Estimation of Heterosis for Yield and Yield Related Traits in Bread Wheat (*Triticum aestivum* L.)

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Abstract

Selection of promising genotypes from diverse genetic base and their subsequent utilization for hybridization is one of the strategies for improving productivity of bread wheat (Triticum aestivum L.) in Ethiopia. Thirty-six genotypes were evaluated in triplicated randomized complete blocks to estimate the extent of mid and better parent heterosis for yield and yield related traits using 8 × 8 half-diallel cross during the 2005 season at Sinana, Ethiopia. Significant differences among all the genotypes were noticed for all traits, except for biomass per plant.. The highest heterosis over mid and better parent as well as economic heterosis for grain yield was recorded in Dashen × Meda-Welabu hybrid with corresponding values of 63%, 52% and 44%, respectively. The crosses that showed heterosis for grain yield were also heterotic for most of the yield related traits. The negative heterosis observed for plant height and maturity traits in most of the crosses was in the desired direction. The negative mid and better parent heterosis observed for tillers per plant and spike traits in several of the crosses, however, was undesirable heterosis in bread wheat improvement. The study revealed good scope for commercial exploitation of heterosis as well as selection of pure lines among the progenies of heterotic F_1s for improvement of yield in bread wheat.

Keywords: bread wheat, diallel cross, heterosis, hybrid, *Triticum aestivum*

Introduction

Bread wheat (*Triticum aestivum* L.) is a member of the tribe *Triticeae* of the family *Poaceae* to which all the major cereals belong. It is an autogamous allo-hexaploid species (2n = 6x = 42) and three genomes, designated as A, B and D (AABBDD), that were involved in its evolution (Morris and Sears, 1967). It combines the genomes of three diploid ancestrals, *Triticum urartu* (2n = 14, AA), *Aegilops squarrosa* (2n = 14, DD) and *Aegilops* species (2n = 14, BB). Bread wheat is the world's leading food crop for bread making due to the viscoelastic properties of its endosperm gluten proteins. Wheat domestication occurred in primitive farms of southwestern Asia, in the "Fertile Crescent" of Mesopotamia, between 7,000 and 9,000 BC (Bell, 1987) and has been cultivated for more than 10,000 years (Poehlman and Sleeper, 1995).

Being originated in southwestern Asia, bread wheat is an introduced crop in Ethiopia. Ethiopia is the largest producer of wheat in sub-Saharan Africa, where the country ranks first in area coverage and second in production (FAO, 2005). An estimated area of 1.4 million hectares is under wheat production (CSA, 2005). Bread wheat production is rapidly increasing in the country because of its higher productivity and broad adaptation. Moreover, the use of semi-dwarf and input responsive high yielding improved varieties has significantly contributed to its increased production from almost nil to 60% of the national wheat area (Amsal *et al*., 1995; Payne *et al*., 1996).

Despite the significant increase in acreage, the mean national wheat yield of Ethiopia is 1.5 t/ha (CSA, 2005). This low productivity may be partially attributed to the prevalence of virulent pathogens, lack of durable resistant variety to wheat rust diseases, soil nutrient depletion and problem of grass weeds in major wheat producing areas. Choice of promising genotypes from diverse genetic base and their subsequent utilization for hybridization and selection is one of the strategies for improving productivity of bread wheat. Therefore, advanced materials from international and national wheat improvement programs have been the immediate sources of bread wheat varieties for release or for use as parental stocks (Amsal *et al*., 1996; Getachew *et al*., 1997).

Estimate of heterosis is an important measurement to indicate the potential improvement that can be achieved through the use of hybrids. To this end, several studies have consistently showed the presence of considerable amount of heterosis in bread wheat cultivars of diverse genetic bases (Fabriozino *et al.,* 1998). These hybridization studies further showed the great potential that exists to maximize heterosis in wheat by crossing elite materials of diverse heterotic groups as parents (Jordaan, 1999). In self pollinated crops like wheat, the superiority of hybrids particularly over better parent is more useful in determining the feasibility of commercial exploitation of heterosis and helps to indicate the parental combinations capable of producing the highest level of transgressive segregants (Singh *et al*., 2004). The same authors reported maximum over mid and better parent heterosis for grain yield per plant of 126% and 121%, respectively. High magnitude of over better parent heterosis (hetrobeltiosis) suggests the possibility of commercial exploitation of hybrid vigor. Wheat breeders dealing with various aspects of hybrid wheat found that the standard heterosis for grain yield, on a large plot basis, ranged from 6% to as high as 41% (Pickett, 1993; Rajaram and Dubin, 1999).

