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Complementarity between parents for earliness and grain yield in soybean

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Abstract – The objective of this work was to determine the general and specific combining ability (GCA and SCA, respectively) of six soybean (*Glycine max*) parents, in order to identify the promising ones and their best combinations for the development of superior lines for earliness and grain yield, as well as the best evaluation season. Six parents and their 15 hybrids were evaluated in a randomized complete block design, during the 2014 winter and 2015/2016 summer, in a greenhouse. The data obtained for number of days to flowering, cycle, and grain yield were analyzed by Griffing's method 2, model 1. Contrasting results were obtained for the two seasons, with a shorter cycle and a higher yield in the summer. The highest GCA for cycle is observed for the 'MSOY6101' and 'MSOY9144RR' parents, with negative and positive signs, respectively. 'TMG123RR' shows the highest GCA for grain yield. The highest SCA for days to flowering and cycle is associated with the 'SYN9078RR' × 'MSOY9144RR' and 'TMG123RR' × 'MSOY9144RR' crosses, respectively. However, the highest SCA for grain yield is observed for 'MSOY6101' × 'MSOY9144RR', with a positive value, and for 'TMG801' × 'MSOY9144RR', with a negative value, during the summer.

Index terms: *Glycine max*, combining ability, early maturity, parent selection.

Complementaridade entre genitores quanto à precocidade e ao rendimento de grãos em soja

Resumo – O objetivo deste trabalho foi determinar a capacidade geral e a específica de combinação (CGC e CEC, respectivamente) de seis genitores de soja (*Glycine max*), para identificar aqueles que são promissores e suas melhores combinações para o desenvolvimento de linhagens superiores quanto à precocidade e à produção de grãos, bem como à melhor época de avaliação. Seis genitores e seus 15 híbridos foram avaliados em blocos ao acaso, durante o inverno de 2014 e o verão de 2015/2016, em casa de vegetação. Os dados obtidos para número de dias para florescimento, ciclo e produção foram analisados pelo método 2 de Griffing, modelo 1. Resultados contrastantes foram obtidos para as duas épocas, com ciclo mais curto e maior produtividade no verão. A maior CGC quanto ao ciclo é observada nos progenitores 'MSOY6101' e 'MSOY9144RR', com sinal negativo e positivo, respectivamente. 'TMG123RR' apresenta a maior CGC quanto à produção de grãos. A maior CEC quanto ao número de dias para o florescimento e ao ciclo está associada aos cruzamentos 'SYN9078RR' x 'MSOY9144RR' e 'TMG123RR' x 'MSOY9144RR', respectivamente. No entanto, a maior CEC quanto à produção de grãos é observada em 'MSOY6101' x 'MSOY9144RR', com valor positivo, e 'TMG801' x 'MSOY9144RR', com valor negativo, durante o verão.

Termos para indexação: *Glycine max*, capacidade de combinação, maturação precoce, seleção de genitores.

Introduction

In Brazil, it is possible to grow two crops in the same agricultural year. Soybean [*Glycine max* (L.) Merrill] is grown in the first crop or summer crop (September to February), and corn (*Zea mays* L.) is sown after soybean, making up the off-season or second crop (Bezerra et al., 2017b; Ribeiro et al., 2020). To be successful in this system, the growing of early cycle soybean cultivars is necessary, to enable corn sowing during a period of favorable climatic conditions. For this purpose, soybean breeding programs in Brazil aim to launch high-yield genotypes with the greatest earliness (Bezerra et al., 2017a; Ribeiro et al., 2020; Santana et al., 2022).

In the last years, some studies were carried out focusing on the development of superior genotypes for these traits, by the selection of parents (Daronch et al., 2014; Rocha et al., 2018, 2019), genetic control (Carpentieri-Pipolo et al., 2014; Bezerra et al., 2017a), adaptability and stability of cultivars (Costa et al., 2022), and new methodologies of selection (Ribeiro et al., 2020; Santana et al., 2022).

An alternative for combining both high yield and early maturity in the segregating population is the crossbreeding of parents with high performance for these traits (Ribeiro et al., 2020). However, breeding programs have been spending time and labor in the evaluation of hundreds of soybean genotypes annually, in an inefficient process because crosses made between parental combinations that fail to produce useful cultivars consume over 99% of the resources (Witcombe et al., 2013). For these researchers, the efficiency of breeding programs would be increased by making fewer crosses among more carefully chosen parents. Bezerra et al. (2017b) reported that the main source of parents used in breeding programs for increasing grain yield are the superior lines and commercial cultivars, as they bring together a high frequency of favorable alleles that have been selected over years of breeding.

