The Effect of Outdoor Climate Conditions on Passive Greenhouse Design

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Abstract

The objective of this paper is to demonstrate the need for a generic design tool to adapt greenhouses to local climate conditions. To illustrate this need, we determined the effect of design parameters on greenhouse climate and crop yield of a passive greenhouse, for 2 different climate zones. The investigated climate zones were Mediterranean (Almería, Spain) and equatorial highland (Addis Ababa, Ethiopia). Design parameters investigated in this research were: 1) the NIR transmission of the cover, 2) the ventilation area, 3) the heat capacity and 4) the heat exchange coefficient of a passive heat storage facility. First, we developed a generic model to link the crop yield to the design parameters, through their effect on the greenhouse climate. Thereafter, the sensitivity of the greenhouse climate and the crop yield to the design parameters was analysed for the two greenhouse locations. Results show that the effect of a particular design parameter on greenhouse climate, and thus on crop yield, depends strongly on the outdoor climate conditions. For example, one percent increase of the heat exchange coefficient of the passive heat storage facility resulted in Ethiopia in a crop yield increase of 0.010 % while in Almería the crop yield was not affected. In conclusion, this work proves a) that the greenhouse design should be based on the climatic context in which the greenhouse is going to operate and b) that for each location different design parameters are important. These aspects should be taken into account when designing the greenhouse, resulting in a multi-factorial design approach. In view of this time consuming and complex design approach, there is a need for a generic design tool able to automatically perform the optimization of the greenhouse design parameters for each location on earth.

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. All present systems are the result of a “local evolution”, since 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). 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. Therefore the objective of this paper is to demonstrate the need for a generic design tool to adapt greenhouse design to local climate conditions. To illustrate this need, we determined the effect of design parameters on greenhouse climate and crop yield of a passive greenhouse, for 2 different climate zones. The investigated climate zones were Mediterranean (Almería, Spain) and equatorial highland (Addis Ababa, Ethiopia). The paper is organized

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as follows. First a model that links the design parameters to crop yield through their effect on greenhouse climate is described. Thereafter the greenhouse climate management procedure is presented and a method (sensitivity analysis) to compare the effects of the different design parameters on indoor climate and crop yield is proposed. Finally the sensitivities of the greenhouse climate and crop yield to the design parameters for 2 different climate zones are determined and compared with each other.

MATERIALS AND METHODS

Model to Link Design Parameters to Crop Yield

A greenhouse design consists of several design parameters. We analyzed the effect of the following design parameters: the NIR transmission of the cover, τ_{NIR}, the roof ventilation area A_{vent}, the heat capacity Cp_{soil} and the heat exchange coefficient of the passive heat storage facility, $\alpha_{SoilAir}$ (see Fig 1). In order to determine the effect of these design parameters on greenhouse climate and crop yield, the relationships described in Fig. 1 were built into a dynamic crop-greenhouse model (Vanthoor et al., 2008). The inputs of the model were management of the ventilation windows and of the whitewash, hourly outdoor climate data for one full year and the design parameters. The outputs of the model were the resulting greenhouse climate and crop yield. Because the calculated crop yield was a function of the indoor climate variables such as PAR light, canopy temperature and CO_2 concentration of the greenhouse air, the influence of the design parameters on indoor climate is described here.

An increased NIR transmission of the greenhouse cover raised the amount of the absorbed NIR radiation by the crop which increased the canopy temperature. A higher canopy temperature had a positive effect on crop yield in cold periods when the increased NIR radiation was a useful heat source. In hot periods a higher canopy temperature resulted in crop stress and lower crop yield. The influence of the ventilation area on crop yield was twofold: a higher ventilation area was able to release more heat to the outside and to gain more CO_2 inside the greenhouse. The resulting lower temperature and higher CO_2-concentration had generally a positive effect on crop growth.

The Passive Heat Storage Facility

Several technologies for passive heat storage exist. They can be categorized in: water storage, latent heat storage, rock bed storage and soil storage with buried pipes (Santamouris et al., 1994). In this work we implemented a generic description that represented the most important physical characteristics of these passive heat storage technologies. The generic description was that a certain soil layer represented the passive heat buffer. The heat flow from the buffer to the greenhouse air depended on the heat exchange coefficient of the passive heat storage facility and the temperature difference between the passive heat buffer and the greenhouse air:

$$P_{SoilAir} = \alpha_{SoilAir}\left(T_{so3} - T_{air}\right) \qquad [\mathrm{W.m^{-2}}] \quad (1)$$

