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Optimal Light Integral and Carbon Dioxide Concentration Combinations for Lettuce in Ventilated Greenhouses

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Carbon dioxide enrichment and supplemental lighting in greenhouse facilities are common procedures for improving production rates. Carbon dioxide enrichment is usually used to decrease the amount of supplemental lighting, as it is a much less expensive process. However, it is economically prohibitive to maintain elevated CO_2 concentrations inside the greenhouse during periods of high ventilation rates. In this work, a crop-specific model is developed for lettuce. The model searches for the economically optimal daily light (photosynthetically active radiation—PAR) integral and CO_2 concentration combinations. This takes into account the ventilation rate, the environmental PAR integral, and the acceptable values of target combinations of PAR integral and CO_2 concentration, for the specific crop plant (lettuce). The optimal combinations achieve operating savings for the greenhouse facility.

1. Introduction

One advantage of growing crops in greenhouses is that the environment inside the greenhouse can be controlled. Therefore, successive generations of crops can be grown in the same environmental conditions, resulting in more predictable crop yields. Additionally, even in harsh climates it is possible to operate a greenhouse and achieve environmental conditions that might not otherwise be feasible. Two of the primary variables that affect plant growth in greenhouses are carbon dioxide (CO_2) concentration and the amount of photosynthetically active radiation (PAR) accumulated over the day.

Aikman (1996) has shown that crop production can be improved by supplemental lighting and CO_2 enrichment. Recently, it has been shown that different combinations of PAR and CO_2 enrichment can result in the same level of crop production (Both *et al.*, 1997). Therefore, it may not be necessary to maintain the greenhouse at the same environmental conditions every day of the entire growing season. Instead, it may suffice to maintain the greenhouse at some point along the optimal parameter curve computed by Both *et al.* In this case, the cost of crop production may be optimized by considering the cost of both supplemental lighting and CO_2 enrichment.

The techniques of supplemental lighting and carbon dioxide enrichment both have important limitations on their usage. For example, supplemental lighting is an expensive process. Generally, electrical charges are a major component of operating costs (Ilaslan, 2000). Controlling CO_2 enrichment is more complicated due to fluctuations in the greenhouse environment. During warm months, ventilation of the greenhouse makes maintenance of CO_2 levels above ambient levels difficult. The constant need to suspend ventilation to readjust CO_2 levels is a costly operation. It has been shown that the optimal CO_2 enrichment scheme required to maintain a certain level in the greenhouse depends on the weather (Ioslovich *et al.*, 1995). Ioslovich showed that for slowly changing weather patterns a quasi-static CO_2 enrichment scheme could be implemented. However, as the change in weather accelerates, the quasi-static state becomes less and less desirable. This suggests that increasingly complicated enrichment schemes must be used.

Peet and Willits have studied the effects of different enrichment schemes in a number of different variables on

Notation

PAR	daily integral of photosynthetically active radiation, mol/m^2 day
T	time interval, h/day
$[CO_2]$	CO_2 concentration, p.p.m.
$[\dot{C}O_2]$	rate of CO_2 enrichment, m^3/h
V	volume of the greenhouse, m^3
$\dot{v}$	ventilation rate, air changes per hour
$\dot{I}$	infiltration rate, air changes per hour
L_i	light intensity, mol/m^2 h
C	daily cost, \$/day
P	unit price, \$/unit
L	number of sodium luminaires
W	power for each luminaire, kW

Subscripts

e	environmental
n	natural
t	target
d	desired
s	supplemental
CO_2	of CO_2
light	of lighting
L-off	of electricity during off-peak hours
L-on	of electricity during on-peak hours
total	total

cucumber and tomato plants (Peet & Willits, 1987; Willits & Peet, 1989). It was concluded that the effectiveness of a specific enrichment scheme depends heavily on the type of greenhouse (rockstorage or conventional) and on the season during which enrichment occurred (autumn or spring) as well as on the actual enrichment level of CO_2. However, while the effectiveness of enrichment changed, enrichment in general provided an overall improvement compared to the control groups in the studies, confirming the beneficial effects of enrichment.

