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Mathematical Modelling of Crop Water Productivity for Processing Tomato

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ABSTRACT

Crop water productivity models (CWPMs) are of great importance in evaluating different irrigation programs. The mean goal of the study was to evaluate the performance of the Jensen, Minhas, Blank, Stewart and Rao CWPMs in predicting fruit yield of processing tomato. Field experiments were conducted for two consecutive growing seasons. The soil water stress sensitivity indices of the CWPMs were determined using experimental data from the second crop growing season. Yields simulated by the CWPMs were compared with the experimental data for the first season. The sensitivity indices for the crop growth stages were taken into account as appropriate weights of the soil water sensitivity of the vegetative, flowering, yield formation and ripening stages of the processing tomato crop. The results give evidence that processing tomato is much more sensitive to soil water stress during flowering and yield formation stages whereas the adverse impact of water stress on yield is very limited at vegetative stage. The highest modelling efficiency (0.96) between field-measured and simulated yield by the model, the lowest arithmetic mean of errors (0.04), mean absolute deviation (0.07), mean square error (0.02), absolute percentage error (12.76), root mean square error (0.15) and coefficient of residual mass (0.05) were achieved by Minhas model and followed by Rao model based on same parameters of statistical analyses. Both the Minhas and the Rao models with their soil water stress sensitivity indices generated for the different growth stages obtained in this study are recommended for the processing tomato in the sub-humid environments.

Keywords: Deficit irrigation; Relative evapotranspiration; Relative yield; Stress sensitivity indices

1. Introduction

Crop-water productivity model (CWPM) which is known as the relationship between seasonal crop evapotranspiration (ET) and fresh or dry yield is of great interest among scientists who work on soil, plant and water. As it was stated in Kipkorir et al (2002) and Igbadun et al (2007); CWPM can be mainly divided into two parts; one relates yield to seasonal ET (e.g., Stewart & Hagan 1973; Doorenbos & Kassam 1979; Hanks 1983), another relates yield reduction to water deficit at some crop growth stages (Jensen 1968; Minhas et al 1974; Sudar et al 1981).

Based on Igbadun et al (2007); dependent variables associated with water may be expressed in two types: additive and multiplicative (Tsakiris 1982). The multiplicative-type assumes that water deficit in two or more crop growth stages reduces yield in a multiplicative way (Jensen 1968; Minhas et al 1974; Bernardo et al 1988), while additive-type predicts that crop yield may be reduced by water deficit in two or more crop growth stages in an additive way (Stewart et al 1977; Bras & Cordova 1981).

CWPMs are crucial for irrigation water management. Irrigation water management aims to accomplish optimal crop production and higher water use efficiency or a reliable, continuous, and equitable irrigation water supply to water users (Tarjuelo & de Juan 1999).

Reliability and practicability over 300 CWPMs were tested by Clumpner & Solomon (1987). They found major differences on growing season-to-season and site-to-site basis as well as the impacts of crop growth stages (Al-Jamal et al 2000; Igbadun et al 2007). In as much as dependent and/or independent variables of CWPMs are strongly influenced by crop characteristics and environmental conditions, there is no universal CWPM for all crops, growth stages and climates (Rhenals & Bras 1981). For that reason, performance evaluation should be carried out for different crops and location before using CWPMs in irrigation water management and in developing water management strategies (Igbadun et al 2007).

In this study, a comparative analysis of various additive and multiplicative type CWPM models which relates crop yield to relative evapotranspiration (ETa/ETm) considering crop growth stages was carried out under sub-humid climatic conditions. The aim of this study is to test the model performance in predicting the fruit yield of processing tomato in the sub-humid climate conditions.

2. Material and Methods

2.1. Crop water production models

In this study, 5 CWPMs related to relative ET or relative ET deficit, developed by the various researchers were used for the predicting relative yield or relative yield decrease of a processing tomato crop (Table 1).

