The Combined Effect of Cover Design Parameters on Production of a Passive Greenhouse

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Abstract

The objective of this paper is to demonstrate the need of a multiple design parameter approach to greenhouse design. To illustrate this need, we determined the combined effect of cover design parameters on production of a passive greenhouse, that is a greenhouse with only natural ventilation and seasonal whitewash for climate management. The design parameters investigated in this research were the transmission of the cover for photosynthetically active radiation (PAR) and near infrared (NIR) radiation, the emission coefficient for long wave radiation of the cover and the ventilation area. First, we developed a model to link the tomato yield to the cover design parameters, through their effect on greenhouse climate. The model was validated by comparing the simulated greenhouse climate and yield with data obtained from field studies conducted in Almería, Spain. Thereafter, the sensitivity of the yield to the cover design parameters was analysed for three greenhouse configurations. This analysis gave insight into the effect of the cover design parameters on yield. Results show that the sensitivity of the yield to a single design parameter depends on the absolute values of the other ones. For example, the yield in a greenhouse with a high ventilation capacity is most sensitive to PAR transmission (0.45% more yield for each 1% increase of PAR transmission) while in a greenhouse with a low ventilation capacity the crop yield is most sensitive to the ventilation area (0.63%) and NIR transmission (-0.56%). In addition, the sensitivity of the yield to the design parameters also depends on time because of changing outdoor climate conditions. In conclusion, a significant improvement of greenhouse design can be attained only through a multifactorial approach that accounts for the joint effect of design parameters, local climate and desired production period upon crop yield.

INTRODUCTION

An enormous variety of protected cultivation systems can be found throughout the world. They range from a fully passive “solar greenhouse” with a thick energy storage wall in China, to the high-tech “closed greenhouses” in Western Europe. Such variety is brought about by the local conditions such as climate, economical, social aspects, availability of resources and legislation.

However, the optimization of a greenhouse design with respect to local climate and economic conditions still remains a challenge for the designer (von Elsner et al., 2000). A lot of the research that has been done to adapt greenhouses to their local conditions has been limited to optimization of greenhouse designs to one specific location or to one single design parameter (Campen, 2005; Zaragoza et al., 2007). In fact, because of the wide range of boundary conditions and design parameters, this is best approached as a multifactorial design and optimization problem (van Henten et al., 2006). Failure to do that, leads to sup-optimal protected cultivation systems.

The objective of this paper is to demonstrate the need of a multiple design parameter approach to greenhouse design. To illustrate this need, we determined the joint effect of cover design parameters on production of a passive greenhouse, by developing a model that links the outdoor climate and greenhouse construction to tomato yield, through their combined effect on indoor climate. The cover design parameters investigated in this research were the PAR and NIR transmission of the cover, the emission coefficient of the cover and the ventilation area. The model was validated with data obtained from field experiments in Almeria, Spain, in a non-heated greenhouse with natural ventilation and seasonal whitewash. Finally, we determined the sensitivity of the yield to the design parameters for three different greenhouse configurations.

MATERIALS AND METHOD

Model to link design parameters to crop yield

The most important relations (and not all the ones implemented in the model) between the outdoor climate, cover design parameters, the indoor climate and tomato yield are shown in Fig. 1. Although the moisture balance (e.g. evaporation and condensation processes) was included in the model, effects of humidity upon yield were not taken into account and are consequently not shown in Fig. 1.

A detailed description of the model lies outside the scope of this paper. The model is largely based upon the work of De Zwart (1996). For this study we made some adjustments and simplifications to these model equations. The ventilation rate of a greenhouse with both roof and side ventilation was determined according the ventilation equation of Kittas et al. (1997). The photosynthesis rate was calculated by the photosynthesis function of Tap (2000) and the photosynthesis rate only depended on the absorbed PAR of the canopy and the CO_2-concentration of the greenhouse air. The small influence of the temperature upon the photosynthesis rate (e.g. Heuvelink and Dorais, 2005) was thus neglected. However, sub- and supraoptimal temperatures are common in passive greenhouses and their inhibitory effect on photosynthesis cannot be ignored. Therefore we applied a trapezoid filter to the photosynthesis (Boote and Scholberg, 2006) to account for temperature inhibition. Photosynthesis rate was zero below 2°C and above 45°C and maximal between 12°C and 30°C for momentaneous temperatures. A similar filter was applied to daily means, with threshold values respectively 7°C, 32°C, 18°C and 24°C.