Optimization of enrichment strategies has been undertaken by Aikman (1996), who presents a model that includes a number of variables, including predictions of future market value of crops, greenhouse temperature and time-dependent distribution of photosynthates. Using these data, Aikman is able to obtain a figure for amount of monetary gain due to a given enrichment scheme. The cost of the scheme is easily calculated from the ventilation rate and CO_2 prices. Therefore, the benefits of a particular scheme can be directly compared to the cost of such a scheme.

In the present paper, instead of considering the balance between revenue and cost, only the cost of operating the greenhouse and how that may be minimized is considered. Therefore, it is assumed that achieving a certain lettuce head mass in a fixed number of days is desired and that the environmental PAR and CO_2 level curve that would be needed to achieve this mass is known (as in Both *et al*., 1997). The effects of both light supplementation and CO_2 enrichment to achieve the minimum operating cost, are taken into consideration.

Both *et al.* (1997) showed that to achieve a lettuce shoot dry-mass of 7 g (or 190 g fresh mass) 35 days after seeding, the following combinations of PAR (in mol/m^2 day) and CO_2 (in p.p.m.) concentrations can be implemented: 11/1500, 12/1250, 13/1000, 14/750, 15/530, 16/400, 17/360. These combinations lead to maximum growth without tipburn. A least-squares regression was used to fit a second-order polynomial to these data [Eqn (1)], so that there is a continuous relation between the desired integrated PAR and CO_2 concentrations. The total cost of maintaining a specific daily integrated PAR and a specific CO_2 concentration in the greenhouse, related by the before mentioned function [Eqn (1)], is given by the sum of the electricity cost for the supplemental lighting and the cost of the added CO_2. The objective of this work was to find the combination that gives the minimum total cost. As there are the limitations of supplemental lighting and CO_2 enrichment, the total cost of this process, and therefore the optimal combination of integrated PAR/CO_2 concentration, depends mainly on the ventilation rate of the greenhouse and the integrated amount of natural lighting of each day.

2. Model development

As can be seen in the general graph of *Fig. 1*, the PAR integral/CO_2 concentration plane can be divided into three areas. For combinations of PAR integral and CO_2 concentration on the right-hand side, no supplemental lighting is needed. When the combinations enter in the area in the middle, supplemental lighting is needed but only off-peak hours of the electric rate schedule are needed for this lighting. Finally, for the combinations in the area on the left-hand side of the graph, supplemental lighting during on-peak hours is also needed.

The optimization model searches for the economically optimal combinations of PAR integral and CO_2 concentration and takes this structure of the PAR integral/CO_2

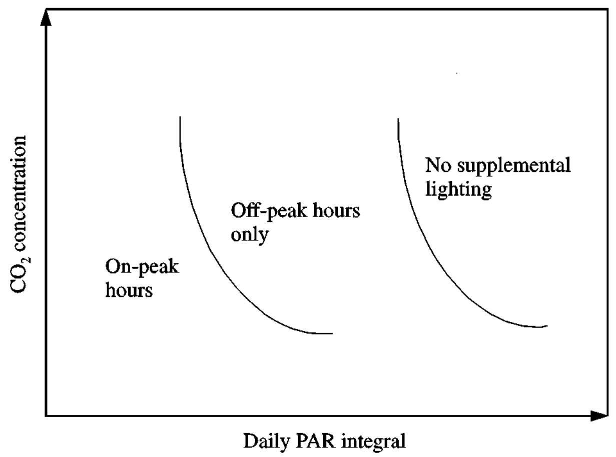

Fig. 1. General structure of the photosynthetically active radiation (PAR) integral and CO_2 concentration plane, showing the anticipated supplemental lighting requirements

concentration plane into account. The program (written in FORTRAN) runs dynamically as the environmental conditions of the greenhouse change with time. In this work, however, a simulation version of the program was used in order to investigate a range of ventilation rates and environmental (natural) PAR integrals, *i.e.* accumulations of PAR given by natural lighting.

