The Greenhouse Effect in the High Tropics of Colombia: a Modeling Approach

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Abstract

Throughout this presentation the Colombian tomato production in the high tropics is discussed as an example. The high altitude tropical climate of the Bogota plateau is characterized and the necessity for protected tomato cultivation is explained. As a consequence of the specific climate conditions in the high tropics and the climate demand of tomatoes, several adaptations to the classical Colombian plastic greenhouse, originally developed for rose and carnation, were tested. The following strategies, mainly aiming at increased greenhouse night temperatures are discussed: glass versus polyethylene, additional heating, screening, closing of the vents. The presented research methodologies heavily rely on system dynamic modeling and simulation. This methodology allows optimization of the plant-climate interaction over a vast range of different micro-climates, typically the situation that occurs in the high tropics, without extensive and expensive needs for local experimentation. It is demonstrated that the limited greenhouse effect for night time temperature buffering in Colombian plastic greenhouses is mainly due to tropical day length effects and to a lesser extent to greenhouse structures and coverage. The extreme day and night temperatures are the main problem in the optimization of the choice of specific locations for protected tomato cultivation in the high tropics. As a conclusion some perspectives for the Colombian protected tomato industry in particular and for the high altitude tropical production systems in general are presented.

INTRODUCTION

High altitude plateaus and valleys are found all over the world (e.g., Colombia, Ecuador, Peru, Bolivia, Kenya, Tanzania) at varying altitudes ranging from 1500 up to 3500 m above sea level. The Bogota plateau (5° north of the equator) is one of such locations where moderate day temperatures and cool nights represent the predominant daily climate. An average light integral of 14.4 MJ m^{-2} d^{-1} (Cooman, 2002) resembles those found in Mediterranean climates. These favorable climate conditions have allowed the development of protected horticultural production systems (Cooman and Schrevens, 2007). The main objective of using greenhouses for growing species such as tomato (*Solanum lycopersicum*) in such environment is to give some protection against cold during the night and also against adverse climate events (e.g., thunderstorms and hailstorms). Nevertheless, the success in the implementation of greenhouse tomato production systems has been limited in comparison to the well-established cut-flowers protected cultivation found in this location. The present work gives an overview of the greenhouse tomato production systems in the Bogota plateau and analyzes its actual constraints mainly related with the climate patterns and the limited greenhouse effect

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generated by the protected structures used nowadays. The first part of this study analyzes the climate conditions of the Bogota plateau. Subsequently the use of diverse climate optimization alternatives is analyzed by using a modeling approach. Finally some concluding remarks and final recommendations are given to optimize the actual production systems.

MATERIALS AND METHODS

The greenhouse climate effects in the Bogota plateau were analyzed using a dynamic systems modeling approach. Climate data coming out from several growing cycles planted in greenhouses of a local research institute (74°00’49”W; 04°53’04”N and at an altitude of 2650 m) was used to assess the greenhouse effect of the local structure. A greenhouse climate model was calibrated with these data and used to analyze the solar gain of the actual plastic greenhouse as well as some devised alternatives. This mechanistic model takes into account all energy and water vapour flows in order to estimate the energy balance of a greenhouse at a given time. The model followed the basics of Bot (1983) and was extended with the work developed by de Zwart (1996). Moreover, we did some simplifications for the heating and cooling system. The transpiration model of Stanghellini (1987) was added as a subroutine to the model. As a result the inside climate conditions are predicted. The inputs required for the model are the outside climate (i.e., diffuse, direct, PAR and IR radiation, temperature, relative humidity, wind speed and -direction) as well as the properties of the greenhouse (i.e., geographical location, structure and glazing material properties). By using this model, the performance of two cover materials were evaluated, i.e., polyethylene and glass. The model allowed the calculation of the greenhouse effect for the structures under full closure and in consequence the capacity to heat the greenhouse by radiation. This solar gain calculation is the basis for any feasibility study of greenhouse production.