The influences of the design parameters upon tomato yield are discussed here. Fig. 1 shows that an increased PAR transmission increased the PAR inside the greenhouse which favored photosynthesis and raised the canopy temperature. An increased NIR transmission raised the NIR inside the greenhouse which increased the canopy temperature. By using whitewash the PAR and NIR inside the greenhouse decreased. The emission coefficient and the sky temperature determined partly the temperature of the cover. An increased emission coefficient of the cover resulted in a lower cover temperature leading to a lower canopy temperature. The ventilation area, outside temperature, wind speed and the ventilation control influenced the ventilation rate of the greenhouse. An increased ventilation area resulted in a higher ventilation rate, which normally resulted in a higher CO_2- concentration and a lower air temperature in the greenhouse. Higher CO_2-concentration favored the photosynthesis and a lower air temperature decreased the canopy temperature.

All four design variables influenced indirectly the canopy temperature which influenced the yield through crop stress and maintenance respiration. Crop stress occurred when the momentaneous and/or mean daily temperature became sub- and/or supraoptimal. An increased canopy temperature raised the maintenance respiration resulting in a lower yield.

Only the ventilation area and the PAR transmission influenced the photosynthesis. An increased photosynthesis had a positive effect upon the crop yield. Tomato yield expressed in fresh weight was derived from dry matter yield, accounting for an estimated harvest index of 0.7 and a dry matter content of 0.05.

Greenhouse climate management

The greenhouse climate was managed by controlling dependently the aperture of the roof and side ventilation and by applying seasonal white wash. As information about the aperture of the ventilators was not available, we implemented a control strategy based on common local practice. The decision about the aperture is based upon the daily global radiation sum and outside temperature. It was also assumed that the windows were controlled manually which implied that their aperture was controlled twice a day (sunset and sunrise). This control strategy was used for validating the model and for the sensitivity analysis. The seasonal white wash was applied to the greenhouse in the beginning and at the end of the production period.

Sensitivity Analysis of the Design Parameters

The relative sensitivity, *S*, of the crop yield up to time *t*, to the design parameters was calculated by (van Henten, 1994):

$$S(t) = \frac{Yield_{p_{nom}+\Delta p}(t) - Yield_{p_{nom}}(t)}{Yield_{p_{nom}}(t)} * \frac{p_{nom}}{\Delta p} \qquad (1)$$

where p_{nom} is the nominal value of a design parameter and Δp is the design parameter increase. To compare the sensitivity of the crop yield to different design parameters the perturbation factor *h* was introduced:

$$\Delta p = h * p_{nom} \qquad (2)$$

The perturbation factor, *h*, ensured that all the nominal design parameters were equally deviated. We applied an *h*-value of 0.01. The relative sensitivity could be interpreted as the percentage change of the crop yield when the design parameter was increased with 1% of its nominal value. For example, when *S(t)* is 4 this implies that the crop yield increases with 4% when the nominal value of the design variable increases with 1%.

Also the variation in time of the sensitivity was calculated as the change of the weekly accumulated harvest when the nominal value of the design variable increases with 1%. Although the first harvest moment was on 11th October, the ‘virtual crop yield’ and consequently the sensitivity results were already determined from the 4th August. The ‘virtual crop yield’ accounted for the period between fruit set and harvest moment (7 weeks). By doing this, the influence of design parameters upon the future crop yield could be investigated.

