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Prediction of corn yield loss due to different redroot pigweed density and irrigation level using empirical models

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Abstract

Models which can predict crop yield loss using weed density or weed relative leaf area can be valuable decision-making tools for integrated weed management. Two field experiments were conducted to evaluate the goodness of fit of different yield loss models in corn-redroot pigweed system, during 2008 and 2009 growing seasons at the research field of Agricultural College of Shiraz University. The yield loss of the crop was recorded in experimental plots laid out in split plot design with three replicates. Main plots included five weed densities (0, 5, 10, 20, 30 and 40 weeds m^{-1}) with subplots assigned with each of three different irrigation treatments as follows: T1=full irrigation and increasing soil moisture content in root depth to field capacity, T2=T1+25% and T3=T1-25%. Three empirical models characterized the relationship between redroot pigweed density or relative leaf area and corn yield loss under different irrigation conditions. These models included Cousens hyperbolic, Spitters, and Kropff & Lotz (6, 8 and 10 weeks after planting sampling dates). Both Cousens and Kropff & Lotz (8WAP) models showed consistently lower constant and systematic biases and therefore high precision and accuracy which were not affected by strength of water stress. Kropff and Lotz model at 6 and 10 WAP require elaboration of further adjustments to overcome the location and scale shifts in yield loss predictions under water stress conditions and improve its predictability. Cousens model generally is recommended as an appropriate yield loss predictor of corn competing with the redroot pigweed under water stress conditions.

Keywords: Yield loss prediction, Model diagnostics, Irrigation levels, Redroot pigweed.

Introduction

Crops and weeds compete in the capture and utilization of the shared resources such as light, water and nutrients. Traditionally, the focus of research has been on the effect of resource capture by weeds on growth and production of the crop. Zimdahl (2004) and Oerke et al. (1994) estimated a globally 10% loss of agricultural production due to the competitive effect of weeds despite intensive control of weeds in most agricultural systems. Several studies have reported corn significant yield losses due to weed competition. Because water is a finite and increasing cost resource in arid and semi arid regions, it should not be wasted. Knowing the amount of water wasted due to weeds allows field managers to have better weed management plans. It is clear that water does not have a role of equal magnitude in all crop-weed interactions (Zimdahl, 2004). For example, Kropff et al. (1992) showed with a simulation model that water shortage only influences the competitive strength of common lambsquarters when the weed grows above sugarbeets.

Redroot pigweed is a common weed in more than 40 crops, particularly corn (*Zea mayz*), sugar beet (*Beta vulgaris* L.), soybean (*Glycine max* L.), and potato (*Solanum tuberosum* L.) (Moussavi, 2001; Crook and Renner, 1990). Previous studies have shown various economic yield losses due to the redroot pigweed infestation, in different crops ranging from 11% - 22% yield loss in corn (Becket *et al.,* 1988; Turner *et al.,* 1996), to 36% in barley (*Hordeum vulgare* L.) (Conn and Thomas, 1987) and 48% in sugar beet (Scheweizer, 1983). There are several empirical models to relate crop yield losses to the weeds density (Cousens 1985; Cousens et al. 1987; Dew 1972; Kropff et al. 1995; Lotz et al. 1996). These models explain yield loss as a function of weed density (Cousens 1985; Dew 1972), weed and crop densities (Cousens 1985), weed density and relative time of emergence compared to the crop (Cousens et al. 1987), and relative leaf area of weeds (Kropff and Spitters 1991; Lotz et al. 1992). Edalat *et al.,* (2010) developed a polynomial model for estimating corn yield loss, based on corn water stress index due to competition with red root pigweed in different densities. Statistical comparison between various equations showed that a rectangular hyperbola with weed density as the explanatory variable for a range of crop-weed density combinations at the field level resulted in the best description of the weed caused crop yield losses (Cousens, 1985). Spatiotemporal discrepancies in yield loss predictions of the Cousens model even at the same weed density have been reported (Cowan 1998, Jasieniuk et al. 1999). For example, a study in Illinois reported maximum corn yield loss of 12% from common lambsquarters was in 1985, but

Table 1. Monthly average temperature and rainfall values during the years of experiment and 30-year means at Agricultural Research Center (Badjgah), Shiraz. Iran.

Month	*Rainfall (mm)*			*Temperature(°C)*		
	2007-2008	2008-2009	1977-2007	2007-2008	2008-2009	1977-2007
Apr-May	3.50	18.50	13.60	14.70	12.30	15.70
May-Jun	0.00	0.00	0.80	25.50	23.90	20.20
Jun- Jul	0.00	0.00	0.30	23.60	22.00	23.76
Jul-Aug	0.00	0.00	0.50	25.40	25.50	23.72
Aug-Sep	0.00	0.00	0.40	23.50	25.70	20.40

no yield loss was observed in 1986 or 1987 (Beckett et al. 1988). Langston and Harvey (1994) reported nine giant foxtail plants per foot of row did not reduce corn yield in 1993 but reduced yield by 18% in 1994. Lindquist et al. (1996) suggested caution should be practiced when estimating crop yield loss solely on weed density in bioeconomic weed management models. Leaf area based crop yield loss models have been developed to minimize location and year variability. These models account for some of the variability associated with different times of weed emergence (Kropff and Spitters 1991) and also to explain differences in weed crop interactions at various locations (Kropff, 1988; Kropff and Spitters, 1991; Kropff et al., 1995; Lotz et al. 1996). Analyses of the Kropff and Lotz ecophysiological model for competition and validation results of hyperbolic yield loss weed-density function supported the new model. This model describes the relationship between yield loss and relative weed leaf area shortly after crop emergence using two parameters, the “relative damage coefficient” as a main model parameter and the “maximum relative yield loss”.