The second version of the tomato growth model Tomgro (Bertin, 1993; Gary et al., 1995, 1996) was used to evaluate another two greenhouse climate optimization strategies. This photosynthesis-driven model describes the phenological development and the increase in dry matter of the different plant organs from the planting date to the end of harvest, under dynamically varying solar radiation intensities, greenhouse temperatures and CO_2 concentrations (Cooman and Schrevens, 2006). The model was calibrated for the conditions of the Bogota plateau and a detailed description of the model can be found in Cooman (2002). The first devised climate optimization strategy was to supply additional heat to the greenhouse during the night with two set-points (15 and 18°C). For the simulation exercise, night temperatures were leveled up to each one of these two set-points. It was assumed that additional heating was supplied by a central system and distributed by polypropylene hot water lines along the entire area of the greenhouse. An alternative of using a thermal screen was also studied. An average increase of 1°C during the night hours was considered as the effect of the thermal screen. It was assumed that the screen was fully extended over the entire cropping area just before sunset and then, during the morning of the next day, rolled up around 7 am. A climate input file with hourly values of global solar radiation intensity (W m^{-2}), greenhouse air temperature (°C), vapour pressure deficit (kPa) and ambient carbon dioxide concentration (ppm) was configured for each climate strategy. Tomgro simulations for each climate strategy were performed considering the following crop management practices: 250-day crop growth cycle duration, a planting density of 2.7 plants m^{-2}, plants with 10 nodes at the beginning of the simulation, an initial leaf area index of 0.473 m^2 leaf m^{-2} soil, all trusses pruned to five fruits and a greenhouse light transmission of 80% (i.e., plastic greenhouse).

RESULTS AND DISCUSSION

The greenhouse used in the Bogota plateau is defined as a multi-, wide span structure covered with a single layer polyethylene including fixed open ridges and manually adjustable side vents. This low cost greenhouse gives adequate protection against thunderstorms and evacuates efficiently the heavy rain load. This structure has been used for more than 30 years in the Bogota plateau for the cultivation of cut roses and carnations. However, as presented next, this structure is not the most suitable for growing crops with higher temperature demands such as tomatoes in the Bogota plateau.

Bogota Plateau Climate

As recorded by a local weather station during 2007, the average daily radiation integral for the Bogota plateau is 11.9 MJ m^{-2} d^{-1} with a range between 4.2 and 21.5 MJ m^{-2} d^{-1}. The average 24-h temperature was 13.5°C ranging from 10.9 to 15.5°C and with an annual precipitation of 885 mm y^{-1}. Two dry seasons and two wet seasons can be clearly distinguished throughout the year. Dry seasons are present between January-March and June-September while wet seasons are between March-April and October-December. Figure 1 presents the annual profile of total radiation and temperature for the Bogota plateau. It can be seen that limited seasonal climate differences are present during the year. Large variation in temperature in one day is the common trend under high altitude tropics condition. Due to its geographical position the difference between the longest and shortest day is only 35 min.

Greenhouse Effect in the Bogota Plateau

The climate of two selected days was used to assess the possible solar gain of the actual greenhouse used for tomato production in the Bogota plateau. The selected days were characterized as a dull day with a maximum global radiation of 600 W m^{-2} and a clear day with a maximum global radiation of 1000 W m^{-2}. For the dull day, it was shown that outside as well as inside temperatures remain the same during the night hours. The latter means that there is no heat buffer effect at all during the night due to the radiation received during the day. On the contrary, when clearer days are present the inside temperatures are higher. A limited buffer effect was quantified especially for the final hours of the day. The results of the model based scenario evaluation of solar gain between glass and polyethylene covers at full closure are presented in Figure 2. The results indicated a similar pattern for both glazing materials despite of their differences on infrared transmissivity (glass: 3%; polyethylene: 73%). Although glass has better opportunities for heat recuperation due to its optical properties, the similar length of day and night coupled to low night temperatures generate considerable nightly heat losses independent from the material type.

