Simulation of Greenhouse Management in the Subtropics, Part I: Model Validation and Scenario Study for the Winter Season

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Adaptation of greenhouse climate management strategy to local climatic conditions is very important for the improvement of resource use efficiency of greenhouse crop production. The objective of this study was to explore alternatives to the existing Venlo-type greenhouse climate control policy under Chinese subtropical climate conditions, through simulation analysis using the Greenhouse Process (KASPRO) model. Experiments were carried out in a Dutch Venlo-type glasshouse on a farm in Shanghai (31°31′N, 121°41′E), to collect climate and crop data to validate the model. The results show that using outside hourly weather data as inputs, the KASPRO model generally gives satisfactory predictions of greenhouse air temperature and humidity, and of canopy transpiration rate under both summer and winter climate conditions for subtropical China. After the model validation, scenario studies were carried out to investigate the possible responses of crop biomass production and energy consumption to different nighttime and daytime air temperature set points and canopy size based on leaf area index (LAI), under the winter climate conditions typical of subtropical China. The scenario analysis shows that, during winter, the highest biomass production is achieved when the daily mean air temperature in the greenhouse is 19.7 °C, which is realised when day and night air temperature set points are 23 and 18 °C, respectively. The highest energy use efficiency for biomass production is achieved when daily mean air temperature in the greenhouse is 18 °C, which is realised by setting the set points of air temperature at 19 and 15 °C, respectively. During winter, crop biomass production reaches the maximum at a LAI of 3. The energy consumption increases with the canopy LAI. It is concluded that both from the biomass production and energy saving point of view, an air temperature set point of 19 °C for daytime and 15 °C for nighttime and a canopy LAI of 2–3 provides the most energy-efficient conditions for greenhouse cucumber crop production under the winter climate conditions in subtropical China.

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1. Introduction

In China, protected horticulture has developed rapidly in the past 20 yr, along with the general economic development of the country and an enhancement of standards of living. In south-east China, the most developed and populated area in the country, where land resources are limited and the market capacity for horticultural products is very high, greenhouse crop production has been greatly promoted in the past 10 yr, along with rising expectations for high output and high efficiency of land use. The vast majority of greenhouses in China consist of traditional, low-investment, non-heated, plastic-covered shelters. However, modern greenhouses equipped with computerised climate-control systems already cover over 200 ha and this is steadily increasing. Most of those high-investment greenhouses were imported (largely from Europe) as show-cases of modern agriculture. In fact, few of such showcase greenhouses have been
Greenhouse climate simulation models quantitatively describe the relations and the interactions between greenhouse crop processes (photosynthesis and transpiration) and climate, accounting for the effects of greenhouse structure, physical properties of cover materials, outside weather conditions, and action of controllers on greenhouse microclimate. Therefore, such a model can serve for the optimisation of greenhouse design, climate and crop management. Research on energy balance and process-based greenhouse climate simulation, and its applications to greenhouse climate control was conducted in the early 1980s (Bot, 1983; Udink ten Cate, 1983). Over the past two decades, the greenhouse simulation research by various authors has contributed to our understanding of the physical aspects of greenhouse climate such as light transmission (Kurata et al., 1991; Pieters & Deltour, 1997; Boulard & Wang, 2000); ventilation (De Jong, 1990; Boulard & Baille, 1995; Boulard et al., 1997, 1999; Wang, 1988); and eco-physical processes in the greenhouse such as crop transpiration (Stanghellini, 1987; Boulard & Wang, 2000); and photosynthesis (Gijzen, 1992; Chalabi & Fernandez, 1994; Nederhoff & Vegter, 1994). Based on greenhouse energy and mass balances, De Zwart (1996)

