Estimation of Growth Curve Parameters for Pepper (Capsicum annuum cv. Kapija) Under Deficit Irrigation Conditions

This study was conducted to estimate growth curve parameters for pepper (Capsicum annuum cv. Kapija) by using different growth curve models under deficit irrigation conditions. Plant height, plant x-x and y-y diameter and chlorophyll readings (ChRs) were measured to estimate plant growth during 12 weeks. Use of Linear, Gompertz and Logistic models for plant height and diameter, and the linear, W(t)=A.t^B.exp(-k.t), W(t)=A(1-Bt) models for ChRs were found to be best for pepper under deficit irrigation. R^2 values for x-x and y-y diameters were in between 99.1% and 99.9%, and for ChRs 38.8-82.8%. Since ChRs values were not continually increased throughout the growth period, R^2 values for ChRs were less than other models.
In addition, there are several different growth models were used to predict PGR such as Linear, Gompertz, von Bertalanffy, Birch, Michaelis-Menten, Logistic and Richard's equations (Werker and Jaggard, 1997; Yıldızbakan, 2003; Glick et al., 2007; Damgaard and Weiner, 2008).

Since pepper is an important plant in Turkey, projection of future growth rate is critical. Pepper is produced during summer when there is little rainfall in Turkey. To produce marketable pepper in Turkey, irrigation is necessary during the growth period. The main objective of this study was to determine the kapıja pepper’s growth rate by using linear and nonlinear growth models using ChRs, plant height, x-x and y-y diameters under deficit irrigation conditions in the field.

**MATERIAL AND METHOD**

**Study Area and Research Design**

This research was conducted during the growing season of 2009 at the Dardanos Agricultural Experimental Station of Çanakkale Onsekiz Mart University, Çanakkale, Turkey. The location of the experimental area is showed in Figure 1. The soil is mostly clay-loam in the research area. Some physical soil parameters used for the study are presented in Table 1.

![Figure 1. The location of the field experiment (Komsat satellite image (1 m))](image)

<table>
<thead>
<tr>
<th>Soil Depth (cm)</th>
<th>Texture Class</th>
<th>Bulk weight (gr/cm³)</th>
<th>Field Capacity</th>
<th>Wiling point</th>
<th>Available Water Holding Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-30</td>
<td>CL</td>
<td>1.30</td>
<td>40.30</td>
<td>22.39</td>
<td>53.73</td>
</tr>
<tr>
<td>30-60</td>
<td>SCL</td>
<td>1.53</td>
<td>34.14</td>
<td>18.97</td>
<td>45.52</td>
</tr>
<tr>
<td>60-90</td>
<td>SL</td>
<td>1.67</td>
<td>28.61</td>
<td>15.89</td>
<td>38.15</td>
</tr>
<tr>
<td>Total (0-90)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>137.40</td>
</tr>
</tbody>
</table>

Soil moisture levels were measured and all treatments were given field capacity by initial irrigation. The soil water content in plots was determined by gravimetrically in the soil layers 0-30, 30-60 and 60-90 cm during growing period. The experimental field was divided into three replications as per field capacity 100% (S1), 66% (S2), 33% (S3) and 0% (S4), respectively. S1 irrigation treatment was applied to consume available soil moisture in the root zone (0-90 cm) for a 7-day interval. S2; 66% of applied water to S1, S3; 33% of applied water to S1 and S4 treatment was not irrigated except that first irrigated. Row and within row spacings were 0.70 and 0.33 m, respectively. There were 32 plants in each plot with a gap of 2.5 m width between each plot to prevent water movement among the treatments. The main and manifold pipes have 75 mm diameter and 6 atm operating pressure were used. The plots were irrigated by drip irrigation. Laterals which 16 mm diameters were laid in each plant row and inline emitters which discharge rate of 4 l h⁻¹ and a dripper spacing of 0.33 m intervals. The system was operated at 100 kPa during growing season. The control unit of the system has a pump, control valves, disk filters, and water counter. The plots were fertilized on May 14, 2009 with the N₁₅P₁₅K₁₅ type of fertilizer as 5 kg da⁻¹.