This model gives a better explanation of the effects of both weed density and relative time of weed emergence because leaf area can be accounted for as an indicator of both weed density and age (Kropff and Spitters, 1991). If the data are from multiple spatiotemporal studies, relative weed leaf area is a preferred explanatory variable over plant density (Lotz et al., 1996).

Inversion relationship of individual-plant biological yield or seed yield with weed density as independent variable was also shown to give good estimates of the weed competitive ability (Spitters, 1983). A criticism to empirical models is that narrow classes of models with very specific assumptions are developed as a consequence of wide reliance on empiricism in modeling. The suitability of these models is however more determined on the biological assumptions they are based on (Schabenberger and Pierce, 2002). Corn as a summer crop in Iran is grown under relatively drier months of year, thus potentially could experience various levels of water stress. Our objectives were (i) to evaluate the performance of frequently used empirical models in predicting yield loss under different water stress regimes and (ii) to evaluate the predictability of different yield loss models in corn-redroot pigweed systems.

Materials and methods

Field experiment

experiments were conducted under field conditions at the research field of Agricultural College of Shiraz University ,located at a latitude of 29° 44' N, a longitude of 52° 37' E, and an altitude of 1810 m during 2008 and 2009 growing seasons The research area has hot and dry summers and cold and rainy winters. Data on monthly average temperature and rainfall for two years of study and 30-years means of the region is shown in Table1. The research area was cultivated and sown with corn the SC704 cultivar (8 plant m^{-2}), a widely used cultivar in Shiraz region, and the redroot pigweed seeds in May 2008 and 2009. The weed seeds were sown at 10 cm horizontal distance from corn rows, and at the four-leaf stage, thinned to obtain 0, 5, 10, 20, 30 and 40 plant m^{-1} weed densities. As a nitrogen source, the plots were fertilized with urea (175 kg N ha^{-1}) on 17th of May and 20th of June and super phosphate (100 kg P_2O_5 ha^{-1}) on 17th of May. Furrow irrigation was applied to irrigate the plots. Land preparation practices included plowing, disking and ridging plots. The experimental plots were 4 m wide and 5 m long, laid out according to split plot design with each treatment replicated three times. The experimental plots were designed according to split plot with irrigation treatments (three levels) as main plots and weed densities (six levels) as split plots. Irrigation treatments included: T1=full irrigation and increasing soil moisture content in root depth to field capacity, T2=T1+25% and T3=T1-25%. Irrigation interval was 10 days for all treatments. The amount of applied water for each round of irrigation was measured by time-volume technique (Grimes et al. 1987).

Selected models

1. Cousens hyperbolic model- Cousens model predicts the yield loss as a reciprocal function of weed density with the slope parameters "*I*", as an indicator of the outcome of weed crop competition and "*A*" as the curve asymptote which is the upper limit of the loss function when weed density approaches infinity (Eq. 1).

$$Y_L = IN_w(1 + \frac{IN_w}{A}) \qquad \text{Eq. (1)}$$

in which Y_L is the relative yield loss expressed as a fraction, *Nw* is the weed density in number per m^2, and “*A”* is the initial slope of the curve relating yield loss to weed density, indicating the Y_L per unit weed density as $Nw \rightarrow 0$. In this empirical yield loss function, the outcome of competition is expressed by parameter “*A”*.

2. Kropff and Lotz model- Analyses of the Kropff and Lotz ecophysiological model for competition and validation results of hyperbolic yield loss weed-density function supported the new model. This model describes the relationship between yield loss and relative weed leaf area shortly after crop emergence using two parameters, the "relative damage coefficient "*q*" as a

Table 2. Estimates of parameters of Kropff and Lotz model for predicting corn yield loss at 6, 8 and 10 weeks after planting (WAP) under different water stress regimes with their 95% confidence limits at two 2008-2009 consecutive years.