In this context, diallel crosses have been carried out with success in the parental selection of soybean grain yield (Lopes et al., 2001; Daronch et al., 2014; Rocha et al., 2018), for grain yield and other agronomic characters (Rocha et al., 2019), and for physiological traits Teodoro et al. (2019). In all these works, only Lopes et al. (2001) and Teodoro et al. (2019) considered the environmental effect in the evaluation of crosses. For soybean, due to its cultivation covering large areas of Brazil at different latitudes, climate conditions, and soil types, it is important to evaluate the diallel in the experiments across several environments, to obtain consistent information.

The objective of this work was to determine the general (GCA) and specific (SCA) combining ability of six soybean cultivars, aiming to identify the promising ones and their best combinations for the development of high-performance lines for earliness and grain yield, as well as to determine the best evaluation season.

Materials and Methods

Six commercial soybean cultivars (MSOY6101, RSF6563IPRO, TMG123RR, SYN9078RR, TMG801, and MSOY9144RR) were crossed in a complete, non-reciprocal diallel scheme, thus obtaining 15 hybrids. The chosen cultivars show differences for the number of days to maturity, leaf type, and resistance to herbicides and diseases, among other characteristics. Furthermore, they belong to different relative maturity groups (RMG), covering the entire Brazilian area used to cultivate soybean (Table 1). The six parents and their 15 hybrids (21 treatments) were evaluated in a greenhouse, in the Department of Agronomy of the Universidade Federal de Viçosa (Viçosa, MG, Brazil, 20º45'S, 42º52'W, at 663 m altitude).

The experiments were carried out in two seasons. The first sowing was in May 2014, characterizing the winter or off-season period. The second sowing was performed in September 2015, characterizing the summer, or crop season. Data on climatic conditions during the experimental period were monitored at a meteorological station inside the greenhouse (Figure 1).

A randomized complete block design, with six replicates was adopted. Each plot consisted of a 3 dm^3 pot with one plant. The substrate used was a mixture of 3:1 ratio of soil and bovine manure. The corrections of pH and fertility of the substrate and other cultural treatments complied with the technical recommendations for the crop (Sediyama et al., 2015). Soybean seed were treated with pyraclostrobin (25 g L^{-1}) + thiophanate-methyl (225 g L^{-1}) + fipronil (250 g L^{-1}), corresponding to 200 mL 100 kg^{-1} of seed of the fungicide/insecticide Standak Top (BASF S.A., São Paulo, SP, Brazil), then they were inoculated with *Bradyrhizobium japonicum* and, subsequently, sown in trays (42×28×10 cm length, width, and depth, respectively) containing washed sand. After the emergence, hybrids were identified by morphological markers such as hypocotyl color, pubescence color and trifoliolate leaf type. Hybrids in which at least one of the parents had Roundup Ready herbicide resistance genes, RR1 and RR2, were selected by applying 2.0 L ha^{-1} glyphosate, using a CO_2 spray at 2.0 bar pressure equipped with 0.5 m bar with two fan-type tips (Teejet TTI11002), which resulted in the application of 200 L ha^{-1} spray volume, in the vegetative cotyledonary (VC) stage. When neither parent was resistant to the herbicide, the hybrids were confirmed by checking morphological markers such as leaf type, pubescence color, anthocyanin pigments in the hypocotyl and others (Pereira et al., 2012; Dorneles et al., 2020). After the selection, the seedlings confirmed as hybrids were transplanted into the pots.

The number of days to flowering, the number of days to maturity (cycle), and grain yield (g per plant) were counted. The number of days to flowering corresponds to the number of days between the emergence and appearance of the first flower in any node of the main stem, and the cycle corresponds to the number of days elapsed between the emergence and physiological maturity of the plant.

Individual and joint analyses of variance (winter and summer) were performed for each evaluated trait. Diallel analysis was then performed, using the method 2, model 1 (parents and F_1 hybrids) of Griffing

Table 1. Characterization of soybean (*Glycine max*) cultivars used as parents in diallel crosses for the evaluation of the general and specific combining abilities.

Parent (P)	Type of growth	RMG(1)	NGV(2)	Leaf format	Resistance to herbicides
MSOY6101 (P1)	Indeterminate	6.1	2 to 3	Pointed oval	-
RSF6563IPRO (P2)	Indeterminate	6.3	2 to 3	Oval	Glyphosate
TMG123RR (P3)	Determined	7.4	3 to 4	Lanceolate	Glyphosate
SYN9078RR (P4)	Indeterminate	7.9	2 to 3	Pointed oval	Glyphosate
TMG801 (P5)	Determined	8.2	2 to 3	Pointed oval	-
MSOY9144RR (P6)	Determined	9.1	2 to 3	Pointed oval	Glyphosate

(1) RMG, relative maturity group. (2) NGV, variation in the average number of grains per pod.