The greenhouse used in the optimization model was assumed to have a volume of 326 m^3 and equipped with three ventilation fans (of different sizes) and 21 high-pressure sodium 400 W lamps. Inside temperature was assumed to be maintained at 24°C during daytime and 19°C during night. The CO_2 addition was assumed only in the presence of light (natural or supplemental). The local price of CO_2 is \$0·265/kg (liquid), or \$0·47/m^3 (vapour). Electric rates were taken from the local electric rate schedule. The on-peak rate charged from 7 a.m. to 10 p.m. is \$0·08755/kWh, while the off-peak rate charged from 10 p.m. to 7 a.m. is \$0·05599/kWh (NYSEG, 1996). The 'demand rate' is considered to be constant for every month, so that only the 'use rate' affects the optimization process.

2.1. *Model outline*

The optimization model assumes the existence of a prediction of the natural PAR integral and the time period of the natural lighting of each day. This prediction is made by an algorithm (Albright *et al.*, 2000) at an early stage of the day and updated hourly. The optimization model uses the predicted environmental PAR integral PAR_e and the predicted time interval of natural lighting T_n for the day. The relationship between the target values of PAR integral PAR_t and desired CO_2 concentration $[CO_2]_d$ for optimum lettuce production is obtained by regression on the optimal combinations given in Both *et al.* (1997), and is

$$[CO_2]_d = 20{\cdot}4 PAR_t^2 - 769{\cdot}6 PAR_t + 7530{\cdot}7 \qquad (1)$$

where PAR_t is the target PAR integral in mol/m^2 day and $[CO_2]_d$ is the desired CO_2 concentration in p.p.m.

The program starts at the initial value of PAR_t (11 mol/m^2 day) and increases this value by a specific fixed step factor. The program performs the following calculations at each value of PAR_t until the value of PAR_t reaches the maximum value of 17 mol/m^2 day.

From Eqn (1) and for each value of PAR_t, a corresponding value of $[CO_2]_d$ is calculated. This is the CO_2 concentration that must be maintained by CO_2 enrichment in the greenhouse for the specific value of PAR_t.

The next step is to estimate the rate of CO_2 that must be added to the greenhouse in order to maintain a concentration equal to $[CO_2]_d$. This CO_2 rate is given by the following mass balance equation, which is a modified version of the one presented by Ehler (1991):

$$[\dot{CO_2}] = (V\dot{v} + V\dot{I})([CO_2]_d - 360)\,10^{-6} \qquad (2)$$

where $[\dot{CO_2}]$ is the CO_2 rate in m^3/h, V is the volume of the greenhouse (equal to 326 m^3), $\dot{v}$ is the ventilation rate in air changes per hour), $\dot{I}$ is the infiltration rate in air changes per hour, $[CO_2]_d$ is the desired CO_2 concentration in p.p.m., 360 is the ambient CO_2 concentration in p.p.m. and 10^{-6} is a factor (mol/mmol) to convert the CO_2 concentrations from p.p.m. to unity. The infiltration rate was considered to be absorbed into the ventilation rate.

The supplemental PAR integral PAR_s that must be added to the environmental light integral PAR_e to reach each target PAR integral, is given by the equation

$$PAR_s = PAR_t - PAR_e \qquad (3)$$

while the time period of the supplemental lighting is given by the equation

$$T_s = \frac{PAR_s}{L_i} \qquad (4)$$

where T_s is the supplemental lighting time period in h/day and L_i is the light intensity (0·828 mol/m^2 h). As CO_2 enrichment is only beneficial when light is available (Both *et al.*, 1997), the CO_2 enrichment cost is given by.

