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Critical Period of Weed Control in Three Winter Oilseed Rape (*Brassica napus* L.) Cultivars

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Abstract: Field experiments were carried out at the Agricultural Research Station, Faculty of Agriculture, University of Tabriz, in 2004-2005 and 2005-2006. Three winter oilseed rape cultivars (Okapi, Licord, and SLM046) with 12 weed interference durations were evaluated in a factorial experiment based on a randomized complete block design with 3 replications. The experiments consisted of 2 sets of treatments. In the first set, the crop was kept weed-free until the growth stages of 4-leaf, 8-leaf, stem elongation, flowering, and podding. In the second set, weeds were permitted to grow within the crop until the above-mentioned growth stages. Weedy and weed-free checks were also included in the study. Different weed interference durations and interaction of cultivar * year affected significantly the grain, oil, and biological yield, but not the percentage of oil. Minimum values of these traits were observed under the full weed-infestation condition. Maximum values for grain yield, oil and biological yield belonged to the weed free control and SLM046 cultivar in both years. Regression models showed that in order to prevent >10% grain and oil yield loss, canola must be kept weed free between the 6-leaf stage and initial flowering (47-110 DAE) and for biological yield between the 7-leaf stage and stem elongation (52-94 DAE).

Key Words: Biological yield, canola, critical period, grain yield, oil yield, weed interference

Abbreviations: CPWC, critical period of weed control; DAE, days after emergence; MWF, minimum weed-free period; MWI, maximum weed-infestation period; CP, critical period; IWM, integrated weed management

Introduction

High yielding ability and better quality are considered the 2 main objectives in crop production. In order to achieve these goals, some agronomical principles and methods should be applied. One of the main problems that affect yield and quality of crops is weeds' interference and their competition with the crop (Hager et al., 2002). At present, more money is spent by growers on weed control than other crop inputs. The value of the global pesticide market was $29 billion in 2000, divided approximately between herbicides (48%), insecticides (27%), fungicides (19%) and other products (6%) (CPA, 2002). Thus, maximum yields could not be obtained without controlling weeds.

Developing a suitable integrated weed management (IWM) system requires the precise study of weeds and their interference with crops (Cruse et al., 1995). The critical period of weed control (CPWC) is a key component of an IWM program. It is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses (Knezevic et al., 2002). Studies carried out about the critical period of weed control showed that the duration of CPWC depends on several factors, including cultivars (Seem et al., 2003), climate, weed population density, and dominant weeds in the region (Martin et al., 2001; Seem et al., 2003), crop planting date (Martin et al., 2001), and other factors. Knowledge of critical periods may be used in bioeconomic models to improve the timing of herbicide applications for integrated weed management (Eyherabide and Cendoya, 2002).

Canola, like other members of its family, is a smother crop, because of its large leaves, rapid growth, and early closing of the canopy. However, weed competition with

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oilseed rape in the early growth stages is a critical problem (Ahmad Khan et al., 2003). According to McMullan et al. (1994), infestation of wild mustard (*Brassica kaber*) with canola until the 4- to 6-leaf stage, did not cause considerable yield loss. These studies, however, do not show the complete features of the critical period of weed control in canola, because only the critical period of weed removal was considered. In addition, in most studies, only one weed species was included in the experiment, whereas in actual conditions there are usually a range of weed species with different emergence patterns, which could greatly affect the critical period of weed control (Baldwin and Santelmann, 1980).

The objectives of this research program were to study the effect of different weed interference durations on yield quantity and quality of winter oilseed rape cultivars, considering mixed weeds populations similar to actual field conditions and to determine the critical period of weed control.

