Nondestructive leaf-area estimation and validation for green pepper (*Capsicum annuum* L.) grown under different stress conditions

B. CEMEK[*,+], A. UNLUKARA[**], and A. KURUNC

Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Ondokuz Mayis University, 55139 Samsun, Turkey[*]
Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Erciyes University, Kayseri, Turkey[**]
Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Akdeniz University, 07058 Antalya, Turkey[***]

Abstract

Leaf area of a plant is essential to understand the interaction between plant growth and environment. This useful variable can be determined by using direct (some expensive instruments) and indirect (prediction models) methods. Leaf area of a plant can be predicted by accurate and simple leaf area models without damaging the plant, thus, provide researchers with many advantages in horticultural experiments. Several leaf-area prediction models have been produced for some plant species in optimum conditions, but not for a plant grown under stress conditions. This study was conducted to develop leaf area estimation models by using linear measurements such as lamina length and width by multiple regression analysis for green pepper grown under different stress conditions. For this purpose, two experiments were conducted in a greenhouse. The first experiment focused to determine leaf area of green pepper grown under six different levels of irrigation water salinity (0.65, 2.0, 3.0, 4.0, 5.0, and 7.0 dS m^{-1}) and the other under four different irrigation regime (amount of applied water was 1.43, 1.0, 0.75, and 0.50 times of required water). In addition to general models for each experiment, prediction models of green pepper for each treatment of irrigation water salinity and of irrigation regime experiments were obtained. Validations of the models for both experiments were realized by using the measurements belong to leaf samples allocated for validation purposes. As a result, the determined equations can simply and readily be used in prediction of leaf area of green pepper grown under salinity and water stress conditions. The use of such models enable researchers to measure leaf area on the same plants during the plant growth period and, at the same time, may reduce variability in experiments.

Additional key words: green pepper; irrigation regime; irrigation water salinity; leaf area estimation; nondestructive methods.

Introduction

Accurate and simple measurements of leaf area (LA) of a crop are essential to understand the interaction between plant growth and environment since it is an indicator of plant growth and productivity. It is also a determinant factor in mechanisms such as light interception, photosynthetic efficiency, evapotranspiration, energy exchange and responses to fertilizers and irrigation (De Jesus *et al.* 2001, Blanco and Folegatti 2005, Demirsoy *et al.* 2004).

The total leaf area of a plant can be obtained by either direct or indirect methods. Direct methods consist of removing and measuring of all leaves in the plant by using instruments, tools and machines such as hand scanners and laser optic apparatuses developed for leaf area measurements. This method requires labor, time, adequate, potentially expensive equipment and the excision of leaves from the plants. Therefore, it may cause problems to other measurements or experiments since plant canopy is damaged. Indirect methods are, however, nondestructive, user-friendly, less expensive, and save time compared with geometric measurements

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[+]Corresponding author; phone: +90 0362 312 1919, e-mail: bcemek@omu.edu.tr
Abbreviations: AI – amount of applied irrigation water; C_{AW} – water application coefficient; ECi – electrical conductivity of irrigation water; I – water application rate compared to crop water needs; IR – irrigation regime; IWS – irrigation water salinity; L – leaf length; LA – leaf area; $\overline{LA}$ and $\overline{LA_{model}}$ – average values of the corresponding variable; LA_{model} – estimated leaf area value; LF – leaching fraction; MAE – mean absolute error; MBE – mean bias error; PS – plant species; PW and PW_{FC} – pot weight just before irrigation and at field capacity; r^2 – coefficient of determination; RMSE – root mean square error; SE – standard error; W – leaf width.

and can provide accurate leaf-area estimates (Robbins and Pharr 1987, Norman and Campbell 1989). Indirect methods are especially useful when necessary equipments are not available or nondestructive measurements are needed, such as field conditions or low plant density growing in pots of controlled experiments. If the mathematical relationships between leaf area and one or more dimensions of the leaf could be clarified, the method would be more advantageous than the direct method (Villegas *et al.* 1981, Beerling and Fry 1990). Therefore, one of the most frequently used indirect method is estimating leaf area from mathematical equations involving linear measurements such as leaf length (L) and width (W), petiole length, or some combination of these variables, which usually have high accuracy, like cucumber (Robbins and Pharr 1987, Blanco and Folegatti 2005), grape (Elsner and Jubb 1988), rabit-eye blueberry (NeSmith 1991), onion (Gamiely *et al.* 1991), cherry (Demirsoy and Demirsoy 2003), chestnut (Serdar and Demirsoy 2006), faba bean (Peksen 2007), coffee (Antunes *et al.* 2008), sunflower (Rouphael *et al.* 2007), and rose (Rouphael *et al.* 2010).