Greenhouse Climate Optimization Alternatives

As presented before it is a difficult task to overcome low night temperatures due to limited greenhouse effect mainly driven by the fast heat loss through the open ridges of the greenhouse. Figure 3 presents the daily temperature profiles of the climatization alternatives described in the Materials and Methods section, including the actual greenhouse design. The output of the simulations done with the Tomgro model for the actual greenhouse climate and the three proposed alternatives are shown in Figure 4. Nodes number and mature fruit fresh weight were selected as representative output variables of the model to show the results of the devised scenarios. An improvement on crop performance was obtained when night temperatures were higher. A low cost alternative such as the thermal screen allowed the development of only two additional nodes in comparison with the current greenhouse management. In consequence, a final fruit fresh weight of 11.5 kg $plant^{-1}$ was simulated which represented an increase of 3.8% in comparison with the reference situation.

As expected, addition of heating during the night exerted a stronger climate effect and increments on growth were higher than those simulated with the thermal screen. Final number of nodes for the scenario with heating at 15°C was 99 nodes while at 18°C the final nodes were 103. Higher accumulations of dry matter were simulated for those scenarios, yielding a final fruit fresh weight of 13.1 kg $plant^{-1}$ for heating at 15°C and 14.8 kg $plant^{-1}$ for heating at 18°C. With respect to the reference situation, these results implied increments in fruit weight of 17.6 and 33.7%, respectively.

The results obtained by using the modeling approach demonstrated the feasibility of greenhouse tomato production in the high altitude tropics. However these results have to be analyzed in its proper context. The Tomgro model is a potential growth and development model which means that no restrictions (e.g., water or nutrients deficiencies, diseases and plagues) are present during the cropping cycle. In reality this is not the case and the results presented here have to be contrasted against local evaluations considering technical and social constraints. Model based approaches have limits such as the necessity for verification of the results with experimental data; the higher amount of empirical knowledge involved and, for the present case, the dynamical analysis of heat balances of leaves and crops are still a major problem.

CONCLUSIONS

The present work has analyzed the actual constraints and the opportunities of the tomato production system in the high altitude tropics of Colombia (i.e., Bogota plateau). It is concluded that there is a high correlation between inside and outside climate as a result of the absence of active climate control and management. During the night low temperatures are achieved, setting this situation as the most limiting factor for high altitude tomato cropping. The main factors characterizing the climate under this geographical location are temperature and radiation which in turn, are a consequence of latitude and altitude. The use of a dynamic systems approach indicated the feasibility of protected tomato cropping in the Bogota plateau but solutions to this issue have to be found without any additional heating or construction costs. The latter implies an adaptation of overall greenhouse technology for tomato. Modification of the actual open ridge structure must be a precondition in order to be able to gain control on the climate dynamics inside the greenhouse. Addition of low cost climate strategies such as screening and forced ventilation can be an alternative to optimize the climate and reduce the inadequate behavior observed nowadays. A more drastic alternative will be to move the production towards more optimal regions with lower altitudes and higher air temperatures. In Colombia, various high mountain micro-climates can be suitable for tomato production but here also, adaptation of greenhouse and cultivation technology entails a challenge for the future.

