Data analysis of a multi-climate controller in tomato greenhouse production and the implications of ICT convergence: The TOMGRO model

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Abstract. This study tests a growth model of the greenhouse tomato by analyzing a set of data collected from a multi-climate control system, and suggests an application of the test results. The TOMGRO Model is used to examine the growth of tomatoes. The results show that the stem elongation rate is affected by mean air temperature and CO₂ concentration. R² is 0.25, while the fit of the model is intermediate. There are two applications of this study. One application is to adjust the shipping date by utilizing wholesale market price data and predicting the growth of crops. The other application is to have a dashboard or smart phone available for the results of the model analysis.

Keywords: multi-climate controller, tomato greenhouse, TOMGRO, ICT convergence

1 Introduction

Presently, information and communications technology (ICT) has expanded its capability to the agriculture industry. New technologies have received attention as possible solutions to overcome problems such as population aging in rural areas and increasing labor and operating costs. The farms that have adopted multi-climate control systems for greenhouse technology increased productivity from 25 to 30 percent[1]. However, in South Korea (henceforth, Korea), most farms have not applied the best use of ICT. For example, there are some limitations of data-driven climate control systems. The system is used at a basic level, which is only possible to control at the facility. Therefore, more interest in data analysis is needed to improve greenhouse management and to develop future value of the technology.

This study investigates data analysis from a multi-climate controller. We test the suitability of the growth model, TOMGRO (TOMato GROwth) for the greenhouse tomato and examine methods for applying the model results.
2 Literature Review

2.1 Intention of ICT Technology Acceptance of Farms

In 2010, 40.5% of farms in Korea grow crops in greenhouse facilities. According to Statistics Korea, the largest portion of cultivated crops is tomato (12%), strawberry (11.6%), watermelon (8.1%), and tangerine (7.6%) [2]. 10,306 farms cultivate tomatoes on 4,331ha of land. 6.7% of all tomato farms utilize ICT, which is a higher level in comparison to other crops. In addition, 69.1% of the farms with automated features such as automatic switches, irrigation facilities, and temperature-humidity measuring sensors have intentions to adopt ICT [3].

2.2 Greenhouse Multi-climate Control Technology

Some pioneering studies on climate control of greenhouse facilities started in the late 1960s [4], [5], [6]. However, before these studies were conducted, there were commercialized systems that controlled the environment inside the greenhouse by injecting artificial CO$_2$ into the greenhouse. Many affecting factors such as temperature, amount of sunlight, CO$_2$ concentration, and water and nutrient supply were considered in these commercialized systems. In turn, more precise models to control growth and climate control systems based on these models were developed. After the 1990s, climate control systems have been applied to agriculture and livestock [7], [8].

2.3 TOMGRO Model

The TOMGRO Model is applied in this study to measure the amount of tomato growth. First, dry weight and the number of leaves are set in the model as dependent variables and indicators of tomato growth (Jones et al., 1991). The general equation of the model is represented as

$$W = E[P_g(T, S_{PAR}, CO_2) - R_m(T)W], \quad N = r_m r(T),$$

where $W$ and $N$ are dependent variables that represent the total dry weight of the crop and the number of leaves, respectively. For the explanatory variables, $T$ denotes temperature measured in Celsius, $S_{PAR}$ indicates the photosynthetically active radiation, and $CO_2$ is the concentration of carbon dioxide in parts per million (ppm). In addition, $r(T)$ is an interval linear temperature that is applied by the TOMGRO model, while $R_m(T)$ is the respiration rate of the leaves. Function $P_g(T, SPAR, CO_2)$ is the canopy gross photosynthesis rate. $E$ is the conversion efficiency of formaldehyde (CH$_2$O) to plant tissue and coefficient $r_m$ is the maximum rate of leaf appearance per hour [9].
However, this study applies a simplified version of the TOMGRO model instead of applying the full model. We define the dependent variable as the stem elongation rate (SER) to efficiently measure the relation between growth and other climate factors.

3 Methodology

3.1 Data Collection

Data for this study is collected from a tomato greenhouse located in Hwasung-si, Gyeonggi-do, Korea. The farm applies a multiple climate control system, which is available through a smart phone and personal computer. We used data collected from July 2013 to June 2014. Observed and accumulated items are divided into five categories: outside weather conditions, inside greenhouse climate, facility control, irrigation, and growth status. Data is saved on a weekly basis. Detailed information about individual measurement items are provided in Table 1.

Table 1. Data collection description

<table>
<thead>
<tr>
<th>Category</th>
<th>Items</th>
<th>Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather Condition</td>
<td>4</td>
<td>Temperature, Rainwater, Wind Direction, Wind Velocity</td>
</tr>
<tr>
<td>Greenhouse climate</td>
<td>5</td>
<td>Temperature, Humidity, CO₂ Concentration, Insolation, Soil Temperature, Soil Humidity</td>
</tr>
<tr>
<td>Facility Control</td>
<td>15</td>
<td>Ventilation Temperature, Double-Ventilation Temperature, Heating Temperature, Skylights, Side Windows, Curtains, CO₂ Operation</td>
</tr>
<tr>
<td>Irrigation</td>
<td>10</td>
<td>Supply Frequency, Supply Amount, Total Capacity, Drainage Rate, G-EC Supply, G-pH Supply, Slab-EC Medium, Slab-pH Medium, Medium Water Containment, Medium Temperature</td>
</tr>
<tr>
<td>Growth Status</td>
<td>12</td>
<td>Growth Length, Leaf Length, Leaf Width, Leaves Number, Stem Thickness, Flower Cluster Height, Blooming, Fruiting, Harvesting, Fruits Number, Harvesting Amount, Average Fruit Weight</td>
</tr>
</tbody>
</table>

3.2 Applied TOMGRO Model

We use an applied model from the TOMGRO model. A simplified equation of the model is represented as

\[
SER = \alpha + \beta_T \cdot T + \beta_{CO_2} \cdot CO_2 + \epsilon,
\]

where SER indicates stem elongation rate (centimeters per day), T is the mean air temperature measured in Celsius, and \(CO_2\) is the concentration rate of carbon dioxide.
Since the collected data contains many null-observations, we organized the data at an average level on a weekly basis to obtain the results.