EXPERIMENT

Model Validation

The model was validated by comparing the simulated greenhouse microclimate and yield with data obtained from field studies conducted in Almeria, Spain, from the 4^{th} of August 2006 till the 27^{th} of December 2006. The greenhouse was a 3 span plastic house, of area 630 m^2, with roof (84 m^2) and side ventilation (56 m^2). The whitewash, present at the beginning, was removed on the 29^{th} of August. The model was validated on two periods of 5 days each: a relatively warm period with a small crop and a cold period with full-grown plants were selected. The above described control strategy for the aperture of the roof and side ventilation area was used as control input for the ventilation aperture for the model. Subsequently the estimated crop yield was validated with the harvested crop yield.

Sensitivity Analysis of the Cover Design Parameters

The sensitivity of the yield to the design parameters was determined for 3 different greenhouse configurations. First, the sensitivity of the greenhouse used for the validation (now without whitewash) was determined. Subsequently, the ventilation area was decreased and finally whitewash was applied. The nominal values for the PAR and NIR transmission, the emission coefficient for long wave radiation of the greenhouse cover and the ventilation areas for the 3 different greenhouse configurations are shown in Table 1.

The sensitivity analysis was performed for a long production cycle that started on August 4^{th} and ended on July 31^{st} of the next year. Weather data from 2002 were used here, since the weather data used for the validation did not cover a whole year. For greenhouse configuration 3, whitewash was applied from the beginning of the production period till August 29^{th} and from March 16^{th} till the end of the production period.

RESULTS

Model Validation

Reasonable fits between the simulated and measured air temperature and CO_2-concentration were obtained for both periods (one is shown in Fig. 2). Deviations between the simulations and the measurements (particularly the drop in simulated CO_2 concentration at the beginning of the day) could follow from a mismatch between the ventilation strategy implemented here and the real one, of which there was no record. A reasonable fit for the yield was obtained for the period for which there were yield data (Fig. 3).

Sensitivity Analysis of the Cover Design Parameters

The crop yield for the validation configuration and the three sensitivity configurations are shown in Fig. 4. The final tomato yield for the validation configuration and the three sensitivity configurations were 36.1, 27.6, 22.1 and 21.4 $kg.m^{-2}$, respectively. The decline of the crop yield at the end of the production period of configuration 2 and 3 arose from the fact that the crop yield was more affected by the maintenance respiration than by the photosynthesis rate. Table 2 shows that the relative sensitivities of the crop yield to the design parameters for each greenhouse configuration differs considerable. For configuration 1 the most sensitive design parameter was the PAR transmission (0.45%), while for the configuration 2 the most sensitive design parameter was the ventilation area (0.63%) followed closely by the NIR transmission (-0.56%) whereas for configuration 3 the most sensitive parameter was again the PAR transmission (1.01%). Observe in Fig. 5 that the sensitivity shows a strong variation in time. The effect of the design variables on weekly accumulated harvest changed during the production period and the weekly accumulated harvest was most sensitive to the PAR transmission of the greenhouse.

DISCUSSION

The highest crop yield was obtained in greenhouse configuration 1 because the high ventilation area favored crop growth through a lower temperature and a higher CO_2-concentration (Fig. 4). The validation configuration resulted in a lower yield level because the whitewash had a negative effect upon crop growth. The applied whitewash in configuration 3 did not directly increase the crop yield which suggests that the whitewash was applied too early and/or too densely. Nevertheless, too much whitewash is better than none, since the final yield in configuration 3 is higher than in configuration 2. However it is clear that timing and density of the whitewash application have a large bearing on productivity.

