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Use of geostatistical and crop growth modelling to assess the variability of greenhouse tomato yield caused by spatial temperature variations

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A B S T R A C T

Users of potential crop growth models have generally assumed homogenous greenhouse climate conditions for simulation purposes. Geostatistics offers the possibility to represent the spatial dependence of climate variables such as temperature distribution in greenhouses. In order to obtain insight in the relevance of temperature distribution on the performance of a crop, geostatistical and crop growth modeling tools were combined in the present work. A plastic greenhouse with the size used in commercial practices, was used to assess temperature distribution by installing a 25-sensor grid, during a 28-day measurement period. Geostatistical analyses were performed on the temperature data, previously divided in five ranges that were established as a function of solar radiation intensity. Estimated semivariograms were fitted to theoretical spherical model for posterior estimation at unsampled points by ordinary kriging method. Results of this analysis indicated an increasing temperature spatial dependence as global radiation augmented. Crop growth simulations with the Tomgro model applied to the estimated temperature distribution, quantified the faster plant development rates in the central zone of the greenhouse, resulting in plants with one additional truss and a significant higher yield, when compared to plants next to the side walls. The results of this work suggest that the location of the climate sensor station is a sensible factor when using crop simulation models for greenhouse conditions. Final predictions done by crop growth simulation models may be biased and the results cannot be generalized for the entire greenhouse area when microclimate patterns are not considered. Application of geostatistics enabled to assess temperature patterns inside greenhouse and to analyze the relationship with global outside radiation.

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1. Introduction

Crop simulation models have been applied to represent adequately growth, development and yield of a wide variety of crops (Jones and Ritchie, 1990). In some models, spatial and temporal variability of weather conditions are an important source of uncertainty when applying crop simulation models over large areas (de Wit and van Diepen, 2008). In consequence,
research efforts have been made to link crop modeling with spatially weather data to project crop production at a regional level (Yun, 2003; de Wit et al., 2005; Mo et al., 2005). These studies are based on the evidences that a large amount of physical, chemical and biologic properties in agroecosystems are variable in space, even at small distances (Sparovek and Schnug, 2001). The study and understanding of this variability has been essential for the development of precision agriculture systems (Wong and Asseng, 2006) at farm or plot level.

Most of researchers in greenhouse environment consider the climate inside a greenhouse as uniform, without differentiating volume occupied by the crop and the volume above the plants (Kittas and Bartzanas, 2007). Climate models are generally assuming well-mixed greenhouse conditions, while spatial heterogeneity is inherent to the biological and physical aspects of agricultural systems, and as a result, patchiness is the rule in the occurrence and distribution of these phenomena (Nelson et al., 1999). Geostatistics uses the understanding of statistical variation as an important source of information for improving the estimation of an attribute at unsampled locations, given a limited set of measurements. By doing so it brings major improvements to the understanding of uncertainty for spatial and temporal modeling (Burrough, 2001). To date, no previous work was found on the study of crop growth variability under greenhouse conditions, using geostatistical modeling tools combined with dynamic crop growth models. Most greenhouses present temperature gradients in vertical as well as horizontal direction (Nederhoff, 2003). Vertical temperature distribution has been analyzed for naturally ventilated greenhouses (Zhao et al., 2000) or with the objective to evaluate the effect of different heating system positions (Kempkes and van de Braak, 2000; Kempkes et al., 2000). For the present work, horizontal temperature gradients were studied by using geostatistical methods, commonly used to analyze different types of abiotic variables on horizontal planes.

The present research used the second version of the tomato growth and development model called “Tomgro” (Bertin, 1993; Gary et al., 1995, 1996), previously calibrated for high altitude tropics conditions by Cooman (2002). The Tomgro model describes the phenological development and the increase in dry matter of the different tomato plant organs from the planting date to the end of harvest, under dynamically varying solar radiation intensities, greenhouse temperatures and CO2 concentrations. Cooman and Schrevens (2007) analyzed the effect of variations in air temperature, carbon dioxide concentration and solar radiation intensity on the sensitivity of the Tomgro model. This study reported an important effect of air temperature on total leaf area, vegetative plant weight and fruit dry weight explained by the fact that in Tomgro model, temperature affects both leaf expansion and dry matter distribution.