Materials and Methods

The field experiments were conducted at the Research Station (lat 38°15′N, long 46°17′E, 1360 m altitude) of the Faculty of Agriculture, University of Tabriz, Tabriz, northwest Iran, in the 2004-2005 and 2005-2006 growing seasons. According to the weather data (Table 1) both years had relatively normal weather conditions. Mean monthly temperatures during the growing season were approximately similar for both years. However, precipitation was higher for 2004-2005. Soil was sandy loam with pH 7.6 and 0.8% organic matter. Each year, the land was ploughed and cultivated before planting. Then the fertilizers, including urea, super phosphate and potassium sulfate, were applied based on the soil test at rates of 100, 200, and 100 kg ha^{-1}, respectively. Prior to seeding, canola seeds were treated with benomyl at 0.2% (wt/wt) in order to protect them from soil-borne diseases. The planting dates were September 10, 2004, and September 8, 2005. The plots were irrigated as needed. The experiments were factorial, based on a randomized complete block design with 3 replications for both years. The experimental factors included 3 winter oilseed rape cultivars (Okapi, Licord, and SLM046) and 2 sets of weed interferences (weed-free and weedy conditions). In the weed-free set, weeds were removed until the stages of 0-leaf, 4-leaf, 8-leaf, stem elongation, initial flowering, and initial podding. Weeds were removed by hand weeding in the above-mentioned durations. In the weed-infested set, weeds were permitted to grow within the crop until the 0-leaf, 4-leaf, 8-leaf, stem elongation, initial flowering, and initial podding stages, and then after the above treatment times the weeds were hand weeded until crop harvest time. Plot size was 2 m × 3 m, consisting of 8 rows of canola with 25-cm between-row and 5-cm within-row spacing. After emergence, crop development stages were recorded at 7-day intervals on 20 successive plants for each of the 6 central rows in each plot (120 plants in each plot).

Table 1. Weather data during the growing season for 2 years (2004-2005 and 2005-2006).

Month	2004-05			2005-06		
	Temperature (°C)		Precipitation mm	Temperature (°C)		Precipitation mm
	Mean max	Mean min		Mean max	Mean min	
September	29.12	12.63	1.5	28.62	11.65	0
October	23.88	6.03	2	21.44	6.85	11.5
November	13.45	2.32	41	12.29	-0.65	16.4
December	2.17	-8.13	21.5	10.81	-2.47	0
January	1.59	-9.92	10	0.75	-8.50	59.5
February	-0.70	-10.01	23.6	3.30	-7.07	56
March	9.23	-2.64	18.5	10.65	-2.12	4
April	13.87	1.96	62	16.80	3.21	20.5
May	20.67	7.58	114.7	20.69	6.95	45
June	26.81	10.68	18.5	29.47	12.23	5

High natural weed populations were observed in both years. Experiments were carried out on the same fields; therefore, there were similar weed communities. In both years, the dominant weeds were *Descurainia sophia* L. (flix weed), *Anchusa officinalis* L. (Bogloss), *Chenopodium album* L. (common lambsquarters), *Cynodon dactylon* L. (bermudagrass), *Acroptilon repense* L. (creeping knapweed), *Sonchus arvensis* L. (perennial sowthistle), *Polygonum aviculare* L. (knotgrass), and *Convolvulus arvensis* L. (field bindweed). The total weed density for full-season weed-infested plots was 97 and 79 plants per square meter in 2005 and 2006, respectively. At the stage of maturity a 3-m^2 area from the center of each plot was harvested on June 26, 2005, and June 22, 2006, in the first and second years, respectively, and canola grain yield, oil yield, and biological yield were determined. Percentage of seed oil was measured using a near infrared (NIR) system.

Data analysis

Since in the preliminary tests a logistic model provided the best fit for the maximum weed-infested period, it was used to describe the effect of increasing duration of weed infestation on the yield of canola (Ratkowsky, 1990). The model was as follows:

$$Y = C + D/(1 + \exp(-A + BT)) \qquad [1]$$

where Y is the yield as a percentage of the weed-free control, A and B are parameters that determine the shape of the curve, C is the lower asymptote, D is the difference between the upper and lower asymptotes, and T is days after canola emergence (DAE), which is equal to weed infested duration from canola emergence time until weed removal and control time.

The Gompertz model was applied to describe the effect of increasing length of weed-free period on canola yield (Ratkowsky, 1990):

$$Y = A \exp(-B \exp(-KT)) \qquad [2]$$

where Y is the yield as a percentage of the weed-free control, A is the upper asymptote, B and K are parameters that determine the shape of the curve, and T is DAE, which is equal to the weed-free period from canola emergence time.