Although several leaf-area prediction models have been produced for some crop species such as mentioned above, a leaf-area prediction model has not been developed for a plant grown under salinity and water stress. Examining the equations produced for different crops in literature shows that the coefficients as well as type of equations are crop-specific. Therefore, in this study, it was aimed to develop reliable nondestructive leaf-area estimation models using linear measurements such as L and W of green pepper and to evaluate the effects of irrigation water salinity (IWS) and irrigation regime (IR) on the estimative.

Materials and methods

Leaf samples used as materials in this study were obtained from two experiments conducted in a greenhouse located at experimental area of Gaziosmanpaşa University in Tokat/Turkey. In experiments, green pepper plants (*Capsicum annuum* L. var. cayenne) were exposed to different salinity levels in irrigation water and different IR after transplanting of seedling. The experiment was divided into two parts: IWS experiment and IR experiment. The soil was collected from a nearby field and sieved through a 4-mm screen to remove large particles and dry soil lumps. Some physical and chemical properties of the sandy-loam textured soil used for the experiments were presented in Table 1. A 45 kg of air-dried soil was filled into the pots with 35.6 dm^3 in volume. To determine the field capacity of each pot at the beginning of the experiment, they were saturated with tap water and top of the pots was covered with a plastic sheet in order to prevent evaporation. The water content of the pots after the drainage stopped was assumed to be at its field capacity (W_{FC}).

Amounts of applied fertilizers were calculated by considering as 135 kg ha^{-1} for N, as 37.5 kg ha^{-1} for P_2O_5 and as 75 kg ha^{-1} for K_2O suggested by Doorenbos and Kassam (1986). Before transplanting, whole of P and K and half of N were applied to pots. Another half of N was applied after 20 days from seedling transplantation. Diammonium phosphates (DAP) for P and potassium sulphate (K_2SO_4) fertilizer for K were used. Some part of N was derived by application of DAP and the rest by ammonium nitrate fertilizer.

Table 1. Some physical and chemical properties of the experimental soil.

Bulk density [g cm^{-3}]	1.49
Electrical conductivity (ECe) [dS m^{-1}]	0.63
pHe (paste)	7.34
Particle size distribution [%]	
Sand	64.3
Silt	20.0
Clay	15.7
Soil water contents (dry mass basis) [%]	
Saturation	38.6
Field capacity	21.8
Wilting point	5.1

In IWS experiment, green pepper plants were irrigated with six different rates of saline waters. Electrical conductivities of irrigation water used for this experiment were 0.65, 2.0, 3.0, 4.0, 5.0, and 7.0 dS m^{-1} (Table 2). Saline irrigation waters were prepared by using $CaCl_2$, $MgSO_4$, and NaCl salts. Sodium adsorption ratios (SAR) of each treatment were maintained around 1.0 in order to eliminate the effects of SAR on soil and/or plant. To do this, calculated amounts of $CaCl_2$, $MgSO_4$, and NaCl were mixed to prepare irrigation water with desired salinity level for each treatment. EC_i values of saline waters used to irrigate treatments were periodically checked in the laboratory. Saline waters were stored in a 100-l plastic containers throughout the experiment.

In the second experiment, IR, amount of irrigation water (treatments) as 1.43 (I_1), 1.00 (I_2), 0.75 (I_3), and 0.50 (I_4) times of crop requirement were applied to green pepper plants (Table 1). So, the first treatment was exposed to excess water, the second treatment to complete water (control), and the third and fourth treatments to limited water applications. Tap water (ECi = 0.65 dS m^{-1}) was used to irrigate pepper plants in the drought experiment. It is important to note that the control treatment of salinity experiment (S_0) was also used as an excess water treatment for IR experiment (I_1). Both experiments were conducted as a randomized block design with 5 replications. Throughout the experiments, minimum and maximum values of temperature, relative humidity, and solar radiation were ranged from 19.4 to 42.5°C, 41.0 to 97.4%, and 34.37 to 280.82 [W m^{-2}], respectively. Research was conducted during the time period of June-September 2006.

Amount of irrigation water to be applied was determined by weighing the pots just before irrigation. The difference between pot field capacity mass and pot mass just before irrigation were accepted as crop requirement. Amount of applied irrigation water (AI) was calculated by using Eq. 1 for IWS experiment and Eq. 2 for IR experiment:

$$AI = \frac{PW_{FC} - PW}{1 - LF} \qquad (1)$$

$$AI = (PW_{FC} - PW) \times C_{AW} \qquad (2)$$

where leaching fraction was taken as 0.30 (Table 2).

Table 2. Treatments and symbols of the experiments. IWS – irrigation water salinity; IR – irrigation regime; ECi – electrical conductivity of irrigation water; C_{AW} – coefficient for irrigation water application.