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Figures

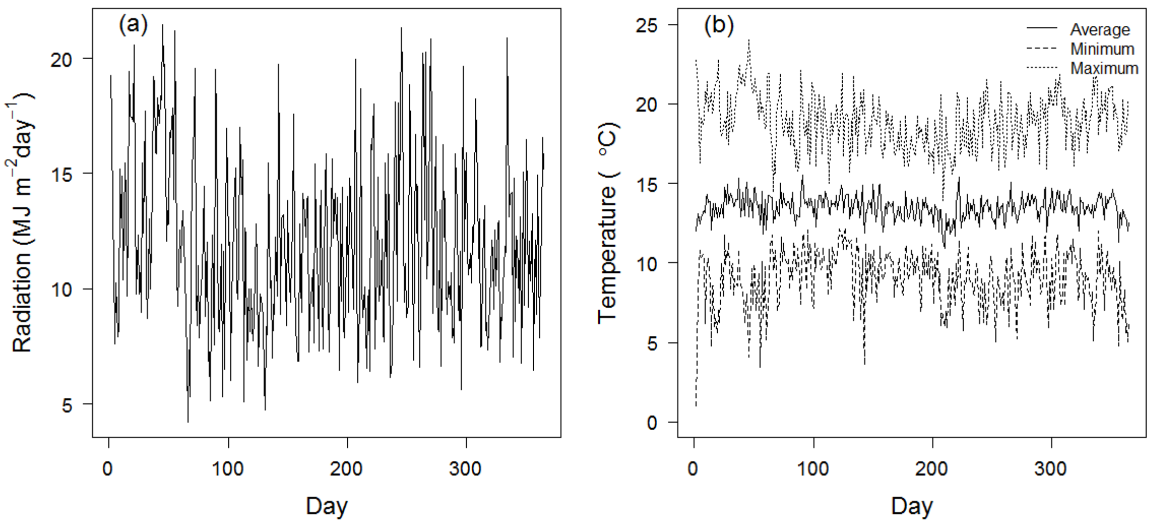

Fig. 1. Daily light integral (a) and air temperature profiles (b) throughout year 2007 for the Bogota plateau, Colombia.

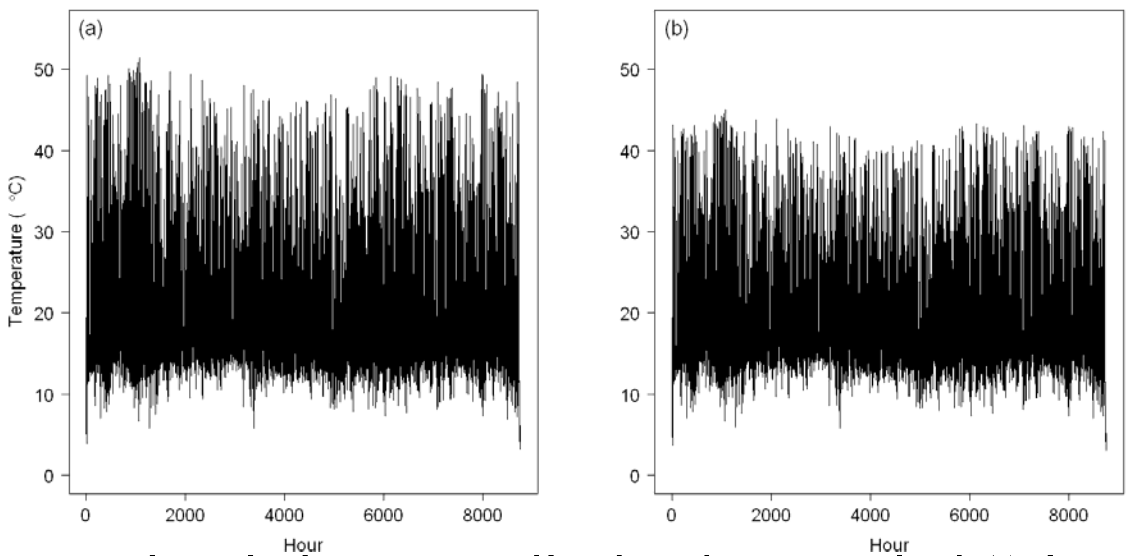

Fig. 2. Yearly simulated temperature profiles of greenhouses covered with (a) glass and (b) polyethylene under the Bogota plateau climate. The simulations in both cases were carried out for fully closed empty greenhouses.

