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Field screening of canola (*Brassica napus*) cultivars against wild mustard (*Sinapis arvensis*) using competition indices and some empirical yield loss models in Golestan Province, Iran

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ABSTRACT

In order to evaluate the competitive ability (CA) of canola cultivars against wild mustard, two experiments were conducted at the Gorgan Institute in Iran during the 2005–2007 cropping seasons. The experimental factors were canola cultivars (1st year: Zarfam, Option500, Hayola330, Hayola401, Talayh, RGS003 and Sarigol; 2nd year: Zarfam, Hayola330, RGS003 and Option500) and weed density (1st year: control and 30 plants m^{-2}; 2nd year: control, 4, 8 and 16 plants m^{-2}). The result of the first year of experiment indicated that the grain yield and competitive indices differed significantly between the cultivars. Cultivar Zarfam showed a high ability to withstand competition (AWC = 47%), high competitive indices (CI = 1.79 and CI_2 = 10 1.83) and low grain yield in the weed-free plots (1729 kg ha^{-1}). The cultivar Option500, a less competitive cultivar had the lowest ability to withstand competition (AWC = 4%) and the lowest competitive indices (CI = 0.09 and CI_2 = 0.11) amongst the cultivars. However, the cultivar Option500 showed more grain yield in the weed-free plots (2333 kg ha^{-1}) than cultivar Zarfam. In the second year of the experiment, the result of the yield loss models showed that the lowest and highest yield loss belonged to cultivars Zarfam and Option500 (50 and 95% respectively). A comparison of different empirical models revealed that the empirical yield loss model based on weed relative leaf area was more reliable for predicting canola yield loss according to a high coefficient of determination ($R^2 = 0.99$). The relative damage coefficient (q) of the weed relative leaf area model showed that wild mustard was more competitive than canola ($q > 1$).

1. Introduction

Increasing costs of herbicide inputs in intensive crop production systems and the incidence of herbicide resistance in weeds have renewed interest in exploiting crop competitiveness to reduced herbicide use (Lemerle et al., 2001). Variation in their competitive ability against weeds exists not only between crop species, but also within cultivars of a given species. Increased competitive ability among cultivars has been variously attributed to early seedling emergence, seedling vigour, rapid root growth and rate of leaf expansion, early root and shoot biomass accumulation and canopy closure, and plant height (Huel and Hucl, 1986; Blackshaw, 1994; O'Donovan et al., 2000; Ni et al., 2000; Zand, 2000).

Two factors contribute to crop competitiveness against weeds: ability to withstand competition (AWC), or the ability to maintain high yields in the presence of weeds, and weed suppressive ability (WSA), the ability of the crop to reduce weed biomass and seed production (Jannink et al., 2000). WSA and AWC are often difficult to separate in field experiment data (Lemerle et al., 2001). However, there are indications that varietal variation in WSA may be grater than that of AWC (Jordan, 1993). In addition, WSA may be considered the most agronomically desirable trait, since it controls weed population in the long-term and therefore has greater implications for weed management programmes.

In an integrated weed management system, weed control is initiated only when justified by economic or other objective criteria. This requires not only appropriate detection and quantification of weed populations at the early stages of crop development, but also accurate prediction of the outcome of competition. In recent years, several techniques for weed population estimation have been developed (Lutman, 1992; Lotz et al., 1994; Bussler et al., 1995; Carson et al., 1995; Andreasen et al., 1997; Andrieu et al., 1997; Ngouajio et al., 1998). These include simple methods such as the determination of density, destructive measurement of the leaf area, measurement of

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plant volume, indirect estimation of the Leaf Area Index (LAI), measurement of photosynthetically active radiation (PAR) within the plant canopy, and canopy evaluation using optical devices.

Weed density is often used to predict yield loss from weed interference (Dew, 1972; Cousens, 1985). Weed density is relatively easy to measure on a small scale. However, accurate determination of population density on the large scale common in crop production situations may be difficult. Weeds are commonly distributed in patches of different densities and weed seedlings usually emerge in successive flushes (Brain and Cousens, 1990; Wiles et al., 1993). Destructive measurements of leaf area samples using a leaf area meter can overcome many of the major obstacles in estimating weed population density for yield loss prediction (Kropff and Spitters, 1991; Kropff et al., 1995). Leaf area estimates have increased the accuracy of yield loss prediction models in many cases (Kropff and Lotz, 1992; Lotz et al., 1994, 1995; Dieleman et al., 1995; Knezevic et al., 1995; Florez et al., 1999; Ngouajio et al., 1999).