			6WAP					
		Year	*2008*			*2009*		
		Irrigation[1]	T1	T2	T3	T1	T2	T3
Parameters	*q*	*Estimate*	0.753	0.568	1.134	0.533	0.481	0.987
		SEM[2]	0.102	0.093	0.049	0.064	0.087	0.175
		95% CL[3]	0.470	0.310	0.997	0.357	0.24	0.886
			1.037	0.826	1.271	0.710	0.723	1.088
	m	*Estimate*	0.727	0.881	0.792	0.67	0.655	0.659
		SEM[2]	0.039	0.083	0.011	0.03	0.048	0.092
		95% CL[3]	0.62	0.649	0.761	0.585	0.522	0.403
			0.834	1.112	0.824	0.754	0.787	0.915
			8WAP					
		Year	*2008*			*2009*		
		Irrigation[1]	T1	T2	T3	T1	T2	T3
Parameters	*q*	*Estimate*	1.288	1.125	1.913	0.946	0.899	1.679
		SEM[2]	0.247	0.255	0.58	0.221	0.117	0.217
		95% CL[3]	0.601	0.417	0.302	0.54	0.543	0.737
			1.975	1.833	3.523	1.352	1.255	2.621
	m	*Estimate*	0.692	0.677	0.718	0.597	0.629	0.625
		SEM[2]	0.037	0.048	0.054	0.05	0.045	0.042
		95% CL[3]	0.59	0.543	0.57	0.458	0.504	0.509
			0.795	0.812	0.867	0.737	0.754	0.741
			10WAP					
		Year	*2008*			*2009*		
		Irrigation[1]	T1	T2	T3	T1	T2	T3
Paramete	*q*	*Estimate*	0.596	0.352	0.978	0.64	0.564	1.142
		SEM[2]	0.09	0.122	0.06	0.168	0.094	0.183
		95% CL[3]	0.265	0.012	0.583	0.174	0.304	0.634
			0.927	0.692	1.373	1.106	0.823	1.649
	m	*Estimate*	0.833	0.857	0.915	0.598	0.608	0.603
		SEM[2]	0.097	0.189	0.048	0.044	0.033	0.028
		95% CL[3]	0.564	0.332	0.783	0.475	0.516	0.525
			1.102	1.382	1.048	0.72	0.699	0.68

1. T1=full irrigation to field capacity in soil water content, T2=T1+25% and T3=T1-25%.
2. Standard Error of Mean
3. 95% confidence limits

Table 3. Estimates of parameters of Spitters model under different water stress regimes with their 95% confidence limits at two 2008-2009 consecutive years.

		Year	2008			2009		
		Irrigation[1]	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*
Parameters	*bc0*	*Estimate*	0.00138	0.00112	0.00162	0.00134	0.00128	0.00159
		SEM[2]	0.000064	0.000095	0.000156	0.000043	0.000018	0.000126
		95% CL[3]	0.0012	0.00104	0.00118	0.00122	0.00123	0.00124
			0.00156	0.00156	0.00205	0.00146	0.00133	0.00193
	bci	*Estimate*	0.000028	0.000026	0.000027	0.000027	0.000017	0.000035
		SEM[2]	2.84E-06	4.22E-06	6.95E-06	1.92E-06	7.89E-07	5.59E-06
		95% CL[3]	0.00002	0.000014	7.40E-06	0.000022	0.000014	0.000019
			0.000036	0.000037	0.000046	0.000032	0.000019	0.00005

1. T1=full irrigation to field capacity in soil water content, T2=T1+25% and T3=T1-25%.
2. Standard Error of Mean
3. 95% confidence limits

main model parameter and the maximum relative yield loss *"m"*:

$$Y_L = \left(\frac{qL_w}{\left[1 + \left(\frac{q}{m} \right) - 1 \right] L_w} \right) \quad \text{Eq. (2)}$$

L_w, "the Relative leaf area" of the weed (redroot pigweed), was calculated from the following equation:

$$L_W = \left(\frac{\mathrm{LAI}_{\mathrm{weed}}}{\left(\mathrm{LAI}_{\mathrm{crop}} + \mathrm{LAI}_{\mathrm{weed}} \right)} \right) \quad \text{Eq. (3)}$$

3. *Spitters model*- Inversion relationship of individual-plant biological yield or seed yield with weed density as independent variable was also shown to give good estimates of the weed competitive ability (Spitters, 1983).

$$W^{-1} = b_{co} + b_{cc} N_c + b_{ci} N_w \quad \text{Eq. (4)}$$

where "W^{-1}" is the inversion of individual crop plant seed yield or biomass, "N_C" is the crop density, "N_w" is the weed density, "b_{co}" is the actual inversion of individual-crop plant seed yield or biomass without competition, "b_{cc}" is "intraspeciefic competition index" of crop, and b_{ci} is "interspecific competition index" of crop and weed. Where due to fixed crop density, the intraspeciefic competition of crop isn't practically calculable; the equation 4 reduces to the following equation:

$$W^{-1} = b_{co} + b_{ci} N_w \quad \text{Eq. (5)}$$

Field measurements

Water required at each irrigation level was determined as moisture percent by monitoring soil water content of the field in each plot by the gravimetric method at 30 cm intervals down to 150 cm. Irrigation depth for a certain treatment was calculated by the following equation (7):

$$D = \frac{\left\{ \sum \left(\mathrm{FCi} - \theta \mathrm{i} \right) \Delta z \right\}}{100} \quad \text{Eq. (7)}$$

where *"D"* is the depth of irrigation water (cm), *"FC_i"* is the field capacity moisture in depth of *i* ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$), *"$\theta_l$"* is the wilting point moisture in depth of *i* ($\mathrm{cm}^3\ \mathrm{cm}^{-3}$) and *"$\Delta Z$"* is the measurement depth (cm). The leaf area indices (LAI) of the crop and the weed were measured on two samples of 10 plants each, at 6, 8 and 10 weeks after planting (WAP) in both years of experiments. Leaf area was estimated by measuring the green leaf area of all leaves with a leaf area meter (Model Delta-T, Delta-T Devices, UK). The crop yield was determined by manually harvesting the middle 1.5 m of the two central rows of each plot in September. The corn grain yield was determined after oven drying for 48 h at 75 °C.

