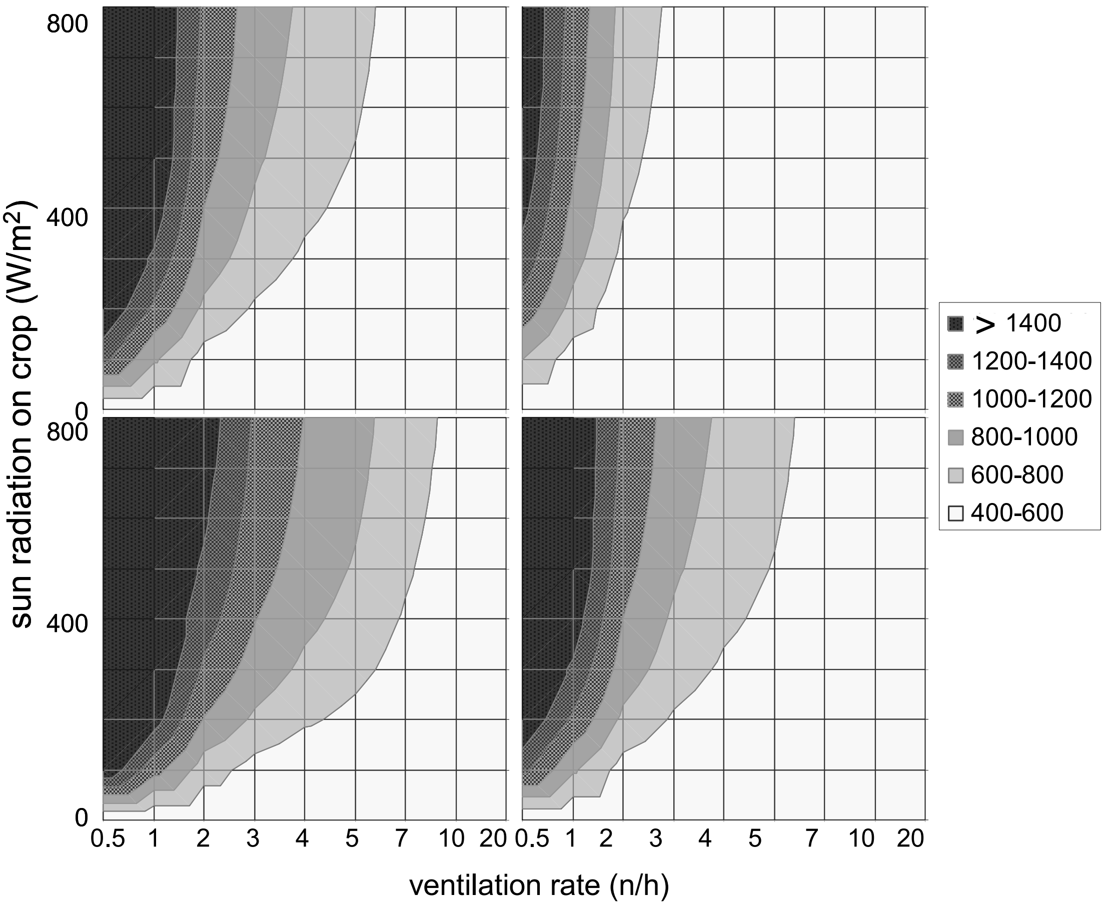

Fig. 2. Carbon dioxide concentration that warrants the highest profit, eq(3), depending on sun radiation at the top of the crop, and the air exchange rate in a greenhouse of 4 m mean height. The four panels are calculated under various combinations of prices. Clockwise from upper left: bottled CO_2 0.10 € kg^{-1} and tomato 0.40 € kg^{-1}; bottled CO_2 0.20 € kg^{-1} and tomato 0.40 € kg^{-1}; bottled CO_2 0.20 € kg^{-1} and tomato 0.80 € kg^{-1}; bottled CO_2 0.20 € kg^{-1} and tomato 1.20 € kg^{-1}.