IWS experiment Treatments	ECi [dS m^{-1}]	IR experiment Treatments	C_{AW}
S_0	0.65	I_1	0.50
S_1	2.0	I_2	0.75
S_2	3.0	I_3	1.00
S_3	4.0	I_4	1.43
S_4	5.0		
S_5	7.0		

At the end of the experiment, all of the green pepper plants were cut. Leaves from each replication of each treatment were placed on A4 sheets and then scanned. The width (W, at the widest point perpendicular to the midrib) and length (L, from lamina tip to the point of petiole intersection along the midrib) of each leaf were measured to the nearest 0.1 cm for each treatment. Also, actual leaf areas (LA) were measured by using a *Placom Digital Planimeter* (*Sokkisha Planimeter Inc., Model KP-90*, Japan). Data for four out of five replications from each treatment of both experiments were used as materials to develop models and the fifth replication as validation of the developed models. Means, standard deviations, minimum and maximum values of leaf area, leaf length and width for green pepper grown under different levels of IWS and IR were given in Tables 3 and 4, respectively. In addition, values from fifth replications used for validation purposes were also presented in these tables. In this research, leaf area was estimated by using 4,740 values from different plant. When validating the model, values from 1,197 different plant was used. Since totally 5,937 values were used during estimating process, our data base covered not only young leaf but also older ones. Leaf area in this research varied from 1.0–63.3 cm^2 and covered all age groups (Tables 3, 4).

In addition to our models, other models developed and suggested by Ray and Singh (1989), Uzun and Çelik (1999) and De Swart *et al.* (2004) to estimate leaf area of the pepper were tested by using our leaf areas values from fifth replications. In order to evaluate the accuracy of the forecasting and to compare the models, four forecast accuracy measures including coefficient of determination (r^2), root mean square error (RMSE), mean bias error (MBE) and mean absolute error (MAE) defined below were used (Waller 2003).

Table 3. Some statistical values of studied green pepper leaves from irrigation water salinity experiment. *n* – number of leaves.

Water salinity [dS m^{-1}]	*n*	Leaf length [cm] Mean ± SD	Min	Max	Leaf width [cm] Mean ± SD	Min	Max	Leaf area [cm^2] Mean ± SD	Min	Max
For modelling										
S_0(0.65)	526	7.56 ± 2.53	1.8	14.0	3.94 ± 1.49	1.0	9.9	20.41 ± 12.63	2.1	63.3
S_1(2.0)	540	7.41 ± 4.90	1.6	10.8	3.73 ± 1.32	1.1	10.7	17.86 ± 10.66	1.9	52.5
S_2(3.0)	540	6.87 ± 2.20	2.6	12.1	3.60 ± 1.38	1.1	15.1	16.80 ± 10.02	1.8	46.2
S_3(4.0)	478	6.60 ± 2.22	0.9	12.0	3.43 ± 1.51	0.8	14.0	15.45 ± 9.13	1.3	44.7
S_4(5.0)	409	6.43 ± 2.21	1.7	12.5	3.83 ± 1.68	0.9	9.9	16.36 ± 10.57	1.9	58.5
S_5(7.0)	311	6.19 ± 2.50	1.5	17.7	3.15 ± 1.10	0.6	6.6	13.40 ± 8.00	1.0	44.6
For validation										
S_0(0.65)	132	7.66 ± 2.12	2.3	11.7	3.98 ± 1.18	1.4	7.3	19.75 ± 9.64	2.4	40.9
S_1(2.0)	123	6.93 ± 2.16	2.2	11.0	3.50 ± 1.14	1.3	6.1	16.16 ± 9.28	2.7	43.7
S_2(3.0)	131	8.09 ± 1.93	4.0	12.2	4.28 ± 1.08	1.8	6.9	22.13 ± 9.75	3.6	50.3
S_3(4.0)	109	6.53 ± 2.43	2.0	10.4	3.40 ± 1.38	0.9	6.9	15.93 ± 10.25	1.4	41.2
S_4(5.0)	145	6.34±1.75	2.8	9.9	3.40 ± 0.99	1.4	5.7	13.95 ± 7.11	2.8	30.6
S_5(7.0)	86	5.75 ± 1.56	1.8	8.7	3.04 ± 0.87	0.7	5.2	11.66 ± 5.81	1.2	28.4

Table 4. Some statistical values of studied green pepper leaves from irrigation regime experiment. *n* – number of leaves.

Irrigation regime	*n*	Leaf length [cm] Mean ± SD	Min	Max	Leaf width [cm] Mean ± SD	Min	Max	Leaf area [cm^2] Mean ± SD	Min	Max
For modeling										
I_1(0.50)	629	6.48 ± 2.25	1.1	12.1	3.32 ± 1.24	1.0	10.7	14.85 ± 9.48	1.5	43.0
I_2(0.75)	669	6.96 ± 2.07	2.1	12.6	3.56 ± 1.23	1.1	11.5	16.68 ± 9.70	2.2	49.5
I_3(1.00)	638	7.43 ± 2.27	1.8	14.4	3.91 ± 1.45	1.1	11.2	19.46 ± 11.60	2.1	60.1
I_4(1.43)	526	7.56 ± 2.53	1.8	14.0	3.94 ± 1.49	1.0	9.9	20.41 ± 12.63	2.1	63.3
For validation										
I_1(0.50)	152	5.82 ± 2.35	2.1	11.7	3.05 ± 1.32	0.9	5.9	12.96 ± 9.63	0.9	39.3
I_2(0.75)	157	6.93 ± 2.16	2.2	11.0	3.50 ± 1.14	1.3	6.1	16.16 ± 9.28	2.7	43.7
I_3(1.00)	162	8.09 ± 1.93	4.0	12.2	4.28 ± 1.08	1.8	6.9	22.13 ± 9.75	3.6	50.3
I_4(1.43)	132	7.66 ± 2.12	2.3	11.7	3.98 ± 1.18	1.4	7.3	19.75 ± 9.64	2.4	40.9