Statistical and reliability analyses

The relative yield loss (Y_L) of the crop challenged by weed competition under field conditions was estimated using equation 6:

$$Y_L = 1 - \left(\frac{Y_{CW}}{Y_{CM}} \right) \quad \text{Eq. (6)}$$

where *"Y_{CW}"* and *"Y_{CM}"* are crop yield in competition with weed and crop yield in a weed free condition, respectively. The empirical yield loss models were fitted to the data of grain yield loss and LAI using Proc Nlin (nonlinear procedure) of the statistical software SAS 9.1(SAS, 1989). The parameter values that minimized the squared sum of deviations were estimated through the Gauss-Newton optimization method. The F-statistic value ($P<0.05$) was used as primary model goodness of fit statistic to choose models that better explain the yield loss/weed density relationship. High values of coefficient of determination (adjusted R^2) and low values of RMSE (root mean square error) along with a randomly scattered residual plot were used as complementary model diagnostics to decide on accepting the fit of the data to a certain nonlinear model (Schabenberger and Pierce, 2002). Eventually, a reliability analysis was conducted to help identify the best model. To evaluate the precision and accuracy of the models in their predictions, estimate of Lin's concordance correlation coefficient (ρ_c) for each model was calculated using the following equation:

$$\rho_c = \frac{2\sigma_{UW}}{(\mu_U - \mu_W) + \sigma_U^2 + \sigma_W^2} \quad \text{Eq. (7)}$$

where μ_U, μ_W, σ_U^2, σ_W^2 and σ_{UW} are respectively predicted (U) and observed (W) yield loss means, variances, and covariances (Meek et al., 2009; Madden et al., 2007). The estimate of ρ_c *(r_c)* was obtained by replacing sample based estimators of the terms of Eq. (7) as follows:

$$r_c = \frac{2s_{UW}}{(\overline{U} - \overline{W}) + s_U^2 + s_W^2} \quad \text{Eq. (8)}$$

Equation 8 can be written as $r_c = rC_b$ with *r* as Pearson Correlation Coefficient (a measure of precision) and C_b as an indication of deviation of the best fitting line ($U = \beta_0 + \beta_1 W$) from the perfect agreement (concordance) line ($U = W$) (Lin, 1989). C_b may be decomposed into $C_b = 2/(v + 1/v + u^2)$ where $v = \sigma_U/\sigma_W$ (systematic bias a measure of Lin's scale shift) and $u = (\mu_U - \mu_W) / \sqrt{\sigma_U \sigma_W}$ (scaled constant bias, measuring Lin's location shift). If $r_c = 1$, there is a perfect agreement between predicted (*U*) and observed (*W*) values, which indicates model precision ($r = 1$) and accuracy ($C_b = 1$). Deviation of r_c from unity as a result of $r < 1$ specify variability about the best fitting line. A $C_b < 1$ is an evidence of systematic bias ($v < 1$) and /or constant bias ($u \neq 0$).

Results and discussion

The models used in this study to predict the crop yield loss based on the weed density or the weed relative leaf area under different irrigation treatment generally showed a satisfactory fit to the data with significant F values. A summary of the parameter estimates and model diagnostics for all three models is shown in Tables 2 to 6. Adjusted R- squares of the

Table 4. Estimates of parameters of Cousens model under different water stress regimes with their 95% confidence limits at two 2008-2009 consecutive years.

		Year	2008			2009		
		Irrigation[1]	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*
Parameters	*I*	*Estimate*	6.618	5.025	10.600	4.061	5.212	9.220
		SEM2	0.429	0.663	1.133	0.548	0.581	1.731
		95% CL3	4.305	3.183	7.455	2.540	3.599	6.395
			8.931	6.867	13.745	5.581	6.824	12.045
	A	*Estimate*	89.28	95.334	84.742	89.996	81.786	78.529
		SEM2	3.366	9.407	3.674	10.23	5.911	16.371
		95% CL3	79.935	69.216	74.543	61.594	65.375	33.076
			98.628	121.500	94.942	118.400	98.197	124.000

1. T1=full irrigation to field capacity in soil water content, T2=T1+25% and T3=T1-25%.
2. Standard Error of Mean
3. 95% confidence limits

Table 5. Diagnostics of Kropff and Lotz model for predicting corn yield loss at 6, 8 and 10 weeks after planting (WAP) under different water stress regimes

