Asian Journal of Crop Science

ISSN 1994-7879

Asian Journal of Crop Science 2 (1): 1-11, 2010
ISSN 1994-7879

Magnitude of Combining Ability and Heterosis as Influenced by Type of Soil in Grain Sorghum (*Sorghum bicolor* L. Moench)

Adel M. Mahmoud and Talaat A. Ahmed
Department of Agronomy, Faculty of Agriculture, Assiut University, Assiut, Egypt

Abstract: The aim of this study is to estimate the magnitude of GCA and heterosis for grain yield and productivity-related traits and study the influence of soil type on GCA and level of heterosis in grain sorghum. This study was carried out at the Experimental Farm of Faculty of Agriculture, Assiut University, Assiut, Egypt during 2007 and 2008 seasons. Combining ability and heterosis are important factors for efficient choice of breeding methods and parental materials in developing breeding programs to increase grain sorghum production under different types of soil. Twelve parental lines including three restorers and eight male-sterile A-lines were crossed according to line×tester method to assess the combining ability and magnitude of heterosis in grain sorghum under both of clay and sandy soil. Under clay soil and surface irrigation, female line B11 and male line R-272 were the best general combiner for grain yield/plant and their GCA effects were 14.19 and 11.29, respectively, while under sandy soil and drip irrigation, the female line B93 and male line R-273 were the best general combiner for grain yield/plant and their GCA effects were 7.42 and 5.15, respectively. Heterosis results showed that male line R-273 is the best for developing sorghum hybrids under both of clay and sandy soil as heterosis for grain yield/plant in its hybrids was high under the two types of soils (101.94 and 94.18% under clay and sandy soil, respectively). However, mean heterosis of 143.90% over females line, for grain yield/plant under clay soil was obtained when male line R-272 was used as a pollinator gave the priority for this parent to be used for developing sorghum hybrids under clay soil condition. Seven and four hybrids surpassed significantly with 15 and 20% of the hybrid check cultivar (Shandaweel-6) for grain yield/plant over under both of clay and sandy soil, respectively. Most hybrids that have the line R-273 as male parent surpassed check cultivar under sandy and clay soils. Therefore, it is recommended to use that line in developing sorghum hybrids under both of clay and sandy soil.

Key words: Sorghum, combining ability, heterosis, sandy soil, clay soil

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is a major cereal crop in the semi-arid regions of the world as it is an important food and feed crop. It can also be used as raw material for industry and can be processed into malted foods, beverages and beer (Uptmoor *et al*., 2006; Palmer, 1992). In Egypt, grain sorghum is the fourth cereal crop, ranking after wheat, maize and rice where the total production of grain sorghum was 843,840 MT in 2007 (FAO, 2007). Improvement of sorghum through selection within traditional cultivars or progeny from

Corresponding Author: Talaat A. Ahmed, Department of Biological and Environmental Sciences, Qatar University, Qatar

crosses between similar traditional cultivars has generally not been promising in enhancing yields (House, 1995). The demand for cereals in Egypt calls for an increase in the production of sorghum that comes mainly from increased yield per unit area. Developing high yielding and adapted sorghum hybrid is one approach to resolve cereal grain deficits. The improvement of sorghum production was mainly achieved through breeding of high yielding cultivars coupled with improved agronomic practices. One of the remarkable successful breeding stories is the development of commercial single cross hybrids in sorghum following the discovery of cytoplasmic male sterility (Reddy *et al*., 2007). Hybrids offer some advantages over pure line varieties in that complementary traits from parental lines can be combined in a single F_1 genotype with resulting adaptation to different stress environments. In addition, hybrids offer some incentive to private sector involvement in cultivars development because hybrids are proprietary and producers purchase seeds every season. In recent years, several national research programs in the semi-arid regions have shown an increased interest in hybrids (Axtell *et al*., 1999). The immediate task that faced those breeding programs is to gain information on the combining ability of various varieties and populations developed and improved over the years. Information on combining ability is needed to identify potentiality superior parents and hybrids and would also help to define the pattern of gene effects in the expression of quantitative traits (Goyal and Kumar, 1991). The General Combining Ability (GCA) of each parent should be examined when the objective is the development of superior genotypes. The estimation of GCA under different types of soil will be helpful to decision regarding the commitment of breeding resources to develop and evaluate efficient methods of producing commercial F_1 hybrids under different types of soil. Parents that will contribute favorable combination of genes for yield and other agronomic traits are the most sought.