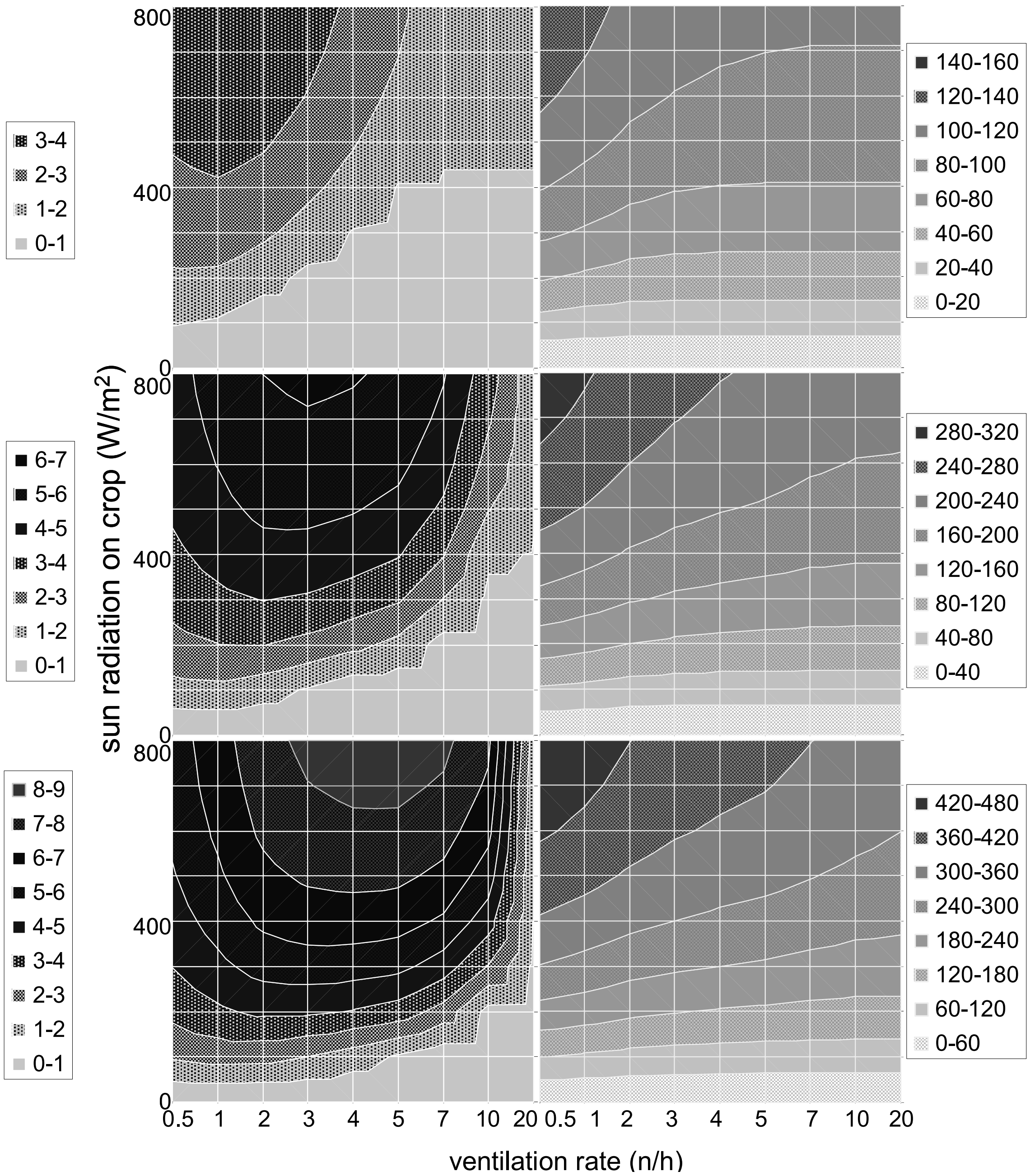

Fig. 3. Optimal carbon injection rate (mg m^{-2} s^{-1}, left) and expected profit (€ h^{-1} ha^{-1}, right–only variable cost of CO$_2$ supply are considered), for various combinations of sun radiation and ventilation rates. Price of bottled carbon dioxide is assumed to be 0.20 € kg^{-1} throughout, and value of produce is 0.5, 1.0 and 1.5 € kg^{-1}, respectively, from top to bottom.