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The Heterosis and Combining Ability of Diallel Crosses of Rapeseed Inbred Lines

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Abstract

The heterosis and combining ability of four rapeseed (*Brassica napus* L.) genotypes were estimated using diallel crosses. An experiment was conducted at Uludag University, Bursa, Turkey, during the 2005-2006 and 2006-2007 growing seasons using 4x4 full diallel crosses. All of the 12 F_1 hybrids and their parents were planted in a randomized complete block design with three replications. The data obtained from the experiment were subjected to an analysis of variance. The analysis of variance indicated significant differences among parents and their hybrids in the F_1 generation for all the characters studied except for 1000-seed weight, which was non-significant. Positive better-parent heterosis for seed yield per plant were found in all 12 hybrids tested. An analysis of the components of combining ability showed that general combining ability (GCA) and reciprocal combining ability (RCA) were highly significant ($p \leq 0.01$) for plant height and number of pods per main raceme, whereas specific combining ability (SCA) was highly significant for all traits but 1000-seed weight. The parent genotypes PR_1, PR_3 and PR_4 with the hybrids PR_1 x PR_3 and PR_1 x PR_4 showed higher GCA and SCA effects, respectively, and therefore could be used to develop high-yielding lines.

Keywords: *Brassica napus* L., better-parent, combining ability, seed yield, yield components

Introduction

Rapeseed (*Brassica napus* L.) is one of the most important edible oilseed crops in the world, as well as a major potential source for bio-diesel production in Europe (Wang, 2005). In Turkey, rapeseed is a potential source of edible oil as an alternative to sunflower. New cultivars having high yield and quality should be developed because rapeseed is second only to sunflower as a major source of edible oil in the country. Studies on the breeding of rapeseed are limited, and introduced material generally has shown low adaptability in Turkey. Winter rapeseed cultivars can be grown successfully under the country's arid and semi-arid conditions. Early-maturing and high-yielding cultivars of winter rapeseed are especially necessary to ensure successful cultivation of the crop in Turkey.

The commercial use of synthetic and hybrid cultivars in rapeseed is a reality (Mc Vetty, 1995; Pandey *et al.*, 1999). Development of synthetic or hybrid cultivars has been successful in oilseed *Brassica* sp. (Becker *et al.*, 1999; Miller, 1999). Combining ability and hybrid vigor are the most important genetic parameters for breeding improved cultivars. The variances of general combining ability (GCA) and specific combining ability (SCA) are related to the type of gene action involved. The variance for GCA includes the additive portion of the total variance, whereas that for SCA includes the non-additive portion of the total variance, arising largely from dominance and epistatic deviations (Malik *et al.*, 2004). Information on the relative importance of the additive (GCA) and non-additive (SCA) gene actions within a breeding population is significant because it is used to determine which breeding procedure will efficiently improve the performance of the characters of interest (Dudley and Moll, 1969). Most previous studies on combining abilities have shown significant GCA and SCA effects for yield and its component characters. These results indicate that both additive and non-additive gene action are important in the inheritance of these traits (Akbar *et al.*, 2008; Brandle and Mc Vetty, 1989; Huang *et al.*, 2010; Pandey *et al.*, 1999; Rameah *et al.*, 2003).

It is necessary to have detailed information about the desirable parental combinations in any breeding program that can involve a high degree of heterotic response. Therefore, heterotic studies can provide the basis for the exploitation of valuable hybrid combinations in future breeding programs (Turi *et al.*, 2006). Heterosis can also be partially utilized by developing synthetic cultivars (Becker *et al.*, 1999). Studies on better-parent heterosis in rapeseed are limited. Brandle and Mc Vetty (1989) reported better-parent heterosis of up to 120% for seed yield in rapeseed. Maximum values of 72% better-parent heterosis for yield and 5% for oil content have been found in a study of spring rapeseed (Grant and Beversdorf, 1985).

For faster advances in breeding, it is necessary to know the variability and combining ability of the breeding material, *i.e.,* the modes of inheritance of certain traits. Topcross, polycross and diallel crossing methods are used for the assessment of variability and combining ability. The objectives of this study were to use diallel crossing to determine the general and specific combining abilities of four rapeseed cultivars, the gene effects for five yield components and the heterotic performance of the F_1 progeny.