$$C_{CO_2} = [\dot{CO_2}]\, P_{CO_2}(T_n + T_s) \qquad (5a)$$

where C_{CO_2} is the daily cost of CO_2 enrichment in \$/day, $[\dot{CO_2}]$ is the previously calculated rate of the CO_2 enrichment in m^3/h, P_{CO_2} is the price of CO_2 per unit volume (\$0·47/m^3), T_n is the natural lighting time period in h/day and $T_n + T_s$ is the total time period in h/day that the greenhouse is lit by natural lighting plus supplemental lighting. In the case that the required time period of supplemental lighting is longer than the period of darkness of a specific day ($24 - T_n$), then for some period natural lighting and supplemental lighting occur simultaneously (*i.e.* $T_n + T_s > 24$) and the greenhouse is lit for 24 h, so Eqn (5a) becomes

$$C_{CO_2} = 24\,[\dot{CO}_2]\,P_{CO_2} \tag{5b}$$

To calculate the supplemental lighting cost, the model assumes the lighting period is delayed until the off-peak hours and the on-peak hours are only used when the desired light integral cannot be achieved with off-peak lighting alone (Albright *et al.*, 2000). For an off-peak period of 9 h/day, the supplemental lighting cost is given by the following equations.

If $T_s \leqslant 9$ h/day, only off-peak rate is used, then

$$C_{light} = P_{L-off}(T_n + T_s)\,LW \tag{6a}$$

If $T_s > 9$ h/day, then on-peak rate is used for the supplemental hours, then

$$\begin{aligned} C_{light} &= 9P_{L-off}LW + P_{L-on}LW(T_n + T_s - 9) \\ \Rightarrow C_{light} &= LW\,[9P_{L-off} + (T_n + T_s - 9)P_{L-on}] \end{aligned} \tag{6b}$$

where C_{light} is the cost of supplemental lighting in \$/day, T_s is supplemental lighting time period in h/day, T_n is natural lighting time period in h/day, P_{L-off} is the off-peak electricity rate in \$0·05599/kWh, P_{L-on} is the on-peak electricity rate in \$0·08755/kWh, L is the number of high-pressure sodium luminaires of the greenhouse (21 luminaires), W is the rated power of each luminaire (0·4 kW) and 9 [in Eqn (6b)] is the maximum number of off-peak hours in h/day.

The sum of the CO_2 enrichment and supplemental lighting costs is calculated by

$$C_{total} = C_{CO_2} + C_{light} \tag{7}$$

This total cost C_{total} is calculated by the program for all possible values of target PAR integral from 11 to 17 mol/m^2 day (with a given step size, usually 0·5 or 1 mol/m^2 day) and the corresponding CO_2 concentrations. Finally, the minimum of these different costs is chosen and the corresponding combination of PAR integral and CO_2 concentration is the economically optimal one for the specific ventilation rate, the predicted environmental (natural) light integral of the day and the predicted time period of daylight.

3. Results

The results presented in this section were obtained by running the model in 'simulation' mode. This means that several ventilation rates and environmental PAR integrals were presented to the model in order to explore both the behaviour of the optimal combinations of PAR integral and CO_2 concentration, and the behaviour of minimum total costs and the savings that can be achieved when these optimal combinations are applied as compared to a constant PAR integral of 17 mol m^{-2} d^{-1} and ambient CO_2 concentration. To simplify the simulation, the natural lighting time period is considered to be constant and coincident with the on-peak hours.

3.1. *Behaviour of the optimal combinations of PAR integral and CO_2 concentration*

The model results for several different ventilation rates and specific values of environmental PAR integral indicate that CO_2 enrichment stops being economically profitable at low ventilation rates (*Fig. 2*). The actual ventilation rates at which this happens vary with the environmental PAR integral values. For example, for environmental PAR integral of 10 mol/m^2 day, CO_2 enrichment stops being profitable at ventilation rates greater than 3 air changes per hour, while for an environmental PAR integral of 8 mol/m^2 day, the ventilation rate limit increases to 4 air changes per hour. The optimum CO_2 concentration always starts at 1500 p.p.m. for a ventilation rate of 1 air change per hour. Then, as the ventilation rate increases, it drops rapidly to values close to the ambient CO_2 concentration. This drop also depends on the environmental PAR integral (*Fig. 2*). The 'PAR = 10' curve has a different pattern from the other two curves because, for environmental PAR this high, the optimization process never uses Eqn (6b) in the objective