The discovery of effective chemical hybridizing agents (CHAs); chemical compounds able to selectively induce male sterility in wheat, has greatly stimulated investigations relating to the introduction of F_1 hybrid wheat into practical agriculture (Pickett, 1993; Borghi and Perenzin, 1994). McRae (1985) suggests that CHA is sufficiently broad to embrace all modes of action and does not equate gamete with pollen. Since the early report, there have been significant advances in the development of CHA technology (Mock, 1995). Compared with cytoplasmic male sterility (CMS) systems, an effective CHA allows the production of large numbers of parental combinations and permits the evaluation of a number of inbreds for combining ability and/or breeding value. This substantially reduces the time required for hybrid development, as noted by a number of authors (e.g. Bruns and Peterson, 1998; Wilson, 1984).

The registration of GENESIS as a chemical hybridizing agent for wheat by Monsanto Company (Miskin *et al.*) and other hybridizing agents, such as the Sogital compound SC2053, continue to be widely utilized in the development of hybrid wheat. As a result, there has been a substantial decline in research activity on cytoplasmic male sterility (CMS) as a hybrid production system (Cisar and Cooper, 2002). Genesis, the first effective and approved chemical hybridizing agent, allows the screening of thousands of lines for potential inbreeds and eliminates the need for maintainer lines and the problems with restorer genes (Miskin *et al.*). A number of hybrids have been submitted for commercial registration in several European countries and have entered the marketplace in both Europe and the United States.

Multinational organizations like Pioneer Hi-Bred International and Monsanto Hybritech Seed International as well as national institutions such as Hybrinova (France), Hybrid Wheat Australia (Australia), SENSAKO and CARNIA (South Africa) are involved in hybrid wheat production of hybrid seed and marketing of hybrids in the world. The only government known to be involved is the Peoples Republic of China (Duvick, 1999; Jordaan *et al.,* 1999). Some of these companies used CMS as sterility factors in commercial production of hybrid seed.

Therefore, the present study was undertaken to estimate the mid and better parent heterosis for yield and yield related traits so as to identify parental lines that could be used for commercial production of hybrid wheat.

Materials and Methods

Estimation of heterosis for yield and yield related traits in bread wheat (*Triticum aestivum* L.) using 8 × 8 half-diallel cross was conducted at Sinana Agricultural Research Center (SARC) during the 2005 main season. The center is characterized by bimodal rainfall; hence, wheat is produced twice a year. The climatic data for the last 16 years (1990-2005) showed that average total annual rainfall was 752 mm and ranged from 535 to 1018 mm. Annual rainfall in the main season ranges from 230 to 546 mm with an average of 353 mm with the lowest value observed in 2005. The short rainy season rainfall in the same period ranged from 225 to 560 mm with an average 364 mm. The corresponding mean annual maximum and minimum temperature are 21.2 ^{0}C and 9.4 ^{0}C, respectively. The dominant soil type is pellic Vertisols with pH 6.

The experimental materials consisted of a total of 36 genotypes, which comprised the parents and 28 F_1's obtained from 8 × 8 half-diallel crosses of genetically diverse bread wheat cultivars selected based on their individual merits. The parents basically originated from CIMMYT/Ethiopia and were adapted and released as high yielding varieties by the National Agricultural Research System (NARS) during the period 1984 – 2001 (Table 1). These parents have genetic variability for yield, disease resistance as well as for various yield components. Crosses were made at SARC in 2004 in both the short rainy and seasons in the field and in greenhouse.

The resulting seeds of 36 genotypes (28 F_1s and 8 parents) were sown in triplicated randomized complete blocks at Sinana Agricultural Research Center on August 24, 2005. Planting was done manually by drilling two seeds per hill, and later thinning to one plant. Each plot consisted of four rows of 1.5 m length with the spacing of 20 cm between rows and 15 cm between plants. Recommended doses of 41-46 kg N-P_2O_5/ha fertilizers were applied at planting, and hand-weeding was done three times. DAP and Urea fertilizers were used with nitrogen fertilizer applied in split. The systemic fungicide, Propiconazole (Tilt) was sprayed at a rate of 0.5 l/ha (125 g a.i/ha) at booting and heading to control yellow and stem rust, respectively.

Five plants, randomly taken from two central rows of each plot, were used for recording plant height, spike length, flag leaf area, tillers/plant, seeds/spike, seeds/spikelet, spikelets/spike, seeds weight/spike, grain and biomass yield/plant, and harvest index. Days to head, days to maturre, days to grain filling and thousand kernel weight were recorded on plot basis from two central rows.