We conducted two field experiments aiming at (1) determining the competitive ability of the canola cultivars and introducing more competitive cultivars in competition with wild mustard, and (2) evaluating, assessing and comparing the reliability, accuracy and usefulness of different empirical yield loss models in predicting the effect of different densities of wild mustard on canola yield.

2. Materials and methods

Two field experiments were conducted during the 2005 and 2006 growing seasons at the Gorgan Institute in Iran (36°45′N, 54°25′E, 5_masl) in order to study the competitive ability of canola cultivars against wild mustard and the effect of different densities of wild mustard on canola yield loss. The climate of this region is warm and humid with an annual precipitation of 500 mm and a mean long-term annual temperature of 28 °C. The soil type was silty loam. The experimental designs were randomized complete blocks with a factorial arrangement of treatments and three replications. The experimental treatments were canola cultivars (1st year: Zarfam, Option500, Hayola330, Hayola401, Talayh, RGS003 and Sarigol; 2nd year: Zarfam, Hayola330, RGS003 and Option500) and density (1st year: control and 30 plants m^{-2}; 2nd year: control, 4, 8 and 16 plants m^{-2}) of wild mustard. The cultivars used in Exp. 1 are prevalent in Golestan Province and were selected on the basis of their competition indices. In Exp. 2, four canola cultivars from the more competitive to the less competitive were selected. In fall, before the establishment of the experiments, the field was fertilized with 125 kg N ha^{-1} and 100 kg P ha^{-1} for Exp. 1 (2005) and 140 kg N ha^{-1} and 110 kg P ha^{-1} for Exp. 2, (2006). Top dressed urea was also applied at the rate of 50 kg N ha^{-1} at the beginning of the stem elongation stage of canola. The soil preparation consisted of December mouldboard ploughing (20–25 cm) followed by October discing and smoothing with a land leveller. Plots were 8 m long with 10 rows spaced 24 cm apart.

All the cultivars were planted at their optimum density (80 plants m^{-2}), as proposed by the Iran Seed and Plant Improvement Institute (Omidi et al., 2005). They were seeded on 15 November in both 2005 and 2006, with 5 cm between holes within rows and, finally, thinned to one seed of canola per hole at 2–3 leaf stage in order to obtain target density. Wild mustard seeds were collected from canola fields infested by wild mustard in Gorgan. Pre-chilling was applied to break the wild mustard seed dormancy, in which seeds were kept 10 days at 2 °C (Goudy et al., 1987). The weed seeds were sown at high density at both sides of the canola rows and, finally, thinned to target densities at the 2–3 leaf stage of canola. All other weeds were removed throughout the season by hand every 2 weeks. After planting, the entire field was sprinkler irrigated until seedling establishment and then relied upon precipitation for the remainder of the season in both years.

Measurements of canola and wild mustard LAI were taken from 50 cm length of one row of each plot. Plant samples were taken approximately every 2 weeks in both of years. Sampling started from day 35 after emergence and involved 10 plants from the selected sampling area. Leaf area was estimated by measuring the green leaf area of all leaves with a leaf area meter (Model LI- 3000, LI-CORInc., Lincoln, NE). The crop was harvested manually in May when seed moisture reduced to 14%. At harvest, the middle 4 m of the centre two rows of each plot (a total area of 1.92 m^2) was harvested. Canola grain yield was determined after oven drying for 48 h at 75 °C. WSA of the canola cultivars was calculated using Equation (1) (Zand, 2000) which was obtained from Callaway and Francis (1993) with a few modifications (Table 1).

Equation (2) was applied (Table 1) in order to evaluate WSA of the cultivars in reducing wild mustard seed production.

Table 1
Nomenclature.