Materials and methods

Four winter rapeseed varieties, 'Bristol' (PR_1), 'Chang' (PR_2), 'Samurai' (PR_3) and 'Quinta' (PR_4), were used in this study. The genetic material used in the experiment consisted of F_1 hybrid seed resulting from 4 x 4 diallel crosses among these four parent varieties, including self and reciprocals (Griffing, 1956). The varieties were crossed in diallel fashion during April 2005 and April 2006. At the budding stage for emasculation and crossing, young buds in the inflorescence of the female and male parents were covered with a white paper bag before blooming. The flowers of the female plants were emasculated before blooming. The flowers of the emasculated female plants were then pollinated manually with pollen collected from the male parents.

The field experiments were conducted in Bursa (latitude 40°11´N, longitude 29°04´E, altitude 155 m). Bursa is located in the southern Marmara region. It has an average annual rainfall of 713 mm and a mean monthly temperature of 14.4°C. The soil was clayey and low in fertility. A soil analysis indicated that the phosphorus and potassium levels were medium or high and that the organic matter was low (1.2%). The nitrogen levels in the soils were also low.

The field experiments used a randomized complete block design with three replications. Twelve F_1 seeds from a 4 x 4 diallel cross, along with their parents, were sown during October 2005 and October 2006. Each plot consisted of four rows, 5 m in length, with 45 cm-interrow and 10 cm-intrarow spacings. All cultural practices (soil preparation, sowing, fertilizer and cultivation) followed recommended procedures. Weeds were controlled by hand pulling and hoeing. The field experiments were harvested with a small-plot combine in June 2006 and June 2007.

The following agronomic traits were recorded from the same 20 randomly selected plants of the central row of each plot just prior to harvest: plant height, number of pods per main raceme, and number of seeds per pod. After harvest, seed yield per plant and 1000-seed weight were measured for each plot.

The analysis of variance was performed according to Steel and Torrie (1980). The analysis of diallels for combining ability was performed using mean values, following Model I Method II of Griffing's method (1956). The t-test was applied to examine the effects of general combining ability (GCA), specific combining ability (SCA) and reciprocal combining ability (RCA). Significant differences between hybrids and parents were detected using the F-test.

Better-parent heterosis (BPH) is expressed as a percentage and is calculated using the formula

$$BPH = [(H-P_1) / P_1] \times 100$$

where H is the performance of the hybrid for the character of interest and P_1 is the equivalent value for the best parent.

All statistical analyses were performed using MSTAT-C (Version 2.1, Michigan State University, 1991) and MINITAB (Version 15, University of Texas, Austin) software.

Results

Analysis of variance

There were significant differences between years and genotypes except for number of seeds per pod because of considerable range in weather conditions especially in flowering and ripening periods. Year x genotype interaction was found significant for plant height, number of pods per main raceme and number of seeds per pod (Tab. 1). Because of significant differences between years, combining ability and heterosis subjects were evaluated separately.

Combining ability

The analysis of variance for the average performance of 12 hybrids along with their parents in 4 x 4 diallel crosses for all characters studied is presented in Tab. 2. The results for the analysis of variance indicated that the differences between genotypes were significant for all traits studied except for the number of seeds per pod in 2006 and the 1000-seed weight in both experimental years. The mean squares due to GCA were highly significant ($p \leq 0.01$) for plant height and for the number of pods on the main raceme in 2007. The mean square values for SCA were highly significant for all characters except for the number

Tab.1. Analysis of variance for yield and some yield components of rapeseed (2-year average)

Source of variance	df	Plant height	Number of pods/ main raceme	Number of seeds/pod	Seed yield/plant	1000-seed weight
		Mean squares				
Year (Y)	1	58115.00**	2062.76**	0.26	266.00**	2.83**
Replication(Year)	4	33.21	5.70	5.69	12.61	0.08
Genotypes	15	190.93**	91.51**	4.46	76.76**	0.06
Y x Genotypes	15	81.81**	48.87**	8.75**	3.08	0.09
Error	60	16.92	6.59	3.27	6.93	0.06

Tab. 2. Mean squares for genotypes, GCA and SCA for various characteristics of rapeseed