Model	Year	IRR[1]	Pr > F[2]	Adj R^2	RMSE[3]	CCC[4]	Precision (r)	Accuracy (Cb)
6WAP	2008	T1	<0.0001	0.9800	0.0200	0.9436	0.9436	1.0000
		T2	<0.0001	0.9900	0.0160	0.9407	0.9450	0.9954
		T3	<0.0001	0.9900	0.0050	0.9369	0.9392	0.9976
	2009	T1	<0.0001	0.9800	0.0180	0.8733	0.8742	0.9990
		T2	<0.0001	0.9900	0.0110	0.9203	0.9233	0.9968
		T3	0.0005	0.9100	0.0340	0.8253	0.8463	0.9752
8WAP	2008	T1	<0.0001	0.8700	0.0870	0.9240	0.9336	0.9898
		T2	<0.0001	0.8300	0.1000	0.9076	0.9144	0.9925
		T3	0.0001	0.8000	0.1180	0.9013	0.9014	0.9999
	2009	T1	0.0002	0.9000	0.0680	0.9342	0.9497	0.9837
		T2	<0.0001	0.7800	0.1040	0.8807	0.8909	0.9885
		T3	<0.0001	0.8000	0.0990	0.9008	0.9045	0.9959
10WAP	2008	T1	<0.0001	0.8400	0.0970	0.9142	0.9188	0.9950
		T2	0.0008	0.8000	0.1070	0.8906	0.9131	0.9754
		T3	<0.0001	0.7700	0.1280	0.8755	0.8805	0.9943
	2009	T1	<0.0001	0.9200	0.0600	0.9586	0.9618	0.9966
		T2	<0.0001	0.8100	0.0960	0.8986	0.9078	0.9898
		T3	<0.0001	0.8100	0.0960	0.8969	0.9104	0.9852

1. Irrigation levels: T1=full irrigation to field capacity in soil water content, T2=T1+25% and T3=T1-25%.
2. Test H0: lack of association between yield loss & weed density.
3. Root Mean Squared Error
4. Concordance correlation coefficient.
5. u =scaled constant or classic bias as an indicator of location shift.
6. υ = systematic bias as an indicator of scale shift.

models varied between 0.73 and 0.99 and RMSE ranged from 0.0005 to 3.002. Cousens model had the smoothest and narrowest range of variation in diagnostics (Table 6). Model parameters did not show any significant difference across years (data not shown). This corresponds to the fact that monthly precipitations and average temperatures at field sites were very comparable to their long term values during months of growing seasons in years of study (Table 1), According to primary and complementary model diagnostics and inspection of residual plots, Cousens model was the most accurate and precise predictor of yield loss under all levels of irrigation (Figure 1 and Table 6). In terms of model behavior, Cousens model was very reliable and consistent in its yield loss predictions across all levels of irrigation (Fig. 1). This model simulated the yield loss at T3 irrigation level with small systematic (0.990 to 1.007) and constant biases (zero to 0.0004). This suggests that the precision of the Cousens model predictions was independent from the level of irrigation (Figure 1). The Kropff and Lotz (8WAS) model showed a good fit to the data comparable to the Cousens model. Both Cousens and Kropff & Lotz (8WAP) models showed consistently lower constant (zero to 0.0008) and systematic (0.8958 to 1.2526) biases and therefore high precision and accuracy irrespective of the strength of water stress (Figure 1). The Kropff and Lotz model was more precise (constant bias 0.0001 to 0.0008) and accurate (systematic bias 0.9874

Table 6. Diagnostics of Cousens and Spitters models for predicting corn yield loss under different water stress regimes.

Model	Year	IRR[1]	Pr > F[2]	Adj R^2	RMSE[3]	CCC[4]	Precision (r)	Accuracy (Cb)
Spitters	2008	T1	0.0003	0.8700	0.00019	0.8291	0.8704	0.9526
		T2	0.0003	0.8300	0.00023	0.9060	0.9115	0.9940
		T3	0.011	0.7300	0.00025	0.7995	0.8721	0.9168
	2009	T1	0.0002	0.8700	0.00007	0.8797	0.9017	0.9756
		T2	0.0002	0.8600	0.00005	0.9760	0.9838	0.9920
		T3	0.0003	0.8000	0.00016	0.8104	0.8853	0.9154
Cousens	2008	T1	<0.0001	0.9900	0.681	0.9688	0.9694	0.9994
		T2	<0.0001	0.9900	1.372	0.9555	0.9563	0.9991
		T3	<0.0001	0.9900	1.108	0.9333	0.9333	1.0000
	2009	T1	<0.0001	0.9900	1.263	0.9542	0.9582	0.9959
		T2	<0.0001	0.9900	1.042	0.9735	0.9857	0.9877
		T3	0.0003	0.9300	3.002	0.9503	0.9503	1.0000

1. Irrigation levels: T1=full irrigation to field capacity in soil water content, T2=T1+25% and T3=T1-25%.
2. Test H0: lack of association between yield loss & weed density.
3. Root Mean Squared Error
4. Concordance correlation coefficient.
5. *u* =scaled constant or classic bias as an indicator of location shift.
6. *υ* = systematic bias as an indicator of scale shift.