Eq. no.	Measurement	Abbreviation and equation	Reference	Description
1	Competition Index	$\mathrm{CI} = \dfrac{\left(\dfrac{V_i}{V_{\mathrm{mean}}}\right)}{\left(\dfrac{W_i}{W_{\mathrm{mean}}}\right)}$	Zand, 2000	V_i = the yield of cultivar I in the presence of weeds V_{mean} = the mean yield of all cultivars in presence of weeds W_i = the weed biomass related to cultivar i W_{mean} = the mean weed biomass in the presence of all cultivars
2	Competition Index_2	$\mathrm{CI}_2 = \dfrac{\left(\dfrac{V_i}{V_{\mathrm{mean}}}\right)}{\left(\dfrac{S_i}{S_{\mathrm{mean}}}\right)}$	Zand, 2000	S_i = the weed seed yield related to cultivar i S_{mean} = the mean weed seed in a mixed stand of all cultivars
3	Ability to withstand competition	$\mathrm{AWC} = \left(\dfrac{V_i}{V_{\mathrm{P}}}\right) \times 100$	Watson et al., 2002	V_{P} = the mean yield of cultivar i in weed-free conditions
4	Yield Loss_1	$\mathrm{YL}_1 = \dfrac{Id}{1 + \left(\frac{Id}{A}\right)}$	Cousens, 1985	A = the asymptotic value of yield loss at high weed density I = the yield loss as weed density approaches zero d = wild mustard density.
5	Yield Loss	$\mathrm{YL} = 100 \times \dfrac{(Y_0 - Y)}{Y_0}$	Cousens, 1985	Y_0 = mean crop yield in weed-free plots Y = observed yield in weed-infested plots
6	Yield Loss_2	$\mathrm{YL}_2 = \dfrac{qL_{\mathrm{W}}}{1 + (q-1)L_{\mathrm{W}}}$	Kropff and Spitters, 1991	q = the relative damage coefficient(yield loss per unit relative leaf area at low weed densities) L_{W} = the wild mustard relative leaf
7	Weed relative leaf area	$L_{\mathrm{W}} = \dfrac{\mathrm{LAI_W}}{\mathrm{LAI_W} + \mathrm{LAI_C}}$	Kropff and Spitters, 1991	$\mathrm{LAI_W}$ and $\mathrm{LAI_C}$ are the weed and crop leaf area index, respectively.

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Table 2
Analysis of variance for grain yield and biomass of canola cultivars.

S.O.V	Df	Mean square	
		Grain yield	Biomass
Replication	2	0.0067 ns	0.02 ns
Cultivar	6	0.16 ns	0.05**
Weed	1	4.4**	1.6**
Weed*Cultivar	6	0.17**	0.06**
Error	26	0.013	0.008
C.V		4.3	2.6

ns = not significant.
* and ** Significant at the 5% and 1% levels of probability, respectively.

Table 4
Correlation coefficients between competitive indices and the weed-free grain yield.

	Weed-free grain yield	AWC	CI	CI_2
Weed-free grain yield	1	−0.817*	0.49 ns	0.43 ns
AWC		1	0.71*	0.7*
CI			1	0.82*
CI_2				1

Ns = not significant.
* Significant at the 5% level of probability.

It is worth mentioning that Equation (2) has been obtained from combining Equation (1) with the amount of wild mustard seed production, instead of wild mustard biomass production. AWC of canola cultivars against wild mustard was calculated from Equation (3) (Table 1), as described by Watson et al. (2002).

Canola yield loss (YL_1) and wild mustard density data were fitted to the nonlinear regression model from Equation (4) (Table 1), proposed by Cousens (1985).

YL_1 was derived from yield data using Equation (5) (Table 1).

Canola yield loss (YL_2) and wild mustard relative leaf area (L_W) were fitted to a nonlinear regression model from Equation (6) (Table 1) proposed by Kropff and Spitters (1991).

L_W can be calculated from Equation (7) (Table 1).

Cluster analysis was performed to classify cultivars in terms of their competitive ability (CA) including the three indices AWC, CI and CI_2. The linkage method was based on the average linkage (between groups) and the dissimilarity metric was squared Euclidean Distance. The effect of weeds on canola cultivars and differences among cultivars were analyzed using the SAS Institute (1998).

The empirical yield loss models (Equations (4) and (6)) were fitted to the values of grain yield and LAI using the statistical programme Sigma plots V8.0 (SPSS Inc.). The coefficient of determination (R^2) was determined for nonlinear regression, as in other studies (Askew and Wilcut, 2001). The R^2 of 1:1 line related to be observed against predicted values was used to determine the goodness and reliability of fit to different yield loss models.