Source of variance	df	Plant height		Number of pods/ main raceme		Number of seeds/pod		Seed yield/plant		1000-seed weight	
		2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
Replications	2	53.31	13.02	2.25	9.14	3.64	9.64*	24.18	1.00	0.08	0.02
Genotypes	15	63.69*	209.04**	91.59**	48.79**	10.30	4.49*	36.04**	45.55**	0.31	0.13
GCA	3	11.52	104.19**	6.75	38.86**	5.47	1.65	0.76	4.88	0.06	0.01
SCA	6	34.39**	60.26**	62.62**	17.43**	4.22	1.75*	28.85**	34.01**	0.13	0.07
RCA	6	12.92	61.84**	10.32**	3.79	1.63	1.17	0.81	1.51	0.10	0.04
Error	30	8.95	2.30	2.55	1.84	2.11	0.60	2.82	2.25	0.08	0.04

df: degrees of freedom; *: significant at p=0.05 probability level; **: significant at p=0.01 probability level; GCA: general combining ability; SCA: special combining ability; RCA: reciprocal combining ability

of seeds per pod in 2006 and the 1000-seed weight in both years. Reciprocal combining ability (RCA) was significant only for plant height in 2007 and for the number of pods on the main raceme in 2006.

The main values and GCA effects for plant height, the number of pods on the main raceme, the number of seeds per pod, the seed yield per plant and the 1000-seed weight are presented in Tab. 3a. In general, the differences between the mean values of genotypes and the GCA effects were non-significant for all traits observed in 2006. In 2007, there were significant differences between genotypes for plant height and for the number of pods on the main raceme. The GCA effects for these traits were also significant. Parents PR_2 and PR_3 gave higher values of plant height and of the number of pods on the main raceme than the other genotypes. These genotypes also showed highly significant and positive GCA effects on plant height. For the number of pods on the main raceme, a positive and significant GCA effect was recorded in PR_3, whereas the maximum negative GCA effect (-3.17**) was detected in PR_4. A non-significant but positive GCA effect was recorded in PR_1 and PR_3 for seed yield per plant. Significant GCA effects indicate that additive gene actions play an important role in hybrid performance. The combining ability of PR_1 and PR_3 was considered to be good because they showed a positive GCA effect for seed yield per plant.

According to the results of the analysis of variance, the SCA effects were significant for plant height, the number of pods on the main raceme and seed yield per plant in both years and for the number of seeds per pod in 2007. However, the RCA effects were significant only for plant height (2007) and the number of pods on the main raceme (2006) in the individual years indicated. The estimates of the SCA effects are presented in Tab. 3b. Of six hybrid combinations, one in 2006 and three in 2007 showed significant and positive SCA effects for plant height. The cross PR_3 x PR_4 had highly significant ($p \le 0.01$) and positive SCA effects in both years. In addition, the maximum positive SCA effects were obtained from the crosses PR_1 x PR_3 and PR_1 x PR_4 in 2007. The crosses PR_1 x PR_3 and PR_1 x PR_4 showed significant ($p \le 0.05$ in 2006 and $p \le 0.01$ in 2007) and positive SCA effects for the number of pods on the main raceme in both years, whereas the crosses PR_1 x PR_2 and PR_3 x PR_4 had highly significant and positive SCA effects only in 2006. The highest values of the number of pods on the main raceme were obtained from the cross PR_1 x PR_2 (43.0 pods/main raceme) in 2006 and the cross PR_1 x PR_3 (52.3 pods/main raceme) in 2007. Differences between the crosses in the number of seeds per pod were not significant in 2006, whereas the crosses PR_2 x PR_3, PR_4 x PR_1 and PR_4 x PR_3 produced higher numbers of seeds per pod than the other crosses in 2007. The SCA effects for the number of seeds per pod were significant only in 2007. The cross PR_2 x PR_3 produced a significant positive SCA effect (1.17*), whereas the crosses PR_1 x PR_3 and PR_2 x PR_4 showed significant negative SCA effects of (-0.92*) and (-1.42**), respectively. The seed yield per plant did not differ significantly among the crosses in 2006, whereas significant differences between crosses were found in 2007. Positive and significant SCA effects were recorded in crosses PR_1 x PR_3, PR_1 x PR_4, and PR_2 x PR_3 in both years. The cross PR_2 x PR_4 showed a significant and positive SCA effect in 2006, whereas the SCA effect of this cross was insignificant and positive in 2007. Therefore, the best combinations were crosses PR_1 x PR_3, PR_1 x PR_4, PR_2 x PR_3 and PR_2 x PR_4, all with significant positive SCA effects for seed yield per plant. In the crosses PR_1 x PR_3 and PR_2 x PR_3, at least one parent had significant positive GCA effects for seed yield per plant. Moreover, the crosses PR_1 x PR_3, PR_1 x PR_4 and PR_1 x PR_2 had significant positive SCA effects on the number of pods on the main raceme and were therefore considered good combinations for this trait. In addition, the cross PR_2 x PR_3, with a significant positive SCA effect, was the best combination for the number of seeds per pod. None of the crosses had significant positive SCA effects for the 1000-seed weight in either year. The crosses PR_2 x PR_1, PR_3 x PR_2 and PR_4 x PR_1 showed significant positive RCA effects for plant height in 2007. However, only the cross PR_3 x PR_1 had a highly positive RCA effect for this trait in 2006. For the number of pods on the main raceme, the crosses PR_3 x PR_1 and PR_4 x PR_3 exhibited significant positive RCA effects in 2006. Reciprocal combining ability effects for the other traits were not statistically significant in either experimental year. Significant RCA effects for plant height and the