Exploitation of heterosis through synthetics and ultimately hybrids could move forward improving yield potential and its components in grain sorghum. Superiority of hybrids over the mid and better parents for grain yield was found to be associated with manifestations of heterotic effects in some yield components i.e., panicle length and width, grain yield/plant and 1000 grain weight. It is clearly stated from the literature that heterotic effects ranges from significantly positive to significantly negative for different yield components and were very prominent in F_1 of grain sorghum especially crosses among widely divergent materials and less occurred in hybrids between local varieties (Corn, 2008; Lippman and Zamir, 2006; Axtell *et al*., 1999; Borgonovi, 1985; Beil and Atkins, 1967; Malm, 1968; Paisan and Atkins, 1977).

The increased productivity of these hybrids was achieved by the exploitation of the high degree of heterosis. Since sorghum is cultivated under diverse conditions ranging from extremely stress to more favorable environments, it is very pertinent to study environmental influence on both of GCA and the heterosis (Degu *et al*., 2009; Lippman and Zamir, 2006; Axtell *et al*., 1999; Borgonovi, 1985; Paisan and Atkins, 1977; Malm, 1968; Beil and Atkins, 1967).

The present investigation was carried out to estimate the magnitude of GCA and the heterosis for grain yield and its components and study the influence of soil type on GCA and the level of heterosis in some grain sorghum genotypes.

MATERIALS AND METHODS

Eight cytoplasmic male-sterile lines (B11, B52, B73, B93, B101, B604, B613 and B614) (A-lines) were crossed to three pollen restorer male-fertile parents (Dorado, R-272 and R-273)

Table 1: Physical and chemical analysis for two types of soil

First location	Values	Second location	Values
Sand (%)	25	Gravel (more than 2 mm (%)	39.4
Silt (%)	29	Sand (%)	93.5
Clay (%)	46	Silt (%)	4.3
Soil texture	Clay	Clay (%)	2.2
Exchangeable ions		pH (1:1)	8.1
P (ppm)	11.3	Ece (dS m^{-1})	2.3
Mn (ppm)	17.5	Na (meq L^{-1})	4.9
Zn (ppm)	1.1	K (meq L^{-1})	1.2
Fe (ppm)	3.8	Ca (meq L^{-1})	11.3
Cu (ppm)	1.3	Mg (meq L^{-1})	5.1
pH (1:1)	8	Soluble anions (meq L^{-1})	
Organic matter (%)	1.7	CO_3+HCO_3	4.8
Total nitrogen	0.08	Cl	6.0
Total $CaCO_3$ (%)	2.00	SOH	14.8

to produce 24 F_1 hybrids in a line×tester design at the experimental farm of Faculty of Agriculture, Assiut University, Assiut, Egypt in Summer 2007. In the following growing season of Summer 2008, the 24 F_1 hybrids, the parents including the eight B-lines and three restorer lines in addition to the commercial cultivar (Shandweel-6) as check variety were grown in two different locations. The first location was the experimental farm of Faculty of Agriculture, Assiut University, where the soil is clay with surface irrigation, while the second location was El-Wady El-Assiuty Research Station. Assiut, where the soil is sandy, low in fertility and organic matter and the irrigation is dipping (Table 1).

In each location, the 36 entries were arranged in a randomized complete block design with four replications. Plot size was one row with 5 m long and 70 cm apart. The two experiments were hand planted on 30 June and sowing was done in hills spaced 20 cm. Thinning was done to two plants/hill after hoeing and after three weeks from the sowing at both locations. All other agronomic practices were done accordingly the recommendations for growing grain sorghum production in Egypt at both locations. The following agronomic traits were measured on a random sample of ten guarded plants from each plot, plant height (cm), flag leaf area (m^2), panicle length (cm) and width (cm), grain yield/plant (g) and 1000 grain weight (g).

Statistical Analysis

A combined statistical analysis over the locations was done according to Gomez and Gomez (1984) for all of the studied traits. The GCA effects for each location were estimated using Line×Tester analysis according to Kempthorne (1957) and as illustrated by Singh and Chaudhary (1977). Heterosis values were estimated as the superiority of hybrid over its male sterility parent, expressed as percentage. The performance of hybrids was compared with Shandaweel-6 hybrid as commercial cultivar, then analysis of variance for hybrids and Check was done for each location according to Gomez and Gomez (1984) for the studied traits.