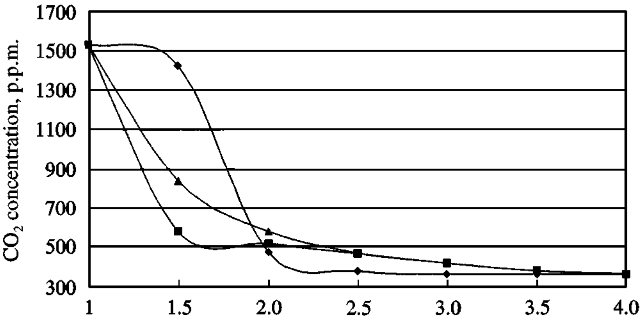

Fig. 2. Optimal CO_2 concentrations versus ventilation rate for several environmental photosynthetically active radiation (PAR) integrals; —▲—, PAR = 6; —■—, PAR = 8; —◆—, PAR = 10

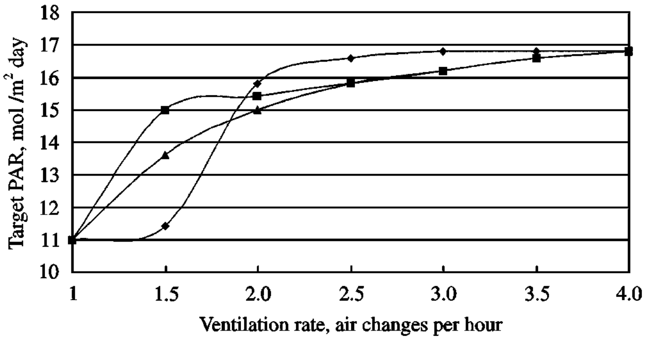

Fig. 3. Optimal target photosynthetically active radiation (PAR) integrals versus ventilation rate for several environmental photosynthetically active radiation (PAR) integrals; —▲—, *PAR = 6;* —■—, *PAR = 8;* —◆—, *PAR = 10*

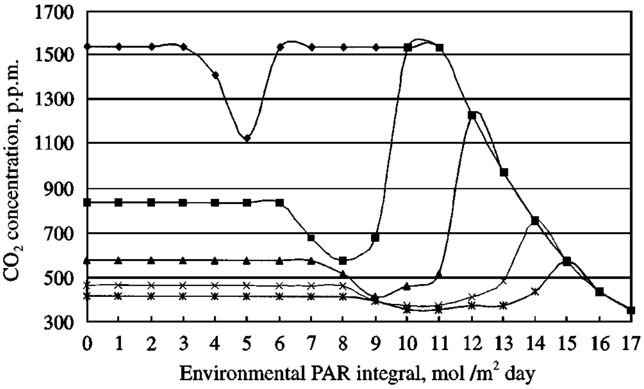

Fig. 4. Optimal CO$_2$ concentrations versus environmental photosynthetically active radiation (PAR) integral for several ventilation rates in air changes per hour (ach): —▲—, *1 ach;* —■—, *1.5 ach;* —◆—, *2 ach;* —×—, *2.5 ach;* —✳—, *3 ach*

function. The off-peak electricity rate is used throughout the entire range of ventilation rates. In the other curves (PAR = 6 and PAR = 8), there is a point of transition from Eqn (6a) to Eqn (6b) because some on-peak electricity is required. The behaviour of the corresponding optimal target PAR integrals, as shown in *Fig. 3*, can be described as a reflection of that of *Fig. 2*. This occurs because of the relationship between the CO$_2$ concentration values and the corresponding PAR integral values from the regression model.