where $P_{SoilAir}$ is the heat transfer from soil layer 3 to the air, $\alpha_{SoilAir}$, is the convective heat exchange coefficient between soil layer 3 and the greenhouse air temperature, T_{so3} is the temperature of the third soil layer (which represented the heat buffer) and T_{air} is the greenhouse air temperature (see
Fig. 1). Subsequently the temperature of soil layer 3 was calculated by:

$$Cp_{Soil}\frac{dT_{So3}}{dt} = H_{So2So3} - H_{So3So4} - P_{SoilAir} \qquad [\mathrm{W.m^{-2}}] \quad (2)$$

where Cp_{Soil} is the heat capacity of soil layer 3, H_{So2So3} and H_{So3So4} are the heat flows by conduction from soil layer 2 to soil layer 3 and from soil layer 3 to soil layer 4 respectively.

Greenhouse Climate Management and Influence on Crop Yield

The strategy to control the ventilators was based upon the set-points of the temperature, CO_2-concentration and relative humidity of the greenhouse air. The ventilators were fully open when the indoor air exceeded a certain maximum temperature set-point, T_{Airmax}. Below this set-point, the ventilators were closed, except in cases when the CO_2-concentration of the air dropped below the CO_2-setpoint, $CO2_{Airmin}$, or the relative humidity exceeded the relative humidity setpoint, RH_{Airmax} and the indoor air temperature was higher than the minimum indoor air set-point, T_{Airmin}.

Sensitivity Analysis of the Design Parameters

Sensitivity analysis was used to compare the influence of different greenhouse design parameters on greenhouse indoor climate and crop yield. To illustrate this method we worked out the calculation of the crop yield sensitivity. In order to investigate the effect of time on final crop yield we first determined the sensitivity of the harvest rate which in turn was linear related to the dry matter production. The relative sensitivity of the harvest rate, $S_{HarRate}$, up to time t, to the design parameters was calculated by modifying the sensitivity equation of Van Henten (2003):

$$S_{HarRate}(t) = \frac{HarRate_{p_{nom}+\Delta p}(t) - HarRate_{p_{nom}}(t)}{\Delta p} * \frac{p_{nom}}{\overline{HarRate_{p_{nom}}}} \qquad (3)$$

where p_{nom} is the nominal value of a design parameter, Δp is the design parameter increase and $\overline{HarRate_{p_{nom}}}$ is the mean value of the harvest rate over the production period. The relative sensitivity could be interpreted as the percentage change of the harvest rate when the design parameter was increased by 1% of its nominal value. To compare the sensitivities of the yield to design parameters we averaged the sensitivities over the production period. The relative sensitivities of the indoor greenhouse climate were calculated analogously to the relative sensitivity of the harvest rate. The analyzed indoor climate variables were the greenhouse air temperature, CO_2-concentration of the air and the vapor pressure of the greenhouse air.

EXPERIMENT

First, the mean relative sensitivities were determined for 2 different locations: a Mediterranean climate in Almería (36°50’N, 2°28’W) at sea level and equatorial highland Addis Ababa (9°00’N, 38°45’E) at 2400 m above sea level (see Fig. 2 a,b). To make a fair comparison between the effects of climate zone we used the same greenhouse configuration and climate control set-points. The greenhouse was a 3 span plastic house, of area 630 m^2, with insect nets in both roof (84 m^2) and side ventilation (56 m^2). The PAR transmission, NIR transmission and the emission coefficient for long wave radiation was 0.58, 0.58 and 0.65 respectively. The heat capacity of soil layer 3 was $2.8 \cdot 10^5$ $J.m^{-2}.K^{-1}$ and the heat exchange coefficient of the passive heat storage facility was 1 $W.m^{-2}.K^{-1}$. The climate control set-points used in this study were: T_{Airmin} = 10°C, T_{Airmax} = 23°C, CO_{2min} = 250 ppm and RH_{Airmax} = 85%. However, due to common horticulture practice different production cycles, crops and whitewash management were applied for the 2 locations. In Almería tomatoes were grown for a long production cycle that started on August 4th and ended on July 31st of the next year. Whitewash was applied from the beginning of the production period to August 29th and from April 16th to the end of the production period. In Addis Ababa roses were grown and due to a 3 year production cycle we assumed that the roses were all year in the generative phase and no crop change occurred. In the Addis case no whitewash was applied because roses demanded a high light level. For Addis Ababa no complete hourly outdoor climate data set was available. Therefore we extended the hourly temperature and relative humidity dataset with an estimated global radiation and wind speed. The global radiation was estimated by adjusting the calculated hourly global radiation (at clear sky conditions) with the measured daily global radiation sum. The hourly wind speed was determined by interpolating wind speed measurements with a 3 hour measurement interval.