Evapotranspiration for each treatment was calculated according to the water balance method (Doorenbos and Kassam 1979):

\[ ET = I + P - Dr - Rf \pm \Delta S \]  \hspace{1cm} (1)

where, \( ET \) : evapotranspiration, \( I \) : irrigation water applied during the growth period, \( P \) : rainfall during the growth period, \( Dr \) : amount of drainage water, \( Rf \) :amount of runoff, \( \Delta S \) : change in the soil water content determined by gravimetric sampling

**Plant Measurements**

Plant height, plant x-x and y-y diameter and chlorophyll readings (ChRs) were measured to determine weekly plant growths. Pepper was planted on May 16, 2009 and harvested on September 29,
2009. First measurement was conducted in June 6, 2009 and ended in August 29, 2009. In each plot, 10 plants were selected for measurements. Total 120 plants were continually measured throughout the study in each measurement time. Plant height, x-x and y-y diameters were measured by tape, and ChRs were acquired using Field Scout CM-1000 chlorophyll meter from the same plant between 11:00-14:00 hours in each measurement day. Plant height was measured from the soil surface to the terminal point and plant diameter was measured over terminal point towards x-x and y-y.

**Statistical Analysis**

Twenty-one different growth models were fitted to week-plant height, week-diameters (x-x and y-y) and week-ChRs in order to describe the growth of peppers under different irrigation practices (S1, S2, S3 and S4). However, Linear (Eq.3), Gompertz (Eq.4) and Logistic (Eq.5) models were chosen to describe week-plant height, week-x-x and y-y diameter while the other models (Eq.6 and Eq.7) were chosen to describe week-ChRs, since those models were found to be more effective than the other models. Statistical analysis was performed on 30 plants. NCSS statistical package program was used to analyze the data (Hintze, 2001). Statistical significance of the model parameters were determined using 95% asymptotic confidence intervals.

In the comparison of effectiveness of models, $R^2$, mean square error (MSE), Jp statistic and AIC were used (Akaike, 1969; Hocking, 1976; Schwarz, 1978; Gage and Tyler, 1985; Lamare and Mladenov, 2000).

In order to test the effect of treatments, 120 individual growth curves were fitted using the linear, Gompertz and logistic model. Each parameter for the individual growth curves was then subjected to one-way analysis of variance, using the following model to test the effect of treatment:

$$Y_{ijk} = \mu + \alpha_i + \epsilon_{ijk}$$  \hspace{1cm} (2)

where, $Y_{ijk}$ is a growth curve parameter, $\mu$ is the overall mean, $\alpha_i$ is the fixed effect of treatment ($i=1, 2, 3, 4$) and $\epsilon_{ijk}$ is the random error term distributed as $N(0, \sigma^2)$ (Mendes et al., 2007).

The arithmetic mean of plant height, ChRs, x-x and y-y diameter for all periods was used for the estimation of average growth functions.

Linear, Gompertz and Logistic model (Equation 3, 4 and 5) were used for plant height and diameter and other models were used for ChRs as defined as:

**Linear model:**

$$W(t) = \beta_0 + \beta_1 t + \epsilon$$ \hspace{1cm} (3)

**Gompertz model:**

$$W(t) = A \exp(-B \exp(-k t))$$ \hspace{1cm} (4)

**Logistic model:**

$$W(t) = \frac{A}{1 + B \exp(-k t)}$$ \hspace{1cm} (5)

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where, W(t): is the expected value of the characteristic at week t,

- $A$: is the maximum value of the characteristic at maturity or limiting size of the plant when time (t) $\rightarrow \infty$,
- $B$: is the growth rate constant or integration constant,
- $K$: is the coefficient of relative growth or maturing index (where a smaller value of $k$ indicates late maturing, and a larger value of $k$ indicates early maturing)

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**Logistic model:**

$$W(t) = \frac{A}{1 + B \exp(-k t)}$$ \hspace{1cm} (5)

**RESULTS**

Irrigation dates and the amount of applied irrigation water in each week are presented Table 2. The amount of total irrigation water, rainfall, the change of soil moisture content ($\Delta S$) and seasonal evapotranspiration are presented in Table 3.