### Notation

- **A<sub>SL</sub>** specific leaf area, m<sup>2</sup> g<sup>-1</sup>
- **C** concentration of CO<sub>2</sub> in greenhouse air, ppm
- **c** fraction of sky covered by cloud
- **e** air vapour pressure, Pa
- **F<sub>LV</sub>** fraction of leaves, i.e. the ratio of leaf dry weight to total plant dry weight
- **H<sub>R,max</sub>** daily maximum relative humidity outside the greenhouse at 1.5 m height, %
- **H<sub>R,min</sub>** daily minimum relative humidity outside the greenhouse at 1.5 m height, %
- **I<sub>dir</sub>, I<sub>diff</sub>** direct and diffuse solar radiation, Wm<sup>-2</sup>[leaf]
- **I<sub>LA</sub>** leaf area index
- **I<sub>s</sub>** mean shortwave radiation flux absorbed by crop canopy, Wm<sup>-2</sup>[leaf]
- **k<sub>s</sub>** canopy light extinction coefficient
- **Q<sub>10</sub>** rate of maintenance respiration increase for every 10°C temperature rise
- **R<sub>d</sub>** daily total global radiation, MJ m<sup>-2</sup> d<sup>-1</sup>
- **r<sub>c</sub>** canopy resistance to water vapour transfer, s m<sup>-1</sup>
- **r<sub>min</sub>** minimum possible canopy resistance, s m<sup>-1</sup>
- **T** temperature, °C and K
- **T<sub>set,day</sub>** daytime air temperature set point, °C
- **T<sub>set,night</sub>** nighttime air temperature set point, °C

### Subscripts

- **air** greenhouse air below the thermal or shade screen
- **can** canopy
- **cov** greenhouse cover
- **flr** greenhouse floor
- **low** lower pipe
- **max** maximum
- **min** minimum
- **out** air outside the greenhouse
- **scr** thermal or shade screen
- **sky** sky outside the greenhouse
- **soil** soil layer 1–7
- **top** greenhouse air above the thermal or shade screen
- **upp** upper pipe

### Economic Success

Economically successful in China. The major causes for the discrepancy in performance of these production systems in Europe and in China have been identified as (1) significant climatic differences between China (particularly in the subtropical regions) and the countries where the systems were developed, and (2) the lack of experience of local growers for the complex management needed to operate these greenhouses. With respect to climate, China has the harshest type of monsoon climate, characterised by extremely cold winters and hot and wet summers. In Shanghai (31.3°N, 121.4°E), for instance, the 30 yr (1961–1990) average mean and minimum temperature in January, and average mean and maximum temperature and mean relative humidity in July are 3.7, 0.5, 27.8, 31.6°C, and 85%, respectively (the corresponding values of Holland are 5.1, 0.4, 12.9, 21.3°C, and 79%). The ‘wet climate’ in summer limits the use of evaporative cooling. The adaptation of greenhouse climate and crop management measures to the local climate conditions is of prime importance not only for the efficient use of the existing investment in the modern greenhouses in China but also for the improvement of resource use efficiency of greenhouse crop production.
proposed a whole greenhouse-system simulation model, Greenhouse (KAS, in Dutch) Process (KASPRO) model, for the Venlo-type greenhouse. A whole greenhouse thermal model ‘Gembloux Dynamic Greenhouse Climate Model’ (GDGCM) was also reported in 1997 (Pieters & Deltour, 1997). Gary et al. (1998) developed the SIMULSERRE model which serves as an education software, simulating the greenhouse crop system. The KASPRO model also includes the climate controller and the parameterisation of the behaviour of the controller is very similar to what happens in commercial greenhouse climate control. This makes it easy to take into account the typical ways in which growers use their greenhouse and climate control equipment. In addition, the sub-model for crop potential growth simulation incorporated into the KASPRO model to calculate the greenhouse CO₂ balance makes the KASPRO model suitable as a tool to judge the perspectives of new developments in greenhouse construction and climate control with respect to both energy saving and crop production.

The objective of this study is to explore possible alternatives to the existing Venlo-type greenhouse climate control policy under Chinese subtropical climate conditions, through simulation analysis using the KASPRO model. Before this, the model had to be validated at least for the main three different types of weather in Shanghai (winter, dry summer, and wet summer). Experimental data were collected during two summers (2001 and 2002) and one winter (2002) to validate the model. After confidence was established in the accuracy and reliability of the model, scenario studies were carried out to investigate the possible responses of crop biomass production and energy consumption to different nighttime and daytime air temperature set points and canopy size.