The general objective of this study was to quantify the variability in crop growth and development of a greenhouse tomato crop by combining geostatistical and crop growth models in the high-altitude tropics. Specific objectives for the present work were to study the relationship between outside global radiation intensity and greenhouse air temperature distribution; to determine the reliability of the use of geostatistical methods to be applied as a tool for estimating horizontal temperature distribution and; to establish the relevance in terms of plant development and yield of the estimated temperature distribution inside a greenhouse.

2. Materials and methods

2.1. Experimental setup

A multispan plastic greenhouse located in the Bogota Plateau (4° 50′41″N latitude and 74° 10′09″W longitude and at an altitude of 2591 m above sea level), with a total area of 9792 m², was used to estimate temperature spatial variability. The greenhouse was composed of 18 spans, each 8 m wide in the east-west direction, with a north-south length of 68 m. The heights of the gutter and ridge were 3 and 5.3 m, respectively. The greenhouse was naturally ventilated by means of an automated roof ventilation system using roll-up windows and no heating or fog system was present. Window openings were controlled exclusively by temperature with a ventilation set-point of 20 °C for opening and 14 °C for closing.

The greenhouse contained a fully established rose crop. The decision to use temperature measurements made on a rose crop to determine the variability on the yield of a tomato crop was based on the availability of a simulation model calibrated for the local conditions and the similarities between crops. Both crops are planted in rows and have a similar height when fully established and grown in greenhouse conditions of the Bogota Plateau. Also the greenhouse types used for both crops are based on the same ventilation principle. But also particularities arise when comparing the effect of each crop on greenhouse climate. Differences in leaf area index (LAI, m² leaf blade m⁻² soil) affect the level of transpiration and thus, the cooling effect of each particular crop on greenhouse air (Katsoulas et al., 2002; Impron et al., 2008). For fully established tomato crops grown under different greenhouse climate treatments in the Bogotá plateau, Cooman (2002) found a LAI between 3.6 and 4.8 at the flowering of the first truss. The rose plants of the experimental greenhouse were planted at a density of 6 plants m⁻² and grown following the “bending technique” (Kool and van de Pol, 1996). Non-destructive measurements, done on 20 plants, allowed a LAI determination with values between 3.5 and 4.2. Due to the similar LAI values for both crops, the effect of transpiration on temperature may be assumed similar and the possible differences in climate caused by these species were neglected for the objective of the present study.

A regular and horizontal grid with rectangular cells of 20 x 22 m was situated over the experimental area. At each node, one sensor was installed, as result 25 points were placed along the whole greenhouse (one sensor per each 392 m²). No records can be found in the literature referring to an optimum number of sensors for the quantification of temperature variability within greenhouses when using geostatistics. However, Carrera-Hernández and Gaskin (2007) used 200 weather stations with the objective to analyze spatio-temporal variation of rainfall and temperature covering an area of 16,800 km². Benavides et al. (2007) used 96 weather stations to model air temperature in a mountainous region of 10,604 km².

A sensor grid was located in the upper third of the canopy which corresponded to a 1.5-m height above soil surface.
Copper-constantan thermocouples were protected from direct solar radiation by means of a white, reflecting shield. Before the experimental setup, all sensors were calibrated against ice point temperature with an accuracy of ±0.01 °C according to the procedure suggested by the manufacturer (Escort DLS, 2008). Data loggers registered air temperature on a 6-min basis during a 28-day period between December 14, 2007 and January 2008. Outside climate conditions were recorded with the use of an automated weather station.

2.2. Geostatistical analyses

For the measurement period, maximum and minimum outside global hourly radiation intensity values (I, W m⁻²) were determined and the obtained range was divided into five segments with equal bandwidth. Next, each hourly temperature dataset was classified in one of the segments, according to the hourly I at the time of measurement. Finally, all hourly values of each particular point were averaged segment by segment. As a result, five datasets of temperature distribution in the greenhouse were obtained, with one average value for each of the 28 points.

The first step of data analysis was an exploratory assessment of the collected data without considering their spatial location, in order to identify statistics of data distribution. Afterwards, the semivariogram (quantifying spatial correlation) was built for each of the five radiation intensity segments, by using the temperatures at different locations. The geostatistical analysis was performed in statistical software R (version 2.6.1.; R Development Core Team, 2007) using the geoR package (Ribeiro and Diggle, 2001).