Tab. 3a. Mean values of parents (M) and general combining ability (GCA) effects for measured characteristics

Parents	Plant height (cm)				Number of pods / main raceme				Number of seeds / pod				Seed yield / plant (g)				1000-seed weight (g)			
	2006		2007		2006		2007		2006		2007		2006		2007		2006		2007	
	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA	M	GCA
'Bristol' (PR$_1$)	113.6	1.73	149.0 b	-2.31**	25.0	0.48	38.0 bc	0.33	26.3	-0.67	30.3	0.54*	19.5	0.12	21.9	0.04	3.27	- 0.10	3.0	-0.06
'Chang'(PR$_2$)	112.6	-0.81	163.0 a	1.69**	30.0	0.98	45.7 a	0.96*	30.0	1.21*	28.3	-0.54*	19.6	-0.21	24.3	-0.46	3.40	-0.02	2.9	0.02
'Samurai' (PR$_3$)	108.3	-0.10	161.3 a	4.23**	25.3	-1.10*	43.7 ab	1.87	29.3	-0.25	28.3	-0.12	20.9	0.37	23.7	1.08*	3.37	0.02	3.3	0.02
'Quinta' (PR$_4$)	102.7	-0.81	145.3 c	-3.60**	26.3	-0.35	35.3 c	-3.17**	25.7	-0.29	29.7	0.12	18.8	-0.29	22.6	-0.67	3.53	0.10	3.1	0.02
LSD (% 5)	ns	-	1.85	-	ns	-	5.87	-	ns	-	ns	-	ns	-	ns	-	ns	-	ns	-
S. Error (g$_i$)	-	0.92	-	0.46	-	0.49	-	0.41	-	0.44	-	0.24	-	0.51	-	0.46	-	0.08	-	0.06

ns: non significant; *: significant at p=0.05 probability level; **: significant at p=0.01 probability level ; M: means of parents; GCA: General combining ability; Means in the same column followed by the same letter were not significantly different at the 0.05 level in the Least Significant Difference (LSD) test

Tab. 3b. Estimates of special combining ability (SCA) effects and mean values (M) of the hybrids