2. Materials and methods

The experiments were carried out in a Dutch Venlo-type glasshouse on a farm in Shanghai (31.3°N, 121.4°E) during two summers (from August 14 to 19, 2001 and from June 24 to July 12, 2002) and one winter (January 27–February 5, 2002). The greenhouse was composed of 26 spans, each 3.2 m wide in the east-west direction, with a north-south length of 55 m. The heights of gutter and ridge were 4 and 4.8 m, respectively. There were 14 ridge ventilators on each of the east and west sides of the roof, respectively. Each window area was 1 m (length) × 0.5 m (width) with a fully open height of 0.4 m. The ground surface of the greenhouse was covered with plastic film, with the exception of a 2.5 m wide, concrete path situated along the north wall. The cucumber (Cucumis sativus L. cv printo) crop was planted in trays with perlite substrate. The crop was at the harvesting stage during the experimental periods. Drip irrigation was used for crop fertigation.

2.1. Modelling approach

2.1.1. Model description

The Greenhouse Process (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 state variables and boundary conditions in the KASPRO model are shown in Fig. 1. Full details of the model can be found in De Zwart (1996).

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 radiative heat exchange processes are computed from the Stefan–Boltzman equation, taking into account the aspect factors and the emission and transmission coefficients of the radiating surfaces: the greenhouse cover; the inside thermal or shade screen; the upper heating pipes; the canopy; the lower heating pipes; and the greenhouse floor. The convective heat exchange between all the surfaces is calculated using the standard heat exchange theory.

The climate controller of KASPRO enables climate management by means of heating, ventilation, de-humidification, moistening, shading, artificial illumination and carbon dioxide supply. The model also describes the behaviour of the boiler, short-term and seasonal heat storage facilities, co-generation of heat and electricity and heat pumps. However, in view of the facilities of the experimental greenhouse, only heating, ventilation, carbon dioxide supply and boiler are simulated in this study.

All controllers are proportional. The control of heating is performed through daytime and nighttime set points of temperature, below which the heating system is switched on. The temperature in the house is allowed to exceed that, until the set point of ventilation is reached, where the windows are opened (25% opening for 1 °C temperature excess). In addition, both heating and ventilation set points are raised whenever sun radiation exceeds a given value. Windows are open (disregarding temperature set points) whenever humidity inside the greenhouse exceeds a set point (95% for winter and 85% for summer, in our case, 25% opening...
for 1% relative humidity excess). In this paper, reference to temperature set points denotes the heating set point. The ventilation set point was constantly set 1 °C higher and the radiation allowance was 2 °C for winter and 0 °C for summer at 50 W m$^{-2}$.

2.1.2. Estimation of sky temperature

The KASPRO model needs sky temperature $T_{sky}$ as an input. This is seldom routinely measured and empirical formulas have been proposed, for instance by Monteith (1973): 

$$T_{sky} = ((1 - c)e_{sky, clear}T_{out}^4 + c(T_{out}^4 - 9/\sigma))^{0.25}$$  \hspace{1cm} (1)

$$e_{sky, clear} = 0.53 + 0.006e_{out}^{0.5}$$  \hspace{1cm} (2)

where: $e_{sky, clear}$ is the emissivity of clear sky, dimensionless; $T_{out}$ the air temperature outside the greenhouse in K; $e_{out}$ the air vapour pressure outside the greenhouse in Pa; $c$ the fraction of sky covered by cloud and $\sigma$ the Stefan–Boltzmann constant ($= 5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$). For the purposes of this study, sunshine percentage was used to estimate the cloud cover. There is little variation of the relevant climate factors during a year in Shanghai: the yearly average vapour pressure is 1.65 kPa with a variation from 1.56 to 1.69 kPa from winter (January and February) to summer (July and August) and the average value of sunshine fraction is 0.47, with a range of 0.40 to 0.57. Therefore, an estimate was used based on the yearly means of air temperature (16 °C), vapour pressure, and the sunshine fraction, which result in an estimated sky temperature of about 8.7 °C lower than the air temperature according to Eqs (1) and (2). Given the roughness of this estimate, $T_{sky} = T_{out} - 9$ was used in this study.

2.1.3. Canopy resistance to water vapour estimation

During daytime, the canopy resistance $r_c$ to water vapour transfer was estimated according to a simplification of the model proposed for tomato by Stanghellini (1987)

$$r_c = r_{min}F_l[\gamma(CO_2)]$$  \hspace{1cm} (3)

$$r_l = (I_s + 4.3)/(I_s + 0.54)$$  \hspace{1cm} (4)

$$\eta(CO_2) = 1 + 6.1 \times 10^{-7}(C - 200)^2$$  \hspace{1cm} (5)

where: $r_{min}$ is the minimum possible canopy resistance, here taken to be 82-0 s m$^{-1}$ according to Stanghellini (1987); $I_s$ is the mean shortwave radiation flux absorbed by the canopy in W m$^{-2}$[leaf]; $C$ is the CO$_2$ concentration of greenhouse air in volume ppm. At night, a constant $r_c$ value of 658.5 s m$^{-1}$ (according to Stanghellini,1987) was used in this study.