Another type of simulation was performed to give optimal combinations of target PAR integral and CO$_2$ concentration for different ventilation rates using the environmental PAR integral as the variable (*Figs 4* and *5*). From the graph in *Fig. 3* it is obvious that optimal CO$_2$ concentrations are higher for lower ventilation rates. This offers further confirmation that CO$_2$ enrichment is not economically effective at high ventilation rates. For low environmental PAR integrals and for constant ventilation rates, the optimal concentrations stay constant.

The downward fluctuations in optimal CO$_2$ concentrations and then return to normal (*Fig. 4*) are caused by the alternations of the minimization function [Eqn (7)] as influenced by either the use of Eqn (5a) or (5b) as well as Eqn (6a) or (6b). This means that the whole minimization function changes according to the combination of lighting used: no supplemental light; only off-peak hour lighting; or both off-peak and on-peak hours. The discontinuity in the objective function appears in the solution in this fashion. This can be visualized by looking at the graph of *Fig. 1* and seeing that the optimal combinations of PAR integral and CO$_2$ concentration start at the right hand side area of the plane, then move to the left and pass into the middle area of the plane, and finally pass into the left-hand side area (*Fig. 6*).

When the PAR integral enters the area of the regression model (above 11 mol/m^2 day) the optimal concentrations agree with the regression curve on the data of Both *et al.* (1997). The corresponding optimal target PAR integrals again form reflection curves of the optimal CO$_2$ concentration curves, as every PAR integral value is calculated by the regression model (*Fig. 5*). It should be mentioned here that it seems that for ventilation rates of 2·5 and 3 air changes per hour, it is profitable to add supplemental light even when environmental PAR integral is above 11 mol/m^2 day but below the target integral. For these ventilation rates CO$_2$ enrichment in more costly than supplemental lighting.

3.2. *Cost reduction efficiency*

Figure 7 shows the minimal costs for several ventilation rates and environmental PAR integrals, that is the minimal total costs that are achieved by using the

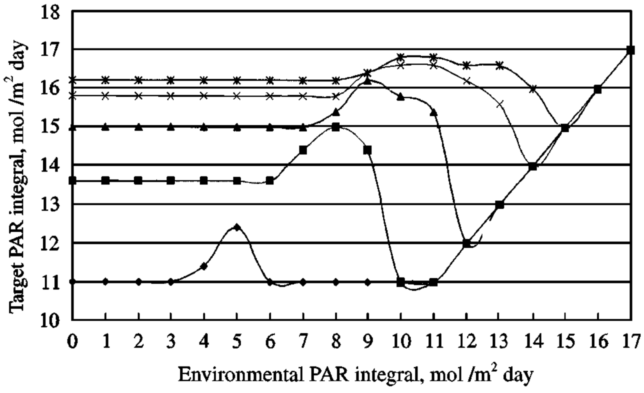

Fig. 5. Optimal target photosynthetically active radiation (PAR) integral versus Environmental PAR integral for several ventilation rates in air changes per hour (ach): —◆—, *1 ach;* —■—, *1.5 ach;* —▲—, *2 ach;* —×—, *2.5 ach;* —✳—, *3 ach*

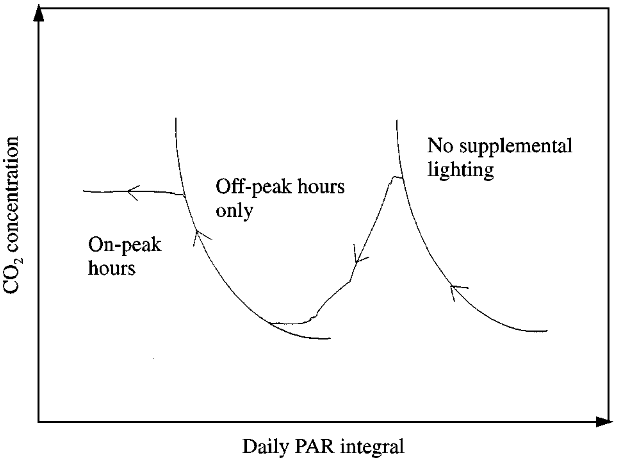

Fig. 6. General route of the optimal photosynthetically active radiation (PAR) integral/CO$_2$ concentration combinations in the 'PAR integral/CO$_2$ concentration' plane