to 1.1994) at 8WAP than 6WAP (constant bias from 0.0003 to 0.0011 and systematic bias from 0.9923 to 1.2526 biases) and 10WAP (constant bias from 0.0002 to 0.0010 and systematic bias from 1.0875 to 1.2513 biases). The Kropff and Lotz model predictions were also more erroneous at T3 irrigation treatment, indicating a greater systematic bias at more intense water shortages (scale shift between 0.9874 and 1.2526 at T3 irrigation level). Overall, compared to the Cousens model (RMSE 0.681 to 3.002), Kropff & Lotz model predicted the yield loss with lower overall error rate (RMSE 0.005 to 0.128). Comparison of Kropff and Lotz model diagnostics at 8WAP with other two sampling dates (6 and 10WAP) showed that the model precision in predicting yield loss was generally comparable between 6WAP (r = 0.8463 to 0.9436), 8WAP (r = 0.8909 to 0.9497) and 10WAP (r = 0.8805 to 0.9618). Among the models used in this study, Spitters model showed the poorest performance in prediction of yield loss particularly at T3 irrigation level. This model had the highest constant bias (0.0013 to 0.0031) and its systematic bias depended on changing the water conditions (Figure 1). Greater constant/systematic biases of the Spitters model (0.0031/1.5624 and 0.0024/1.5321 for years 2008 and 2009, respectively) in yield loss predictions at T3 irrigation suggest that the model requires further adjustments to correct both kinds of biases in predictions. The accuracy of yield loss prediction of Spitters was poorer than Kropff & Lotz and Cousens models at T3 irrigation (Figure 1), although the two models were comparable at T1 and T2 irrigation levels. The Spitters model had the lowest RMSE value and this apparently small RMSE was not the result of using a better predictor, but was more of a direct result of using small values of yield loss produced by reciprocal transformation of individual biological yield values. Relative leaf area of the weed used as the predictor of the Kropff & Lotz model increased following increase in weed density at all levels of irrigation. This parameter increased through the growing season and reached its maximum at 8WAP in both years of study. Although the growth rate of the relative leaf area is not constant across irrigation levels and years (Figure 2), there was a similarity between 6, 8 and 10 WAP in this regard for both years. As shown in other studies, the leaf area sampling period (4 or 8-leaf stage of corn) did not affect the precision of the corn yield loss predictions by the Kropff & Lotz model (Ngouajio et al., 1999). The high predictability of the Kropff & Lotz model in simulating the crop yield loss and its potential for implementation in integrated weed management system has also been emphasized in independent studies (Dieleman et al., 1995; and Knezevic et al., 1995). The deviation between model prediction and the actual level observed is called the residual which is an estimate of model error. A residual plot is a very useful tool for inspecting the overall fit and the constant variance criterion. The residual plots for all models are shown in Figure 3. As shown in this figure, the Kropff and Lotz (8WAP) model had the lowest error (2-year average data). The highest and lowest errors of the model occurred respectively at 20 and 0 & 40 plant m^{-1} weed densities for all sampling dates. The error was low for 5, 10 and 30plant m^{-1} densities which is an indication of variance non constancy. For Cousens model, the residuals were randomly scattered along weed density axis, with the lowest errors at zero and 5 weed m^{-1}. Spitters model had the high value of errors for all weed densities, even for zero and 5 weed m^{-1}. These data revealed that the Cousens hyperbolic model is a more reliable predictor of the yield loss of corn competing with the redroot pigweed, across an agronomically reasonable range of weed density, and under water stress conditions. Since model parameters present the outcome of all ecological factors, effect of water availability on model parameters was considered as an indicator of biological function of water stress on crop yield loss. Initial slope (*I*) of the Cousens model is considered as a competition index which measures the competition between the crop and the weed. The competition between the two species increased as the intensity of water stress was increased (2-year average