3. Results

3.1. First year

3.1.1. Canola grain yield and competitive ability

The analysis of variance (ANOVA) showed that there were significant interactions between canola cultivars and weed infestation for canola grain yield and biomass (Table 2). The percentage yield loss (AWC) was different among the cultivars (Table 3); cultivars Zarfam and Talayh showed the highest AWC, while cultivar Option500 had the lowest AWC. High AWC in cultivars Zarfam and Talayh was accompanied by low grain yield in the weed-free plots (1729 and 1802 kg ha^{-1}, respectively). Hence, there was a significant negative correlation between weed tolerance ability and yield potential in the weed-free plots, which is consistent with the results of correlation analysis ($r = -0.817^*$) (Table 4). The negative relationship between AWC, as an indication of canola CA, and the weed-free yield potential is of concern (Donald and Hamblin, 1976). In the UK, wheat varieties that produced the greatest grain yield in weed-free plots were the most severely affected by weed competition (De Lucas and Froud-Williams, 1994). In contrast, no relationship was observed in Australia between weed-free yield and percent yield loss (Gill and Coleman, 2000; Lemerle et al., 2000).

In the case of CI, our result also indicated significant difference between cultivars. Cultivar Zarfam had the highest CI (1.79) which could be attributed to its higher grain yield under weed-infested conditions (870 kg ha^{-1}) and its ability to reduce wild mustard biomass (1148 kg ha^{-1}). Also, no significant correlation was found between grain yield under weed-free and weed-infested conditions (coefficient of correlation = 0.223). Conversely, Australian data showed a strong positive correlation between weed-free and weed-infested grain yield (Cousens and Mokhtari, 1998; Gill and Coleman, 2000). Bussan et al. (1997) announced the possibility of introducing a soybean cultivar which is able to reduce weed biomass whilst keeping its grain yield high, as did Zarfam and Talayh in this experiment (Table 3).

Cultivars Hayola330, Hayola401, RGS003 and Sarigol as moderate competitive genotypes had high yield, both under weed-free and weed-infested conditions. Cultivar Option500 had the lowest CI amongst the cultivars which was due to high weed biomass and very low grain yield (101 kg ha^{-1}) in the presence of wild mustard (Table 3). Gill and Coleman (1999) also reported a strong association between yield reduction in wheat and *Lolium rigidum* biomass in southern Australia.

Wild mustard seed production was highest when it was grown with the cultivar Option500 (i.e.157 CI_2). Wild mustard seed production and biomass were reduced by the same cultivar and a significant correlation was found between AWC, CI and CI_2 (Table 4). For instance, cultivar Zarfam, which had a high CI, possessed high CI_2 and AWC. Lemerle et al. (2001) stated that AWC and WSA might not necessarily be present in the same variety. Nevertheless,

Table 3
Mean comparison for grain yield, canola biomass, wild mustard and seed production, AWC, CI and CI_2 of canola cultivars under weed-free and weed-infested.

Cultivar	Grain yield (Kg ha^{-1})		Canola biomass (Kg ha^{-1})		Wild mustard production (Kg ha^{-1})		AWC (%)	CI	CI_2
	Weed-free	Weed-infested	Weed-free	Weed-infested	Biomass	Seed			
Hayola401	2317 a*	636.8 a	10739 a	4216 a	2089 ab	104 ab	28 ab	1.03 ab	0.94 b
Hayola330	2836 a	870.9 a	9418 a	4841 a	1448 b	93 b	30 ab	1.16 ab	1.3 ab
RGS003	2605 a	635.3 a	9659 a	4026 a	2130 ab	104 ab	25 b	1.01 ab	0.95 b
Option500	2333 a	101 b	9659 a	1530 b	2951 a	134 a	4 c	0.09 b	0.11 c
Sarigol	2605 a	653 a	10838 a	4415 a	1545 b	89 ab	25 ab	1.15 ab	1.22 ab
Zarfam	1729 b	867.9 a	8034 b	5308 a	1148 c	54 c	47 a	1.79 a	1.83 a
Talayh	1802 b	641.2 a	8030 b	3758 a	1288 bc	65 c	40 a	1.61 a	1.62 a

* Means of each column having similar letter are not significantly different at the 5% level of probability, according to Duncan Multiple Test.