2.1.4. Estimation of canopy biomass using leaf area index

The crop biomass simulation module in KASPRO is based on the model described by Goudriaan and van Laar (1994). Actual biomass of indefinite growth fruit vegetable crops does not accumulate in the same way as with one-harvest field crops, but oscillates throughout the harvest season due to multiple harvests. This creates a problem for the estimation of canopy maintenance respiration, in the crop biomass simulation module. In practice, it is easier to do non-destructive measurements of leaf area than of biomass. If leaf area index (LAI) data are available, biomass can be estimated through the relationship between dry matter.

![Fig. 1. State variables and boundary conditions in the KASPRO model.](image-url)
and LAI as follows:

\[ I_{LA} = A_{SL} \times W_L \]  
\[ W_L = F_{LV} \times W_T \]  
\[ W_T = \left( \frac{1}{A_{SL} \times F_{LV}} \right) \times I_{LA} \]

where: \( I_{LA} \) is the LAI; \( A_{SL} \) is the specific leaf area in \( m^2 g^{-1} \); \( W_L \) is the leaf dry weight in \( g m^{-2} \); \( F_{LV} \) is the ratio of \( W_L \) to the total biomass \( W_T \) (\( F_{LV} = W_L/W_T \)).

The specific leaf area (SLA) and \( F_{LV} \) vary with crop development stage. Since the early harvesting stage is the most vigorous growth period of cucumber crops, the crop is very sensitive to the greenhouse microclimate conditions during this period. Therefore, for the scenario analysis in this study, the responses of crop biomass production to different climate management strategies under subtropical winter climate conditions were investigated for a cucumber crop at the early harvesting stage. According to our destructive measurements in this stage (Table 1), a value for \( W_T \) of 0.052 \( I_{LA} \) \( kg m^{-2} \) was used to estimate the biomass for the calculation of canopy maintenance respiration in this study. Values of the other parameters of the crop biomass simulation module are listed in Table 2.

In the KASPRO model, the crop growth module simulates potential biomass production, that is the production determined by solar radiation and temperature without water and nutrient stress and pest infection. The growth of the experimental crop was far from this 'ideal', due to the mildew infection and the fact that mismanagement of water and nutrition happened occasionally; therefore, the potential biomass production module could not be validated.

2.2. Model validation

2.2.1. Experimental measurements

The outside air temperature, air humidity, wind speed and global radiation were automatically monitored by the greenhouse computer control system. The ranges of the outside weather conditions during the experimental periods are listed in Table 3. Inside the greenhouse, the system monitored air temperature and humidity at 1.5 m height in the middle of the greenhouse, \( CO_2 \) concentration, heating pipes temperature, and the opening degree of the greenhouse ventilation windows.

The crop transpiration rate was measured by weighing a tray with three plants, using an electronic balance every 30 min, from 06:30 to 18:00 during summer, and from 07:30 to 17:00 during winter. Since water loss caused by evaporation from the perlite substrate surface was very small, the weight change of the tray plants was regarded as the water loss caused by crop transpiration. The measurement error was less than 5 g.

### Table 1

**Cucumber (Cucumis sativus L. cv printo) crop information**

<table>
<thead>
<tr>
<th>Date</th>
<th>Development stage</th>
<th>Crop height, m</th>
<th>( k_s^* )</th>
<th>LAI</th>
<th>( F_{LV}^* )</th>
<th>SLA, m² g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>14–19 Aug 2001</td>
<td>103–108 days after planting</td>
<td>2.3</td>
<td>1.1</td>
<td>2.56</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>27 Jan–5 Feb 2002</td>
<td>79–88 days after planting</td>
<td>1.6</td>
<td>0.8</td>
<td>1.0</td>
<td>0.59</td>
<td>0.0326</td>
</tr>
<tr>
<td>24 Jun–12 Jul 2002</td>
<td>136–154 days after planting</td>
<td>2.3</td>
<td>1.1</td>
<td>1.5</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

*Canopy light extinction coefficient.