For each configuration the relative sensitivity of the crop yield to the design parameters is different, as Table 2 shows. The relative sensitivities of the crop yield to the design variables can thus be explained by the nominal values of the cover design parameters and by using Fig. 1. Configuration 1 had relative high ventilation areas in comparison with configurations 2 and 3 which favored higher CO_2-concentrations and lower canopy temperatures. Consequently, the most limiting factor for crop growth was the PAR transmission of the greenhouse cover (0.45%). Configuration 2 did not use whitewash and had a relative small ventilation capacity compared to configuration 1. This configuration resulted in supraoptimal temperatures, as it can be deduced from the relative sensitivities for the NIR transmission (-0.56%) and the emission coefficient (0.09), because both design parameters only influenced the canopy temperature. Configuration 3 had small ventilation areas and used whitewash. Because of the whitewash, configuration 3 had less heat stress than configuration 2 as can be seen in Table 2, the influence of the NIR transmission on yield for configuration 3 is less than the influence of the NIR transmission for configuration 2, -0.08% and -0.56% respectively. But the increase of the relative sensitivity to the PAR transmission is considerable, from -0.04% to 1.01%, which implied that the whitewash decreased the PAR transmission too much. The crop yield for configuration 3 can be increased by increasing the PAR transmission of the whitewash. A whitewash that only decreases the NIR transmission and not the PAR transmission could be a solution.

Obviously, which design parameter is the most limiting or the most effective for crop growth, and how much, depends also on the time course of the weather, as fig. 5 makes clear. In the summertime, an increase of the PAR transmission had a negative effect upon the crop yield because high crop temperatures resulted in heat stress and high maintenance losses. Outside this period the PAR transmission had a positive effect upon the crop yield. In the wintertime, the NIR transmission had a positive effect on the crop yield since it reduced incidence of sub-optimal temperatures. The emission coefficient of the greenhouse cover for long wave radiation negatively influenced the crop yield in wintertime. An increase of the emission coefficient resulted in lower canopy temperatures and consequently in more cold stress. In the summer, the emission coefficient positively influenced the crop yield because it lowered canopy temperature, which resulted in less heat stress and lower maintenance losses. Only in the summertime did the ventilation area of the greenhouse significantly influence the crop yield.

CONCLUSION

Results show that the sensitivity of the yield to a single design parameter depends on the absolute values of the other ones and that the sensitivity of the yield to the design parameters depends on time because of changing outdoor climate conditions. Therefore, all relevant design parameters of a greenhouse should be selected dependently from each other, and the local climate and desired production period must be accounted for from the very early stages of the design process. Consequently a significant improvement of greenhouse design can be attained only through a multifactorial approach that accounts for these influences upon crop yield. Solving such a multifactorial optimization problem is rather difficult. Therefore there is a need for generic tools that are able to solve this problem independently from particular conditions. Developing such a tool is the next objective of our group.

ACKNOWLEDGEMENTS

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Tables

Table 1 Four different greenhouse configurations. The validation configuration is used to validate the model. Greenhouse configuration 1, 2 and 3 are used for the sensitivity analysis.

Design parameter	Greenhouse configuration			
	Validation	1	2	3
PAR transmission (-)	0.58	0.58	0.58	0.58
NIR transmission (-)	0.58	0.58	0.58	0.58
Emission coefficient (-)	0.65	0.65	0.65	0.65
Side ventilation (m^2)	56	56	14	14
Roof ventilation (m^2)	84	84	21	21
Whitewash	Yes	No	No	Yes

Table 2 Relative sensitivity of the crop yield to the selected cover parameters for 3 different greenhouse configurations

Design parameter	Relative sensitivity (%)		
	Configuration 1	Configuration 2	Configuration 3
PAR transmission	0.45	- 0.04	1.01
NIR transmission	- 0.19	- 0.56	- 0.08
Emission coefficient	- 0.04	0.09	- 0.13
Ventilation area	0.18	0.63	0.22