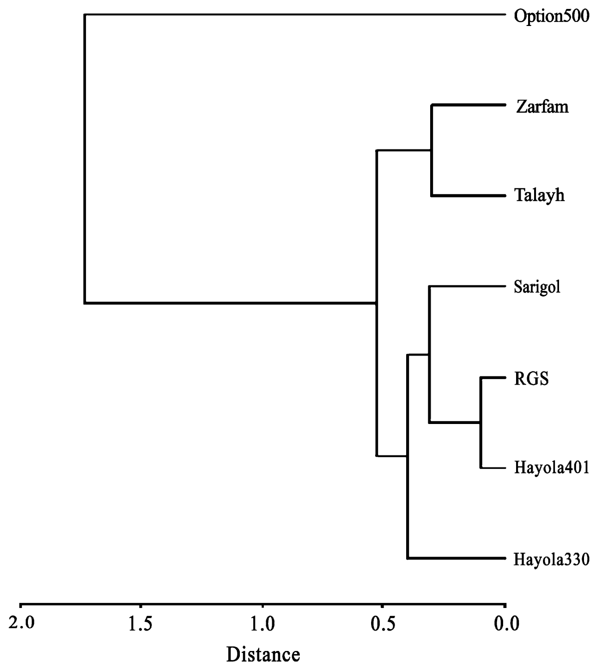

Fig. 1. Cluster analysis of canola cultivars based on three competitive indices (AWC, CI & CI_2).

in the present study it was observed that the weed tolerant cultivars Zarfam and Talayh also had high CI_2.

3.1.2. Determination of less and more competitive cultivars

Generally, an ideal crop cultivar should have high yield potential under both weed-free and weed-infested conditions, the ability to withstand weed growth, and a weed growth suppressive ability (Bussan et al., 1997). Using these criteria, no ideal cultivar was identified in the present study. For instance, cultivar Zarfam which showed high AWC, CI_2 and CI and produced low grain yield in the weed-free plots (Table 3). Our results also did not show any significant correlation between the weed-free grain yield and competitive indices (Table 4). Therefore, we may not be able to introduce a cultivar which has a high grain yield in the weed-free plots, while maintaining a high CA. However, it is possible to introduce relatively ideal cultivars using these criteria. Following this line of thought, cluster analysis grouped the canola cultivars into groups based on their AWC, CI and CI_2 (Fig. 1).

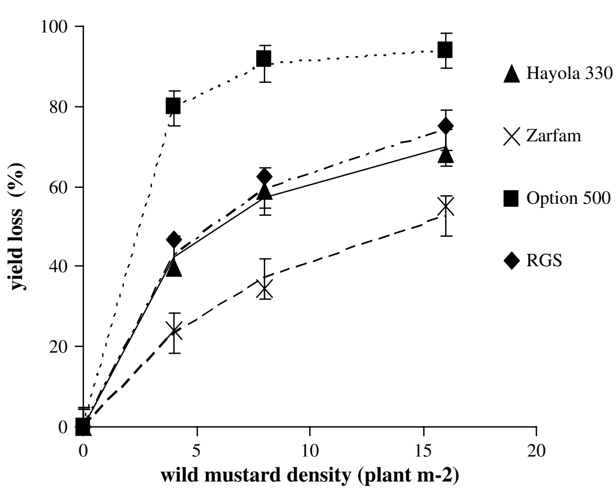

Fig. 2. Fitting canola yield loss due to wild mustard using the empirical yield loss model based on weed density (YL_1).

Table 5
Parameter (±SE) and corresponding R^2 of canola yield loss using empirical yield loss model based on weed density (Eq. (4)).

Cultivars	R^2	I	A
Zarfam	0.95	9.8 ± 1.5	88.8 ± 12.4
Hayola330	0.97	20.25 ± 2.44	90.9 ± 5.2
RGS003	0.95	22 ± 6	94 ± 3.4
Option500	0.96	35.1 ± 4	98 ± 1.6

The cultivar Option500 was grouped as one of the less competitive cultivars (with high weed-free yield), Zarfam and Talayh as more competitive cultivars (with low weed-free yield), and Hayola330, Hayola401, RGS003 and Sarigol as an intermediate group (with high weed-free yield). Overall, the cultivars Zarfam and Option500 would be introduced as the greater and lesser competitive cultivars, respectively.