Theoretical variograms for the dataset of each I-segment were fitted to the empirical variogram \( \gamma(h) \), assuming a spherical correlation function, according to the formula (Cressie, 1993):

\[
\gamma(h) = c_0 + c_1 \left[ \frac{3}{2} \left( \frac{h}{a} \right) - \frac{1}{2} \left( \frac{h}{a} \right)^3 \right] \quad h < a (2b) \gamma(h)
\]

\[
\gamma(h) = c_0 + c_1 \quad h \geq a
\]

where \( a (\text{m}) \) is the range of influence; \( c_0 (\text{°C}^2) \) represents the nugget; \( c_1 (\text{°C}^2) \) is the structural component of variance; \( c_0 + c_1 \) equals the sill of the semivariance, which represents the ordinary sample variance; and \( h (\text{m}) \) is the lag which is defined as the distance between data pairs that represent measurements of the same variable. The parameters of the theoretical semivariogram models were estimated by using the restricted maximum likelihood method (Farrington and Manning, 1990). From the estimated temperature values, on a regular 1 m \times 1 m grid, temperature distributions were mapped using the block ordinary kriging technique.

In order to test model fitting, two types of cross validations were performed considering measured temperatures at each position. The first validation was done with the average temperature datasets by removing each data location from the data set, and the temperature at this position was predicted using the remaining positions, for the given model. For the second validation, spatial prediction was done on each dataset coming from each one of the measurement days and applying the same procedure of the first validation. In order to test the results for both validations, observed data against estimated values were plotted and a regression line was built. Finally, the coefficient of determination was calculated in each case. The number of validations for each model depended on the number of available temperature datasets for each radiation level. Geostatistical analyses were done only considering day between 7 and 17 h, as preliminary analysis had shown fairly homogeneous microclimate conditions during the night.

2.3. Crop growth modeling

The second version of Tomgro model was used to determine the effect of greenhouse temperature distribution on plant growth and development. A detailed explanation of the model, calibration and validation for the high altitude tropics conditions and a complete description of the parameters used by the model can be found in Cooman (2002). Original code of Tomgro was written in Fortran, but a version of the model implemented into Matlab (MathWorks, 1999) was used for the present work.

A climate file with hourly values of global solar radiation intensity (W m⁻²), greenhouse air temperature (T, °C), vapor pressure deficit (VPD, kPa) and ambient carbon dioxide concentration (C_a, ppm) is required for running the Tomgro model. The required climate file was built by selecting the measured data from the sensor near the center of the greenhouse. Global solar radiation data was taken from the outside weather station. As only a 28-day measurement period was available, temperature and VPD were reproduced eight consecutive times to configure a reference climate file of 224 days. This period was established as it is representative for greenhouse tomato production practices in the Bogota Plateau. During the entire simulated growth cycle C_a was assumed at a constant level of 350 ppm.

With the objective to assess the effect of temperature variation inside a greenhouse, a particular climate file was then built for each square meter of the experimental greenhouse. For each level, differences between predicted values by kriging at unsampled positions and the reference location at the center of the greenhouse were calculated. Next, each temperature observation between 7 and 17 h within the reference climate file was classified into one of the five predefined levels for geostatistical analysis according to the solar radiation. Calculated temperature differences were added to the temperature reference values of reference climate file, and climate files were rebuilt to represent temperature variations for each square meter of the greenhouse. The remaining climate parameters were not varied as a function of the position in the greenhouse.

A total of 9792 Tomgro simulations were performed considering the following crop management practices: 224-day crop growth cycle duration, a planting density of 2.7 plants m⁻², plants with 10 nodes at the beginning of the simulation, a leaf area index of 0.473 m² leaf m⁻² soil, all trusses pruned to five fruits and a greenhouse light transmission of 80%. The output generated by Tomgro includes many plant physiological parameters and indexes but for the present work only node
number, representing plant age, and crop yield are presented and discussed. A node is interpreted as any deviation from the main stem to form either a leaf or a truss. In Tomgro, Cooman (2002) fitted a function to the node appearance rate as a function of temperature (\( \text{NAR}(T) \)), nodes \( d^{-1} \) between 10 and 28 °C, according to the following formula,

\[
\text{NAR}(T) = 0.2078 + 0.0204 \times T
\]

where \( T \) (°C) is the average 24-h greenhouse temperature. Above 28 °C, NAR(T) decreases and reaches 0 at 50 °C (Jones et al., 1991). Below 10 °C, the function declines until reaching 0 at 5 °C.

Total fruit weight in Tomgro is computed from state variables like number of inflorescences on the plant, number of inflorescences bearing fruit, number of fruits that appeared on truss number \( i \) and the development stage and the weight of fruit on position \( j \) on truss number \( i \) (Cooman, 2002). Final growth rates depend on the ratio of carbon supply to demand or source-sink ratio.