In Table 1, *Ya* actual yield (t ha^{-1}) from the plot with soil water stress during the growing season (called as fruit yield in this study); *Ym* (t ha^{-1}) is the maximum yield from the plot without water stress during the growing season; ETa_i actual evapotranspiration (mm) from the plot with water stress during the growing stage *i*; ETm_i maximum evapotranspiration (mm) from the plot without

Table 1- Crop water production functions

Source	*Crop water production function*	*Type/Independent variable*
Jensen (1968)	$\frac{Ya}{Ym} = \prod_{i=1}^{n} \left(\frac{ETa_i}{ETm_i}\right)^{\lambda_i}$	Multiplicative/Relative evapotranspiration (ET)
Minhas et al (1974)	$\frac{Ya}{Ym} = \prod_{i=1}^{n} \left[1 - \left(1 - \frac{ETa_i}{ETm_i}\right)\right]^{\delta_i}$	Multiplicative/Relative ET deficit
Blank (1975)	$\frac{Ya}{Ym} = \sum_{i=1}^{n} A_i \left(\frac{ETa}{ETm}\right)_i$	Additive/Relative ET
Stewart et al (1977)	$\left(1 - \frac{Ya}{Ym}\right) = \sum_{i=1}^{n} ky_i \left(1 - \frac{ETa}{ETm}\right)_i$	Additive/Relative ET deficit
Rao et al (1988)	$\frac{Ya}{Ym} = \prod_{i=1}^{n} \left[1 - K_i \left(1 - \frac{ETa_i}{ETm_i}\right)\right]$	Multiplicative/Relative ET deficit

water stress during the growing stage *i*; *n* the number of crop development stages; ∏ multiplicative sign; Σ additive sign and, λ_i, δ_i, A_i, ky_i *and* K_i sensitivity indices of the crop to water stress during the growing stage *i*.

2.2. Field experiments and irrigation treatments

Irrigation experiments were carried out on the experimental farm of Mustafakemalpasa Vocational School of Bursa Uludağ University, Turkey (40°02′N, 28°23′E). Average rainfall amounts were 121 and 52 mm, mean temperatures were 25.3 and 23.8 ºC, and the relative humidity were 64 and 66% for both growing seasons of experimental years, respectively. The experimental site has a clay-loam Entisol soil. Soil samples were taken from each 0.30 m layers of 0-1.2 m soil profile prior to irrigation treatments. Based on results of soil samples analyses, electrical conductivity, lime content, pH and the available water holding capacity (the difference between the water content at FC and PWP) were 0.02-0.04 dS m^{-1}, 4-11%, 7.7-8.0 and 183 mm/0.90 m. A total of 180 kg N ha^{-1} and 120 kg P_2O_5 ha^{-1} fertilizer was applied. All agricultural inputs (fertilizer, pesticide etc.) other than water were assumed constant.

The hybrid cultivar Shasta variety (Campbell's Seeds™ Inc, CA, USA) was planted in the growing seasons of 2010 and 2011. Each experimental plot was 5.10 m long by 5.60 m wide (28.56 m^2), with 4 rows per plot. A buffer zone spacing of 2.00 m was provided between the plots. The row spacing and plant–plant spacing were 1.40 and 0.30 m, respectively (Kuşçu et al 2014). Seedlings at the 3-4 true leaf stage were transplanted to the treatment plots, on 15 May 2010 and 20 May 2011. The irrigation experiments were conducted using randomized block design and repeated three times. Fifteen different irrigation treatments considering vegetative, flowering, yield formation, and the ripening stages of crop development were planned to assess the effects of water deficit in the soil (Table 2).

Irrigation interval was 3 days at all crop growth stages with irrigation (VFYR). Irrigation was applied once in every 3 days to the treatments specified as (+) symbol in Table 1. Irrigation at each growth stage was applied with the amount of

Table 2- Irrigation treatments

Treatments	*Crop development stages*			
	Vegetative (V)	*Flowering (F)*	*Yield formation (Y)*	*Ripening (R)*
VFYR	+[a]	+	+	+
FYR	–	+	+	+
VFY	+	+	+	–
VFR	+	+	–	+
VYR	+	–	+	+
VF	+	+	–	–
VR	+	–	+	–
VY	+	–	–	+
FY	–	+	+	–
FR	–	+	–	+
YR	–	–	+	+
V	+	–	–	–
F	–	+	–	–
Y	–	–	+	–
R	–	–	–	+

[a] (+), irrigation at specified crop development stages; (–), no irrigation at specified crop development stages; (V), vegetative stage; (F), flowering stage; (Y), yield formation stage; (R), ripening stage

irrigation water required to fill the moisture content of 0-90 cm soil layer to field capacity.