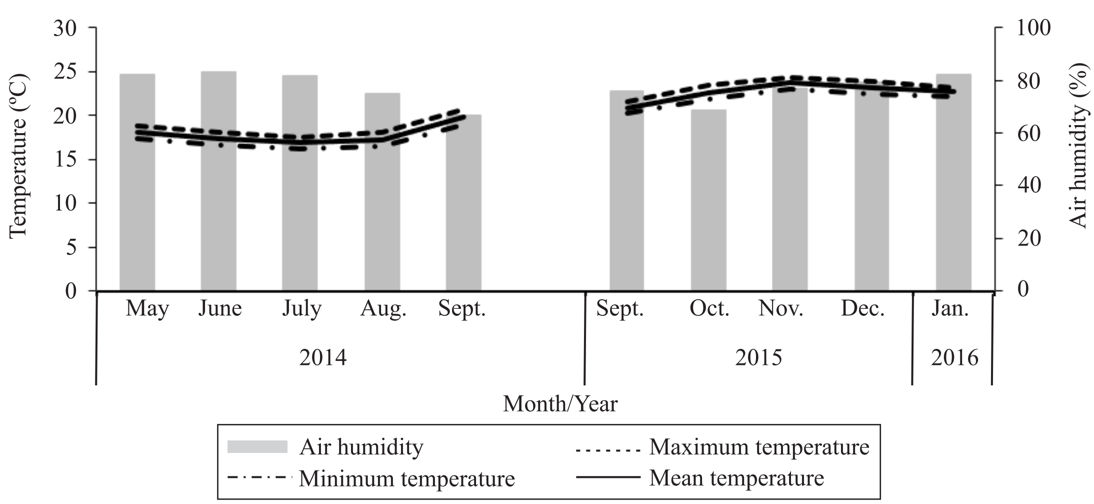

Figure 1. Monthly average air humidity and temperatures from May to September in 2014 and from September 2015 to January in 2016, in a greenhouse in the municipality of Viçosa, in the state of Minas Gerais, Brazil .

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(Griffing, 1956) to determine the GCA and SCA. This methodology is based on the following statistical model:

$$\hat{Y}_{ijk} = \mu + E_k + g_i + g_j + s_{ij} + E_{gik} + E_{gjk} + Es_{ij} + \hat{\mu}_{ijk},$$

where: μ is the overall mean of the diallel (fixed); E is the effect of the environment (season) assumed as random; g_i and g_j are the effects on the GCA of parents i (i = 1, …, 6) and j (j = 1, …, 6), respectively (assumed as fixed); s_{ij} is the effect on the SCA of parents i and j (assumed as fixed); s_{ii} is the effect on the SCA of the parental i with itself (assumed as fixed); ε_{ijk} is the medium experimental error; and the other parameters correspond to the interactions of the effects (g_i , g_j and s_{ij}) with seasons.

Statistics analysis were performed by using the Genes software (Cruz, 2013).

Results and Discussion

The main sources of variation (parents, crosses, and contrast) were highly significant. However, the effect of crosses for grain yield and the contrast for days to flowering in the winter was not significant (Table 2). Therefore, there was no difference between the averages of the hybrids and parents in the winter for days to flowering and the averages of hybrids for grain yield. The average days to flowering in the summer was 20.6 days lower than that obtained in the winter. This result indicates that the winter is less favorable to evaluate that trait. Thus, the study of interactions with environments (locations, years, and sowing dates) are important, especially when investigating the time to flowering (Lopes et al., 2001).

The genetic control of flowering time in short-day conditions (winter) is determined by a genetic system that is different and independent from the one that determines flowering under long-day conditions (summer). Late flowering in short-day conditions is controlled by recessive alleles, whereas dominant alleles control early flowering in long-day conditions (Watanabe et al., 2012).

The cycle in the summer was 8.2% longer than the cycle in the winter, and grain yield was approximately 2.2 times higher than the average observed in the winter. In this case, such a result is expected because the winter has fewer hours of daylight than the summer, resulting in shorter plants with fewer nodes on the main stem (Carpentieri-Pipolo et al., 2014).

Regarding the experimental accuracy, the errors, random causes of cycle characteristics, and grain yield were superior in the summer experiment, while for days to flowering the opposite was observed. Although the coefficient of variation for grain yield in the summer was higher, the other values observed in the present study are in agreement with previous results reported in the literature (Gavioli et al., 2008; Daronch et al., 2014) and showed very satisfactory levels of experimental precision. These results were expected because the climatic conditions that occurred

Table 2. Summary of individual analysis of variance for days to flowering, cycle, and grain yield in soybean (*Glycine max*), during two seasons (winter and summer).