3. Results

3.1. Exploratory data analysis

The average outside temperature during data collection period is compared with the inside temperature of the greenhouse in Fig. 1. Average temperature for the outside was 12.3 °C, while average temperature inside the greenhouse was 13.3 °C. During day hours (7–17h), average greenhouse temperature was 16.5 °C, representing an increment of 1.3 °C in comparison with the condition registered for the outside. During the night, the plastic greenhouse was only 0.7 °C warmer than the outside. Average 24-h global radiation during data acquisition period ranged from 78.6 to 235.2 W m\(^{-2}\) with an average of 148.6 W m\(^{-2}\). This range of variation indicates different climate conditions among days and can be defined as a representative measurement period for the study zone. Additionally, average wind direction and speed were 175° and 0.52 m s\(^{-1}\), respectively for the data collection period. Average relative humidity was 84.4% and total rainfall for this period was 37 mm.

Descriptive statistics were calculated for each temperature dataset in order to determine the data distribution function (Table 1). Kurtosis values around 3 and skewness values close to 0 are the limits often used to define if the distribution of a dataset is close to normality (Lipschutz and Schiller, 2000). According to the results, temperature distribution for each radiation levels was close to normality, one of the desirable characteristics for geostatistical analysis.

3.2. Geostatistical analysis

The parameters for the fitted spherical theoretical semivariograms that were calculated for each of the five segments are presented in Table 2. A negligible nugget effect can be observed indicating that a small portion of temperature spatial dependence is due to experimental error. This result is confirmed by low percentages of nugget to sill ratio. This ratio, expressed as percentage, can be used to classify the spatial dependence of the studied variable (Chien et al., 1997). Percentages values between 0 and 25 reveal a strongly structure spatial dependence (Cambardella et al., 1994) and according to our results incoming global radiation is one of the intrinsic factors that determines the spatial dependence.

Increasing sill and range were observed along with increments in global radiation intensity. Higher sill values represent greater spatial temperature variability, as can be seen in fitted semivariograms (Fig. 2). Low global radiation levels are related with a more homogeneous air temperature condition inside the greenhouse. Despite of range increments as a function of radiation, the differences between absolute values at different radiation levels were proportionally lower than those observed for the sill (Table 2). At lower radiation levels, the distance which temperature at any point is correlated with another was lower than those calculated at the highest radiation levels.

Temperature ranges at unsampled positions are presented in Fig. 3. Estimated average temperature differences of no more than 1 °C were observed at radiation intensities below 170 W m\(^{-2}\) (Fig. 3a), but when the global radiation reached levels above 752.8 W m\(^{-2}\), average temperature variations were as high as 2.2 °C, as depicted in Fig. 3e. A consistent tempera-

![Fig. 1 – Daily course of average inside (\( T_{\text{in}} \)) and outside (\( T_{\text{out}} \)) temperatures and global solar radiation intensity during data acquisition period.](image-url)

### Table 1 – Descriptive statistics of greenhouse temperature as a function of outside radiation.

<table>
<thead>
<tr>
<th>Radiation level (W m(^{-2}))</th>
<th>Hourly datasets averaged</th>
<th>Mean (°C)</th>
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<tbody>
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<td>&lt;177.2</td>
<td>113</td>
<td>14.51</td>
<td>2.48</td>
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</tr>
<tr>
<td>177.2–380.9</td>
<td>78</td>
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ture distribution pattern can be observed for all the prediction maps. Higher temperatures were predicted around the center but with a little displacement to the top left zone of the greenhouse. Cooler zones were established near the greenhouse walls. The temperature differences between extreme locations, although only 1°C higher during the day, can determine differential behaviours on plant growth and development. The spatial dependence (range) increased with the increase in the solar radiation. As a consequence, the estimated temperature at a specific location is influenced by a major number of points in the space.

Temperature predictions at unsampled locations can be considered satisfactory for the fitted semivariograms and consequent kriging standard error as presented in Fig. 4. Ordinary kriging method gave similar values to those observed with no restriction when considering outside radiation levels. On average, difference between measured and predicted data was 0.3°C. For modeling purposes and in order to include microscale temperature variations inside the experimental greenhouse, the second validation carried out on original hourly data gave also acceptable results (Fig. 4b) and allowed us to incorporate this factor to T omgro model. The results for this validation indicated a difference of 0.4°C between the average datasets and the hourly measured data.