RESULTS AND DISCUSSION

Variances and Mean Performances at the Two Locations

The combined statistical analysis of variance (Table 2) over the two locations revealed highly significant differences among tested entries for plant height, flag leaf area, panicle length and width, grain yield/plant and 1000 grain weight, which indicate a wide range of genetic variability for them and hence, the feasibility for genetic improvements using such genetic pools of grain sorghum.

Table 2: Combined mean squares of all grain sorghum genotypes for the studied traits over two locations in 2008

		Mean squares					
Source of variation	df	Plant height (cm)	Flag leaf area (m^2)	Panicle length (cm)	Panicle width (cm)	Grain yield/ plant (g)	1000 grain weight (g)
Location (L)	1	201589.9**	0.00117**	5062.6**	210.2**	101570.8**	448.3**
Replication/L	6	44	0.00001	4.5	1.1	20.3	0.1
Genotypes (G)	34	11763.4**	0.00008**	61.5**	6.1**	2020.2**	61.2**
Parents (P)	10	3156.6**	0.00010**	68.1**	5.7**	323.5**	56.0**
P vs. C	1	182949.1**	0.00001	488.4**	66.0**	40845.7**	558.4**
Crosses (C)	23	8062.7**	0.00007**	40.0**	3.7**	1069.8**	41.8**
Female (F)	7	9791.2**	0.00002	58.4	7.3*	2305.1*	85.7*
Male (M)	2	48530.1**	0.00002	92.8*	6.5**	1495.1*	41.5
F×M	14	1417.3**	0.00010**	23.3**	1.4**	391.4**	19.9**
G×L	34	2524.0**	0.00016**	15.8**	2.1**	916.6**	22.3**
P×L	10	705.6**	0.00010**	8.4**	0.9**	274.7**	12.5**
P vs. C×L	1	32260.0**	0.00044**	227.2**	6.9**	11139.0**	71.0**
C×L	23	3021.8**	0.00018**	9.9**	2.4**	751.3**	24.5**
F×L	7	891.8**	0.00014**	11.6**	4.0**	1074.4**	20.2**
M×L	2	9379.5**	0.00036**	14.6**	3.6**	2244.8**	15.9**
F×M×L	14	1535.7**	0.00017**	8.4**	1.5**	376.4**	27.8**
Error	204	66.2	0.00001	2.1	0.3	11	0.3

* and ** indicate significant at 5 and 1% level, respectively

Table 3: Average performance of 35 sorghum genotypes including 24 hybrids, 8 B-lines and 3 restorer-lines under clay and sandy soil in 2008

Soil conditions	Plant height (cm)	Flag leaf area (m^2)	Panicle length (cm)	Panicle width (cm)	Grain yield/ plant (g)	1000 grain weight (g)
Clay	188.7	0.03	25.2	5.7	68.5	23.7
Sandy	135.0	0.02	16.7	4.0	30.4	21.1

The data in Table 3 revealed that values for all studied traits under clay soil condition were higher than values under sandy soil condition. Differences between the two locations indicate the wide range in climatic and edaphic factors prevailing at the two locations, the high performances of all studied traits under clay soil condition are due to desirable condition for growing under this type of soil such as fertility and desirable soil water content. These results are in harmony with Kenga *et al.* (2004), who studied the performance of genotypes of grain sorghum under different environments and found that the mean squares due to environment, genotypes and environment-genotypes interactions were significant, indicating the diversity of the genotypes and their differences in environmental response.

Combining Ability

The selection of parental lines for hybrid programs was one of the objectives of this study. Thus, the estimates of the general combining ability of a parent provide important indicators of its potential for generating superior lines. A low GCA estimate, whether positive or negative, indicates that the mean of a parent in crossing with the other, does not differ greatly from the general mean of the crosses. On the other hand, a high GCA estimate indicates that the parental mean is superior or inferior to the general mean. This gives information about the concentration of predominant genes with additive effects (Kenga *et al.*, 2004).

General Combining Ability for Female Lines

Estimates of GCA effects for all studied traits for eight female lines used in this study under clay and sandy soil are shown in Fig. 1-6.