$$r^2 = \frac{\left[\sum_{i=1}^{n}(\mathrm{LA_i}-\overline{\mathrm{LA_i}})(\mathrm{LA_{model,i}}-\overline{\mathrm{LA_{model,i}}})\right]^2}{\sum_{i=1}^{n}(\mathrm{LA_i}-\overline{\mathrm{LA_i}})^2\sum_{i=1}^{n}(\mathrm{LA_{model,i}}-\overline{\mathrm{LA_{model,i}}})^2} \quad (3)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{LA_i}-\mathrm{LA_{model,i}})^2}{n}} \quad (4)$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n}\left(\mathrm{LA_i}-\mathrm{LA_{model,i}}\right)}{n} \quad (5)$$

$$\mathrm{MAE} = \left|\frac{\sum_{i=1}^{n}\left(\mathrm{LA_i}-\mathrm{LA_{model,i}}\right)}{n}\right| \quad (6)$$

where *n* is the number of leaves.

Multiple regression analysis of the data was performed for each green pepper experiment, separately. For this reason, analysis was conducted with various subsets of the independent variables, namely, 'leaf length' (L) and 'leaf width' (W) to develop the best model for predicting leaf area by using the *Excel 7.0* package program. The unknown fitting parameters in equations were estimated through an optimization procedure by using *MS Excel Solver*. The multiple regression analysis was carried out until the deviation sum of squares was minimized. To validate the equations, leaf area values obtained from each model were plotted against actual leaf areas measured for the fifth replication of the respective treatment by using a planimeter. The *MS Excel 7.0* package program was also used for this procedure.

Results and discussion

For green pepper grown under different levels of IWS and IR, regression analysis showed that the variation in leaf area values can be explained by leaf length and width. The best leaf area model for each treatment and the general model for each experiment were chosen by considering standard error of estimation and model fit. The chosen model was the one, which had the smallest standard error. Six and four models for the treatments of green pepper IWS and IR experiments, respectively, were given in Table 5. In all of these models, leaf area was selected as dependent whereas leaf length and width as independent variables. The variation in the parameters was ranged from 98.0 to 99.0% among treatments.

Validation of the obtained best leaf area models for each treatment was realized by using values from the fifth replication of the respective treatment. For this purpose, a comparison was carried out between actual and predicted values from the fifth replication of each treatment to determine the degree of accuracy of the models. In order to obtain actual leaf area values of the fifth replication, a repetitive measurement was done by a digital planimeter. It was obtained that the relationship (r^2 values) between the actual and predicted leaf areas varied from 96.70 and 99.10% (98.20, 98.80, 96.70, 99.10, 98.10, and 98.30% for S_0, S_1, S_2, S_3, S_4, and S_5 treatments, respectively) for IWS (Fig. 1) and from 97.70 and 99.20 % (98.80, 99.20, 97.70, and 98.20% for I_1, I_2, I_3, and I_4 treatments, respectively) for IR experiment (Fig. 2).

In addition to the models developed for each treatment of both experiments, general models for each experiment were obtained in order to include the effects of IWS or IR on leaf area of green paper into the model.

Table 5. The developed leaf area models for each treatment of green pepper experiments. IWS – irrigation water salinity [dS m^{-1}]; IR – irrigation regime; LA – leaf area [cm^2]; W – leaf width [cm]; L – leaf length [cm]; SE – standard error; * – significant at 0.1% probability level; r^2 – coefficient of determination; MBE – mean bias error; MAE – mean absolute error; RMSE – root mean square error.