Source of variation	DF	Days to flowering		Cycle		Grain yield	
		Winter	Summer	Winter	Summer	Winter	Summer
Blocks	5	124.36	55.12	10.69	70.82	35.03	174.90
Treatments	20	58.77**	206.21**	20.24**	180.56**	21.96**	71.37**
Parents (P)	5	102.18**	417.71**	11.13*	470.32**	35.74**	53.18*
Crosses (F1)	14	47.05**	178.37**	21.81**	80.47**	14.49^{ns}	53.09**
P vs F_1	1	6.23^{ns}	88.54*	46.33*	133.41*	57.28*	417.81**
Residual	100	17.82	16.27	4.37	23.05	10.54	17.52
General mean		57.56	45.67	118.25	108.53	10.32	23.05
Mean of parents		57.15	46.78	119.21	110.42	9.26	19.68
Mean of hybrids		57.64	45.47	117.87	108.15	10.75	23.73
CV (%)		7.54	8.80	1.77	4.41	31.44	18.55

** and *Significant at 1% and 5%, by the F-test. ^{ns}Nonsignificant. DF, degrees of freedom.

in both seasons were different (Figure 1) and affected the plant development.

All sources of variation were significant for days to flowering and cycle, except for the “contrast” (parents × crosses) for days to flowering, and the “contrast” × season interaction for cycle (Table 3). The hybrid means were significantly smaller than the parental means for days to flowering in the summer. For cycle, the hybrid means were significantly smaller than the parental means in both seasons. For grain yield, significant sources of variation included the season, treatments, “contrast” (parents × crosses) and the “contrast” × season interaction. The hybrid means were significantly greater than the parental means for grain yield in the summer.

Despite the lack of significance of the crosses × season interaction showed in the joint analysis, based on the results of the individual analyses (Table 2), there was an interaction between the crosses and seasons studied. The mean square of crosses was not significant in the winter, but it was significant in the summer. The occurrence of this interaction is also one of the possible reasons why crosses were not a significant source of variation in the joint analysis.

The parents × season and crosses × season interactions from the joint analysis of variance were significant for days to flowering and cycle, but they were not significant for grain yield. These results indicate that days to flowering and cycle were less stable over both seasons than grain yield, justifying the evaluation of these two traits in different environments.

The sources of variation were significant for the general (GCA) and specific (SCA) combining abilities of all studied traits (Table 4), showing the existence of variability of additive and nonadditive genetic effects among the evaluated genotypes (Gavioli et al., 2008; Matos et al., 2021). Moreover, for all the studied traits, the magnitude of the GCA mean square estimate was greater than that estimated for the SCA, indicating the predominance of additive genetic effects in their determination at the expense of nonadditive genetic effects (Matos et al., 2021). These results are in agreement with those found by Bezerra et al. (2017a) for the same traits.

Carpentieri-Pipolo et al. (2014) and Bezerra et al. (2017a) concluded that the main component of genetic variation to determine time to flowering is additive. The results obtained in the present study corroborate those reported by Daronch et al. (2014). However, for cycle, the results of the present study contradict those obtained by Gavioli et al. (2008), in which they did not find significant nonadditive or dominant effects for this trait. However, those authors did not consider genetic and environmental interactions, unlike the present study. The significance of the SCA × season interaction for cycle (Table 4) underscores this statement.

The interactions of genetic effect × season were significant for cycle and days to flowering. These

Table 3. Summary of the analyses of joint variance for days to flowering, cycle, and grain yield in soybean (*Glycine max*), during two seasons (winter and summer).

Source of variation	DF	Days to flowering	Cycle	Grain yield
Season (S)	1	8584.34**	5633.62**	9448.55**
Treatment (T)	20	187.43**	105.58**	70.64**
Parent (P)	5	392.51**	261.04**	12.22^{ns}
Cross (F1)	14	130.73**	45.57**	20.82^{ns}
P vs F1 (G)	1	23.89^{ns}	168.49**	110.32**
T x S	20	77.58**	95.35**	22.68^{ns}
P x S	5	127.38**	220.42**	16.61^{ns}
F1 x S	14	94.69**	56.70**	20.55^{ns}
G x S	1	82.89*	11.14^{ns}	82.89*
Residual	200	17.05	13.71	14.03
Mean		51.62	113.40	16.68
CV (%)		7.99	3.26	22.77

** and *Significant at 1% and 5%, by the F-test. ^{ns}Nonsignificant. DF, degrees of freedom.

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results indicate that, for these characteristics, parents and crosses should be selected and recommended for a specific season. However, for grain yield none of the interactions were significant. Some studies on soybean have shown interaction between genetic effects (the GCA and SCA) and the environment (Paschal & Wilcox, 1975; Lopes et al., 2001), but it is also common to find reports with no interactions (Teodoro et al., 2019; Chiipanthenga et al., 2021). The lack of significance of the interactions allows of the selection and recommendation of parents and crosses for both seasons. However, on the basis of magnitude, grain yield was much more favored in the summer (Table 2).