<table>
<thead>
<tr>
<th>Treatments</th>
<th>16.05.09</th>
<th>23.06.09</th>
<th>02.07.09</th>
<th>09.07.09</th>
<th>16.07.09</th>
<th>23.07.09</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>30</td>
<td>27</td>
<td>13</td>
<td>76</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>S2</td>
<td>30</td>
<td>18</td>
<td>8</td>
<td>50</td>
<td>34</td>
<td>32</td>
</tr>
<tr>
<td>S3</td>
<td>30</td>
<td>9</td>
<td>4</td>
<td>25</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>S4</td>
<td>30</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>30.07.09</td>
<td>30</td>
<td>27</td>
<td>13</td>
<td>76</td>
<td>51</td>
<td>48</td>
</tr>
<tr>
<td>S1</td>
<td>66</td>
<td>52</td>
<td>57</td>
<td>50</td>
<td>48</td>
<td>49</td>
</tr>
<tr>
<td>S2</td>
<td>43</td>
<td>34</td>
<td>38</td>
<td>33</td>
<td>31</td>
<td>32</td>
</tr>
<tr>
<td>S3</td>
<td>22</td>
<td>17</td>
<td>19</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>S4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. Irrigation dates and applied irrigation water amounts
The amount of total irrigation water in S1, S2, S3 and S4 treatments were found to be 567, 383, 207 and 30 mm, respectively. Also, seasonal ET was changed between 333-855 mm.

The Linear, Gompertz and Logistic models for plant height and x-x, y-y diameter and the linear, $W(t) = A t^{0.8} \exp(-kt)$, $W(t) = A(1-Bt)$ models for ChRs were chosen to describe time-characteristics relation in plants. These growth models were found to be more effective than the other growth models such as Weibull, Monomolecular, Richards and Von Bertalanffy in the preliminary analysis. When $R^2$ values only are considered, almost all of the models fit the height, diameters (x-x, y-y) and ChRs. In addition, when all factors ($R^2$, MSE, Jp statistic and AIC) were taken into consideration, the appropriate model was selected for all treatments (Table 4, 5, 6 and 7). The most appropriate model has the highest $R^2$ and the lowest MSE, Jp statistic and AIC values.
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Table 7. Growth models and statistical parameters for ChRs in plant

<table>
<thead>
<tr>
<th>Variables</th>
<th>Treatments</th>
<th>Model</th>
<th>Parameter Estimates</th>
<th>Confidence interval</th>
<th>R²</th>
<th>MSE</th>
<th>Jp</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>ChRs in Plant</td>
<td>S1</td>
<td>W(t)=A(1-B t)</td>
<td>210.02 0.46 -</td>
<td>185.86 (A) 0.22 (B) 234.17 (A) 0.70 (B)</td>
<td>0.388 899.44 900.61 83.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>Linear</td>
<td>148.15 7.18 -</td>
<td>118.33 (A) 3.13 (B) 177.97 (A) 11.23 (B)</td>
<td>0.609 472.79 473.96 75.72</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>W(t)=AtB.exp(-k.t)</td>
<td>126.89 0.53 0.07</td>
<td>88.90 (A) 0.12 (B) -0.01 (C) 164.88 (A) 0.94 (B) 0.14 (C)</td>
<td>0.699 524.62 525.87 77.69</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>W(t)=AtB.exp(-k.t)</td>
<td>131.49 0.67 0.11</td>
<td>103.88 (A) 0.38 (B) 0.05 (C) 159.10 (A) 0.96 (B) 0.16 (C)</td>
<td>0.828 268.71 269.96 69.67</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Growth in height, diameters (x-x, y-y) and ChRs of plants were affected significantly by applied irrigation conditions. While Gompertz growth model was appropriate for growth definition in that plant height at S4 and S3 irrigation conditions, logistic model was appropriate at S1 and S2 irrigation conditions (Table 4). Estimated growth model with both growth parameters were observed to be statistically significant (p<0.05). Plant heights (58.45 and 59.38 cm) in ripening period of plants at S4 and S3 irrigation conditions were higher than (51.08 and 57.66 cm) was estimated for plants at S2 and S1 irrigation conditions. Also, growth rates of plants (2.53 and 2.53) were found to be higher under S3 and S4 treatments. Therefore, plants grown under these conditions were expected to reach mature plant height rapidly.

While linear growth model was appropriate for plant x-x diameter at S4 irrigation conditions, logistic model was appropriate at S1, S2 and S3 irrigation conditions (Table 5). Plant x-x diameter (53.13 cm) in ripening period at S3 irrigation conditions were higher than (11.60, 49.89 and 50.21 cm) was estimated for plants at S4, S2 and S1 irrigation conditions. Moreover, growth rates of plants were changed between 0.22 and 0.26 under all treatments. Therefore, plants grown under all treatments were expected to reach mature plant x-x diameter similarly.