*Canopy leaf area index.

\( k_s \) Fraction of leaves, i.e. the ratio of leaf dry weight to total plant dry weight.

**Table 2**

<table>
<thead>
<tr>
<th><strong>Leaf photosynthesis</strong></th>
<th><strong>Maximum rate of photosynthesis</strong></th>
<th>40 ( \mu )mol ([CO_2]) m⁻² s⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Maintenance respiration</strong></td>
<td><strong>Respiration rate of whole plant at 25 °C</strong></td>
<td>0.015 ( g ) ([CO_2]) g⁻¹[DM]</td>
</tr>
<tr>
<td></td>
<td><strong>Temperature effect on respiration ( Q_{10} )</strong></td>
<td>2</td>
</tr>
<tr>
<td><strong>Dry matter production</strong></td>
<td><strong>Assimilate requirement for formation of dry matter (DM)</strong></td>
<td>1.15 ( g ) ([CH_2O]) g⁻¹[DM]</td>
</tr>
</tbody>
</table>

* \( Q_{10} \) value of 2 indicates that the rate of maintenance respiration doubles for every 10-degree temperature rise.
transpiration rate was then calculated from the weight change of the tray plants in the time interval, accounting for the plant density in the greenhouse.

The canopy extinction coefficient \(k_s\) and LAI were measured on the starting day of the first two experimental periods (summer 2001 and winter 2002) and twice (beginning and mid-way) during the third experimental period (summer 2002), using a canopy analyser (AccuPAR). During each measurement day, the extinction coefficient for photosynthetically active radiation (PAR), \(k_s\) and LAI were measured three times at 09:00, 12:00 and 15:00, respectively, with five replicates each time. The average values of the measurements were used as the canopy extinction coefficient and LAI. The AccuPAR estimate for LAI was checked through concurrent destructive measurements on three plants, on January 27, 2002. The sampled plants were also used to determine the crop biomass, organ dry weight and specific leaf area. Information about the crop during the three experimental periods is listed in Table 1.

2.2.2. Procedures

The hourly outside weather data, the estimated sky temperature outside the greenhouse, the canopy light extinction coefficient \(k_s\) and the LAI measured during the three experimental periods (Table 1) were input to the KASPRO model. The greenhouse air temperature and the vapour pressure deficit (VPD) at the height of 1.5 m and the canopy transpiration data measured during the three experimental periods (Table 1) were used to validate the model.

2.3. Scenario analysis

Using hourly outside weather data (2002) as input, the KASPRO model was run for the coldest period of the year (from January 20 to February 20), with day and night temperature set points ranging between 13–25 and 13–20 °C, respectively, for the investigation of the effects of day and night temperature set points on crop growth and energy consumption. To investigate the effects of LAI on crop growth and energy consumption, different values of LAI ranging from 1 to 6 were used as an input to run the KASPRO model.

3. Results and discussion

3.1. Model validation

3.1.1. Air temperature inside the greenhouse

The coefficient of determination \(r^2\) and the standard error (SE) between simulated and measured results based on the 1:1 curve fitting (i.e. the curve fitting equation: \(y = x\)) are listed in Table 4. The simulated time course of air temperature inside the greenhouse followed well that of the measured results, in both summer and winter (Fig. 2). The largest difference between the simulated and the measured air temperature inside the house occurred at midday on sunny days. The maximum difference reached about 5 °C on a day with a sudden change of solar radiation at noontime during the rainy period (June 25, 2002). This indicates that the KASPRO model responds to the sudden extreme change of solar radiation faster than the greenhouse air.