Figures

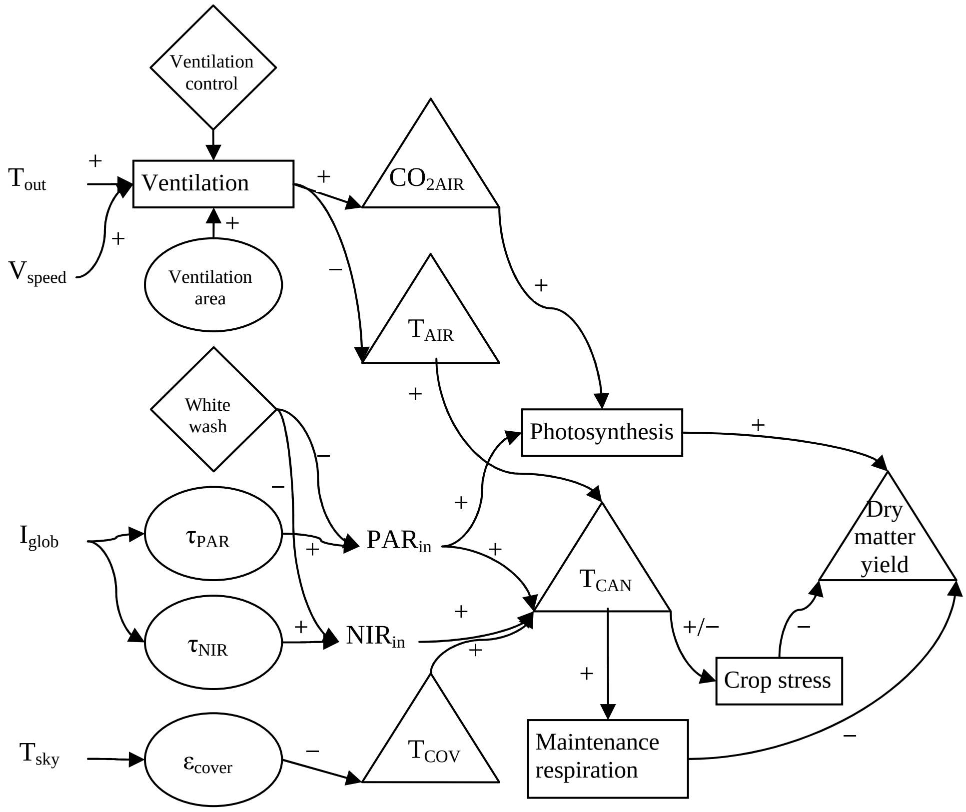

Fig. 1 Relations between outdoor climate (items on the left), the cover design parameters (circles), states of the model (triangles) and the used functions (block).The plus/minus symbols indicate the influence of increasing a measure at the beginning of the arrow upon the measure at the end of the arrow.

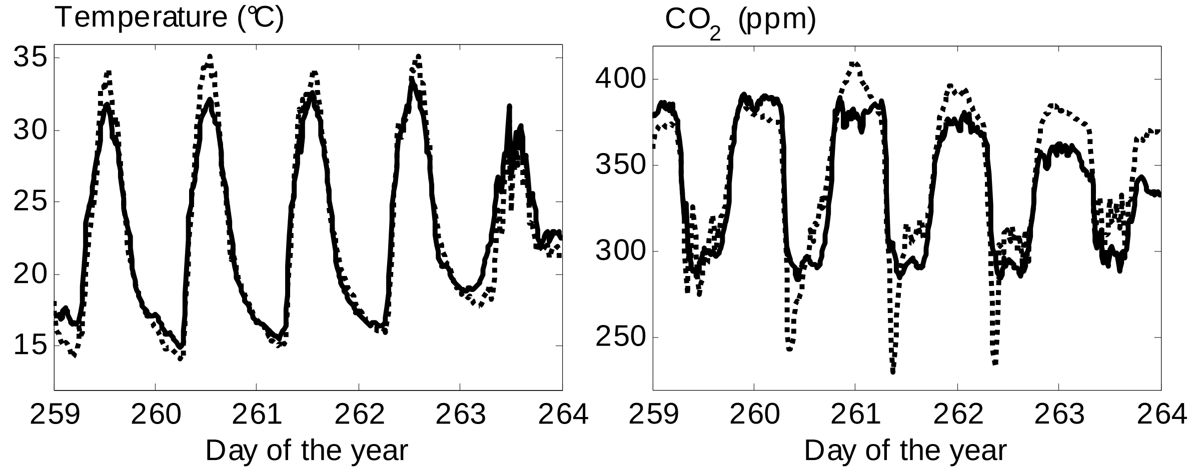

Fig. 2 Measured (solid) and simulated (dotted) air temperature and CO_2-concentration from 16 September 2006 till 21 September 2006