The 'TMG801' and 'MSOY9144RR' parents showed large positive values for days to flowering, which means a tendency to prolong the time to flowering. Conversely, 'RSF6563IPRO' and 'SYN9078RR' had large negative estimates, which gives them the tendency to reduce the time to flowering. On the basis of these findings, the 'TMG801' and 'MSOY9144RR' parents are more appropriate to produce crosses in low-latitude regions, while 'RSF6563IPRO' and 'SYN9078RR' are more appropriate for breeding programs in high latitude.

For cycle, the 'MSOY6101', 'TMG123RR', 'SYN9078RR', and 'MSOY9144RR' parents showed significant GCA values in the winter. Only 'MSOY6101' was significant in the two seasons, with a positive value in the winter and a large negative value in the summer. This behavior indicates that 'MSOY6101' has a tendency to reduce the cycle in the summer.

It is known that the combination of dominant alleles for some loci related to the genetic control of time to flowering in soybean may result in retardation of the expression of the flowering and maturation times (Zhao et al., 2016).

In the winter, the 'MSOY6101', 'TMG123RR', and 'SYN9078RR' parents showed significant GCA values for cycle. 'MSOY6101' showed a positive value, while 'TMG123RR' and 'SYN9078RR' had negative values, indicating a cycle reduction trend. 'MSOY9144RR' showed a significant and positive GCA in the summer, which is the largest value among parents, indicating an increase in the cycle. Considering the joint analysis, 'MSOY6101', 'RSF6563IPRO', 'TMG123RR', and 'SYN9078RR' showed negative GCA values, although their means were not significantly different from zero. In an opposite way, 'MSOY9144RR' was more biased toward prolonging the cycle, which is consistent with the behavior of a cultivar of maturity group 9.1, with a long juvenile period and adapted to low-latitude regions (Carpentieri-Pipolo et al., 2014), such as the north and northeast regions of Brazil. This parent may represent an important source of genes for the development of soybean cultivars adapted to different low-latitude regions or sowing periods in breeding programs.

For grain yield, the 'RSF6563IPRO' and 'TMG123RR' parents showed a significant GCA; however, the value was negative for 'RSF6563IPRO', which is undesirable for grain yield because the objective is to increase it. Contrastingly, the joint analysis showed that 'TMG123RR' had a larger GCA mean in the summer. Therefore, the selection of 'TMG123RR' crosses

Table 4. Joint diallel analysis for days to flowering, cycle, and grain yield in soybean (*Glycine max*), during two seasons (winter and summer).

Sources of variation	DF	Days to flowering	Cycle	Grain yield
Season (S)	1	8583.34**	5633.62**	9448.55**
Treatments (T)	20	187.43**	105.58**	70.64**
GCA	5	575.91**	238.77**	98.69**
SCA	15	57.97**	61.24**	61.26**
T × S	20	77.58**	95.35**	22.68^{ns}
GCA × S	5	233.22**	274.92**	23.53^{ns}
SCA × S	15	25.69^{ns}	35.51**	22.42^{ns}
Residual	200	17.05	13.71	14.03
GCA/SCA		9.93	3.89	1.61

** and *Significant at 1% and 5%, by the F-test. ^{ns}Nonsignificant. DF, degrees of freedom; GCA, general combining ability; SCA, specific combining ability.

associated with a high SCA increases the possibility of selecting genotypes with high performance for desirable characters such as grain yield (Rocha et al., 2019). 'MSOY6101', 'SYN9078RR', 'TMG801', and 'MSOY9144RR' showed small, nonsignificant GCA values. A very low estimate of the effects of GCA indicates that the parental GCA does not differ from the general mean of the diallel (Cruz, 2012). In other words, it is unlikely that these parents would produce promising crosses for grain yield, except for specific cases of allelic complementation.