Analysis of variance (ANOVA) was carried out following the procedures outlined by Steel and Torrie (1980) to determine the presence of significant differences among the genotypes using the SAS soft ware computer program version 9.00 (SAS, 1996). Further analysis was carried out for characters that showed significant differences among the genotypes to estimate mid-parent heterosis (MPH), better parent heterosis (BPH) and standard heterosis (SH) in percent as suggested by Falconer and Mackay (1996) using SPAR-1 computer software (Doshi and Gupta, 1991).

Results and Discussion

The analysis of variance revealed highly significant ($P<0.01$) differences among the 36 genotypes for all traits studied, except biomass yield per plant (Table 2). Further partitioning of the sum of squares due to genotypes into that of parents, crosses and parents *versus* crosses, showed significant differences among parents and F_1 hybrids for almost all of the traits. This indicates the presence of inherent variation among the materials. Highly significant differences between parents *versus* F_1s were also found for most of the traits, indicating the presence of directional dominance that resulted in heterosis for these traits. Similar studies also reported significant differences among genotypes for grain yield and yield related traits in different sets of material of wheat (Menon and Sharma, 1997; Ali and Khan, 1998; Javaid *et al.,* 2001; Solomon, 2002).

Table 1. Name, pedigree and some other attributes of bread wheat varieties used in 8 × 8 half-diallel cross at Sinana Agricultural Research Center in 2005. (The origin/source for all parents is CIMMYT/Ethiopia)

Parents	Pedigree	Year of release	Attributes
P_1 – Wabe (HAR-710)	MRL 'S" - BUC 'S'	1995	High yielder, long spike, susceptible to yellow and stem rusts, and semi-dwarf, white seeded
P_2 – Mitike (HAR	BOW 28 / RBC	1994	Susceptible to yellow rust, moderately high yielder, tall, resistant to stem rust,
P_3 – Dashen	VEE17, KUZ- BUHO "S"x KAL – BB CM33027-F-15M-500y-1M-OY-OPtz-OY	1984	Good baking quality, white seeded, high tillering capacity, susceptible to yellow and stem rust, and high yielder
P_4 – Sofumer (HAR	LIRA'S'/YAN'S'	1999/00	High yielder, susceptible to moderately, susceptible to yellow and stem rusts, frost tolerant, high tillering capacity,
P_5 – Abola (HAR	BOW'S'/BUC'S'	1997	High yielder, susceptible to yellow and stem rusts, and very long spike and
P_6 – Galema (HAR-604)	4777(2)//FKN/GB/3/ PVN "S"	1995	High yielder, late maturing, high tillering capacity, and moderately resistance to
P_7 - Meda-Welabu (HAR-1480)	TL/3/FR/Th/Nar59*2/4/BOL'S'CM56569-/AP-1AP-5AP-2AP-OAP	1999/00	High yielder, has good resistance to yellow rust, susceptible to stem rust, long spike, plump seed
P_8 - Dure (HAR 1008)	BOW"S"/YD"s"/ZZ'S" CM62045-1Y-1M-1Y-1M-6Y-1M-OY	2001	Moderately high yielder, early maturing, white seeded and good for moisture stress area

Estimates of heterosis of F_1 hybrids over mid and better parent for traits that showed significant differences between genotypes were indicated in Table 3. Of the total crosses twenty four exhibited positive mid parent heterosis and twenty one better parent heterosis for grain yield per plant of which seven crosses manifested highly significant heterosis over their respective mid parents and one over better parents. Grain yield heterosis relative to mid and better parent ranged from -9 (Wabe × Sofumer and Dure × Meda-Welabu) to 63% (Dashen × Meda-Welabu) and -15 (Wabe × Sofumer) to 52% (Dashen × Meda-Welabu), respectively. In this study, the lowest and highest percent heterosis over better parent were recorded in the same hybrids that showed the trend in case of mid parent heterosis for grain yield.

Similarly, minimum and maximum economic heterosis of -27% and 44% were recorded in Dure × Meda-Welabu and Dashen × Meda-Welabu, respectively. This has direct practical value in plant breeding, in the sense that hybrids performed better than the best standard variety that would be of commercial importance. In this study, Sofumer was used as parent and to estimate economic heterosis.