optimal combinations of CO$_2$ concentration and PAR integral that the optimization model gives. This graph shows that the lowest cost operation occurs for low ventilation rates on days with high environmental PAR integral. These conditions usually occur during sunny winter days, when ventilation rates are minimal and the accumulated PAR is high during daylight hours. In order to observe the cost reduction of the application of optimal combinations given by the model, these minimal costs are compared with the costs of operating the greenhouse with ambient CO$_2$ concentration and constant PAR integral of 17 mol/m^2 day, which is a common case of operational conditions for lettuce production greenhouses. The savings achieved by using optimal combinations rather than ambient CO$_2$ concentration and constant PAR integral of 17 mol/m^2 day are shown in *Fig. 8*. These savings refer only to the small section of the greenhouse used in the optimization model. It can be seen that for ventilation rates of 1–3 air changes per hour, common values for winter months, application of the optimal combinations is profitable for the whole range of environmental PAR integrals (0–17 mol/m^2 day). Maximum savings are achieved for low ventilation conditions during days with small environmental PAR integrals, *i.e.* common winter days for the region of upstate New York where the greenhouse is assumed to be situated.

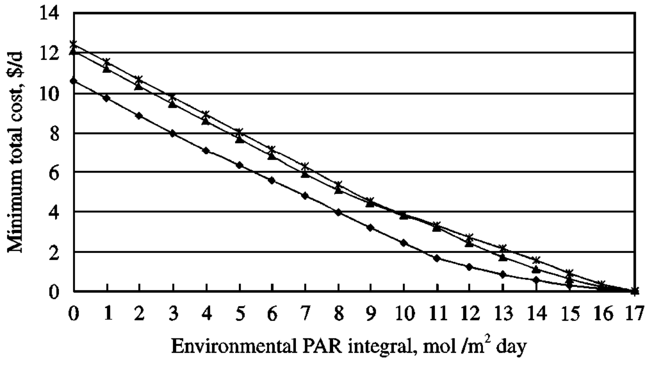

Fig. 7. Minimum total daily costs (CO$_2$ enrichment and lighting) for several ventilation rates in air changes per hour (ach): —◆—, 1 ach; —▲—, 2 ach; —✱—, 3 ach; PAR, photosynthetically active radiation