It should be mentioned that in both models the averages of the 2 years were used and the time between December 10 and March 20 (winter) was omitted from the calculations, because about 80 days after canola emergence, on December 10, the canola plants with 8-9 leaves were at the full rosette stage and entered the winter dormant stage. This stage lasted until March 20; therefore, during this period (winter) canola plants and weeds had no growth. Furthermore, there is no weed competition with canola and weed control operations are not required. A combined analysis of variance was carried out for both years. SAS statistical software (SAS, 1988) was used to analyze the data, including analysis of variance (ANOVA) and comparison of means based on a LSD procedure (Gomez and Gomez, 1984).

Results and Discussion

Analysis of variance revealed significant effects of different durations of weed interference and interaction of variety * year (V * Y) on canola grain, oil and biological yield, but not oil percent. However, the interactions of interference duration * year (D * Y), V * D and V * D * Y were not significant for these traits (data not shown). Therefore, all cultivars showed similar responses to weed interference durations and had similar critical periods. With all weed interference duration treatments, amount of grain, and oil and biological yield of the SLM046 cultivar were higher than those of the others in both years. Moreover, in Table 2, the means of traits are shown as averages of weed interference durations for each cultivar. Grain yield decreased significantly with increasing length of weed interference duration and decreasing length of weed-free period (Table 3). The maximum canola grain yield, 5516.4 kg ha^{-1}, was obtained with the control treatment (full season weed-free). Grain yield decreased 69.39% in the weedy treatment (full season weed-infested) (Table 3). This yield reduction is related to the lower amount of available nutrients, light, and water for the crop plants. However, when weeds were controlled after 46.6 DAE (6-leaf stage, considering 10% yield loss), no significant loss was observed in canola grain yield. Furthermore, when the crop was kept weed-free until the early flowering stage (≥113.8 DAE), the grain yield was not significantly different than that of the weed-free control. This result indicates that there was no appreciable competition between the crop and weeds. Similar results were

Table 2. Means of grain yield, oil percentage, and oil and biological yield of 3 oilseed rape cultivars in the weed interference conditions on the average of 2 years (2004-2005 and 2005-2006).

		Trait			
Cultivar	Year	Grain yield (kg ha^{-1})	Percentage of oil	Oil yield (kg ha^{-1})	Biological yield (g m^{-2})
Okapi	2004-05	3525.9 b *	45.9 a	1616.1 b	1616.3 b
Okapi	2005-06	3591.9 b	45.8 a	1644.8 b	1687.3 b
Licord	2004-05	3422.8 b	45.7 a	1561.7 b	1606.6 b
Licord	2005-06	3712.2 b	45.8 a	1696.9 b	1766.1 b
SLM046	2004-05	4316.1 a	45.8 a	2011.4 a	2058.0 a
SLM046	2005-06	4010.5 a	45.7 a	1829.5 a	1886.8 a
LSD (5%)		274.80	ns	117.71	116.10

ns: no significant difference between cultivars., LSD: Least significant difference (Gomez and Gomez, 1984),
* a and b indicate significant difference of Okapi and Licord with SLM046.

Table 3. Mean values of grain yield, oil percentage, and oil and biological yield under different weed-free (WF) and weed-infested (WI) conditions obtained for the average of 3 winter oilseed rape cultivars and 2 years (2004-05 and 2005-06).

Trait				
Biological yield (g m^{-2})	Oil yield (kg ha^{-1})	Percentage of oil	Grain yield (kg ha^{-1})	Durations of weed interference
1005.7 b	777.8 b	45.47	1688.6 b *	WF 0 DAE
1460.8 b	1266.7 b	46.01	2754.0 b	WF-4L
1751.2 b	1658.1b	45.82	3617.4 b	WF-8L
2084.9 b	2053.6 b	45.95	4473.5 b	WF-S
2223.4 a	2245.8 b	45.64	4921.3 b	WF-F
2296.4 a	2353.7 b	45.55	5174.6 a	WF-P
2346.5 a	2531.4 a	45.90	5516.4 a	WI 0 DAE
2207.6 b	2341.9 b	45.88	5106.3 b	WI-4L
2050.4 b	2120.9 b	45.88	4623.0 b	WI-8L
1522.0 b	1461.0 b	45.43	3157.6 b	WI-S
1242.9 b	1062.9 b	45.89	2295.6 b	WI-F
1050.5 b	846.8 b	45.65	1830.3 b	WI-P
137.19	142.67	Ns	356.67	LSD (5%)