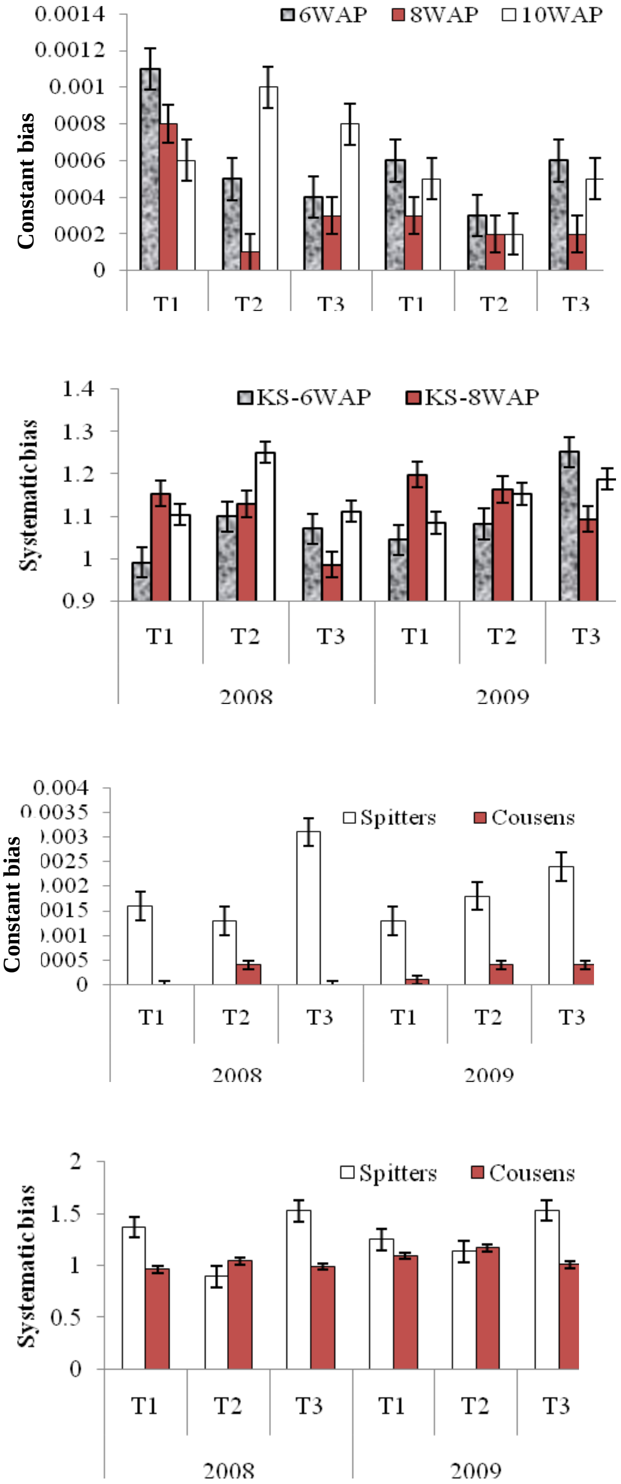

Fig 1. Constant and systematic biases for all models in different irrigation levels and two successive 2008-2009 growing seasons (KL= Kropff and Lotz model; 6WAP=6 weeks after planting, 8WAP=8 weeks after planting, 10WAP=10 weeks after planting)

"*I*" of 5.339, 5.118 and 9.910 at T1, T2 and T3 irrigation levels, respectively). Aghabeigi et al. (2007) in a study on corn and the common lambsquarters under simultaneous emergence of both the weed and the crop in 2001/2002 fitted the Cousens model and estimated the parameter *I* values of 0.38 and 0.26 in two successive years which is close to the values estimated in this study. Although assessment of 95% confidence limits of "*I*", does not show a significant difference of "*I*" across irrigation treatments, it can be regarded as an indication of relative competitive advantage of the redroot pigweed over corn as water becomes less available. Inclusion of an asymptote ("*A*" parameter) in Cousens model to account for the yield loss plateau at high weed densities has made this model a biologically more realistic model (Swinton and Lyford, 1996). The model asymptote, as an indication of the maximum yield loss under very large weed densities, showed a consistent increase with water increased stress (2-year average from 80.6 at T1 to 88.6 at T3 irrigation levels). This is in line with the fact that under more water stress conditions, the redroot pigweed has an increased competitive advantage over the crop suggesting a relative robustness of the Cousens model for prediction of yield loss under water stress conditions as compared to other models (Table 3). The Kropff & Lotz model estimated the yield loss generally well at T1 and T2 irrigation levels (constant bias 0.0008 to 0.00111). At T3 irrigation, the model was very accurate (2-year average constant and systematic biases 0.0003 and 1.0410, respectively) when L_w at 8WAP was used as explanatory variable. With L_w at 6WAP and 10WAP as yield loss predictor however, the model showed greater biases (2-year average constant and systematic biases 0.0005 and 1.1622 for 6WAP and 0.0007 and 1.1509 for 10WAP). This shows that L_w at 8WAP was a better predictor of yield loss as compared to L_w at 6WAP and 10WAP. Parameter *q* "relative damage coefficient" of Kropff & Lotz model represents weed competitivity over the crops with higher values of "*q*", as an indication of the lower competitive ability of the crop over the weed. Our findings suggest an increasing rate of competitive ability of the redroot pigweed over corn with increasing water shortage in both years of study. The competitive ability of the redroot pigweed over corn increased considerably as the irrigation rate was reduced. A higher competitive ability of the weed over the crop at T3 irrigation treatment is in line with the fact that the redroot pigweed has both higher seed germination and root growth rates during the growing season that enable the weed to take advantage of an increased competitive growth over corn. Although parameter "*q*" could represent water stress function on weed/crop competition and add to theoretical significance of the model, the maximum yield loss parameter "*m*" was not biologically meaningful and increased as the competitiveness of the crop over the weed increased. This shortcoming of the model parameter contradicts with the fact that maximum yield loss cannot increase while crop competitiveness over weed increases. Despite the poorer model diagnostics, this model appears to be improper due to the lack of theoretical relevance. These findings suggest some model adjustments in order to improve model inaccuracies in yield loss predictions under water stress conditions. Interspecific competition coefficient (*bci*) of the Spitters model increased about 13% at T3 and decreased 21% at T2 compared to T1 irrigation level (Table 3). This indicates an