3.1.2. Vapour pressure deficit inside the greenhouse

Figure 3 and Table 4 show that the KASPRO model gave the best predictions of the vapour pressure deficit (VPD) inside the house during the rainy summer period (June 24–July 12, 2002). During the drier summer period (August 2001), the predicted time course of the VPD inside followed the measured one as well, but with a bigger prediction error (SE = 1.67 g m\(^{-2}\)) [Fig. 3(a) and Table 4]. In the winter, the model did not give such good predictions of VPD inside the greenhouse as it did in summer. The effect of condensation on the greenhouse cover upon humidity within the greenhouse becomes stronger when there is no ventilation. The condensation

<table>
<thead>
<tr>
<th>Date</th>
<th>Daily air temperature(^*), °C</th>
<th>Daily relative humidity(^*), %</th>
<th>Total global radiation</th>
<th>Mean daily wind speed(^*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum ((T_{max}))</td>
<td>Minimum ((T_{min}))</td>
<td>Maximum ((H_{max}))</td>
<td>Minimum ((H_{min}))</td>
<td>((R_d), \text{MJ} \text{m}^{-2} \text{d}^{-1})</td>
</tr>
<tr>
<td>27 Jan–5 Feb 2002</td>
<td>7.1–12.8</td>
<td>−0.6–4.7</td>
<td>76–96</td>
<td>16–61</td>
</tr>
<tr>
<td>24 Jun–12 Jul 2002</td>
<td>21.7–32.4</td>
<td>20.1–24.0</td>
<td>82–94</td>
<td>38–91</td>
</tr>
</tbody>
</table>

\(^*\)Outside the greenhouse at a height of 1.5 m.

\(^*\)Outside the greenhouse at a height of 6.0 m.
rate depends obviously on the greenhouse cover temperature, which in turn depends very much on the sky temperature. The roughness of the sky temperature estimate may be the major reason why the KASPRO model gives a relatively larger VPD estimate error in winter than in summer.

### Table 4
The coefficient of determination $r^2$ and the standard error (SE) between simulated and measured results based on 1:1 curve fitting (curve fitting equation: $y = x$)

<table>
<thead>
<tr>
<th>Date</th>
<th>Air temperature</th>
<th>Vapour pressure deficit</th>
<th>Canopy transpiration rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r^2$</td>
<td>SE, °C</td>
<td>$r^2$</td>
</tr>
<tr>
<td>14–19 Aug 2001</td>
<td>0.89</td>
<td>1.1</td>
<td>0.73</td>
</tr>
<tr>
<td>27 Jan–5 Feb 2002</td>
<td>0.80</td>
<td>1.5</td>
<td>0.49</td>
</tr>
<tr>
<td>24 Jun–12 Jul 2002</td>
<td>0.80</td>
<td>1.5</td>
<td>0.91</td>
</tr>
</tbody>
</table>

![Graph showing air temperature in the greenhouse for the three experimental periods](image-url)
3.1.3. Canopy transpiration

The simulated and measured canopy transpiration rate agreed well in both summer and winter (Fig. 4). The model gave better predictions of canopy transpiration rate in winter and in the rainy period of summer (late June–middle July) than in the dry period of summer (August, 2001), when the simulated canopy transpiration rate was higher than the measured result [Fig. 4(a)]. This might be attributed to the heat stress the plants suffered before the experiment in August 2001 (from mid-July to early August, the maximum air temperature outside was continuously over 30°C for about 2 weeks), a factor not accounted for by the stomatal resistance model.

The results mentioned above indicate that using weather data outside the greenhouse as inputs, the KASPRO model gives reasonable predictions of greenhouse microclimate, not only for the Dutch weather conditions for which it was originally developed, but also for the much more extreme weather conditions found in subtropical China.

3.2. Scenario analysis

3.2.1. Effects of day and night temperature set point on crop biomass production in winter

Figure 5(a) shows that at a given night temperature set point $T_{\text{set,night}}$, the potential biomass, accumulated over the simulated period, increased with the increase of day temperature set point $T_{\text{set,day}}$ until a maximum after which biomass production decreased slowly with a further increase of $T_{\text{set,day}}$. This is caused by the fact
that at high temperatures, the respiration rate of the canopy increases faster than its gross photosynthesis rate does. The highest biomass production occurred when the daily mean air temperature inside the greenhouse was 19.7°C which was realised with $T_{\text{set,day}}$ of 23°C and $T_{\text{set,night}}$ of 18°C.