### 3.3. Plant growth and productivity

Plant development as a function of spatial temperature variability inside greenhouse is quantified by the number of nodes on the main stem at the end of the simulation period. Fig. 5a depicts spatial distribution of node number after a 224-day crop growth period. A higher node number was reached at the center of the greenhouse where temperatures were higher than in the lateral zones. A difference of 3.6 nodes plant⁻¹ was observed between the locations with the maximum and minimum final simulated values, representing a difference of 4.6%. In an ideal tomato crop, every sympodial unit consists of a stem segment with three leaves and a truss (Cooman, 2002). According to the results, the plants located in the warmer zones were able to produce an additional sympodial unit compared with the greenhouse lateral zones. In terms of productivity this means the plants in warmer zones developed one truss bearing five more fruits than the areas with lower temperatures. Average final node number for the greenhouse area was 76.7 nodes plant⁻¹, while the simulation for the location where the reference climate file was placed resulted in 78.0 nodes plant⁻¹. These results may indicate that original location sensors used to build the reference climate file was not representative for the average temperature or that one exclusive measuring station was insufficient to represent the entire situation of the yield greenhouse.

Yield distribution, in terms of fresh weight, inside the greenhouse is represented in Fig. 5b. Just like for node development the warmer zone of the greenhouse registered the highest yields with a maximum of 9.7 kg m⁻²; this result represents an increment of 3.3 kg m⁻² in comparison with the cooler zones of the greenhouse. An important difference of 34.5% in production was determined between the points where maximum and minimum yields were achieved according to the simulations. The apparent small differences in air temperature provoked differences in plant development resulting in variations of the length of the harvesting period and the number of fruits harvested. The highest fruit dry weight dependence on temperature and the overall sensitivity of T omgro model to climate variation is corroborated in the present work in the same way as Cooman and Schreven's (2007) already presented.

Final yield for the reference climate file location was 9.6 kg m⁻², reaching a close value to the maximum simulated yield. Average yield at the end of the simulation period for the whole greenhouse area was 8.3 kg m⁻², representing a difference of 1.3 kg m⁻² or 13.5% yield decrease in comparison with the reference climate file location. For the present work, sensors located near the center of the greenhouse overestimated the average climate condition resulting in higher plant rate development and affected posterior yields. Considering the interval between the first and third quartile for the simulated yields, 50% of the greenhouse yields are between 7.7 and 9.0 kg m⁻².

### Table 2 – Semivariogram parameters fitted to spherical model as a function of outside radiation.

<table>
<thead>
<tr>
<th>Radiation level (W m⁻²)</th>
<th>Nugget (c₀, °C)</th>
<th>Sill (c, °C)</th>
<th>Range (a, m)</th>
<th>c₀/c (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;177.2</td>
<td>0.001</td>
<td>0.095</td>
<td>105.7</td>
<td>1.2</td>
</tr>
<tr>
<td>177.2–380.9</td>
<td>0.016</td>
<td>0.198</td>
<td>120.2</td>
<td>8.2</td>
</tr>
<tr>
<td>380.9–566.8</td>
<td>0.020</td>
<td>0.514</td>
<td>126.5</td>
<td>3.9</td>
</tr>
<tr>
<td>566.8–752.8</td>
<td>0.010</td>
<td>0.935</td>
<td>131.2</td>
<td>1.0</td>
</tr>
<tr>
<td>&gt;752.8</td>
<td>0.052</td>
<td>1.344</td>
<td>133.4</td>
<td>3.9</td>
</tr>
</tbody>
</table>

**Fig. 2** – Experimental (Obs) and fitted semivariograms for greenhouse air temperature as a function of global outside radiation. Semivariance represents the variation between two points in the space separated by a distance (lag).
4. Discussion

In the present article, geostatistics and crop growth modeling were combined to perform a simulation exercise in order to quantify the effect of greenhouse temperature distribution on the growth of a crop. Greenhouse climate variations have been analyzed previously in the literature but until now no relationship has been established between those spatial distributions and its direct effect on the performance of a crop. The integration of two apparently separated fields of knowledge was used to obtain a much closer representation of the reality.