3.2. Second year

3.2.1. Performance of empirical yield loss model based on weed density (YL_1)

Grain yield declined with increasing weed density (Fig. 2). The rectangular hyperbolic yield loss model based on weed density was fitted to the grain yield values. Results indicated that the parameter I, which describes the yield loss per weed as density approaches zero, were 9.8, 20.25, 22 and 35 in cultivars Zarfam, Hayola330, RGS003 and Option500, respectively (Table 5). The highest yield loss occurred in cultivar Option500. In contrast, least yield loss was observed for cultivar Zarfam. The same response was observed in the case of parameter *A* (the maximum of yield loss), so that the values of parameter *A* were 88.8, 90.9, 94 and 98 in cultivars Zarfam, Hayola330, RGS003 and Option500, respectively (Table 5). Many studies have reported 5% as the maximum acceptable yield loss (McMullan et al., 1994; Martin et al., 2001). Regarding the acceptable level of yield loss, the results of Exp. 2 indicated that there were differences between cultivars. The acceptable yield loss threshold was 0.7, 0.32, 0.3 and 0.06 plants m^{-2} in cultivars Zarfam, Hayola330, RGS003 and Option500, respectively (Fig. 2). This difference between canola cultivars from a threshold level point of view is related to physiological and morphological characteristics, such as canopy architecture and height. Final height and vertical distribution of leaves were the most determinant characteristics of Zarfam which make it more competitive than cultivar Option500 (data not shown). These characteristics act by increasing the crop resource capture at the expense of that of the weeds (Blackshaw, 1994), in particular by reducing light quality beneath the crop canopy and thereby reducing weed seedling growth. Crop cultivar, weed density and species are all important factors influencing the level of acceptable yield loss. For example, 0.23 plants m^{-2} of barnyard grass (*Echinochloa crus-galli*) (Bosnic and Swanton, 1997), 2.2 plants m^{-2} of wild proso millet (*Panicum miliaceum*) (Wilson and Westra, 1991) and 12.5 plants m^{-2} of redroot pigweed (*Amaranthus retroflexus*) had been reported as the damage threshold in maize.

Table 6
Parameter (±SE) and corresponding R^2 of canola yield loss using empirical yield loss model based on weed relative leaf area (Eq. (6)).

Cultivars	R^2	q
Zarfam	0.95	9.8 ± 1.33
Hayola330	0.97	10.6 ± 2.1
RGS003	0.95	11.6 ± 1.44
Option500	0.96	14.9 ± 3

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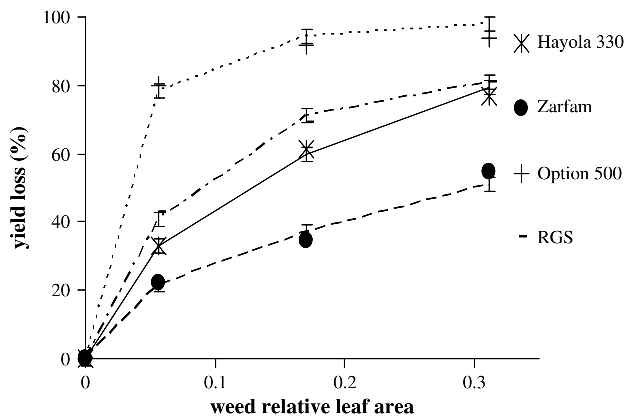

Fig. 3. Fitting canola yield loss due to wild mustard using the empirical yield loss model based on weed relative leaf area (YL_2).

For example, when wild mustard density was increased from zero to 6 plants m^{-2}, the relationship between the crop yield loss and weed density had a linear pattern (Fig. 2).

3.2.2. The empirical yield loss model based on weed relative leaf area (YL_2)

The relative damage coefficient of weed, q, in this model indicates differences between canola cultivars, as varied from 9.8 to 14.9 for Zarfam and Option500, respectively (Table 6). In fact, q demonstrates the relative competitiveness of the weed against the crop. A greater value means stronger competitiveness of the weed resulting in decreased crop yield (Kropff and Spitters, 1992) and so if $q < 1$ then the crop has a relative stronger competitive ability, while the weed is stronger when $q > 1$; when $q = 1$ the crop and weed have equal competitiveness. The regression curve of the crop yield loss on the weed relative leaf area is convex when $q > 1$, concave when $q < 1$ and on the 1:1 line when $q = 1$ (Ngouajio et al., 1999).

