Greenhouse Design and Climate Management Suitable for Subtropical Summer Conditions in China

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Abstract
Adaptation of greenhouse climate management strategy to local climate conditions is very important for the improvement of resource use efficiency of greenhouse crop production. The objectives of this study were to explore the alternatives of the existing greenhouse climate control policy under Chinese subtropical climate conditions, through simulation analysis. Based on the calibrated and validated the Greenhouse Process (KASPRO) model using experimental data from a Dutch Venlo-type glass greenhouse in Shanghai, China, scenario studies were carried out to investigate the possible responses of crop biomass production to affordable means of climate management. In this paper we limited the study to greenhouse ventilation capacity, and canopy size, in a greenhouse without injection of CO2. The results show that for a cucumber crop under the summer conditions typical of Shanghai, an average of 26 volume changes per hour is required, which, in view of the prevailing wind speed, is ensured by a ratio of roof window area to greenhouse floor area about 0.3 (it is about 0.1 in Holland, for instance). A LAI of 4 maximizes crop biomass production, when accounting for the balance of assimilation, respiration and also for the evaporative cooling. The results obtained in this study show that many local climate factors must be taken into account for an optimal management of greenhouse design, crop and climate, and that a greenhouse climate simulator is a good tool for this analysis.

INTRODUCTION
Glasshouses originated in the temperate zones of the Northern hemisphere, mainly for getting subtropical plants through relatively cold winters. Thanks to the increasing cheapness of plastic films, an enormous expansion of protected cultivations has taken place during the last 20 years in subtropical regions. Millions of hectares of unheated plastic structures have sprouted up in the Mediterranean region, southern United States and China, just to name the most important regions. Most are one-crop tunnels that are taken out as soon as climate conditions allow for unprotected growth. However, the need of increasing productivity is causing the quality (and the worth) of the structures to grow so much that the financial investment must be retrieved through multi-year use, with the challenge of growing protected crop also during the summer, when solar radiation heats the air inside the structure, and the cover prevents adequate exchange with the colder upper atmosphere. Getting rid of the heat load is the major concern for greenhouse climate management in such conditions. This can be realised by 1) reducing the income of radiation; 2) removing the extra heat through air exchange; 3) increasing the fraction of energy partitioned into latent heat.

In order to explore means of relieving greenhouse heat load in hot summers, many researches on shading, natural ventilation and evaporative cooling, mainly for the Mediterranean regions, have been reported, whereas few researches on greenhouse cooling have been devoted to the areas with hot and humid summers. Most of the existing reports focus on explaining how those means affects greenhouse microclimate (Baille et
There is a need to develop a blue-print for optimal management in such conditions, that is to assess how such inexpensive greenhouse cooling measures as natural ventilation, shading and passive evaporative cooling (crop transpiration) will affect crop production, under the summer climate conditions typical of subtropical China. To answer this question, scenario studies were carried out to investigate the possible responses of crop biomass production to greenhouse ventilation capacity and canopy size, for the hottest period of the year (July 15th to August, 15th).

MATERIALS AND METHODS

The greenhouse (KAS, in Dutch) process (KASPRO) model was used in this study. The KASPRO model is constructed from modules describing the physics of mass and energy transport in the greenhouse enclosure, and a large number of modules that simulate the customary greenhouse climate controllers. Thus, the model takes full account of mutual dependencies between greenhouse characteristics and climate control. The simulation of the greenhouse physical processes comprises separate computation of convective and radiative heat exchange and also includes latent heat fluxes associated with evaporation. The climate controller of KASPRO enables climate management by means of heating, ventilation, de-humidification, moistening, shading, artificial illumination and carbon dioxide supply. For the full description of the KASPRO model, the readers are referred to de Zwart (1996). The KASPRO model was calibrated and validated in our previous study (Luo et al., 2005). Thereafter, a scenario analysis was done for the hottest period (July 15th to August, 15th) in 2002, during which we had a cucumber crop in the greenhouse and data of both inside and outside climate. Weather conditions outside the greenhouse during the studied period are listed in Table 2.

Carbon dioxide injection, a feature that greatly determines optimal ventilation rate, is seldom available in low-investment greenhouses, therefore we did not account for
the ratio of roof opening area to the greenhouse floor area. The canopy size is denoted by its leaf area index (LAI). The values of the ratio of roof opening area to the greenhouse floor area and LAI used to run the KASPRO model ranges between 0.08 (the real value of the greenhouse under study) to 1 (fully open top) and 1 to 10, respectively.