Abbreviations: WF and WI: Weed-free and weed-infested, respectively. DAE: Days after emergence. 4L, 8L, S, F and P: Growth stages of 4-leaf, 8-leaf, stem elongation, flowering and initial podding, respectively.
* a and b indicate significant difference of treatments with weed-free control.

reported by Ahmad Khan et al. (2003) and Martin et al. (2001). They showed an increase in grain yield by controlling weeds and yield loss as the duration of weed interference with canola increased.

Oil and biological yield were also reduced as weed interference durations increased and weed-free durations decreased. Maximum oil yield (2531.4 kg ha^{-1}) and biological yield (2346.5 g m^{-2}) were obtained for the control treatment (full-season weed-free). In comparison with the control, full-season weed interference decreased oil and biological yield about 69.27% and 57.14%, respectively (Table 3).

Regression analysis

The 2 approaches commonly used to determine the critical period of weed control (CPWC) are: (i) critical weed-free period called the minimum time point weed-free (MWF) and (ii) critical period of weed infestation called the maximum time point under weed infestation (MWI). The time interval between MWI and MWF has been defined as a critical period (CP) for weed control (Martin et al., 2001; Gibson and Liebman, 2003; Knezevic et al., 2003; Seem et al., 2003). In addition, the crossing point of MWI and MWF has been called the equality point of control and interference. In fact, this point determines the equality of increasing or decreasing crop yield in response to competitive conditions (Singh et al., 1996).

Logistic and Gompertz models generally described the data well, as indicated by the coefficients of determination (R^2) (Tables 4). Since the interaction of D * V, D * Y and D * V * Y were not significant, thereafter the average of 2 years were used in these models. Three levels of acceptable yield loss (2.5%, 5%, and 10%) were selected for traits and then the maximum weed-infested period and minimum weed-free period were calculated for each level. Length of critical period for the measured characteristics decreased with increasing value of acceptable yield loss from 2.5% to 10% (Table 5).

The maximum period of infestation at the 3 levels of acceptable yield loss was 14-46.6 DAE for canola (Table 5). For example, to consider 5% grain yield loss, the estimated maximum period of weed infestation was equal to 31.2 days, which overlapped with the 4-leaf stage of canola development. Therefore, in order to prevent > 5% grain yield loss, weeds must be removed from the field after 31.2 DAE. The minimum weed-free duration for the 3 acceptable levels of grain yield loss was between 113.8 and 145.5 DAE. In fact, canola needs a 133.3-day weed-free period to prevent > 5% grain yield loss (Table 5). When considering 10% crop yield loss, the beginning time of the critical period of weed infestation was estimated to be 46.6 DAE (Table 5 and Figure 1). This period coincided with the 6-leaf stage of canola development. In other words, weed infestation until the

Table 4. Estimates of parameters for logistic and Gompertz equations are followed by standard errors in parentheses, respectively (average of 2 years, 2004-05 and 2005-06).

Trait	Parameter estimates for weed infestation periods based on logistic equation				
	A	B	C	D	R^2
Grain yield	4.60(0.58)	0.058(0.007)	29.47(1.90)	69.51(3.11)	0.99
Oil yield	4.56(0.59)	0.057(0.007)	29.55(1.95)	69.46(3.19)	0.98
Biological yield	4.67(0.52)	0.058(0.006)	41.90(1.39)	57.27(2.26)	0.98

Trait	Parameter estimates for weed free periods based on Gompertz equation			
	A	B	K	R^2
Grain yield	109.21(2.93)	1.30(0.04)	0.0168(0.0012)	0.98
Oil yield	108.96(2.70)	1.29(0.04)	0.0166(0.0011)	0.98
Biological yield	106.65(3.15)	0.93(0.04)	0.0179(0.0020)	0.98

R^2: coefficient of determination

Table 5. Maximum period of weed infestation and minimum weed-free duration at the 3 levels of grain, oil and biological yield losses (average of 2 years).