RESULTS AND DISCUSSION

The effect of the design parameters on greenhouse indoor climate and harvest rate differed between the greenhouses in Almería and Addis Ababa (Table 1). Especially the mean sensitivity of the harvest rate to the heat exchange coefficient (HEC) for the Addis Ababa case was reasonable higher than for the Almería case, 0.010 and 0.000 respectively. This indicates that by increasing the HEC of the passive heat storage facility in Addis Ababa the harvest rate will increase. Although the mean sensitivity of the harvest rate to the HEC is rather small compared to the values of the NIR transmission and ventilation area, it is indeed an important design parameter because adapting the HEC of the passive heat storage facility is practical much more feasible.

The trend of the effect of the remaining design parameters was similar for both greenhouses only the absolute values of the mean relative sensitivities differed. The higher absolute values for the Addis Ababa case indicates that heat problems play a more important role in Addis Ababa than in Almería. Further on, the effect of the NIR transmission on indoor climate and harvest rate was higher compared to the effect of the other design parameters. This can be explained by the fact that the NIR transmission had a direct effect on canopy temperature while the ventilation area and passive heat storage facility affected the canopy temperature indirectly via the air temperature. For both locations an increment of the NIR transmission increased the air, canopy and soil temperature resulting in lower harvest (for Almería and Addis -0.102 and -0.257 respectively) which indicates heat stress. A higher ventilation area resulted for both locations in lower air, canopy and soil temperature, air vapor pressure and a higher CO_2-concentration which favored the harvest rate. The effect of the heat capacity of soil layer 3 on indoor climate was for both locations low. We supposed that due to the large energy flow from soil layer 3 to the greenhouse air and to the enclosing soil layers the heat capacity of this soil layer did not play an important role.

The effect of the HEC on indoor greenhouse climate and harvest rate was further investigated because of its different impact for both locations. Fig. 2c shows the strong time dependency of the impact of the HEC on harvest rate. For the Almería case an increment of the HEC resulted in a positive effect on harvest rate during the winter months and in the rest of the year it had a negative influence on harvest rate. The effect of the HEC on harvest rate was high when the outdoor temperature was low (compare Fig. 2a with Fig. 2c) which can be explained by the positive influence of the passive heat storage facility on mean canopy temperature. In Addis Ababa the effect of the HEC on harvest rate was almost all year positive with peaks at the beginning and the end of the year (Fig. 2c). The time dependency of the HEC was, in contrast to the Almería case, not related to the outdoor temperature but was strongly related to the difference between the minimum and maximum outdoor temperature. A large difference between minimum and maximum outdoor temperature resulted in a large effect of the HEC of the passive heat storage facility on the harvest rate and vice versa (compare Fig. 2b with Fig. 2c).

In this study we used for the Addis Ababa case a generated outdoor climate data set which presumable did not correspond exactly with the real outdoor climate. As already demonstrated, greenhouse design depended strongly on outdoor climate conditions and consequently the results of the Addis Ababa case could have been influenced by the generated outdoor climate data. To avoid such possible error sources we need reliable hourly outdoor climate data to perform greenhouse design using these generic design tools.

CONCLUSION

In conclusion, this work proves a) that the greenhouse design should be based on the climatic context in which the greenhouse is going to operate and b) that for each location different design parameters are important. All these aspects should be taken into account when designing the greenhouse, resulting in a multi-factorial design approach. In view of this time consuming and complex design approach, there is a need for a generic design tool able to automatically perform the optimisation of the design parameters for each location on earth.

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Tables

Table 1 The mean relative sensitivities for the greenhouse in Almería and Addis Ababa.