RESULTS

As we will see later, response of biomass production to one factor (opening area) has a saturating trend, whereas response to LAI display a (weak) maximum. Therefore we decided to select first the “optimal” opening area and then determine the best management of canopy size.

Effects of Greenhouse Ventilation Capacity on Crop Biomass Production

In a greenhouse without carbon dioxide injection and with the floor covered by plastic film, the ventilation flow must carry enough carbon dioxide to replace net assimilation \( (\text{Anet} \text{ (kg m}^{-2} \text{ s}^{-1}) = F_{\text{vent}} \text{ (m s}^{-1}) \cdot ([CO2]_{\text{out}} - [CO2]_{\text{in}})(\text{kg m}^{-3}) \)

\( F_{\text{vent}} \) is very simply related to the more commonly used \( n \) (volume air changes per hour), by accounting for \( H \), the mean height of the house:

\[
    n(h^{-1}) = \frac{F_{\text{vent}} \text{ (ms}^{-1}) \cdot 3600 \text{ (s h}^{-1})}{H \text{ (m)}} \tag{1}
\]

The maximal carbon assimilation rate depends on all other conditions (for instance on whether temperature or radiation is limiting) and crop size, whereas the ventilation rate \( F_{\text{vent}} \) increases with the opening surface and with the wind speed. The one design element that can easily be adapted is the amount of opening, which must be sufficient to warrant enough ventilation flow such is required (in the prevailing conditions) by a fully developed crop (LAI ≥ 4).

Obviously, there are other effects of ventilation capacity that may have a (limited) bearing on the net assimilation rate. For instance, since vapour removal is enhanced, the crop transpiration increases with ventilation (Fig. 1b), which has a cooling effect on the canopy (Fig. 1c). What is worth noticing, however, is that the combined effect of these factors on biomass produced (Fig. 1a), has the trend of “law of diminishing return” with a rather sharply defined value beyond which there is little gain in increasing ventilation capacity further, regardless of different canopy size (LAI). Since increasing ventilation capacity has costs associated (the construction must be stronger) and large openings are more difficult to handle, it seems reasonable (although we did not make a serious cost-benefit analysis) to regard this value as “optimal”. In our particular conditions it would seem that the optimal capacity is around 0.3 ratio of opening area to ground area, to warrant enough ventilation flow required (in the prevailing conditions) by a fully developed crop.

Effects of LAI on Crop Biomass Production

Increasing leaf area increases light interception (and thus photosynthetic capacity), but increases as well maintenance respiration. Mutual shading among the leaves ensures that adding a leaf to a dense canopy adds very little to light interception whereas respiration increases in proportion to biomass. By displaying the balance of these effects, Fig. 2a shows that there is a LAI value where biomass production is maximal. In our case, canopy biomass production increases fast with LAI, when LAI is below 3, and then slowly approaches to the maximum value at LAI = 4. Afterwards, biomass production decreases with the increase of LAI (Fig. 2a). Fig. 2b shows that with a LAI above 4, the temperature of both the inside air and the canopy become lower than outside air temperature. From both the biomass production and the greenhouse microclimate point of view, a suitable size of a cucumber crop canopy would be the one with a LAI at least 4 under the summer climate conditions of subtropical China.

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DISCUSSION

What matters for a greenhouse crop is whether the ventilation flow is able to carry enough CO₂ to replace net assimilation. Since greenhouse ventilation rate, \( F_{\text{vent}} \), increases with greenhouse opening area and wind speed, once potential assimilation rate is given, the optimal ratio of greenhouse opening area to ground area depends on the average wind speed of the site. However, since the ratio of greenhouse opening area to ground area strongly depends on greenhouse type, and the volume exchanged depends very much from the position of the openings (Pérez Parra et al., 2004), volume of air exchanges per hour is a more general term to express greenhouse ventilation capacity. In this study, the ratio of greenhouse opening area to ground area necessary to warrant carbon dioxide required by a fully developed crop, was determined to be 0.3, corresponding to about 40 volume of air exchanges per hour (calculated according to Eq. (1) and Fig. 1). This value is close to the minimum 45 volume of air exchanges per hour recommended by the American Standard (Montero and Anton, 2000).