For the SCA, the 'MSOY6101' × 'SYN9078RR' and 'TMG801' × 'MSOY9144RR' hybrids in the summer, and 'RSF6563IPRO' × 'SYN9078RR', in the winter, tended to slow the flowering, showing significant positive values. The 'MSOY6101' × 'TMG801', 'RSF6563IPRO' × 'MSOY9144RR', and 'SYN9078RR' × 'MSOY9144RR' crosses showed a reduction of the flowering time in those season. The 'MSOY6101', 'RSF6563IPRO', and 'SYN9078RR' parents, which had large negative GCA values, were probably responsible for the observed behavior. According to Cruz (2012), the effect of the SCA is interpreted as the deviation of a hybrid from what would be expected on the basis of the GCA of its parents. Therefore, the effects of a small SCA indicate that the hybrids among these parents behave as expected on the basis of the GCA of the parents, while high, absolute SCA values show that the behavior of a particular cross is relatively better or worse than the expected one on the basis of GCA of the parents.

The 'RSF6563IPRO' × 'SYN9078RR', 'MSOY6101' × 'RSF6563IPRO', and 'MSOY6101' × 'SYN9078RR' crosses showed the largest SCA values for the winter cycle; however, only 'RSF6563IPRO' × 'SYN9078RR' was negative (Table 5). In the summer, the 'RSF6563IPRO' × 'MSOY9144RR' and 'TMG123RR' × 'MSOY9144RR' crosses showed the most negative values, while the effect of the crossing 'TMG801' × 'MSOY9144RR' was positive; all these values were significant. The joint analysis showed that the 'RSF6563IPRO' × 'MSOY9144RR', 'TMG123RR' × 'MSOY9144RR', 'TMG123RR' × 'TMG801', 'MSOY6101' × 'MSOY9144RR', and 'SYN9078RR' × 'MSOY9144RR' crosses produced large, significant SCA effects. In each of these crosses, the cycle was reduced. It is worth mentioning that the 'MSOY6101' × 'MSOY9144RR' cross is more suitable for inclusion in breeding programs because of the significant effect of SCA and that at least one of the parents has a large, significant GCA effect (Cruz, 2012; Daronch et al., 2014).

The joint analysis also showed that only the 'RSF6563IPRO' × 'SYN9078RR' cross produced a favorable SCA to significantly increase grain yield. Contrastingly, the 'TMG801' × 'MSOY9144RR' cross showed the greatest negative effect, but it was not significant. During the winter, there was significance only for the 'RSF6563IPRO' × 'SYN9078RR' cross, which also showed the highest magnitude. Despite the lack of significance of the interaction between the effects of SCA and the season for this characteristic (Table 4), the significance of the SCA was observed for some crosses during a specific season, as occurred for days to flowering.

In the summer, the most positive SCA value for grain yield was recorded for the 'MSOY6101' × 'MSOY9144RR' cross, followed by the 'TMG123RR' × 'TMG801' and 'RSF6563IPRO' × 'TMG801' crosses. These values indicate a strong relationship complementarity between these parents for grain yield. The 'TMG801' × 'MSOY9144RR' cross was the only one that showed a negative and significant SCA effect, which is undesirable, as it tends to decrease the grain yield.

Hybrid combinations with high SCA estimates, involving at least one parent with a high GCA effect, are of interest for breeding. Thus, the 'RSF6563IPRO' × 'MSOY9144RR' and 'TMG123RR' × 'MSOY9144RR' crosses could be promising for the selection of early genotypes because these combinations had average effects of large negative SCA estimates, and the 'TMG123RR' parent, in the winter, had a significant GCA effect of satisfactory magnitude in comparison with the others obtained in the diallel. In addition, 'RSF6563IPRO' contributes to the reduction of the vegetative period, which may be an alternative to the reduction of the total cycle (Gavioli et al., 2008). However, the cycle was reduced only in combination with 'MSOY9144RR' in the summer. For grain yield, the 'MSOY6101' × 'MSOY9144RR', 'RSF6563IPRO' × 'TMG801', and 'TMG123RR' × 'TMG801' crosses would be more suitable for the development of lines with a higher average for this characteristic, considering that soybean is grown in the summer.

The SCA value of each parent with itself (S_{ii}) shows a great genetic significance, for both its sign and its magnitude. However, few of these estimates were significant in the present study, since significant S_{ii} values were observed for cycle mainly in the winter, and for grain yield, in the summer. This parameter is an indicator of the diversity of the parent i, in relation to the average of the other parents that make up the diallel. A positive S_{ii} indicates that heterosis manifested in parental i hybrids may be negative, while a negative S_{ii} may be the evidence of positive heterosis (Cruz, 2012; Rocha et al., 2018).