	Almería				Addis Ababa			
	τ_{NIR}	A_{vent}	Cp_{Soil}	$\alpha_{SoilAir}$	τ_{NIR}	A_{vent}	Cp_{Soil}	$\alpha_{SoilAir}$
Tair	0.063	-0.006	-0.001	0.007	0.084	-0.02	-0.002	0.011
Tcan	0.078	-0.007	-0.001	0.006	0.098	-0.023	-0.002	0.010
Tflr	0.121	-0.005	-0.001	0.000	0.131	-0.018	-0.002	0.005
Tso3	0.097	-0.005	-0.001	-0.011	0.108	-0.016	-0.002	-0.003
Tso5	0.032	-0.002	0.000	-0.004	0.037	-0.005	-0.001	-0.001
VPair	0.031	-0.013	-0.001	0.004	0.031	-0.042	-0.002	0.010
CO2air	0.021	0.002	-0.002	0.008	0.041	0.003	-0.004	0.017
HarRate	-0.102	0.031	0.000	0.000	-0.257	0.096	0.000	0.010

Figures

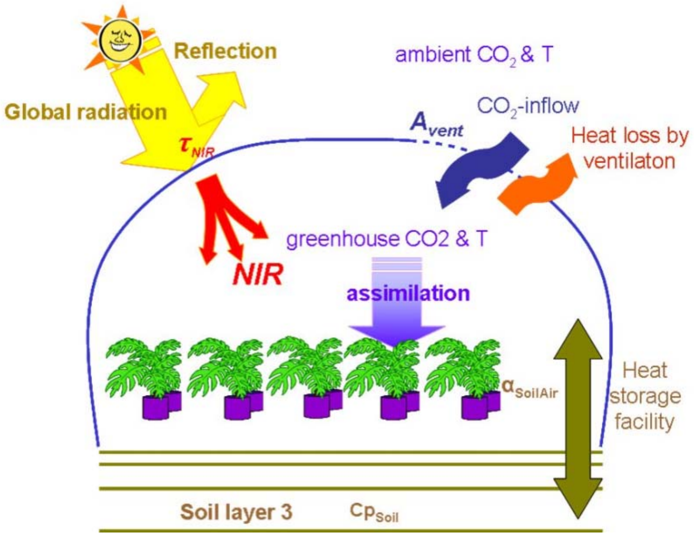

Fig. 1. The greenhouse and the influence of the design parameters on crop yield.

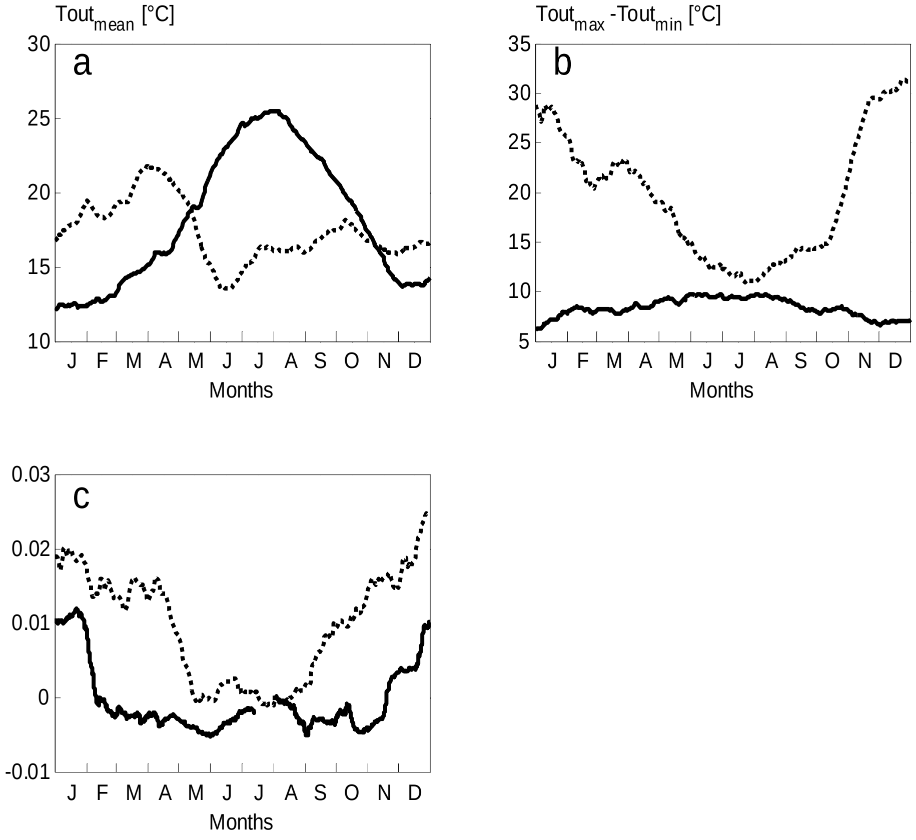

Fig. 2. The monthly mean outdoor temperature, b) the difference between minimum and maximum outdoor temperature and c) the sensitivity of the harvest rate to the heat exchange coefficient for Almería (solid) and Addis Ababa (dotted).