Both Fig. 3 and Table 6 illustrate a yield loss model (Equation (6)) fitted in Exp. 2. As observed, q was 9.8, 10.6, 11 and 14.9 in the cultivars Zarfam, Hayola330, RGS003 and Option500, respectively, where all of them were >1. It can therefore be concluded that wild mustard is more competitive than canola. Among the cultivars, the highest and lowest q belonged to cultivars Option500 and Zarfam, respectively, which indicates that cultivar Zarfam, was more competitive than cultivar Option500 against wild mustard. However, the slope of the regression lines declined with increased weed density.

To evaluate the reliability and accuracy of these two empirical yield loss models based on the weed density (YL_1) and weed relative leaf area (YL_2), parameter estimates and corresponding R^2 and Standard Errors (SE) are given in Tables 5 and 6. Comparison of the R^2 and SE of the predicted parameters showed that, in all of the cases, R^2 is high and, in most cases, SE is very low. Bosnic and Swanton (1997) stated that if the SE of each estimated parameter be less than half of its value, the model is not sufficiently valid and it cannot give a good estimate of yield and loss. So, it can be concluded that by using both models yield loss was reliable in respect to predicting canola yield loss from competition with wild mustard. The linear regression of observed and predicted canola yield loss for the two empirical models showed that they are on the 1:1 line in which the slope of the regression line is not significantly different from 1 and the intercept is not significantly far from 0, the correlation coefficient between the estimated and observed values was also calculated (Fig. 4). As a result, it was concluded that both empirical models provide an adequate fit for predicting yield loss.

Fig. 4 shows the slope of the regression line of weed density as lower than 1 (0.93), which indicates that the predicted yield loss of this model is lower than the observed yield loss. The weed relative leaf area model (YL_2) had the higher R^2 and the slope of regression measured on estimated values of yield loss was near 1 (Fig. 4). The results of the present study revealed that this empirical yield loss model was the more reliable and accurate model to predict canola yield loss due to wild mustard.

4. Conclusion

The results of the present study showed that wild mustard reduced the yield of various canola cultivars. Generally, cultivars Zarfam and Talayh were introduced as highly competitive cultivars against wild mustard. By sowing these cultivars we should be able to reduce herbicide dosage in canola fields for the control of weeds.

Also, among the two models fitted to data of canola yield loss, the rectangular hyperbolic yield loss model on weed relative leaf area (YL_2) proved more reliable. It is worthy to mention that the empirical yield loss model based on the weed relative leaf area (YL_2) was valid, but lack of a quick method for estimating the leaf area is one of the significant challenges in the case of this model (Knezevic et al., 1995; Lotz et al., 1996; Ngouajio et al., 2001). However, the effect of differing years and locations on the variability of results is extremely important and must be considered.

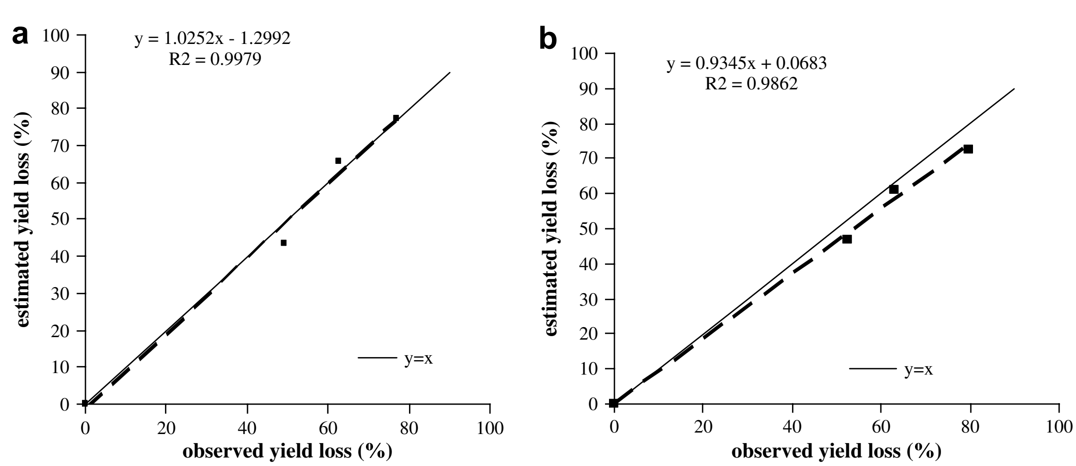

Fig. 4. Comparison between observed yield loss (points) and the predicted values (dash line) by weed relative leaf area model (a) and weed density model (b).

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