2.3. Soil moisture monitoring and evapotranspiration

The soil moisture was monitored in 0.3 m depth increments to 1.2 m prior to and after irrigation from each plot. Soil water content was gravimetrically determined. The soil water contents of 90 cm and 120 cm soil depth were used for determination of water amount applied in each irrigation and seasonal ET, respectively.

The actual crop evapotranspiration was calculated using a soil-water balance equation (Kuşçu et al 2014).

2.4. Fruit yield determination

When ripe fruit ratio was reached to 95%, all experimental plots were harvested by hand on 23 August 2010 and 28 August 2011, respectively. Tomatoes which were harvested from the two center rows were compared with total ground area as fruit yield (t).

2.5. Determination of sensitivity indices of the crop to water stress in the models

Since the rainfall amounts at the crop growth stages of 2011 was lower than those of 2010 (total rainfall amounts: 121 mm for 2010, 52 mm for 2011), sensitivity indices of the crop to water stress in the models were calculated more precisely by using data obtained from the experimental field at growth stages of 2011. All models were converted to multiple linear functions. While relative crop yield decrease (Y_a/Y_m) was taken as dependent variable, relative evapotranspiration deficit (ET_a/ET_m) was assigned as independent variable in this conversion (Igbadun et al 2007). Fruit yield obtained from the field and evapotranspiration associated with crop growth stages were described as relative yield (ratio of yield at some growth stages with no irrigation to yield at full irrigation treatment) and relative evapotranspiration (ratio of crop evapotranspiration at some growth stages with no irrigation to crop evapotranspiration of full irrigation treatment), respectively. In this study, relative yield and evapotranspiration data were used for solution of multiple regression equations for each model in determining the sensitivity indices of crop to water stress at four crop growth stages. The regression equations were realized by using SPSS 23 Statistical Program.

2.6. Model performance evaluation

The performance of the model for the prediction of relative fruit yield was tested by using relative evapotranspiration results obtained from the treatments at crop growth stages of 2010. Both graphical and statistical methods were employed for the assessment of the models. The rates of yield reduction were plotted for measured and simulated values at graphical method. The response of each model could be quantified by this method. In statistical analyses, various performance indicators were used to compare the data observed with the results estimated by the model (Loague & Green 1991; Hagi-Bishow & Bonnell 2000). The performance indicators were given at Equations 1-7.

Arithmetic mean of the errors, $BIAS = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n}$ (1)

Mean absolute deviation, $MAD = \frac{\sum_{i=1}^{n}|O_i - P_i|}{n}$ (2)

Mean square error, $MSE = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}\right]$ (3)

Mean absolute percentage error, $MAPE = \frac{\sum_{i=1}^{n}\frac{|O_i - P_i|}{O_i} * 100}{n}$ (4)

Root mean square error, $RMSE = \left[\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}\right]^{0.5} * \frac{100}{\bar{O}}$ (5)

Modeling efficiency, $EF = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2}$ (6)

Coefficient of residual mass, $CRM = \frac{\sum_{i=1}^{n}(O_i - P_i)}{n\bar{O}}$ (7)

Where; observed values; mean of the observed values; predicted values, and n number of samples.

3. Results and Discussion

3.1. Fruit yield

Fruit yield obtained from different irrigation experiments was given at Table 3a and 3b. Difference between years and fruit yield for 2 experimental years was significant with P<0.01 level based on analysis of variance (ANOVA) results. Difference between years may be attributed to the differences between rainfall amounts (121 mm for 2010, 52 mm for 2011) and temperatures (25.3 ºC for 2010, 23.8 ºC for 2011) in growing season. The highest fruit yield was obtained at reference treatment with 3-day irrigation interval. However, there was no significant difference on term of statistical analysis between

Table 3a- Evapotranspiration (ET) and fruit yield (2010)