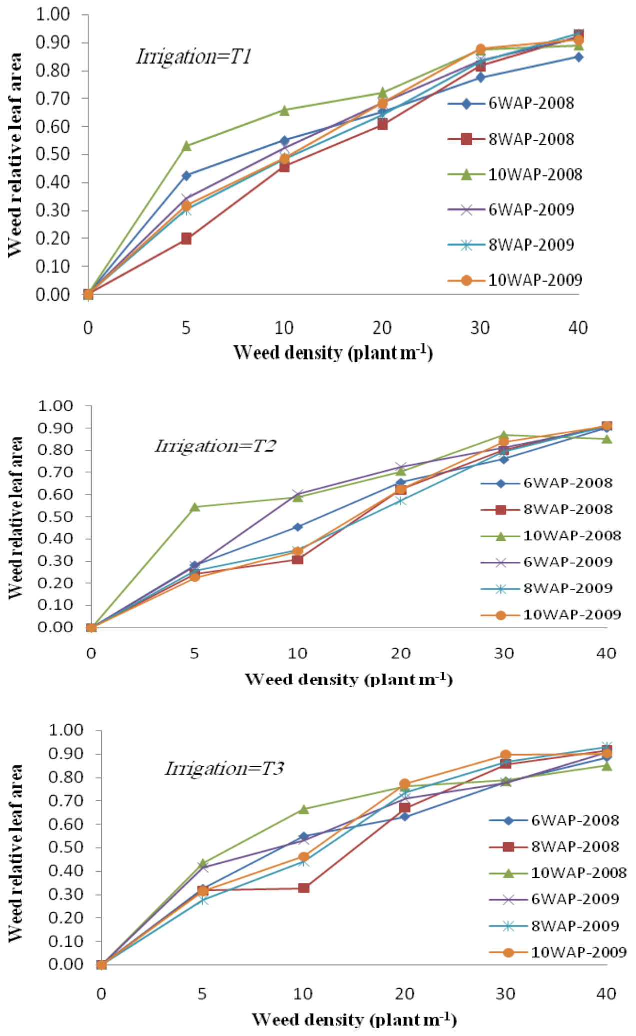

Fig 2. Relationship between pigweed density and its relative leaf area in different irrigation levels and two successive 2008-2009 growing seasons.

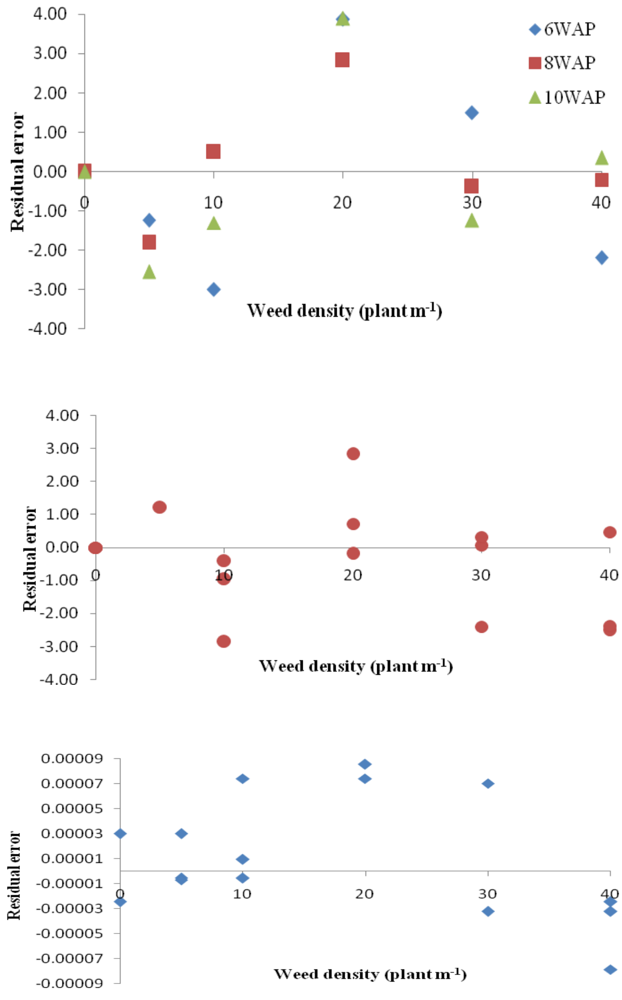

Fig 3. Deviation (residual error) of the predicted and observed values of yield loss for Kropff & Lotz, Cousens and Spitters models in different pigweed densities.

increased competition between the crop and the redroot pigweed conceivably due to limited water availability. The results also showed a basic pattern of change in the "bc_0" parameter or "the inverted yield of an individual plant without weed". The "bc_0" parameter increased with water stress intensity across irrigation treatments from 0.00120 to 0.00161 . The inverted yield of an individual plant without weed at T3 irrigation level was higher than those at both T1 and T2 irrigation treatments, suggesting a better yield production for the crop at higher water stress conditions provided no weed present (Table 3).

Conclusion

The fit of the data to the empirical models varied with irrigation level and weed density. In this study, both the crop and the weed were challenged by irrigation to evaluate the robustness of the model yield loss predictions across various weed densities. The three models predictions at T3 irrigation were not generally as good as their predictions under T1 and T2 irrigation levels, however, Cousens model predicted the yield loss equally well across all irrigation treatments. Cousens model is recommended as an appropriate model for yield loss prediction of corn competing with the redroot pigweed under water stress conditions. The Kropff and Lotz model (8WAP) fit to the data was comparable to the Cousens model. Both Cousens and Kropff & Lotz models showed consistently lower constant and systematic biases and therefore higher precision and accuracy than other models. The reliability of these two models was not affected by strength of water stress. The Kropff and Lotz model (6 and 10WAP sampling dates) requires elaboration of further adjustments in the models to overcome the location and scale shifts in yield loss predictions under water stress conditions and improve its predictability. Discrepancies in the simulations made by the models under various irrigation treatments could conceivably be due to differential functional responses of the crop and the weed to various levels of water shortage. The magnitude and direction of the effect of irrigation-weed interaction on model parameters was used as an indicator of biological relevance of the models and parameters of Cousens model represented the water stress function very well. Supplementary field validation studies with the Cousens and probably Kropff and Lotz models will also be required to validate their predictability in the corn-redroot pigweed system.

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