The genotype × season interaction influenced the magnitude and signs of S_{ii}. A similar result was reported by Lopes et al. (2001) for soybean grain yield evaluated in two locations. In the summer, the S_{ii} effect of the 'MSOY9144RR' parent for the cycle was much higher than that in the winter. In addition, because all parents showed positive S_{ii} values, except for 'MSOY6101', which showed negative values, the effects of the S_{ij} of 'MSOY6101' hybrids were predominantly positive, that is, their hybrids are biased to prolong the cycle. The same result can be observed for grain yield, in which the S_{ii} values were all negative, and the effects of S_{ij} were mostly positive. Another aspect related to grain yield is that the 'RSF6563IPRO', 'TMG801', and 'MSOY9144RR' parents had larger S_{ii} values significantly different from zero in the summer.

Table 5. Estimates of the general combining ability (GCA) and the specific combining ability (SCA) for days to flowering, cycle, and grain yield in soybean (*Glycine max*), during two seasons (winter and summer).

Parent	Days to flowering			Cycle			Grain yield		
	Winter	Summer	Mean	Winter	Summer	Mean	Winter	Summer	Mean
				General combining ability (GCA)					
P_1 - MSOY6101	1.69*	-1.52*	0.09^{ns}	0.83*	-3.00**	-1.08^{ns}	-0.78^{ns}	-0.80^{ns}	-0.79^{ns}
P_2 - RSF6563IPRO	-1.98*	-4.73**	-3.35**	0.58^{ns}	-1.16^{ns}	-0.29^{ns}	-1.21*	-1.22^{ns}	-1.21^{ns}
P_3 - TMG123RR	0.48^{ns}	0.19^{ns}	0.33^{ns}	-0.87**	-1.20^{ns}	-1.04^{ns}	1.02^{ns}	2.38**	1.70**
P_4 - SYN9078RR	-1.88*	-2.62**	-2.25**	-1.05**	-1.06^{ns}	-1.06^{ns}	-0.56^{ns}	0.23^{ns}	-0.17^{ns}
P_5 - TMG801	1.96*	3.77**	2.87**	0.68^{ns}	0.34^{ns}	0.51^{ns}	0.60^{ns}	-0.15^{ns}	0.23^{ns}
P_6 - MSOY9144RR	-0.27^{ns}	4.90**	2.31**	-0.18^{ns}	6.09**	2.96**	0.92^{ns}	-0.44^{ns}	0.24^{ns}
				Specific combining ability (SCA)					
S_{11} (1)	-1.49^{ns}	-1.39^{ns}	-1.44^{ns}	-1.72*	-0.59^{ns}	-1.16^{ns}	-0.54^{ns}	-2.27^{ns}	-1.41^{ns}
S_{22}	-1.37^{ns}	0.95^{ns}	-0.21^{ns}	0.94^{ns}	1.04^{ns}	1.00^{ns}	-2.63*	-3.99**	-3.31*
S_{33}	0.88^{ns}	-0.88^{ns}	-0.01^{ns}	1.48*	0.61^{ns}	1.05^{ns}	-0.84^{ns}	-2.33^{ns}	-1.58^{ns}
S_{44}	-1.91^{ns}	2.08^{ns}	0.09^{ns}	1.85*	1.16^{ns}	1.50^{ns}	-0.63^{ns}	-2.46^{ns}	-1.54^{ns}
S_{55}	0.25^{ns}	2.62^{ns}	1.44^{ns}	1.57^{ns}	0.84^{ns}	1.21^{ns}	-1.32^{ns}	-2.95*	-2.14^{ns}
S_{66}	1.54^{ns}	2.37^{ns}	1.96^{ns}	1.61*	6.69**	4.15*	-0.42^{ns}	-3.27*	-1.85^{ns}
S_{12}	2.78^{ns}	1.92^{ns}	2.35^{ns}	2.33*	0.70^{ns}	1.51^{ns}	0.07^{ns}	0.33^{ns}	0.20^{ns}
S_{13}	-0.35^{ns}	2.33^{ns}	0.99^{ns}	-0.89^{ns}	2.91^{ns}	1.01^{ns}	0.21^{ns}	1.68^{ns}	0.94^{ns}
S_{14}	2.48^{ns}	3.98*	3.23*	2.16**	2.27^{ns}	2.22^{ns}	-0.46^{ns}	-2.47^{ns}	-1.46^{ns}
S_{15}	0.84^{ns}	-4.58**	-1.87^{ns}	0.24^{ns}	-1.47^{ns}	-0.62^{ns}	0.43^{ns}	0.31^{ns}	0.37^{ns}
S_{16}	-2.76^{ns}	-0.88^{ns}	-1.82^{ns}	-0.41^{ns}	-3.21^{ns}	-1.81*	0.85^{ns}	4.69**	2.77^{ns}
S_{23}	-2.49^{ns}	0.87^{ns}	-0.81^{ns}	-0.30^{ns}	2.74^{ns}	1.22^{ns}	-0.91^{ns}	-1.66^{ns}	-1.28^{ns}
S_{24}	3.86*	-0.48^{ns}	1.69^{ns}	-2.46**	-0.32^{ns}	-1.39^{ns}	3.82**	3.50^{ns}	3.66*
S_{25}	-0.15^{ns}	-0.88^{ns}	-0.51^{ns}	-0.18^{ns}	0.03^{ns}	-0.08^{ns}	1.91^{ns}	3.80*	2.85^{ns}
S_{26}	-1.25^{ns}	-3.34*	-2.29^{ns}	-1.33^{ns}	-5.22**	-3.27*	0.38^{ns}	2.01^{ns}	1.19^{ns}
S_{34}	1.24^{ns}	-0.23^{ns}	0.50^{ns}	-0.83^{ns}	1.80^{ns}	0.48^{ns}	0.26^{ns}	-1.26^{ns}	-0.49^{ns}
S_{35}	-2.27^{ns}	-1.29^{ns}	-1.78^{ns}	-1.56^{ns}	-2.27^{ns}	-1.91*	1.12^{ns}	4.04*	2.59^{ns}
S_{36}	2.12^{ns}	0.08^{ns}	1.10^{ns}	0.62^{ns}	-6.41**	-2.89*	0.98^{ns}	1.86*	1.42^{ns}
S_{45}	-0.75^{ns}	-2.65^{ns}	-1.70^{ns}	-1.05^{ns}	-2.75^{ns}	-1.89^{ns}	-0.90^{ns}	2.45^{ns}	0.77^{ns}
S_{46}	-3.02^{ns}	-4.78**	-3.89*	-1.52^{ns}	-3.32^{ns}	-2.42*	-1.46^{ns}	2.68^{ns}	0.62^{ns}
S_{56}	1.81^{ns}	4.17*	2.99^{ns}	-0.58^{ns}	4.77*	2.09^{ns}	0.09^{ns}	-4.71**	-2.31*