Experiment	Treatment	Model	r^2	MBE	MAE	RMSE
IWS	S_0(0.65)	LA = 2.2 – 0.026 W^2 L + 0.86 L W – 0.82 L	0.986	0.61	0.78	1.04
		SE (0.50)* (0.004)* (0.052)* (0.19)*	1.49*			
	S_1(2.0)	LA = –9.07 – 0.0055 L^2 W + 0.13 W^2 L + 9.17 W – 1.48 W^2	0.987	–0.11	0.82	0.93
		SE (0.32*) (0.01*) (0.002)* (0.16)* (0.024)*	1.20*			
	S_2(3.0)	LA = 3.62 + 1.12 L W – 0.04657 W^2 L – 0.8045 L – 1.7 W	0.986	0.50	0.83	1.03
		SE (0.45*) (0.025*) (0.0014)* (0.10)* (0.143)*	1.19*			
	S_3(4.0)	LA = –3.037 + 0.0507 L^2 W – 0.041 W^2 L + 3.75 W	0.985	–0.33	0.71	1.01
		SE (0.256*) (0.0004*) (0.001)* (0.116)*	1.12*			
	S_4(5.0)	LA = –4.32 + 0.0107 L^2 W + 0.03 W^2 L + 1.54 L + 1.23 W	0.989	0.10	0.67	0.78
		SE (0.39*) (0.002*) (0.003)* (0.086)* (0.12)*	1.08*			
	S_5(7.0)	LA = 2.2 – 0.026 L W^2 + 0.863 W L – 0.82 L	0.986	–0.30	0.60	0.84
		SE (0.504*) (0.0044*) (0.052)* (0.197)*	1.49*			
IR	I_1(0.50)	LA = –5.51 + 1.36 L + 2.53 W + 0.00387 L^2 W^2	0.990	–0.34	0.57	0.88
		SE (0.19*) (0.04*) (0.067)* (0.001)*	0.93*			
	I_2(0.75)	LA = –7.22 + 1.69 L + 2.54 W + 0.0032 L W	0.980	–0.06	0.90	1.24
		SE (0.27*) (0.04*) (0.091)* (0.001)*	1.21*			
	I_3(1.00)	LA = –8.28 + 1.89 L + 2.5 W + 0.0028 L W	0.980	0.52	1.08	1.14
		SE (0.35*) (0.052*) (0.076)* (0.001)*	1.52*			
	I_4(1.43)	LA = 2.2 – 0.026 W^2 L + 0.86 L W – 0.82 L	0.986	0.61	0.78	1.04
		SE (0.50)* (0.004)* (0.052)* (0.19)*	1.49*			

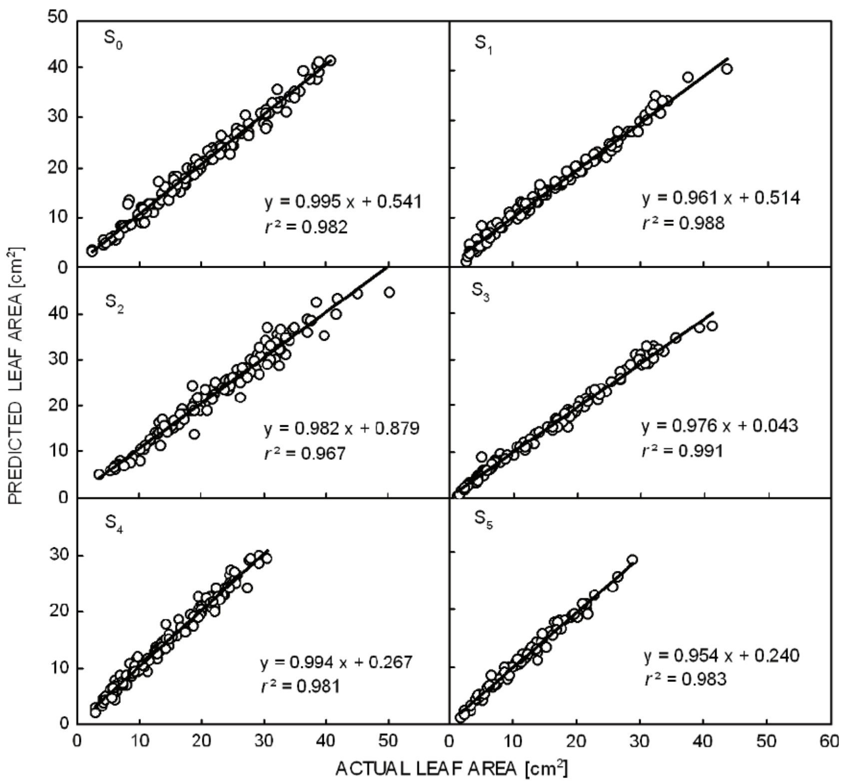

Fig. 1. Relationships between actual and predicted leaf areas of green pepper for each treatment of irrigation water salinity experiment.

for the purposes, IWS level for general model of IWS experiment and constant value of applied water for general model of IR experiment were selected as independent variables. Similar to selection of models for each treatment, the best model was chosen for each experiment is presented in Table 6. In the models, leaf area was selected as dependent whereas leaf length, leaf width, IWS and water application rate as independent