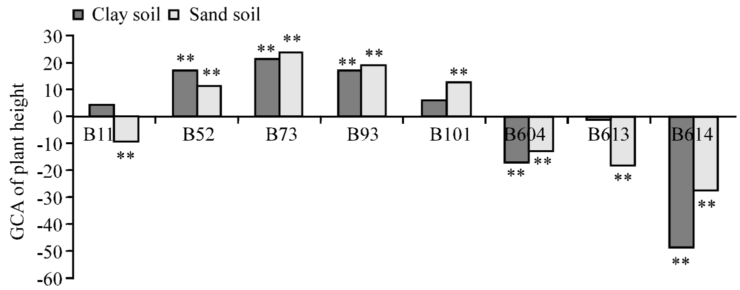

Fig. 1: Estimates of GCA effects of female lines for plant height under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

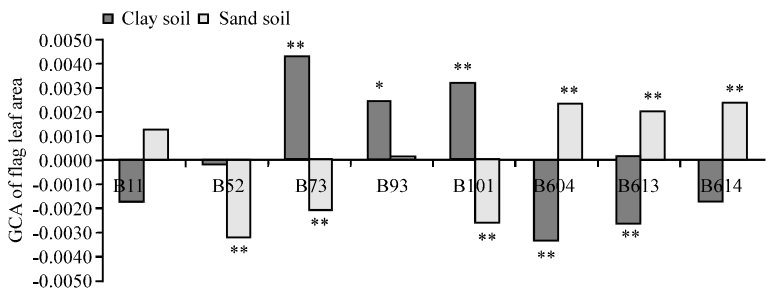

Fig. 2: Estimates of GCA effects of female lines for flag leaf area under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

Female line B73 was the best general combiner for plant height with highly significant and positive GCA effects under the different soils. Also, female lines B52 and B93 were good general combiner for plant height as well. On the other hand, female line B614 showed highly significant and negative GCA effects for plant height under both two conditions. It is, however, a good combiner for dwarf stem length under clay and sandy soil condition (Fig. 1).

Results in Fig. 2 showed that, under clay soil condition, female line B73 was the best general combiner for flag leaf area with highly significant and positive GCA effects. Also, female lines B101 and B93 were the good general combiner for flag leaf area. On the other hand, female line B604 showed highly significant and negative GCA effects for flag leaf area under clay soil condition.

Under sandy soil condition, the female line B614 was the best general combiner for flag leaf area with highly significant and positive GCA effects. Also, female line B613 and B604 had a good combiner for flag leaf area, under sandy soil condition. On the other hand, the female line B52 showed highly significant and negative GCA effects for flag leaf area under sandy soil condition.

Under clay soil condition, female lines B101, B52, B93 and B11 were the best general combiners for panicle length with highly significant and positive GCA effects.

Under sandy soil condition, the female line B93 was the best general combiner for panicle length with highly significant and positive GCA effects.

Female line B604 showed highly significant and negative GCA effects for panicle length under both clay and sandy soil conditions (Fig. 3).

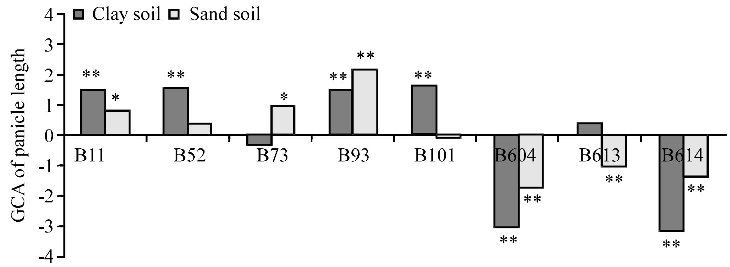

Fig. 3: Estimates of GCA effects of female lines for panicle length under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

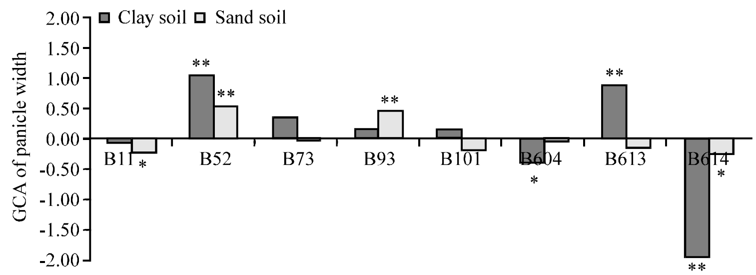

Fig. 4: Estimates of GCA effects of female lines for panicle width under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