** and *Significant at 1% and 5%, by the t-test. ^{ns}Nonsignificant. (1)S_{ij}, specific combining ability of the parents with themselves (when i = j) and in the single hybrids (when i < j).

Positive S_{ii} values from individual parents for the cycle indicate the existence of unidirectional dominance deviations and, consequently, manifestation of negative heterosis in hybrid combinations involving the most divergent parents (Daronch et al., 2014). For grain yield, positive S_{ii} values also indicate the existence of unidirectional deviations of dominance, with manifestation of positive heterosis in hybrids involving divergent parents. The 'RSF6563IPRO' and 'MSOY9144RR' parents showed larger absolute S_{ii} values, a fact that evidences the greater genetic divergence of these parents in relation to the average of the others involved in the diallel, as well as greater varietal heterosis manifested in the hybrids.

Given the findings already reported in the literature, and the results found from the present study, we recommend the use of diallel crosses to understand the genetic control of maturity and grain yield in breeding programs, and to select the best parents and crosses. Understanding the genetic bases and their interactions with the environment (locations, years, and seasons) may therefore be necessary to determine the genotypic combinations that will lead to a higher, or more stable yield performance, for the crop season of a specific region.

Conclusions

1. Summer season cropping is more favorable than the winter one to select parents and crosses, in order to reduce cycle and increase grain yield per plant.
2. The 'RSF6563IPRO', 'SYN9078RR', and 'MSOY6101' parents show the highest GCA values that are favorable to reduce the number of days to flowering; 'SYN9078RR', 'TMG123RR', 'RSF6563IPRO', and 'MSOY6101' are favorable to reduce the cycle; and 'RSF6563IPRO' and 'TMG123RR' are favorable to increase grain yield.
3. 'SYN9078RR' x 'MSOY9144RR', 'RSF6563IPRO' x 'MSOY9144RR', and 'MSOY6101' x 'TMG801' are the most promising crosses for extracting superior soybean lines for time to flowering; 'RSF6563IPRO' x 'MSOY9144RR', 'TMG123RR' x 'MSOY9144RR', 'SYN9078RR' x 'MSOY9144RR', and 'MSOY6101' x 'MSOY9144R' are promising for earliness; 'MSOY6101' x 'MSOY9144RR', 'TMG123RR' x 'TMG801', 'RSF6563IPRO' x 'TMG801', and 'RSF6563IPRO' x 'SYN9078RR' are promising for grain yield; and 'MSOY6101' x 'MSOY9144RR', and 'TMG123RR' x 'TMG801' are promising for both earliness and grain yield.

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