Treatment	*ET for crop development stages (ET_a, mm)*				*Seasonal ET (mm)*	*Fruit yield (t ha^{-1})*
	Vegetative (V)	*Flowering (F)*	*Yield formation (Y)*	*Ripening (R)*		
	Days after planting (day)					
	0-21	*22-44*	*45-66*	*67-100*		
VFYR	85.2	133.8	141.0	152.2	512.2	100.4 a[1]
FYR	78.0	128.0	140.0	150.2	496.2	97.2 b
VFY	85.2	133.8	141.0	105.1	465.1	95.6 c
VFR	85.2	133.8	110.0	135.3	464.3	92.2 d
VYR	85.2	125.0	140.0	150.0	500.2	96.2 c
VF	85.2	133.8	110.0	37.0	366.0	62.8 h
VY	85.2	125.0	140.0	106.4	456.6	80.7 g
VR	85.2	125.0	65.8	93.2	369.2	48.2 k
FY	78.0	128.0	140.0	82.4	428.4	87.2 e
FR	78.0	128.0	93.4	115.7	415.1	85.4 f
YR	78.0	92.0	133.0	143.5	446.5	88.2 e
V	85.2	125.0	65.8	14.3	290.3	30.2 m
F	78.0	128.0	91.4	22.6	320.0	54.9 j
Y	78.0	92.0	133.0	44.3	347.3	61.2 i
R	78.0	92.0	90.0	109.8	369.8	45.2 l

[1], no significant difference at 0.05 level amongst mean values given in the same letters

Table 3b- Evapotranspiration (ET) and fruit yield (2011)

Treatment	*ET for crop development stages (ETa, mm)*				*Seasonal ET (mm)*	*Fruit yield (t ha⁻¹)*
	Vegetative (V)	*Flowering (F)*	*Yield formation (Y)*	*Ripening (R)*		
	Days after planting (day)					
	0-22	*23-45*	*46-67*	*68-101*		
VFYR	84.9	130.4	133.8	153.4	502.5	110.7 a[1]
FYR	75.0	129.8	133.0	152.3	490.1	109.2 a
VFY	85.0	130.0	133.6	122.1	470.7	104.6 b
VFR	84.7	129.6	104.4	138.8	457.5	97.6 c
VYR	85.0	116.0	133.0	153.0	487.0	104.3 b
VF	85.0	130.0	104.0	61.4	380.4	64.2 h
VY	85.0	116.0	133.0	121.0	455.3	87.4 f
VR	85.0	116.0	72.1	85.0	358.1	40.2 k
FY	75.0	130.0	133.3	116.0	454.3	94.2 d
FR	75.0	130.0	105.1	129.0	439.1	92.1 e
YR	75.0	90.0	129.0	135.0	429.0	85.7 g
V	85.0	116.0	72.0	24.0	297.0	31.4 m
F	75.0	130.0	105.0	60.0	370.0	60.1 j
Y	75.0	90.0	129.0	106.0	400.0	63.1 i
R	75.0	90.0	67.0	74.0	306.0	36.2 l

[1], no significant difference at 0.05 level amongst mean values given in the same letters

FVYR and FYR treatments. The lowest fruit yield was observed at treatment which has irrigation only at vegetative period (V) for both experimental years.

On other treatments, yield was reduced based on water deficits of crop growth stages. While yield decrease of treatments with no irrigation was substantial at stages flowering and yield formation, yield was not considerably decreased at vegetative stages with no irrigation. Sensitivity of tomato to water stress was highest at flowering and yield formation stages.

3.2. Evapotranspiration

Both seasonal evapotranspiration and ET for different crop growth stages were given in Table 3a and 3b. The seasonal ET varied between 306 and 512.2 mm. The highest seasonal ET was found in the full irrigation treatment (VFYR) whereas the lowest seasonal ET was recorded in the V treatment, with a prolonged water deficit (79 days) after the vegetative period. Since irrigation was applied uninterruptedly in full irrigation treatment (VFYR), seasonal ET results observed in the field were congruent relative to given amount of irrigation water. On the other hand, seasonal ET observed at FYR treatment (no irrigation at vegetative stage) was quite similar to that of full irrigation treatment (VFYR). This result indicates that tomato adequately benefits from the moisture of the soil root zone at vegetative stage (Table 3a and 3b).

3.3. Sensitivity indices of the crop to water stress

The variation of sensitivity indices of the crop to water stress for crop development stages (V: Vegetative, F: Flowering, Y: Yield formation, R: Ripening) was given at Table 4. The following Equations show functions of the Jensen (1968), Minhas et al (1974), Blank (1975), Stewart et al (1977), and Rao et al (1988) models, respectively, with the sensitivity indices. Although the soil water stress sensitivity indices determined by the additive type of models were the same, the constants were different.