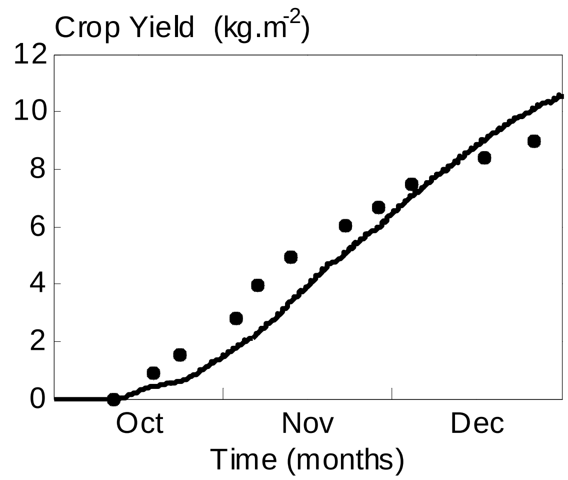

Fig. 3 The simulated (solid) and measured (dotted) cumulative crop yield to validate the model

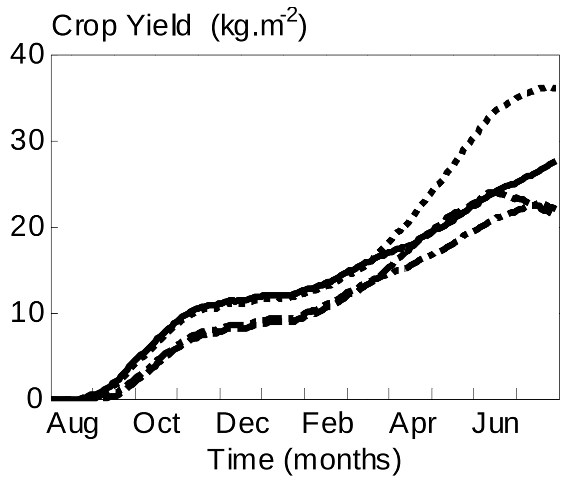

Fig. 4 Crop yield for the validation configuration (solid), configuration 1 (dotted) and configuration 2 (dashed), configuration 3 (dotted-dashed)

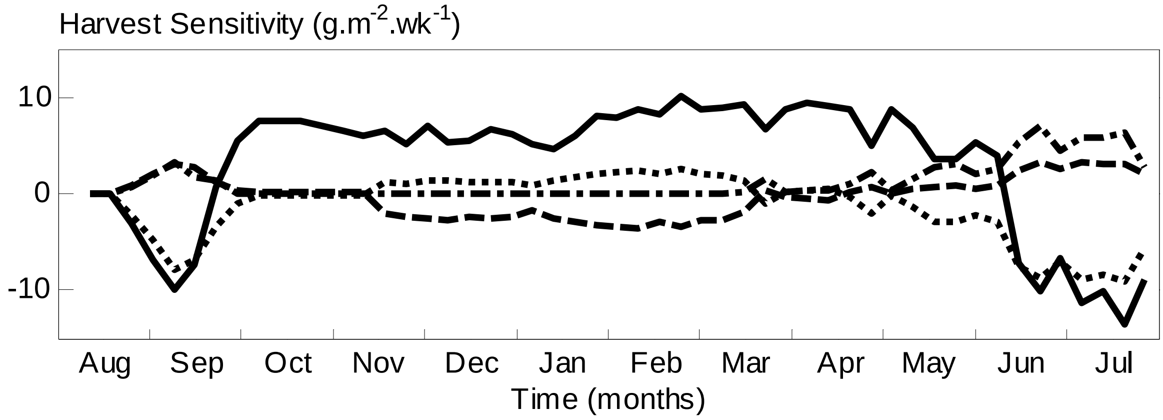

Fig. 5 The weekly accumulated harvest sensitivity of the PAR transmission (solid), the NIR transmission (dotted), the emission coefficient (dashed) and the ventilation area (dotted-dashed) for configuration 1.