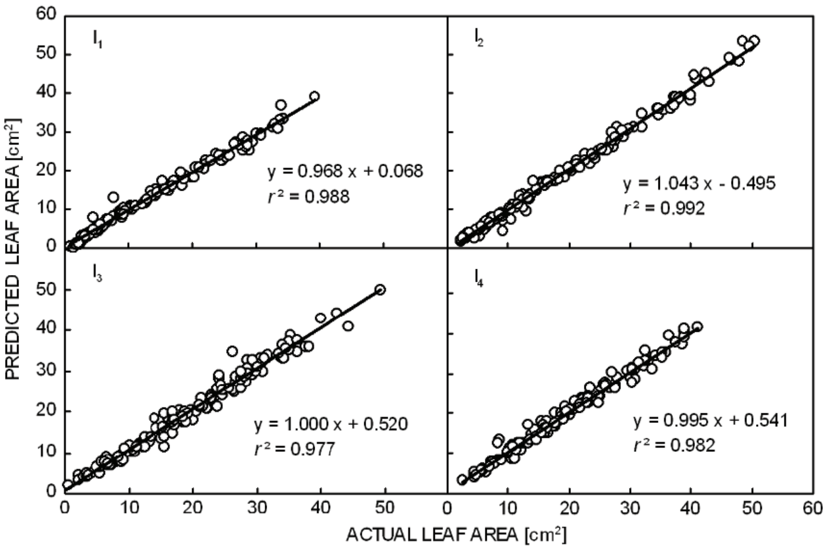

Fig. 2. Relationships between actual and predicted leaf areas of green pepper for each treatment of irrigation regime experiment.

Table 6. The developed general leaf area models for green pepper experiments. IWS – irrigation water salinity [dS m^{-1}]; IR – irrigation regime; LA – leaf area [cm^2]; W – leaf width [cm]; L – leaf length [cm]; SE – standard error; ECi – electrical conductivity of irrigation water [dS m^{-1}]; I – water application rate compared to crop water needs; * – significant at 0.1% probability level; r^2 – coefficient of determination; MBE – mean bias error; MAE – mean absolute error; RMSE – root mean square error.

Experiment	Model	r^2	MBE	MAE	RMSE
IWS	LA = – 3.77 + 2.01 L + 0.055 W^2 L + 1.05 W ECi – 0.0141 L^2 ECi – 0.097 W^2 S – 1.63 ECi SE (0.188)* (0.033)* (0.001)* (0.014)* (0.001)* (0.001)* (0.044)*	0.979 1.52*	–0.19	1.07	1.21
IR	LA = – 4.457 + 0.817 L + 2.696 W + 0.018 L^2 W + 0.017 W^2 L + 0.41 L I – 0.834 W I SE (0.175)* (0.086)* (0.16)* (0.001)* (0.002)* (0.09)*	0.987 1.21*	–0.05	0.83	1.08

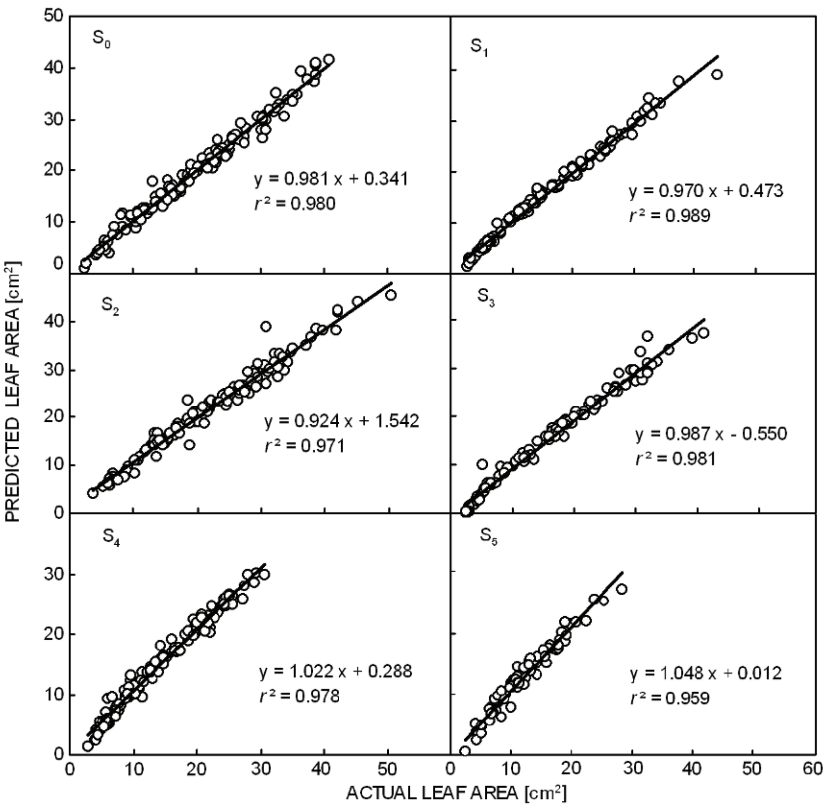

Fig. 3. Relationships between actual and predicted leaf areas from general leaf area model for irrigation water salinity experiment of green pepper.