For a smaller canopy (LAI<2), the CO₂ assimilation is smaller (Fig. 2a) and less ventilation would be necessary. However, greenhouse air temperature would get too high, since the evaporative cooling due to canopy transpiration would be small. Fig. 2b shows that with 26 volume of air changes per hour, it is in the greenhouse warmer than outside, when canopy LAI is below 2. This indicates that with a crop canopy LAI<2, the optimal greenhouse ventilation capacity (needed to maintain the greenhouse not warmer than outside) would be above 26 volume of air changes per hour, in the studied area.

CONCLUSIONS

The main result of this study is that many local climate factors must be taken into account for an optimal management of greenhouse design, crop and climate, so that knowledge about “good practice” in a place may be of little use somewhere else. By analyzing the separate effect of a limited number of possible actions, we have shown that a greenhouse climate simulator is a good tool for selecting the most appropriate manipulations in view of the prevailing conditions in a given place.

In particular, we have shown that when solar radiation is the factor limiting production for a significant fraction of the time, even in summer, rapid release of the energy load is to be preferred to reduction of it. In addition, in the absence of misting or fogging, evaporative cooling should be ensured by maintaining the crop at the largest size that is compatible with balancing maintenance respiration with assimilation.

With respect to the particular case analyzed in this study (summer climate conditions in subtropical China), the following specific conclusions can be extracted:

1. About greenhouse design: balancing the greenhouse construction costs and crop growth, the ratio of roof opening area to greenhouse floor area of a Venlo-type greenhouse should be about 0.3. The optimal greenhouse ventilation capacity to warrant enough ventilation flow required by a fully developed crop is about 40 volume of air changes per hour.

2. About crop management: both in view of biomass production and of the cooling effect, a crop canopy should have a LAI around 4.

ACKNOWLEDGEMENTS

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Literature Cited
Tables

Table 1. Mean climatic values for the months of July and August (Avignon and Shanghai 1960-1990, Almeria last 10 years).

<table>
<thead>
<tr>
<th></th>
<th>Avignon</th>
<th>Almeria</th>
<th>Shanghai</th>
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<tbody>
<tr>
<td>Latitude</td>
<td>46 °N</td>
<td>36.5 °N</td>
<td>31 °N</td>
</tr>
<tr>
<td>Temperature (July-Aug) mean 24 h (°C)</td>
<td>22.5</td>
<td>25.5</td>
<td>27.8</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>62.5</td>
<td>66.2</td>
<td>81</td>
</tr>
<tr>
<td>Global radiation (MJ m⁻² d⁻¹)</td>
<td>22.5</td>
<td>23</td>
<td>15</td>
</tr>
<tr>
<td>Mean wind speed (m s⁻¹)</td>
<td>3.1</td>
<td>2.2</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 2. Outside weather conditions (mean values of July 15th to August 15th, 2002).

<table>
<thead>
<tr>
<th>Tmax(°C)</th>
<th>Tmin(°C)</th>
<th>VPDmax(kPa)</th>
<th>VPD9-18hr(kPa)</th>
<th>VPDMin(kPa)</th>
<th>Rₜ(MJm⁻²d⁻¹)</th>
<th>U (m/s)</th>
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</thead>
<tbody>
<tr>
<td>31.1</td>
<td>24.6</td>
<td>1.64</td>
<td>1.27</td>
<td>0.35</td>
<td>15</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Tmax, Tmin, VPDmax, VPDmin, VPD9-18hr are mean daily maximum and minimum air temperature, saturated vapour pressure deficit and daytime (9:00 to 18:00) mean air vapour pressure deficit outside of greenhouse at 1.5 m height, respectively. Rₜ and U are mean daily total global radiation and wind speed outside greenhouse at 2.0 m height, respectively.

Figures

Fig. 1. Simulated canopy biomass production (a) and canopy transpiration (with canopy LAI=4) (b) accumulated, and daily mean greenhouse air and canopy temperature (with canopy LAI=4) (c) over the simulation period (July 15 to August 15, 2002) with different ratio of roof opening area to greenhouse floor area or daily mean number of (greenhouse) air exchanges (air temperatures for heating at daytime and nighttime are set to be 19 and 15°C, respectively).
Fig. 2. Simulated canopy gross photosynthesis, biomass production and respiration accumulated (a), and daily mean air and canopy temperature (b) over the simulation period (July 15 to August 15, 2002) with different LAI (air temperatures for heating at daytime and nighttime are set to be 19 and 15°C, respectively and the ratio of roof opening area to greenhouse floor area is 0.3).