	Grain yield loss			Oil yield loss			Biological yield loss		
	2.5%	5%	10%	2.5%	5%	10%	2.5%	5%	10%
Maximum duration of weed infestation	14	31.2	46.6	13.5	30.9	46.5	20.4	36.7	52
Minimum duration of weed-free	145.5	133.3	113.8	147.2	134.5	114.5	130.2	114.8	94.5
Length of critical period (day)	131.5	102.1	67.2	133.7	103.6	68	109.8	78.1	42.5

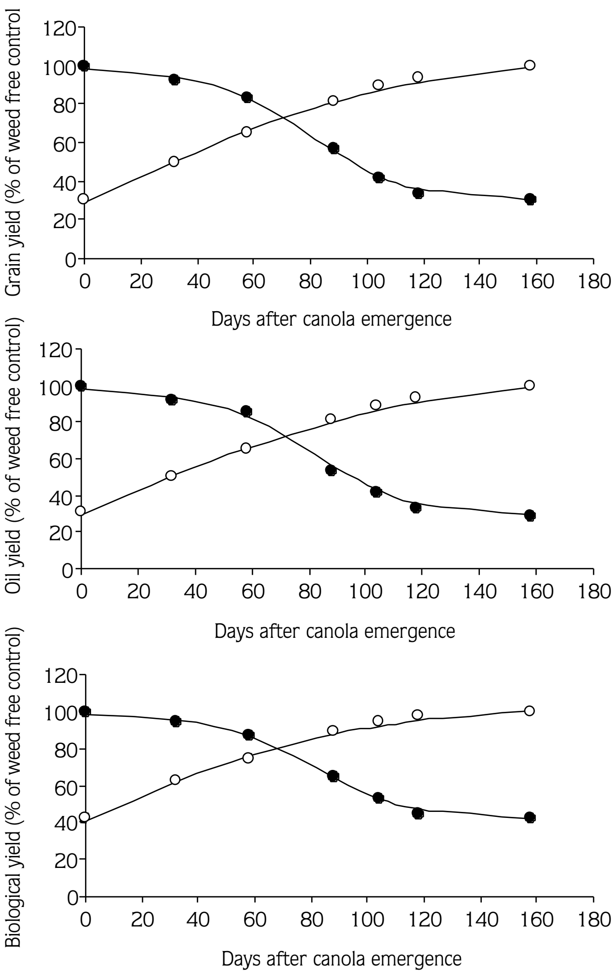

Figure 1. Effect of increase in the duration of weed infestation (●) and length of weed-free period (❍) on grain yield (A), oil yield (B) and biological yield (C)(average of 2 years) of the canola (expressed as a percentage of the weed-free control) as estimated by logistic [Y = C + D/(1 + exp (-A + BT))] and Gompertz [Y = A exp (-B exp (-KT))] equations.

6-leaf stage will not have a significant effect on canola yield, because there was no severe competition between canola and weeds until the 6-leaf stage of canola due to the availability of sufficient resources in the early growing season. Similar results were also reported by McMullan et al. (1994). They showed that the infestation of canola fields by wild mustard (*Brassica kaber*) until the 4- to 6-leaf of canola does not have a negative effect on yield. However, according to Martin et al. (2001), in order to prevent > 10% yield loss, canola must be kept weed-free until the 4-leaf stage of the crop (17-38 DAE) and in early plantings this period must be continued until the 6-leaf stage (41 DAE). In this study, few weeds emerged and acquired little biomass after the 4-leaf stage of the crop. It seems that canopy closure by the canola may have prevented weeds from establishment and growth after the 4-leaf stage (Martin et al., 2001).