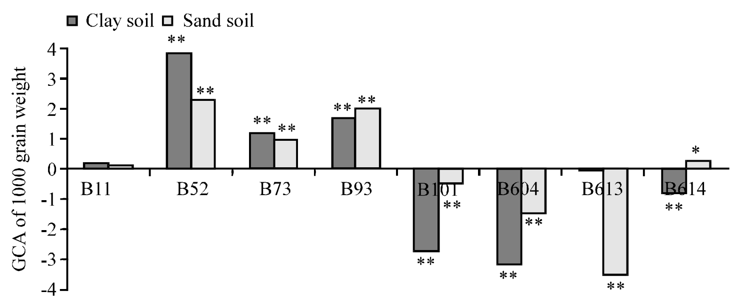

Fig. 5: Estimates of GCA effects of female lines for 1000 grain weight under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

About the panicle width, the female line B52 gave the highest and highly significant positive GCA effects under both of clay and sandy soil (Fig. 4). This means that line B52 is a good general combiner for panicle width for hybrids development under different types of soils. This line could have favorable gene action for panicle width and will be considered as a good combiner for increasing the width of panicle under both of clay and sandy soil conditions. On the other hand, female line B614 gave the highest with highly significant negative GCA effects under both of clay and sandy soil.

B52 female line had the highest and highly significant positive GCA effects under both of clay and sandy soil for 1000 grain weight indicating that this line could be considered as a good combiner for increasing the size of grain under both of clay and

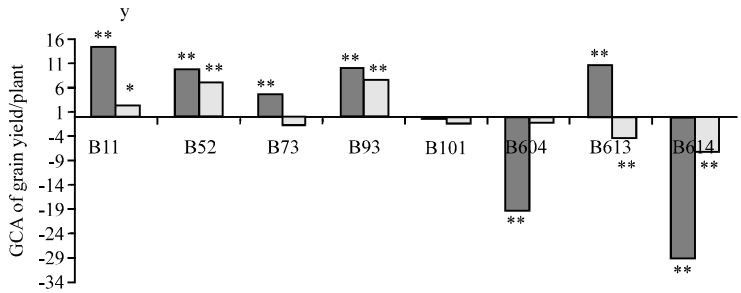

Fig. 6: Estimates of GCA effects of female lines for grain yield/plant under clay and sandy soil. * and ** indicate significant at 5 and 1% level, respectively

sandy soil condition. However, female lines B613 and B604 had the highest and highly significant negative GCA effects under and clay soil, respectively (Fig. 4).

Results presented in Fig. 6 exhibit that, under clay soil condition, female line B11 was the best general combiner for grain yield/plant with highly significant positive GCA effects. Moreover, female lines B613, B93, B52 and B73 were good general combiner for grain yield/plant with highly significant positive GCA effects. On the other hand, female lines B604 and B614 showed highly significant and negative GCA effects for grain yield/plant.

Under sandy soil condition, the female lines B93 and B52 were good general combiner for grain yield/plan with highly significant positive GCA effects. On the other hand, the female lines B613 and B614 showed highly significant and negative GCA effects for grain yield/plant. Similar results were obtained by Degu *et al.* (2009), who stated that the GCA effect differed in magnitude among lines for grain yield/plant, plant height, leaf area, panicle width and length and 1000 grain weight.

GCA for Male Lines

General Combining Ability (GCA) effects of the three male lines at two locations for all studied traits are shown in Fig. 7a-f.

The estimates of GCA effects for three male lines (Dorado, R-272 and R-273) under clay soil revealed that, male line R-272 was the best general combiner for grain yield/plant, panicle width, panicle length, flag leaf area and plant height, because this line had a highly significant and positive effects (Fig. 7). But parent Dorado had highly significant and negative GCA effects for grain yield/plant, panicle width, panicle length, flag leaf area and plant height (Fig. 7), indicating that Dorado had favorable gene action for shortness and will be considered as a good combiner for shortness under clay soil condition. Under sandy soil condition, male line R-273 was the best general combiner for all studied traits except panicle length (Fig. 7), it had highly significant and positive GCA effects for all studied traits, but for panicle length had a negative and highly significant GCA effect (Fig. 7). This results mean that, line R-273 had favorable genes action for all studied traits except panicle length and will be considered a good general combiner for development of hybrids of sorghum which will be grown under sandy soil condition. Another two male lines, Dorado and R-272 had highly significant and negative grain yield/plant under sandy soil (Fig. 7). Dorado had the highest negative highly significant GCA effects for plant height under both of clay and sandy soil (Fig. 7). That means Dorado had favorable gene action for shortness and will be considered as a good combiner for shortness under both of clay and sandy soil conditions.