Hybrids	Plant height (cm)				Number of pods / main raceme				Number of seeds / pod				Seed yield / plant (g)				1000-seed weight (g)			
	2006		2007		2006		2007		2006		2007		2006		2007		2006		2007	
	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA	M	SCA
SCA Effects																				
PR$_1$ x PR$_2$	114.0	0.77	155.6 d	1.27	43.0 a	5.60**	44.3 c-e	-0.17	30.0	1.25	28.7 b-d	0.00	26.3	1.21	27.0 d	0.42	3.4	0.10	3.2	0.06
PR$_1$ x PR$_3$	109.6	-0.44	166.7 ab	4.06**	32.3 d	2.35*	52.3 a	3.42**	26.7	-0.79	27.6 cd	-0.92*	28.4	1.96*	33.5 ab	4.04**	3.2	-0.11	3.1	0.06
PR$_1$ x PR$_4$	113.3	2.27	147.6 e	3.06**	37.3 bc	2.44*	43.0 d-f	3.12**	30.0	1.08	29.3 bc	0.83	28.8	2.79**	30.7 a-d	2.62**	3.7	0.31	3.1	-0.10
PR$_2$ x PR$_3$	109.6	-1.89	168.0 a	-0.10	34.3 cd	0.19	48.3 b	0.79	28.7	-0.67	30.0 ab	1.17*	27.9	1.96*	34.2 a	2.04*	3.5	0.31	2.9	-0.19
PR$_2$ x PR$_4$	113.3	-0.35	160.0 cd	1.23	37.3 bc	0.60	41.0 f	-0.67	32.0	1.04	27.0 d	-1.42**	27.9	2.12*	32.0 a-c	0.96	3.5	-0.27	3.3	0.31*
PR$_3$ x PR$_4$	116.0	6.60**	167.0 ab	5.19**	34.0 cd	4.35**	42.3 d-f	-0.42	28.3	0.83	29.0 b-d	0.33	27.5	1.21	31.0 a-d	1.42	3.8	0.02	2.9	-0.02
Reciprocal Effects																				
PR$_2$ x PR$_1$	115.0	0.50	169.7 a	7.00**	40.0 ab	-1.50	45.3 b-d	0.50	29.7	1.00	29.6 bc	0.50	26.8	0.17	30.7 a-d	1.67	3.5	0.17	3.2	0.17
PR$_3$ x PR$_1$	118.3	4.33*	169.3 a	1.33	40.0 ab	3.83**	46.3 bc	-3.00**	28.3	0.83	29.6 bc	1.00	27.3	-0.50	28.7 cd	0.50	3.5	0.33	3.1	-0.17
PR$_3$ x PR$_2$	110.3	0.33	167.6 a	4.23**	34.7 cd	0.17	46.3 bc	-1.00	30.3	0.83	29.3 bc	-0.33	26.9	-0.50	29.8 b-d	0.67	3.7	0.17	3.1	0.00
PR$_4$ x PR$_1$	118.7	2.67	170.6 a	11.50**	36.7 b-d	-0.33	45.0 cd	1.00	28.7	-0.67	32.0 a	1.33	27.2	-0.67	29.8 b-d	-1.00	3.5	-0.17	3.1	0.00
PR$_4$ x PR$_2$	108.3	-2.50	162.7 bc	1.33	34.0 cd	-.1.67	40.7 f	-0.17	30.3	-0.83	27.7 cd	0.33	26.1	-1.00	28.9 cd	0.17	3.4	0.01	3.5	0.17
PR$_4$ x PR$_3$	121.0	2.50	168.7 a	0.83	40.7 ab	3.33**	41.7 ef	-0.33	30.7	-0.29	30.0 ab	0.50	26.3	-0.67	0.6 a-d	-0.17	3.5	-0.33	3.3	0.17
LSD (% 5)	ns	-	4.63	-	4.96	-	3.27	-	ns	-	2.24	-	ns	-	4.02	-	ns	-	ns	-
S. Error (s$_{ij}$)	-	1.67	-	0.85	-	0.89	-	0.76	-	0.81	-	0.43	-	0.94	-	0.84	-	0.16	-	0.12
S. Error (r$_{ij}$)	-	2.11	-	1.07	-	1.13	-	0.96	-	1.03	-	0.55	-	1.19	-	1.06	-	0.20	-	0.15

ns: non significant; *: significant at p=0.05 probability level; **: significant at p=0.01 probability level ; M: means of hybrids; SCA: Special combining ability. Means in the same column followed by the same letter were not significantly different at the 0.05 level in the Least Significant Difference (LSD) test number of pods on the main raceme most likely resulted from maternal effects on these traits. Thus, the direction of the RCA effects of the crosses can be considered for two characters. The reciprocal crosses with significant positive reciprocal effects must be used to obtain cross combinations that produce a shorter plant height. To produce cross combinations having a higher number of pods on the main raceme, the reciprocal crosses with significant negative reciprocal effects should be preferred.