The ending time of the critical weed-free period (based on 10% of acceptable yield loss) was obtained as 113.8 DAE (Table 5 and Figure 1), which overlapped with the early flowering of canola. This stage coincided with the full canopy closure of canola; thereafter, growth of weeds decreased because of shading. Martin et al. (2001) also reported that, in canola after canopy closure by the crop, weed establishment and their competitive ability decreased considerably. On the whole, the critical period of weed interference (according to 10% of acceptable yield loss) ranged between 46.6 and 113.8 DAE (Table 5 and Figure 1), which corresponded with the 6-leaf and early flowering stages of canola. Martin et al. (2001) also found that in the late planting of canola the critical period ranged from the 6-leaf to early flowering stages.

Percentage of oil was not affected by different periods of weed infestation or the interaction of V * Y. However, oil yield was significantly affected by these factors (data not shown). Oil yield of SLM046 was significantly higher than that of Okapi and Licord in 2004-2005 (Table 2), which could have resulted from the higher grain yield of this cultivar. Among weed interference periods, the maximum oil yield was obtained in the weed-free control (full-season weed-free), which is also due to its higher grain yield. As the length of weed interference duration increased and the length of weed-free duration decreased, the competition of weeds with canola increased, which subsequently caused a reduction in grain and oil yield. The amounts of oil yield loss under different weed-infested and weed-free conditions, evaluated by the logistic and Gompertz models, are shown in Figure 1. Based on the logistic equation, increasing the length of weed interference duration decreased oil yield, and, based on the Gompertz equation, increasing the weed-free period caused an increase in the oil yield. Considering 10% oil yield loss, the beginning time of the critical period was estimated as 46.5 DAE (Table 5), which overlapped with the 6-leaf stage. The roots and shoots of crop and weeds did not interfere with each other in the early weeks after emergence; thereafter, the crop can tolerate weeds without considerable reductions in growth. However, by increasing the time of weeds presence in the field, crop yield loss will occur. Since oil percentage was not affected by different weed interference durations, oil yield loss in acceptable loss levels from 2.5% to 10% were similar to those of the grain yield. Blackshaw et al. (2002) studied the effect of density and emergence times of wild radish (*Raphanus raphanistrum* L.) on yield quality of canola and reported that densities of 4 and 64 wild radishes per m^2 that emerged with canola reduced canola yield about 9% to 11% and 77% to 91%, respectively. Wild radish that emerged 10 weeks after canola did not reduce canola yield. Wild radish did not directly reduce canola quality, but if wild radish seeds were not separated from canola seed, the amounts of erusic acid and glucosinolates increased.

Weed infestation until 52 DAE (in 10% of acceptable loss) had no effect on biological yield; thereafter until 100 DAE yield decreased rapidly, and after 100 days the rate of decrease was slow (Figure 1 C). The correspondence of results related to biomass and grain yield indicates that the competitive effects of weeds on the crop were severe during the middle growing stages.

Full-season weed infestation resulted in a 57.14% loss in biomass as compared with the weed-free control. Increasing the acceptable loss level from 2.5% to 10% decreased the range of the critical period for biological yield of canola similar to the grain and oil yield and varied between 52 and 94.5 DAE. This period coincided with the 7-leaf and stem elongation stages. The range of the critical period for biological yield was smaller than that for grain and oil yield. This suggests that as the sensitivity of a character in the crop to biotic stresses increases the range of the critical period increases. In addition, the early closure of the crop canopy decreases the sensitivity of biological yield to weed interference. Other scientists also reported similar results (Swanton and Weise, 1991; Martin et al., 2001).

Conclusion

The results indicated that the maximum grain, oil and biological yield were obtained in the SLM046 cultivar in both growing seasons. Increasing weed infested duration and decreasing weed-free period led to decreased canola grain, oil and biological yield. The amount of loss for these characters for full-season weed infestation were 69.39%, 69.27%, and 57.14% as compared to the control (full-season weed-free), respectively. Weed infestation until the 4-leaf stage of canola caused a small loss in the grain and oil yield, but this reduction was not significant. Considering 10% acceptable yield loss, the critical period for the grain yield and oil yield ranged from the 6-leaf to early flowering stages and for biological yield from the 7-leaf to stem elongation stages. Due to the higher sensitivity of grain yield to weed competition, the range of the critical weed interference period was higher than that of the biological yield.

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