4 Results

4.1 Correlation Analysis

The results show that there are several significant correlations between climate factors and growth, and irrigational factors and growth. For example, the growth length of the crop is positively related to the inside and outside temperatures and the supplied amount of irrigation, while negatively related to Slab-EC and Slab-pH mediums. Also, length of the leaf is negatively related to ventilation temperature, outside temperature, insolation, supply frequency, total capacity, and G-pH supply, while positively related to \( CO_2 \) concentration and G-EC supply. The amount of insolation, which is related to leaf condition and fruiting status, is the most relevant climate factor for growth. The second most relevant factor is the outside temperature, which is related to overall length of growth and the leaf, number of leaves, and stem thickness. For the irrigation factors, supplies of G-EC and G-pH are highly related to the growth factor among other factors that affect the leaves and fruits, which are opposite of each other. Table 2 shows climate factor results and Table 3 shows irrigation factor results for this study.

Table 2. Correlation between climate and growth factors

<table>
<thead>
<tr>
<th>Factor</th>
<th>Growth Length</th>
<th>Leaf Length</th>
<th>Leaf Width</th>
<th>Number of Leaves</th>
<th>Stem Thickness</th>
<th>Fruiting</th>
<th>Harvesting</th>
<th>Number of Fruits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation Temperature</td>
<td>0.2126</td>
<td>-0.2901</td>
<td></td>
<td>0.01909</td>
<td>0.1101</td>
<td>0.5657</td>
<td>0.1702</td>
<td>0.5347</td>
</tr>
<tr>
<td>Inside Temperature</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td></td>
</tr>
<tr>
<td>Outside Temperature</td>
<td>0.3496</td>
<td>-0.4694</td>
<td>-0.15644</td>
<td>0.3107</td>
<td>0.3380</td>
<td>0.1063</td>
<td>0.9679**</td>
<td>0.2791</td>
</tr>
<tr>
<td>( CO_2 ) concentration</td>
<td>-0.2481</td>
<td>0.2977</td>
<td>0.17832</td>
<td>-0.0102</td>
<td>-0.2813</td>
<td>-0.1196</td>
<td>-0.3148</td>
<td>-0.1899</td>
</tr>
<tr>
<td>Insolation</td>
<td>0.0136</td>
<td>-0.6785</td>
<td>-0.3583</td>
<td>0.4988</td>
<td>0.1352</td>
<td>0.6029</td>
<td>0.8446</td>
<td>0.5236</td>
</tr>
</tbody>
</table>

*p-value < 0.1, **p-value < 0.05

Table 3. Correlation between irrigation factors and growth

<table>
<thead>
<tr>
<th>Factor</th>
<th>Growth Length</th>
<th>Leaf Length</th>
<th>Leaf Width</th>
<th>Number of Leaves</th>
<th>Stem Thickness</th>
<th>Fruiting</th>
<th>Harvesting</th>
<th>Number of Fruits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Freq.</td>
<td>-0.0396</td>
<td>**</td>
<td>-0.4309</td>
<td>0.7084</td>
<td>-0.0257</td>
<td>0.6362</td>
<td>0.8575</td>
<td>0.5876</td>
</tr>
</tbody>
</table>

*Correlation values indicate statistical significance at p < 0.01.
### 4.2 TOMGRO Model

The estimation model of stem elongation rate is an applied model from the TOMGRO model. The resulting model equation is represented as

\[
SER = 0.1735 \times T + 0.0047 \times CO_2 - 2.8012, \quad R^2 = 0.25.
\]

By interpreting the estimation model, we can quantify the effect of climate factors. A one degree increase in average weekly temperature can cause a positive effect of 0.17 centimeters per day in the growth rate. Also, 1 ppm increase of \(CO_2\) concentration can cause 0.04 millimeters of positive effect to the SER. However, the estimation model has high variability of data around the mean or regression line since \(R^2\) of this model is 0.25.

### 5 Conclusions

The results of this study can be applied in various ways. A multiple climate control system is connected to the Internet. Thus, appropriate information such as weather or price information from certain databases is easy to obtain. The system can centralize and combine data from different channels and sources to form an accumulated “big data” property. If utilized properly, a centralized database can find out the causes of present problems, suggest reliable clues to solve these problems, or give comprehensive information to farmers to develop optimal conditions for growing crops. Also, relevant information and analysis methods can be easily checked or controlled in real-time with personal devices such as a smart phone or dashboard.

There are two implications and limitations of this study. First, the restricted source of the data could be biased in the analytic model. Additional examination with more
samples will be needed to obtain value from this study. Second, the explanatory power of the model is relatively weak. To increase the model fit, more independent variables such as detailed climate factors need to be considered in order to predict direct productivity of a farm.

Acknowledgements. This research was supported by the MSIP(Ministry of Science, ICT and Future Planning), Korea, under the C-ITRC(Convergence Information Technology Research Center) (IITP-2015-H8601-15-1007) supervised by the IITP(Institute for Information &communications Technology Promotion).

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