Better-parent heterosis

The crosses PR_1 x PR_4 and PR_4 x PR_2 exhibited negative heterosis over the better-parent in both years and were significant in at least one year. These crosses had ideal performance for plant height. A greater number of pods on the main raceme is desirable for higher yields in rapeseed. Therefore, positive heterosis is preferred for the number of pods on the main raceme. In 2006, all of the crosses showed positive heterosis over the better-parent, ranging from 7.66% (PR_1 x PR_3) to 43.31% (PR_1 x PR_2). In 2007, 8 out of 12 crosses exhibited negative heterosis over the better-parent. The maximum positive heterosis value in 2007, 14.44%, was obtained from PR_1 x PR_3 (Tab. 4). In general, heterosis estimates over the better-parent for number of seeds per pod had low or negative values in many of the crosses in both years. The highest positive heterosis values were obtained from PR_2 x PR_4 (6.67%) in 2006 and from PR_4 x PR_1 (5.61%) in 2007 (Tab. 4).

All the crosses had highly positive heterosis estimates over better-parent for seed yield per plant in both years. Over two years, heterosis estimates over better-parent ranged from 11.11% (PR_1 x PR_2 in 2006) to (PR_2 x PR_3 in 2007). Similarly, three crosses (PR_1 x PR_3, PR_2 x PR_3 and PR_2 x PR_4) gave the highest heterosis values over better-parent in both years (Tab. 4). For 1000-seed weight, the highest positive heterosis estimates over better-parent were obtained from the same crosses with 7.65% and 6.13%, respectively, for the two study years. None of the crosses exhibited highly positive heterosis for 1000-seed weight for either year (Tab. 4).

Discussion

The results of this study indicated that high heterotic responses and positively significant GCA and SCA effects were important factors in increasing seed yield. The heterotic performance of a hybrid combination depends upon the combining abilities of its parents (Allard, 1960; Kadkol *et al.*, 1984). The differences in GCA result mainly from additive genetic effects and higher-order additive interactions, whereas the differences in SCA are attributed to non-additive gene effects (Falconer, 1989). Therefore, parents with significant GCA effects resulting from additive gene effects for observed traits are considered to be good combiners. Also, because significantly high SCA effects confirm the importance of non-additive gene effects, crosses having such SCA effects are considered to be good combinations. The best-performing F_1 may be produced by crossing parents with the highest GCA (Teklewold and Becker, 2005). In the present study, the mean squares due to GCA effects were not significant except for plant height and the number of pods on the main raceme. Furthermore, these values were only significant in 2007. Generally, the mean square values for SCA were significant for all traits observed except 1000-seed weight in both years, whereas the mean square values for RCA were not significant for most of the traits studied. Previous studies have reported that the mean squares due to general and specific combining ability were significant for different agronomical traits in *Brassica* species (Singh and Murty,