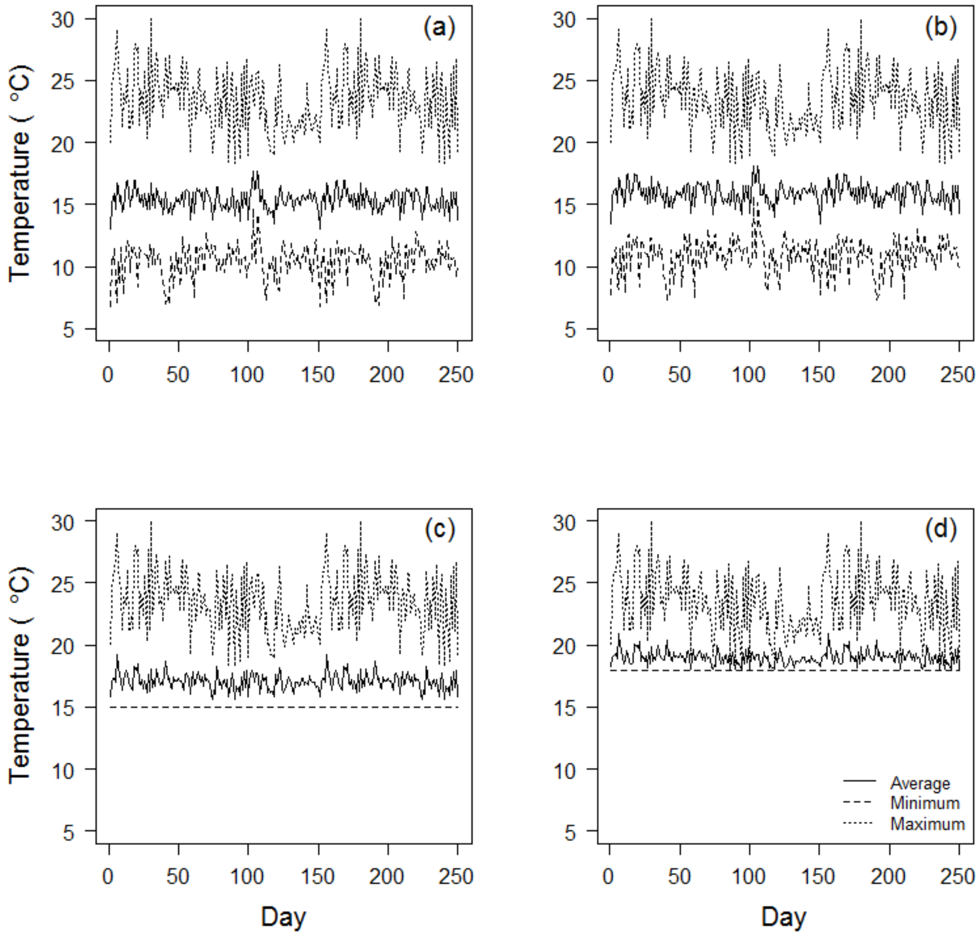

Fig. 3. Daily temperature profiles of the climatization alternatives (current greenhouse design, (a) addition of thermal screen (b) and addition of heating with set-points at 15°C (c) and 18°C (d)) used to evaluate the growth of a 250-day tomato cropping cycle in the Bogota plateau.

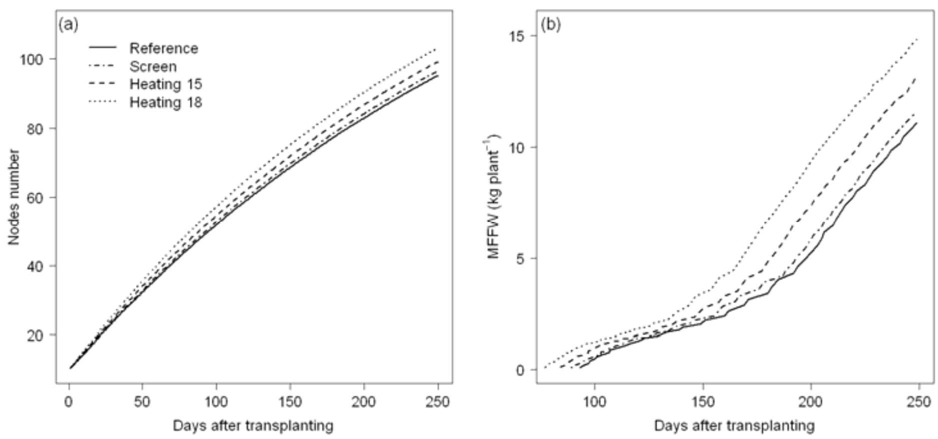

Fig. 4. Simulated (a) nodes number and (b) mature fruit fresh weight (MFFW) for a 250-day tomato cropping cycle grown under protected conditions in the Bogota plateau. The current greenhouse climate (reference) is compared against three climate optimization alternatives: thermal screen (Screen) and heating with set-points at 15°C (Heating 15) and 18°C (Heating 18).