Table 4- Sensitivity indices of the crop to water stress in the models

Model	*Sensitivity indices of the crop to water stress for different crop growth stages*				*Constant*	*r^2*	*Std. error*
	V	*F*	*Y*	*R*			
Jensen (1968)	0.002	0.800	0.849	0.391		0.93	0.043
Minhas et al (1974)	1.547	2.306	2.431	0.543		0.93	0.053
Blank (1975)	0.006	0.628	0.479	0.562	-0.665	0.97	0.226
Stewart et al (1977)	0.006	0.628	0.479	0.562	-0.010	0.97	0.024
Rao et al (1988)	0.006	0.628	0.479	0.562		0.97	0.024

$$\frac{Ya}{Ym} = \left(\frac{ETa}{ETm}\right)_V^{0.002} \times \left(\frac{ETa}{ETm}\right)_F^{0.800} \times \left(\frac{ETa}{ETm}\right)_Y^{0.849} \times \left(\frac{ETa}{ETm}\right)_R^{0.391} \quad (8)$$

$$\frac{Ya}{Ym} = \left[1-\left(1-\frac{ETa}{ETm}\right)_V^2\right]^{1.547} \times \left[1-\left(1-\frac{ETa}{ETm}\right)_F^2\right]^{2.306} \times \left[1-\left(1-\frac{ETa}{ETm}\right)_Y^2\right]^{2.431} \times \left[1-\left(1-\frac{ETa}{ETm}\right)_R^2\right]^{0.543} \quad (9)$$

$$\frac{Ya}{Ym} = 0.006\left(\frac{ETa}{ETm}\right)_V + 0.628\left(\frac{ETa}{ETm}\right)_F + 0.479\left(\frac{ETa}{ETm}\right)_Y + 0.562\left(\frac{ETa}{ETm}\right)_R - 0.665 \quad (10)$$

$$1-\frac{Ya}{Ym} = 0.006\left(1-\frac{ETa}{ETm}\right)_V + 0.628\left(1-\frac{ETa}{ETm}\right)_F + 0.479\left(1-\frac{ETa}{ETm}\right)_Y + 0.562\left(1-\frac{ETa}{ETm}\right)_R - 0.010 \quad (11)$$

$$\frac{Ya}{Ym} = \left[1-0.006(1-\frac{ETa}{ETm}\right]_V \times \left[1-0.628(1-\frac{ETa}{ETm}\right]_F \times \left[1-0.479(1-\frac{ETa}{ETm}\right]_Y \times \left[1-0.562(1-\frac{ETa}{ETm}\right]_R \quad (12)$$

Sensitivity analysis tests were employed to determine the sensitivity indices of crop to water stress for all models. For Jensen model, the index obtained at yield formation stage was higher than those of other stages. On the other hand, sensitivity index of crop to water stress was higher at flowering stages than those of other growth stages for Minhas, Blank, Stewart and Rao models. In general, crop growth stages more sensitive to soil water stress has higher sensitivity index (Zhang et al 2002). Processing tomato is more sensitive to flowering and yield formation stages based on all model outputs, whereas flowering, yield formation and the ripening stages were the most sensitive stages based on Jensen model.

3.4. Model evaluation

Relative yield (Y_a/Y_m) obtained from field measurements and model simulations for different irrigation treatments were presented in Table 5. Table 6 summarizes statistical performance indicators associated with comparison of relative yield from field measurements and model simulations.

BIAS ranged between 0.04 and 0.10. MAD values were ranged from 0.07 to 0.10 and may be considered as very similar for each model. On the other hand, MSE was lowest in the Minhas model (0.02), followed by the Rao model with 0.04 and highest in the Jensen model (0.16). MAPE varied from 12.76 to 15.99. The lower the error measurements (BIAS, MAD, MSE, MAPE, and

Table 5- Relative fruit yield (field measurements vs model simulations)