Tab. 4. Better-parent effects of hybrids

Hybrids	Plant height (cm)		Number of pods/ main raceme		Number of seeds/ pod		Seed yield / plant (g)		1000-seed weight (g)	
	2006	2007	2006	2007	2006	2007	2006	2007	2006	2007
SCA effects										
PR_1 x PR_2	0.26^{ns}	-4.54^{**}	43.31^{**}	-3.06^{ns}	0.00^{ns}	-5.61^{**}	25.51^{**}	11.11^{**}	-3.68^{ns}	-1.84^{ns}
PR_1 x PR_3	-3.52^{*}	2.27^{*}	7.66^{*}	14.44^{**}	-11.00^{**}	-8.58^{**}	35.69^{**}	37.86^{**}	-10.48^{**}	-4.90^{ns}
PR_1 x PR_4	-0.35^{ns}	-9.38^{**}	24.33^{**}	-5.91^{*}	0.00^{ns}	-3.30^{*}	37.60^{**}	26.33^{**}	3.68^{ns}	-4.90^{ns}
PR_2 x PR_3	-3.51^{*}	3.06^{**}	14.33^{**}	5.69^{*}	-4.33^{*}	-0.99^{ns}	33.44^{**}	41.15^{**}	0.00^{ns}	-10.12^{**}
PR_2 x PR_4	-0.35^{ns}	-1.84^{ns}	24.33^{**}	-10.28^{**}	6.67^{**}	-10.89^{**}	33.44^{**}	31.76^{**}	-0.85^{ns}	2.14^{ns}
PR_3 x PR_4	2.02^{ns}	2.45^{*}	13.33^{**}	-7.43^{**}	-5.67^{**}	-4.29^{*}	31.53^{**}	27.57^{**}	7.65^{*}	-8.89^{**}
Reciprocal effects										
PR_2 x PR_1	1.14^{ns}	4.11^{**}	33.33^{**}	-0.87^{ns}	-1.00^{ns}	-1.98^{ns}	28.04^{**}	26.33^{**}	0.00^{ns}	-0.92^{ns}
PR_3 x PR_1	4.04^{*}	3.86^{**}	33.33^{**}	1.31^{ns}	-5.67^{**}	-1.98^{ns}	30.58^{**}	18.11^{**}	0.00^{ns}	-3.98^{ns}
PR_3 x PR_2	-2.99^{ns}	2.88^{*}	15.67^{**}	1.31^{ns}	1.00^{ns}	-3.30^{*}	28.66^{**}	22.63^{**}	5.66^{*}	-4.90^{ns}
PR_4 x PR_1	4.39^{*}	4.72^{**}	22.33^{**}	-1.53^{ns}	-4.33^{*}	5.61^{**}	30.29^{**}	22.63^{**}	1.13^{ns}	-3.98^{ns}
PR_4 x PR_2	-4.75^{*}	-0.18^{ns}	13.33^{**}	-10.94^{**}	1.00^{ns}	-8.58^{**}	24.51^{**}	18.93^{**}	4.53^{*}	6.13^{*}
PR_4 x PR_3	6.42^{**}	3.49^{**}	35.66^{**}	-8.75^{**}	2.33^{ns}	-0.99^{ns}	25.51^{**}	25.92^{**}	-1.70^{ns}	2.15^{ns}

ns: non significant; *: significant at p=0.05 probability level; **: significant at p=0.01 probability level ;

1980; Fray *et al.*, 1997; Teklewold and Becker, 2005). Nassimi *et al.* (2006) have shown that GCA was highly significant for 50% flowering, number of primary branches/plant and number of pods/main raceme, whereas it was non-significant for maturity and plant height. Moreover, the SCA and RCA effects were highly significant for all traits. The present findings for the GCA mean square values for traits that it has been studied are not entirely in agreement with the previous results cited here. It is likely that genetic factors are affected by several environmental factors (especially temperature, precipitation and humidity) as well as genotypic structure (number of homologous copies of chromosomes, chromosome types and identities, and more). The differences between the present results and previous results should be viewed as the results of different environmental conditions and genotypic structure. However, the SCA effects found in this study agree with the findings of Rameah *et al.* (2003), who have observed significant mean squares for specific combining ability for all traits examined except for 1000-seed weight. The low GCA effects for seed yield per plant and other agronomical traits found in the present study did not make it possible to identify good combiners. However, parents PR_1 and PR_3 had positive GCA effects for seed yield per plant and can therefore be considered as promising parents to obtain good combinations. Many earlier studies have determined good combiners with significant GCA effects for yield and its components (Huang *et al.*, 2010; Nassimi *et al.*, 2006; Rameah *et al.*, 2003; Teklewold and Becker, 2005). The present findings on GCA effects are in close agreement with Marjanovic-Jeromela *et al.* (2007), who have reported that the cultivars they examined showed no significant differences in the GCA values for yield per plant.

It has been found in the present study that no crosses that exhibited significant negative SCA effects for plant height. Nassimi *et al.* (2006) noted that in *Brassica* (grown for seed yield), taller plants are susceptible to lodging. Medium-or short-statured plants are therefore desirable, and accordingly negative GCA and SCA values are sought for plant height. The same researchers have found that out of 28 crosses, 13 showed negative SCA effects for plant height. Good general combiners and good combinations for plant height have also been found by many earlier studies (Akbar *et al.*, 2008; Marjanovic-Jeromela *et al.*, 2007; Teklewold and Becker, 2005). The present research, unlike the studies cited above, could not identify good general combiners or good combinations for plant height.