3.2.2. Effects of day and night temperature set point on energy consumption in winter

During the simulated period, the total energy required for heating increased dramatically as long as $T_{\text{set,day}}$ was above 19°C [Fig. 5(b)]. Most greenhouse fruit crops need a daily mean temperature of 18°C for normal growth and development (de Koning, 1996). The less expensive (in terms of energy) combination that could achieve a daily mean temperature of 18°C was $T_{\text{set,day}}$ and $T_{\text{set,night}}$, respectively, 19 and 15°C [Fig. 5(b)]. In this case, the energy required for heating was about 15% lower than with the combination yielding the highest potential biomass production, whereas the potential biomass production was only about 1% lower [Fig. 5(c)]. When $T_{\text{set,day}}$ and $T_{\text{set,night}}$ were both set at 18°C, the energy required for heating was 9.7% higher and biomass production was 1% lower than that when $T_{\text{set,day}}$ was set at 19°C and $T_{\text{set,night}}$ at 15°C. In the Venlo-type greenhouses in Shanghai, however, the day

![Fig. 4. Time course of measured (——) and simulated (—) canopy transpiration rate for the three experimental periods](image-url)
and night temperature set points are normally set at 25 and 16°C, respectively, for cucumber crops during winter. The potential biomass production of the cucumber crop calculated with this combination was almost the same as that when $T_{\text{set,day}}$ was set at 19°C and $T_{\text{set,night}}$ at 15°C, whereas the energy consumption was about 13% higher than in the latter case. Therefore, a temperature set point of 19°C for day and 15°C for night would ensure the highest energy use efficiency for crop production under the present winter climate conditions. The calculations from this point onwards are done with this combination of set points.

In Shanghai, energy consumption is 30–40% of the total cost of greenhouse crop production (Wang et al., 1999). Therefore, the optimum of energy use efficiency is the first step toward the reduction of the cost of crop greenhouse production. However, the investigation of the economic optimum has been left out of this study due to the absence of information on biomass equivalent produce and energy cost.

3.2.3. Effect of leaf area index on energy consumption

The energy required for heating increased with LAI, but the increasing rate was faster when LAI was below 3 than that when LAI was over 3 [Fig. 6(a)]. This was because the canopy transpiration increased faster when LAI < 3 than when LAI > 3 [Fig. 6(b)]. At a fixed
greenhouse temperature set point, a bigger canopy not only requires more energy for heating (since absorption of sun radiation is limited when soil cover approaches 1, the energy required for increased transpiration must come from the heating system) but also results in a higher air humidity [Fig. 6(c)] and thus higher ventilation rates (to prevent conditions favourable to the germination of plant pathogens) and in turn, increased energy requirement. From both biomass production and energy-saving points of view, the LAI of cucumber crops should be kept in winter between 2 and 3. This is indeed usually done in commercial practice, through leaf and side shoot pruning.

4. Conclusions

Crop production using modern greenhouses is quite new in China. Greenhouse crop management is mainly based on the experience with field crops, while climate management is mainly borrowed from the European countries from where most of the Chinese modern greenhouses are imported. The simulation results of this study provide references for improving modern greenhouse climate management under subtropical winter climate conditions, with respect to maximising energy use efficiency of biomass production. Production factors, such as product quality and timing of harvest that are not yet satisfactorily understood, have been left out of this analysis. Nevertheless, a number of relevant conclusions can be drawn from this work.

(1) The KASPRO model gives reasonable predictions of the greenhouse microclimate under both winter and summer subtropical climate conditions; hence it can be a useful tool to explore possible alternatives to the existing Venlo-type greenhouse climate control policy, under such conditions.

(2) In order to maximise energy use, efficiency of biomass production in winter, daytime and nighttime heating set points require to be set at 19 and 15 °C, respectively, and the cucumber canopy LAI (leaf area index) controlled between 2 and 3.

Nevertheless, there are limitations to these results since (1) the economic optimum may not be the same as the maximum energy use efficiency; and (2) the biomass production module is not validated.

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References


Boulard T; Papadakis G; Kittas C; Mermier M (1997). Air flow and associated sensible heat exchanges in a naturally ventilated greenhouse. Agricultural and Forest Meteorology, 88, 111-119

Boulard T; Haxaire R; Lamrani M A; Roy J C; Jaffrin A (1999). Characterizing and modeling of the air fluxes induced by naturally ventilation in a greenhouse. Journal of Agricultural Engineering Research, 174, 135-144


Gary C; Tchamitchian M; Bertin N; Boulard T; Baille A; Charasse L; Rebillard A; Cardi J P; Marcelis L F M (1998). SIMULSERRE: an education software simulating the greenhouse-crop systems. Acta Horticulturae, 456, 451-458