Parameters like solar radiation, natural ventilation and crop transpiration have to be taken into account when designing greenhouses in tropical conditions. In these zones, studies on greenhouse climate have been focused on the understanding and management of differences between greenhouse air...
several contrasting or additive factors (Di Virgilio et al., 2007). Yield. The final yield of a crop depends on conjoint effects of properties variability contributes to the heterogeneity of crop cultivated under greenhouse conditions. Other factors like soil effect of temperature variability on the productivity of a crop study constitute one of the first approaches to quantify the temperature for day hours (7–18 h) of 17.0 C. Temperature within the greenhouse also depends on the type of ventilation; in this case, natural ventilation is a consequence of wind speed and direction at each hour of the day. Including these variables in future studies may improve the temperature prediction at unsampled points within the greenhouse. A greenhouse with a limited climate control system, exclusively naturally ventilated by means of roll-up windows does not improve temperature homogeneity as demonstrated in the present study. Horizontal air movement have been recognized as an important management practice to reduce temperature gradients within greenhouses (Snyder, 2003; Zhang, 2002).

Tomato yield within a greenhouse is strongly affected by temperature variability. Greenhouse microclimate defines plant quality, production and amount of input resources as recognized by Soni et al. (2005). The results presented in this study constitute one of the first approaches to quantify the effect of temperature variability on the productivity of a crop cultivated under greenhouse conditions. Other factors like soil properties variability contributes to the heterogeneity of crop yield. The final yield of a crop depends on conjoint effects of several contrasting or additive factors (Di Virgilio et al., 2007). The present study demonstrates how the joining of different science fields (e.g. geostatistical analysis and crop growth modeling) allows a better representation of the real world.

Nevertheless, the work presents some limitations as a result of the experimental setup. The most important has to deal with the fact of using temperature data collected on a greenhouse planted with roses rather than tomatoes. Despite of the similarities between both crops, significant differences in variables such as transpiration have to be recognized. Future work may assess the variability of the productivity of a rose crop using the existing temperature datasets and, if possible, considering other factors that may improve the temperature prediction at unsampled sites.

For a rose crop grown in the Bogota Plateau, where greenhouse climate control still very limited, it is critical to determine the length of the growing period in order to maximize harvest on the specific dates with peak consumption. Temperature spatial variability within a greenhouse planted with roses may exert variations on the length of the growth period affecting the flushes of flower shoots that are produced year-round. Models such as the one proposed by Pasian and Lieth (1996), designed to time a flush of flower shoots based on the heat units concept, may be used to follow the same methodological approach proposed in the present paper to determine the significance of the variability imposed by temperature variability on a rose crop.

Greenhouse data collection for more prolonged periods of time will contribute to configure more representative climate files of the study location. Also, the analyses can be taken to a next level by considering the three dimensions in space by analyzing the vertical distribution of temperature, not only within the canopy but to the entire height of the greenhouse. This type of analyses and the fine-tuning of the applied geostatistical methods applied will allow a 3D representation of the climate generated within a greenhouse that can be compared later with the results obtained by other tools like computational fluid dynamics (Norton et al., 2007).

Despite of the limitations already mentioned, the results of the present work contribute to gain insight in the knowledge about the effect of climate variations on the yield of a crop. However, other organisms that are part of such agroecosystems can be also influenced by climate variations, like pests and diseases. In consequence, relationships between factors like temperature and pest occurrence and spread can be studied with a similar approach.

5. Conclusions

The solar radiation is one of the major driving forces defining the climate of a greenhouse. Geostatistical analysis was used to represent adequately temperature distribution inside a greenhouse as a function of outside global radiation. An innovative way to apply geostatistics was used for posterior use of crop modeling. Accordingly to the results, higher temperature variations can be expected inside a greenhouse under high radiation levels. This type of situation can be easily achieved under clear sky conditions especially around noon under tropical cool climates where temperature variations along the day are more important than variations within days.

Greenhouse crop growth models have been calibrated and validated with experimental setups considering climate data.
coming from a unique measurement station, normally located close to the center of the greenhouse. The results of the present work demonstrated that crop growth models performance may be comprised due to the lack of consideration of microclimate patterns inside a greenhouse or, on the other hand, this situation may be hid by the error of the model itself. Temperature is one of the major climate variables defining crop growth and in order to keep reliability of a model it is necessary to be aware of temperature variations inside a greenhouse.

The results from the present work suggest the need to integrate climate spatial variation into crop growth models, greenhouse climate control strategies and decision support systems, especially for naturally ventilated greenhouses, where no forced ventilation or heating systems are present that might help to create a homogeneous environment.

REFERENCES