Significant SCA mean squares for pods per main raceme and seed yield per plant indicated that the crosses PR_1 x PR_3, PR_1 x PR_4 and PR_2 x PR_3 were promising combinations, as shown by their high mean values and SCA effects. Previous studies have reported that crosses having highly positive SCA effects were obtained from cross populations of rapeseed (Akbar *et al.*, 2008; Huang *et al.*, 2010; Nassimi *et al.*, 2006; Rameah *et al.*, 2003). The present findings are compatible with the results of the experiments cited above.

None of the crosses showed significant RCA effects for any character, with the exception of plant height in 2007 and the number of pods per main raceme in 2006. Significant RCA effects for plant height and the number of pods per main raceme revealed that the reciprocal crosses with significant positive reciprocal effects should be used to obtain cross combinations with short plant height, whereas the reciprocal crosses with significantly negative reciprocal effects should be chosen to produce cross combinations with a high number of pods per main raceme. Rameah *et al.* (2003) have reported that the direction of crosses is important for yield and yield components and that the reciprocal crosses must be used if crosses have significant negative reciprocal effects. Nassimi *et al.* (2006) have revealed significant SCA effects for plant height, the number of pods per main raceme, the number of primary branches per plant, days to 50% flowering and physiological maturity.

Hybrid vigor is an important component of increased seed yield. In the present study, the F1 hybrids gave 11.11-41.15% higher yield than the better-parents. In both years of this study, the highest better-parent heterosis was obtained from the four crosses PR_1 x PR_3, PR_1 x PR_4, PR_2 x PR_3 and PR_2 x PR_4. Heterosis values for seed yield reaching 120% over the better-parent have been reported in *B. napus* by Brandle and Mc Vetty (1989). Teklewold and Becker (2005) found that relative better-parent heterosis values for seed yield in *B. juncea* varied from 16.2 to 123.6% with a mean of 52.8%, respectively. Other previous studies have found heterosis levels over better-parent for seed yield in *B. napus* of 69% (Brandle and Mc Vetty, 1989) and 67% (Riaz *et al.*, 2001) have been reported. The heterosis levels for seed yield per plant found in this study were similar to those found by Lee *et al.* (1980) and Starmer *et al.* (1998). However, they were lower than those found by Brandle and Mc Vetty (1989), Riaz *et al.* (2001), Teklewold and Becker (2005).

Plant height is an important agronomic character with respect to the risks of wind damage and lodging. In general, small and medium plant height is preferred in *Brassica* because these plants can tolerate heavy winds and can be prevented from lodging; therefore, negative heterosis is a desirable characteristic for producing plants of suitable height (Nassimi *et al.*, 2006). In the present study, the crosses PR_1 x PR_4 and PR_4 x PR_2 exhibited negative heterosis for plant height and can be considered as promising crosses in terms of this trait.

Conclusions

In the present study, the mean squares for GCA effects were significant for plant height and the number of pods per main raceme but for no other trait studied. Moreover, these two mean squares were only significant in 2007.

Therefore, additive gene effects did not affect seed yield per plant and the other agronomic traits because the GCA effects of the parents were not significant for these characters.

Although good combiners were not identified for seed yield per plant and other agronomic traits because the GCA effects of the parents were low, the PR_1 and PR_3 exhibited positive GCA effects for seed yield per plant and could be considered as promising parents in order to obtain good combinations.

The SCA mean squares were significant for all traits but 1000-seed weight. Significant SCA mean squares were attributed to non-additive gene actions. In this study, the crosses PR_1 x PR_3, PR_1 x PR_4 and PR_2 x PR_3 were identified as promising combinations for improving the seed yield per plant and the number of pods per main raceme. In addition, the highest better-parent heterosis levels were also obtained by these crosses.

The results of the present study revealed that the synthetic-variety and hybrid-breeding methods could be used after inbred lines were obtained from the cross population established by this research.

This study found that additive gene effects were not effective determinants of yield and other agronomic characters in the rapeseed lines studied. Therefore, according to these results, selective breeding for high-yielding varieties would not be very fruitful.

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