Logistic growth model was appropriate for plant y-y diameter under all irrigation conditions (Table 6). Plant y-y diameter (49.48 cm) in ripening period at S3 irrigation conditions higher than (39.53, 42.88 and 45.38 cm) was estimated for plants at S4, S2 and S1 irrigation conditions. Also, growth rates of plants (0.30) were found to be higher under the S1 irrigation conditions. Plants x-x and y-y diameters were found to be same results with regard to growth rates of plants.

Linear, Eq.6 and Eq.7 growth models were fit for ChRs. While Eq.6 was appropriate for ChRs of S3 and S4 treatments, Eq. 7 fitted ChRs at S1 treatments. Besides, linear growth model fitted at S2 irrigation conditions (Table 7). Plant ChRs (210.02 and 148.15) in ripening period of plants at S1 and S2 irrigation conditions were higher than (126.89 and 131.49) was estimated for plants at S3 and S4 irrigation conditions. While R² for height, x-x diameter y-y diameter was changed between 99.1% and 99.9%, R² for ChRs was changed between 38.8% and 82.8%.
Growth curves of height, x-x and y-y diameter and ChRs are shown in Figure 2, 3, 4 and 5. Growth curves for height, x-x and y-y diameters are continuously increased. Plant height increased especially until the first seven weeks and then it was noticed that growth increased slowly (Figure 2). Non-irrigated and less irrigated plots (S3 and S4) increased more than S2 and S1 irrigated plots for x-x and y-y diameter until first six weeks, while fully irrigated and S2 plot increased more than less irrigated plots after six weeks (Figure 3 and 4). R² values for height, x-x and y-y diameters were higher than ChRs, since the ChRs values were not uniform but changed during the pepper’s growth period (Figure 5). Although the growth of height and diameter of the plants constantly increased to a certain point during growth periods, ChRs values did not continually increased. ChRs values generally increased to the middle of the growth period and decreased slowly for each treatment.

DISCUSSION

Three models (Linear, Gompertz and Logistic) were found to be suitable to predict the growth rate using pepper’s height and diameters in this study. However, logistic growth model highly explain the pepper growth rate than others. It was assumed that logistic growth model should be first used to estimate the plant growth rate using plant height and diameters.

In the determination of the plant growth, Birch and Richards models were used. Damgaard and Weiner (2008) suggested that the Birch model was explained better than the Richards model for individual plant growth. Werker and Jaggard (1997) tested three empirical models (Gompertz, Richards and Chanter) in sugar beet. They suggested that the Gompertz model was better than the other models for foliage dynamics of sugar beet. After investigating Table 4, 5, 6 and 7, the irrigation water restrictions affect the growth pattern except for y-y diameter. However, models using pepper’s height, x-x diameter and ChRs were affected by water stress. R², MSE, jp, AIC values for each treatment are also found to be similar except ChRs. The highest ChRs values in growth period were seen in week-6. On the contrary, Demirel et al. (2009) reported that determination of the relationship among ChRs, yield and some quality parameters were affected by deficit irrigation (0%, 20%, 40%, 60%, 80%, 100%) in watermelon. They also demonstrated that relationship between ChRs and yield R² under different irrigation applications were found to be between 0.910 (0%) and 0.940 (100%). In this study, ChRs values and curves during growth periods differ than they found due to the different plant materials.

Pepper’s height and diameter growth dramatically increased between week-1 and week-10. After week-10, height and diameter growth gradually increased. At week-12, plant growth was almost completed (Figure 2, 3 and 4). Important differences were not found that affect growth between irrigation treatments because of the falling rain during the development of the plants.

CONCLUSION

This study is demonstrated that plant height, x-x and y-y diameters increased during growth period as expected. However, ChRs did not constantly increase. It was found that Linear, Logistic and Gompertz growth models were appropriate to determine pepper
growth rate using plant height and diameters. It was found that plant height, diameters (x-x, y-y) and ChRs were affected significantly by water stress. Since ChRs values did not continually increased or decreased during growth period, $R^2$ values for ChRs were lower than that plant height and diameters.

It was concluded that one-year data would be enough to determine the pepper growth rate using models. However, in order to predict the yield and quality parameters, at least two years data should be collected.

REFERENCES