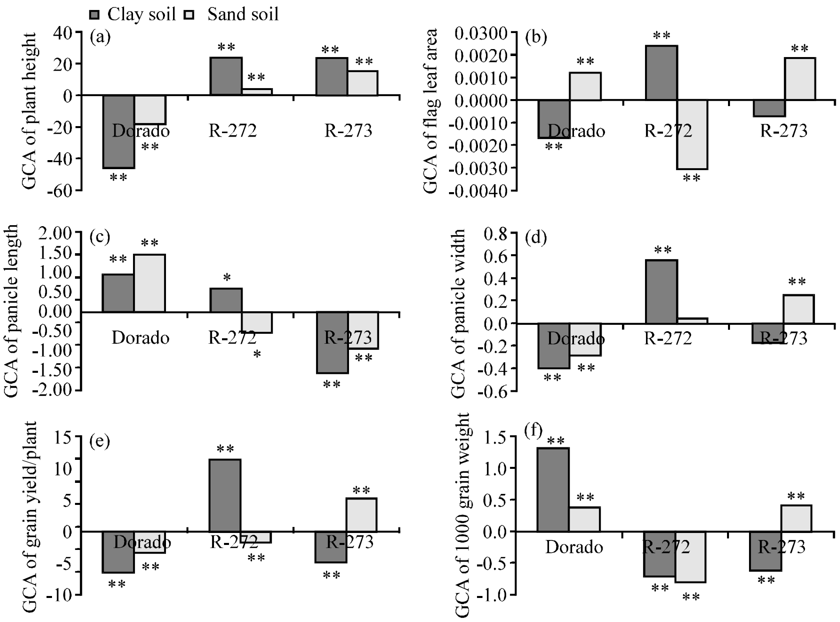

Fig. 7: (a-f) Estimates of GCA effects of male lines for studied traits under clay and sandy soil

Level of Heterosis (%)

The term heterosis usually refers to superiority of F_1 hybrid performance over the performance of its parents (Hayes, 1952). In current study the performance of crosses was constantly compared with that of female line because our objective was to quantify the magnitude of improvement over the female line by using the different pollinators for developing the crosses of sorghum. Data in Fig. 8a-c revealed that, the male line Dorado based on its hybrids showed heterosis ranged from 17.23 % for flag leaf area to 101.55% for grain yield/plant under clay soil (Fig. 8a). On the other hand, heterosis ranged from - 0.77% for flag leaf area to 60.8% for grain yield/plant under sandy soil (Fig. 8a). Based on these results, it could be concluded that Dorado is a suitable parent for development of sorghum hybrids under clay soil compared with sandy soil. Hybrids based on male line R-272, exhibited heterosis ranged from 18.88% for 1000 grain weight to 143.80% for grain yield/plant under clay soil, while under sandy soil the heterosis ranged from -20.73% for flag leaf area to 54.37% for grain yield/plant (Fig. 8b). Therefore, male line R-272 is a good parent under clay soil for most studied traits as it gave the highest heterosis effect under clay soil compared to the other two male parents (Dorado and R-273).

Values of heterosis in hybrids based on R-273 male parent ranged from 14.75% for panicle length to 101.94% for grain yield/plant under clay soil (Fig. 8c). On the other hand, under sandy soil heterosis ranged from 1.33% for panicle length to 94.10% for grain yield/plant (Fig. 8c). Hybrids that were developed using the male line R-273, exhibited the greatest grain yield heterosis (94.10%) under sandy soil (Fig. 8c) compared with those produced by Dorado (60.80%) and R-272 (54.37%) (Fig. 8a, b). It could be suggested that male line R-273 is most suitable line for developing sorghum hybrids under both of clay and sandy soil for grain yield/plant as its hybrids exhibited high values of heterosis (Fig. 8c) under the two types of soils which means that they gain more adaptation to grow well under different soil condition. Apparently, the heterosis estimates for the majority of the studied