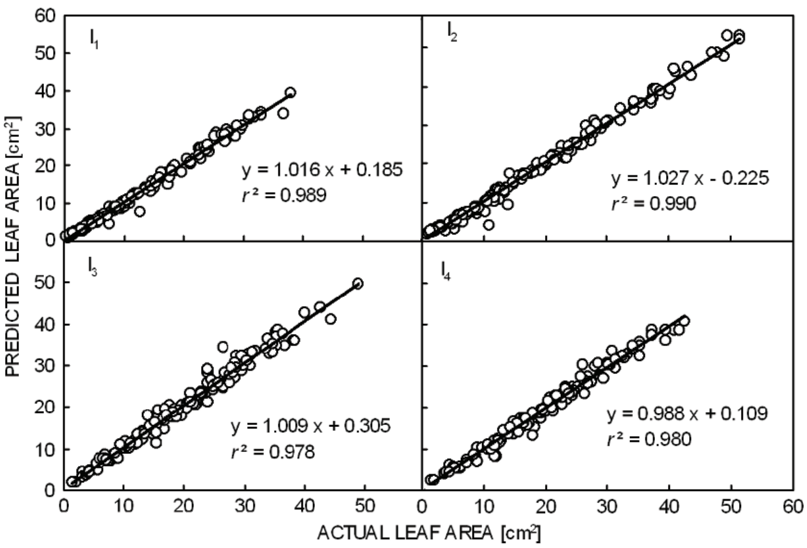

Fig. 4. Relationships between actual and predicted leaf areas from general leaf area model for irrigation regime experiment of green pepper.

variables. The variation in the parameters was 97.9 and 98.7% for IWS and IR experiments, respectively.

Similarly, validation of the general models for each experiment was realized by using the fifth replication of each treatment. Validation results as the relationships between actual leaf area from the fifth replications of the treatments and predicted leaf area obtained from the use of the general model of the respective experiment of green pepper are presented in Fig. 3 and 4 for IWS and IR, respectively. The relationship between the actual and predicted leaf areas varied from 95.90 and 98.90 % (98.80, 98.90, 97.10, 98.10, 97.80, and 95.90 % for S_0, S_1, S_2, S_3, S_4, and S_5 treatments, respectively) for IWS (Fig. 3) and from 97.80 and 99.0 % (98.90, 99.0, 97.80, and 98.0 % for I_1, I_2, I_3, and I_4 treatments, respectively) for IR experiment (Fig. 4).

Leaf area is commonly evaluated as an important variable for most physiological and agronomic studies involving plant growth, light interception, photosynthetic efficiency, evapotranspiration, and response to fertilizers and irrigation (Blanco and Folegatti 2005, Serdar and Demirsoy 2006, Peksen 2007). Because of different rates of photosynthesis and transpiration, the leaf area would also affect growth, development, yield, and quality of the green pepper.

Much research has been carried out to establish reliable relationships between the leaf area and the leaf dimensions of different plant species (Pereira and Splittstoesser 1986, Robbins and Pharr 1987, Rai *et al.* 1990, Gamiely *et al.* 1991, NeSmith 1991, Payne *et al.* 1991, Potdar and Pawar 1991, Panta and NeSmith 1995, Röver and Koch 1995, Uzun and Çelik 1999, Campostrini and Yamanishi 2001, Bhatt and Chanda 2003, Williams and Martinson 2003, Demirsoy *et al.* 2004, de Sousa *et al.* 2005, Gamper 2005, Tsialtas and Maslaris 2005, Serdar and Demirsoy 2006). It has been shown that there were close relationship between leaf width, leaf length, and leaf area (in general r^2 values ranged from 97.9 and 99.0%). Present study results were in accordance with some of the previous studies mentioned above on nondestructive model development for predicting leaf area using simple linear leaf measurements. The validations of the models showed that green pepper leaf area could be measured quickly, accurately, and nondestructively by using these developed models.

Models developed and suggested by Ray and Singh (1989), Uzun and Çelik (1999) and De Swart *et al.* (2004) to estimate leaf area of the pepper were applied to our values from fifth replications used for comparison purposes. These models consider L and W parameters only. Application of these models to our data showed that r^2 values are over 0.95 (Table 7 and Fig. 5). However, as an accuracy measure, r^2 value cannot be enough for comparison purposes. The most important thing is to obtain a low error. Compared to the other developed models (Table 7), in general our models for IWS and IR (Table 6) have higher r^2 and lower RMSE, MBE, and MAE values. In addition, model suggested by Uzun and Çelik (1999) can do satisfactory forecasts for the leaf area over 20 cm^2 (Fig. 5). The reason for better forecasts from our models may result from considering irrigation water quality or IR value as an independent variable in addition to L and W.

For validating the models suggested by Ray and Singh (1989), Uzun and Çelik (1999) and De Swart *et al.* (2004) were run by using the 1197 values from different plant. Models 5 and 6 in the Table 7 were obtained using the 4,740 data and were run by using the 1,197 values from different plant. Then the results of different models were compared with the results of our model. The results of comparative analysis were given in Table 7. It was clear from the upper evidence that our model had the best r^2 and the smallest error. These results were also depicted in Fig. 5.