Treatment	*Relative yield (field measurements)*	*Relative yield (model simulation)*				
		Jensen	*Minhas*	*Blank*	*Stewart*	*Rao*
VFYR	1.00	1.00	1.00	1.00	1.00	1.00
FYR	0.97	0.95	0.98	0.98	0.97	0.96
VFY	0.95	0.87	0.95	0.84	0.84	0.83
VFR	0.92	0.77	0.88	0.85	0.84	0.84
VYR	0.96	0.94	0.99	0.96	0.96	0.95
VF	0.63	0.47	0.56	0.48	0.48	0.51
VY	0.80	0.82	0.94	0.80	0.80	0.79
VR	0.48	0.41	0.40	0.50	0.50	0.56
FY	0.87	0.75	0.87	0.73	0.72	0.72
FR	0.85	0.61	0.71	0.69	0.69	0.71
YR	0.88	0.69	0.77	0.76	0.75	0.76
V	0.30	0.20	0.17	0.21	0.20	0.35
F	0.55	0.32	0.35	0.34	0.34	0.42
Y	0.61	0.44	0.53	0.39	0.39	0.47
R	0.45	0.45	0.53	0.49	0.48	0.56

Table 6- Statistics of comparison between measured and model predicted relative yields

Statistical performance indicators	*Jensen*	*Minhas*	*Blank*	*Stewart*	*Rao*
Arithmetic mean of the errors (BIAS)	0.10	0.04	0.08	0.08	0.05
Mean absolute deviation (MAD)	0.10	0.07	0.09	0.09	0.08
Mean square error (MSE)	0.16	0.02	0.10	0.11	0.04
Mean absolute percentage error (MAPE)	15.99	12.76	14.24	14.24	12.91
Root mean square error (RMSE)	0.40	0.15	0.31	0.33	0.20
Modeling efficiency (EF)	0.71	0.96	0.83	0.80	0.92
Coefficient of residual mass (CRM)	0.14	0.05	0.11	0.11	0.07

RMSE) and the higher modelling efficiency are, the better the forecasting model is. In this study, the highest modelling efficiency (EF= 0.96) between field-measured and simulated yield by the model and the lowest error parameters were achieved by Minhas model and followed by Rao model based on same statistical analyses. Both models showed relatively high modelling efficiency (>0.90). The closer the modelling efficiency is to 1, the better the consistency between the measured and predicted data, and the farther from 1, the greater the error margin in the values simulated by the model. From that point of view, modelling efficiency of Jensen model is relatively lower than those of the others (EF= 0.71). The RMSE values show how much the simulations under- or over-estimate the measurements. When considering whole experimental treatments, RMSE values most close to zero was attained by Minhas model (Table 6). When considering the values of CRM which is a tool for prediction level of the model, models predicted 5-14% lower than the field measurements. While the closest value of simulated relative yield to the field-measured relative yield was predicted by Minhas model (CRM= 5%), the lowest level of prediction was obtained by Jensen model (14%).

As seen in Table 5, the lowest difference between the model predicted and the measured relative yield in the field was found at FYR treatment which has no irrigation at vegetative development stage. The reason is that the soil water stress sensitivity index determined for vegetative stage of processing tomato for all models is much lower than the indices obtained for other crop growth stages. This result suggests that the processing tomato is not very sensitive to water stress occurred at the vegetative stage in sub-humid climates. On the other hand, the biggest differences in between relative fruit yields of field measurements and model simulations were attained at F (irrigation only at flowering stage) and Y (irrigation only at yield formation stage) treatments by Stewart and Blank models, at FR (irrigation only at flowering and ripening stages) treatment by Jensen and Minhas models, and at FY (irrigation only at flowering and yield formation stages) treatment by Rao model (Table 5). These results show that the differences in the soil water stress sensitivity indices of the multiplicative and additive type models lead different reduction levels of relative yields from model to model at different irrigation treatments.

4. Conclusions

In present study, 5 CWPMs related to relative evapotranspiration (ET) or relative ET deficit were used for the predicting relative yield or relative yield decrease of a processing tomato crop. Minhas and Rao models satisfactorily predicted relative fruit yields of processing tomato based on comparative statistical test results. Either Minhas or Rao model may be used for prediction of relative fruit yields associated with deficit irrigation under sub-humid climate conditions. One of the both models which gave the best results could be preferred by considering deficit irrigated periods. To provide better model performance, sensitivity indices of crops to water stress should be calibrated by testing in different locations. Better results may be obtained by considering different growth stages apart from four critical crop growth stages considered in this study. Besides, relative differences in sensitivity indices of processing tomato to water stress may be observed depending upon plantation date and vegetation period.

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