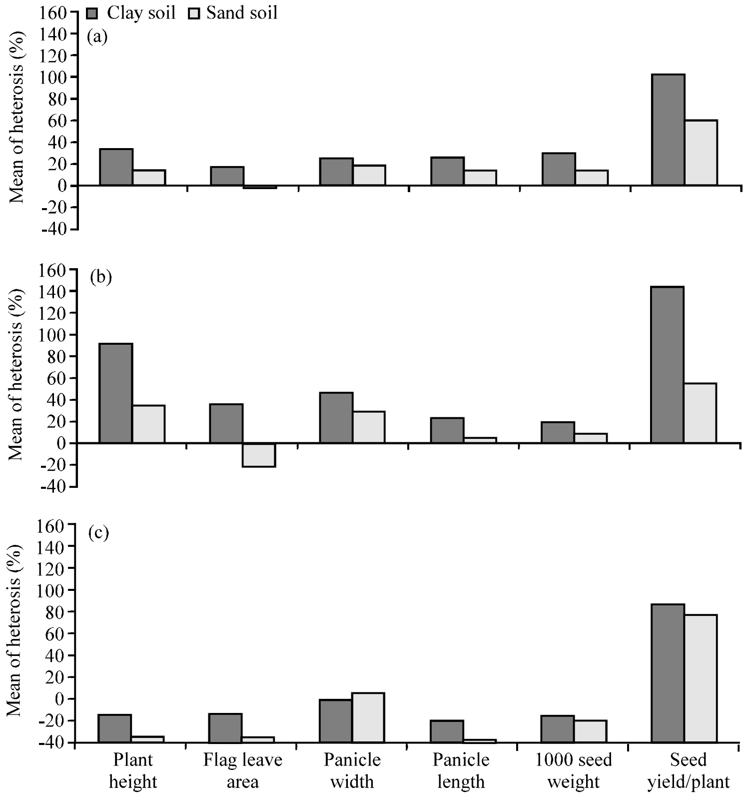

Fig. 8: Mean of the magnitude of heterosis (%) over the male sterility parents in hybrids of sorghum on male line (a) Dorado, (b) R-272 and (c) R-273 for studied traits in two locations

traits indicate that there was sufficient genetic divergence among the parents assessed, resulting in a favorable situation for breeding. Favorable heterosis has been obtained by several researchers for grain sorghum traits which varied according to the cross combinations and traits (Axtell *et al*., 1999; Borgonovi, 1985; Chapman *et al*., 2000; Haussmann *et al*., 2000; Degu *et al*., 2009).

Comparison Between Hybrids and Commercial Variety Shandaweel-6

High average heterosis over the female lines alone may not justify the breeding of hybrids. It is equally important that new hybrids produce higher yielding than the present cultivars available to farmers in the target region. Hence, the performance of hybrids was compared with the commercial variety Shandweel-6 recommended for this region. Number of hybrids displayed significant superiority for most of the studied traits either under clay or sandy soil conditions (Fig. 9). In total, seven and four hybrids surpassed significantly ($p<0.01$) the check variety Shandaweel-6 for grain yield/plant under both clay and sandy soils, respectively (Fig. 9).

It is obvious from the results that, there are good prospects of identifying hybrids which out perform the best available varieties, if sufficiently large numbers of hybrids are tested. These results are in harmony with that obtained by Borgonovi (1985).

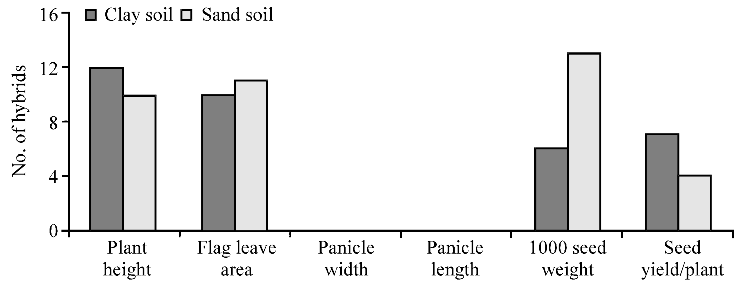

Fig. 9: Number of hybrids surpassed significantly variety Shandaweel-6 in studied traits under clay and sandy soil condition

CONCLUSION

The present study identified number of parental lines that showed positive and significant GCA and in combination exhibited large SCA effects for different agronomic characters as potential materials for inclusion in the grain sorghum cultivar development program. In general, this study demonstrated clear advantages of hybrids over pure line cultivars, suggesting that productivity of grain sorghum in Egypt could be boosted by promoting hybrid cultivars. High potential hybrids in this study are highly promising to breed grain sorghum cultivars, hybrids possessing genetic factors for high yield potential and other desired characteristics.