Determining the plant growth parameters, leaf area is

Table 7. Fitted coefficients (b-e) and constant (a) values of the models used to estimate the pepper leaf area (LA) of single leaves from length (L) and width (W) measurements. r^2 – coefficient of determination; MBE – mean bias error; MAE – mean absolute error; RMSE – root mean square error; *n* – leaf number; PS – plant species (taken as 6). All r^2 values are significant at $p<0.001$.

Model number	Form of model tested	Fitted coefficient and constant a	b	c	d	e	Model testing data (n = 1,197) r^2	MBE	MAE	RMSE
1	LA = a LW (Ray and Singh 1989)	0.604					0.980	–0.34	0.91	1.29
2	LA = a LW (De Swart *et al.* 2004)	0.690					0.978	2.09	2.19	2.83
3	LA = a + b LW (Ray and Singh 1989)	–0.680	0.630				0.980	–0.23	1.00	1.34
4	LA = a + b (L/W) PS+c W+d W^2 PS + eL (Uzun and Çelik, 1998)	–50.63	–1.35	5.347	0.06	5.489	0.953	–20.4	20.55	24.00
5	LA = a LW	0.615					0.985	–0.03	0.78	0.97
6	LA = a + b LW	0.380	0.605				0.985	0.07	0.86	1.03

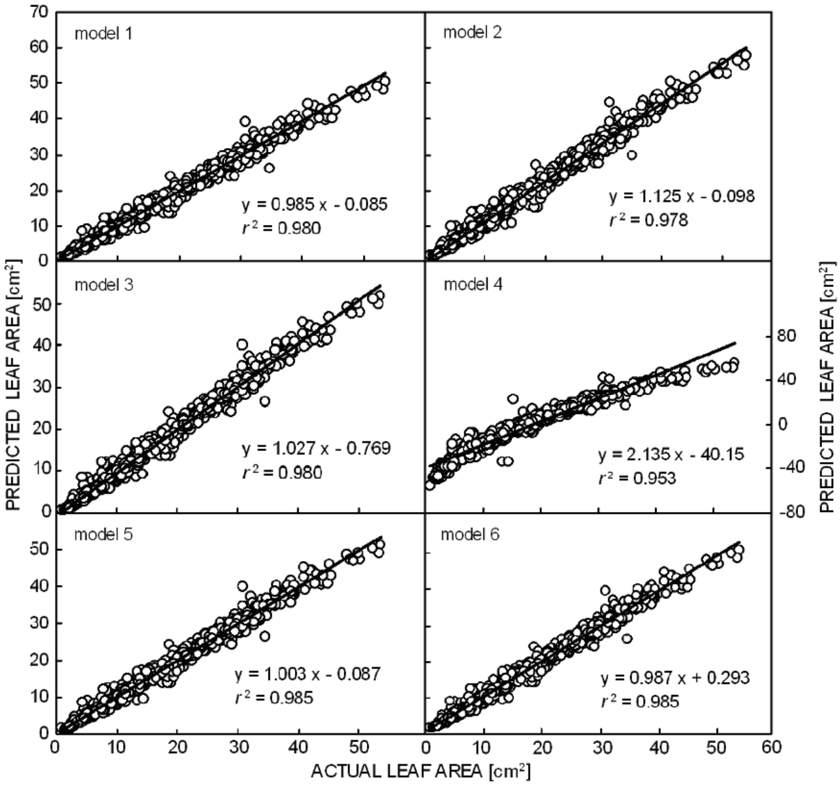

Fig. 5. Relationships between actual leaf areas with the models used to estimate the pepper leaf area.

one of the important variables. In some cases, it will be better to consider the stress conditions in determining growth parameters for example; relative growth rate (increase in dry mass per unit dry mass per unit time) and net assimilation rate (increase in dry mass per unit leaf area per unit time). Similarly, prediction models obtained by considering the stress conditions will give better results for the parameters such as leaf area *vs*. leaf thickness, wet leaf mass *vs*. dry leaf mass *etc*.

Conclusions: Rapid and simple models were developed separately to predict the leaf area of green pepper grown under different levels of IWS and IR in this study. The models were chosen for their simplicities, producing results with the same level of accuracy as other more complex estimation models or expensive equipment. Results obtained from the present study demonstrated that green pepper leaf area could be predicted using simple linear measurements. Dimensions of the leaves can be easily measured in the field, greenhouse, and pot experiments. Use of these equations would enable researchers to make nondestructive or repeated measurements on the same leaves. With this developed models, researchers can estimate the leaf area of green pepper plants in physiological and quantitative studies accurately. In conclusion, the models derived in this study can be reliably used for estimating leaf area of green pepper grown under different levels of salinity and/or water-stress conditions.

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