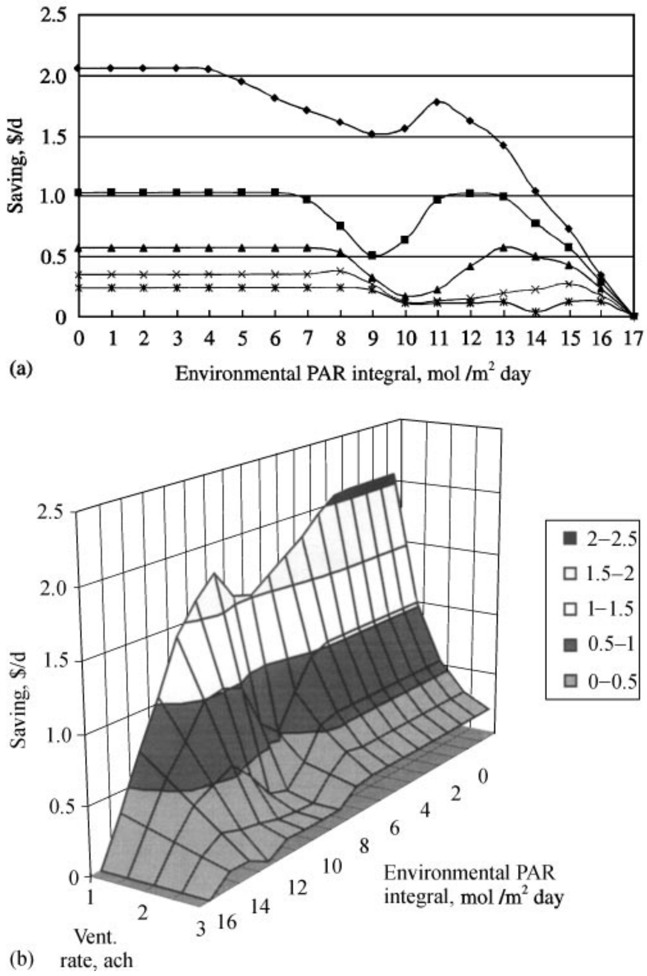

Fig. 8. (a) Maximum savings for several ventilation rates in air changes per hour (ach): —◆—, 1 ach; —■—, 1.5 ach; —▲—, 2 ach; —✕—, 2.5 ach; —✱—, 3 ach and (b) maximum savings surface; PAR, photosynthetically active radiation

4. Discussion

The optimization model presented is used to investigate the behaviour of the economically optimal combinations of target daily PAR integral and CO_2 concentration as influenced by two important parameters: the ventilation rate of the greenhouse and the environmental daily PAR integral. Two major assumptions are considered in these investigations.

(1) The first is the existence of an accurate prediction of the daily PAR integral at an early stage of the day. An example of an algorithm that gives such predictions can be found in Albright *et al.* (2000).
(2) The second assumption was the compromise that the ventilation rate in the greenhouse is constant throughout the day. This is hardly the case in a greenhouse that is subjected to dynamically changing outside environmental parameters.

So, these analyses only approximate the behaviour of the optimal combinations mentioned above for several constant values of ventilation rates. The optimization model runs in 'simulation' mode in order to explore this behaviour. The practical application of this model would require an optimization program that would run dynamically (on-line). The on-line program would run at the beginning of the day for a specific prediction of daily PAR integral and the current ventilation rate and after a given time period or when the ventilation rate would change, it would repeat the optimization with the new value of ventilation rate and a new, more accurate, prediction of the daily PAR integral. A major modification in the program is required, because after the passed time period a specific PAR integral has already been allocated to the plants and also some hours of the day have passed, so the calculations must take all these into account and calculate the new optimal combinations accordingly.

5. Conclusions

From the results presented, it is clear that the application of the optimal combinations of daily photosynthetically active radiation (PAR) integral and CO_2 concentration obtained by the optimization model can significantly reduce the operational cost of the greenhouse. Especially during the winter months when the ventilation rates in the greenhouse are low or even nonexistent and only infiltration exists, the savings obtained can exceed \$2 (USD) per day for just the small section of the greenhouse examined in this study. These savings are equivalent to $\$8/m^2$ yr, which is an improvement of around 15% over only the cost of electricity for the supplemental lighting of these greenhouse facilities for lettuce production in up state New York. When the CO_2 enrichment costs are also considered, the savings are even more significant. Even in days with total ventilation rates (infiltration included) of 3 or 4 air changes per hour, if the environmental PAR integral is quite low, some savings can be achieved. At higher ventilation rates, CO_2 enrichment becomes economically prohibitive because of the high rate of loss of CO_2 from within the greenhouse. In this case, the common practice of having ambient CO_2 concentration as well as maintaining a daily PAR integral of 17 mol/m^2 day is the most economical. However, were the greenhouse to be equipped with an alternative cooling system, such as air conditioning, the need for ventilation could be eliminated during moderately warm days when the cooling load is small but not zero (*e.g.* middays during spring and autumn) and during the winter when ventilation may be imposed to dehumidify the greenhouse. Elevated CO_2 concentrations could, thereby, be maintained during these periods and supplemental lighting reduced.

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