REFERENCES

Axtell, J., I. Kapran, Y. Ibrahim, G. Ejeta and D.J. Andrews, 1999. Heterosis in Sorghum and Pearl Millet. In: The Genetics and Exploitation of Heterosis in Crops, Coors, J.G. and S. Pandey (Eds.). ASA-CSSA-SSSA, USA., pp: 375-386.

Beil, G.M. and R.E. Atkins, 1967. Estimates of general and specific combining ability in F_1 hybrids for grain yield and its components in grain sorghum, *Sorghum vulgare*. Crop Sci., 7: 225-228.

Borgonovi, R.A., 1985. Heterosis in the biological yield of grain sorghum (*Sorghum bicolor* (L.) Moench). Revista Brasileira de Genet., 8: 2-431.

Chapman, S., M. Cooper, D. Butler and R. Henzell, 2000. Genotype by environment interactions affecting grain sorghum. I. Characteristics that confound interpretation of hybrid yield. Aust. J. Agric. Res., 51: 197-207.

Corn, R., 2008. Sweet sorghum heterosis. Joint Annual Meeting, Oct. 5-9, Houston, TX., George R. Brown Convention Centre. http://a-c-s.confex.com/crops/2008am/webprogram/Paper42644.html.

Degu, E., A. Debello and K. Belete, 2009. Combining ability study for grain yield and yield-related traits of grain sorghum (*Sorghum bicolor* (L.) Moench) in Ethiopia. Acta Agronomica Hungarica, 57: 175-184.

FAO., 2007. The agricultural production domain covers. http://faostat.fao.org/site/339/default.aspx.

Gomez, K.A. and A.A. Gomez, 1984. Statistical Procedures for Agricultural Research. 2nd Edn., John Wiley and Sons Inc., New York, pp: 95-109.

Goyal, S.N. and S. Kumar, 1991. Combining ability for yield component and oil content in sesame. Indian J. Genet. Plant Breed., 51: 311-314.

Haussmann, B.I.G., A.B. Obilana, P.O. Ayiecho, A. Blum, W. Schipprack and H.H. Geiger, 2000. Yield and yield stability of four population types of grain sorghum in a semi-arid area of Kenya. Crop Sci., 40: 319-329.

Hayes, H.K., 1952. Development of the Heterosis Concept. In: Heterosis, Gowen, J.W. (Ed.). Iowa State College Press, Ames, IA. USA., pp: 49-65.

House, L.R., 1995. Sorghum: One of the world's great cereals. Afr. Crop Sci. J., 3: 135-142.

Kempthorne, O., 1957. Yield stability of single three way and double cross hybrids. Sorghum Newslett., 33: 59-59.

Kenga, R., S.O. Alabi and S.C. Gupta, 2004. Combining ability studies in tropical sorghum (*Sorghum bicolor* (L.) Moench). Field Crops Res., 88: 251-260.

Lippman, Z.B. and D. Zamir, 2006. Heterosis: revisiting the magic. Trends Genet., 23: 60-66.

Malm, N.R., 1968. Exotic germplasm use in grain sorghum improvement. Crop Sci., 8: 295-298.

Paisan, L. and R.E. Atkins, 1977. Estimates of combining ability and heterosis in converted exotic sorghum. Crop Sci., 17: 47-50.

Palmer, G.H., 1992. Sorghum-food beverage and brewing potentials. Process Biochem., 27: 145-153.

Reddy, B.V.S., S. Ramesh, P.S. Reddy and B. Ramaiah, 2007. Combining ability and heterosis as influenced by male-sterility inducing cytoplasms in sorghum (*Sorghum bicolor* (L.) Moench). Euphytica, 154: 153-164.

Singh, K.B. and B.D. Chaudhary, 1977. Biometrical Methods in Quantitative Genetic Analysis. Kalyani Publishers, New Delhi, India, pp: 304.

Uptmoor, R., W.G. Wenzel, A.H. Abu Assar and G. Donaldson *et al*., 2006. Evaluation of South African sorghum landraces and breeding of varieties suitable for low-input agriculture. Acta Agronomica Hungarica, 54: 379-388.