Table 2. Mean squares due to genotypes, parents, crosses, and parent vs. crosses for 15 yield and yield related traits from the analysis of variance (ANOVA) in 8 × 8 half-diallel cross of bread wheat varieties at Sinana Agricultural Research Center in 2005

Traits	Mean Squares						
	Replications (df=2)	Genotypes (df=35)	Parents (df=7)	Hybrids (df=27)	Parents *vs.* Hybrids (df=1)	Error (df=70)	CV (%)
DH	15.45	74.38**	147.42**	35.86**	603.19**	5.62	2.99
DGF	18.78	51.19**	121.21**	29.43**	148.60**	7.55	2.05
DM	32.62	17.77**	17.19*	12.91ns	153.02**	8.18	1.98
PH	15.94	48.92**	52.89**	47.77**	52.30*	11.22	3.48
TPP	50.77	19.90*	23.79*	19.17*	12.60ns	11.09	19.88
FLA	59.92	62.02**	105.83**	45.70**	195.80**	12.73	7.48
SL	3.26	1.09**	2.76**	0.69*	0.12ns	0.39	5.09
SPS	302.12	149.53**	445.71**	77.70**	15.89ns	38.16	8.06
SPPS	0.69	1.85**	3.71**	1.44*	0.01ns	0.72	3.79
SPSP	1.15	0.34**	0.57**	0.28*	0.35ns	0.16	11.99
SWS	0.17	0.28**	0.24ns	0.20ns	2.69**	0.14	11.21
GYP	268.11	138.20**	30.17ns	142.67*	773.57**	71.58	20.26
BMP	2020.93	595.57ns	303.16ns	654.87*	1041.35ns	379.5	19.54
HI	5.20	28.07**	27.71**	21.54**	206.82**	8.92	7.18
TKW	6.06	35.82**	42.72**	23.24**	327.23**	5.73	5.76

*, **, ns, significant at P≤0.05,P≤0.01 and not significant, respectively. df = *degree of freedom,* DH= Days to heading, DGF = Days to grain filling, DM = Days to maturity, PH = Plant height (cm), TPP = Number of tillers per plant, FLA = Flag leaf area (cm2), SL = Spike length (cm), SPS = Number of seeds per spike, SPSP = Number of seeds per spikelet, SPPS = Number of spikelets per spike, SWS = Seed weight per spike (g), GYP = Grain yield per plant (g), BMP = Biomass per plant (g), HI = Harvest index (%), TKW = 1000 kernel weight (g)

The expression of grain yield heterosis above the mid and better parent was reported by several investigators in bread wheat (Prasad *et al.,* 1998). They reported grain yield to show maximum mid and better parent heterosis than any other character they studied. In the present study also maximum mid and better parent heterosis was observed for grain yield per plant followed by 1000-kernel weight, seeds weight per spike, harvest index and flag leaf area. Negative or lack of significant positive heterosis observed for grain yield and yield-associated trait in the present study is also in conformity with the findings of many previous studies in wheat. Solomon (2002) reported mid and better parent heterosis ranging from -19 to 116% and –31 to 99%, respectively. Hussian *et al. (* 2004) and Singh *et al. (*2004) reported mid and better parent heterosis of -5 to 127% and -22 to114% and -37 to 126% and -39 to 121% in that order. Pickett (1993) and Bori and Perenzin (1994) reported economic heterosis of 10% for wheat.

For 1000-kernel weight, 89% and 71% of the hybrids showed positive heterosis of with 17 (61%) and 11 (40%) crosses revealing highly significant positive heterosis over mid and better parent, respectively (Table 3). This indicates that these hybrids showed better performance than their respective parents in the desirable direction. For this trait, only two crosses, Wabe × Dashen and Wabe × Abola manifested negative and significant better parent heterosis of -12% and -13%, while Wabe × Sofumer recorded lowest mid parent heterotic value of -6.69%. This implies that Wabe contributed negatively to heterosis for 1000-kernel weight. Abola × Meda-Welabu and Dashen x Meda-Welabu crosses showed the maximum mid and better parent heterosis for 1000-kernel weight of 27% and 25%, respectively. These results are in agreement with those of Khan *et al.* (1995) and Singh *et al.* (2004), who reported considerable degree of positive and significant heterosis over better and mid-parent for 1000-kernel weight.

For harvest index, 89% and 64% of the crosses manifested positive mid and better parent heterosis (Table 3). Out of these, 10 and 3 crosses displayed highly significant positive over mid and better parent heterosis, respectively. Maximum mid and better parent heterosis of 29% and 28% were recorded for Abola × Dure, while the lowest heterotic values of -7% and -3% were obtained from Dure × Meda-Welabu crosses, respectively. This result is in conformity with that of Prasad *et al.* (1998) and Akhter *et al.* (2003), who reported mid and better parent heterosis values ranging from -31% to 89% and -16% to 11%, respectively. Singh *et al.* (2004) and Hussian *et al.* (2004) also reported considerable significant positive and negative mid and better parent heterosis for this trait.

For flag leaf area, seven and two crosses revealed significant over mid and better parent heterosis, respectively (Table 3). Maximum significant mid and better parent heterosis of 17% and 16% were obtained from Sofumer × Dure and the lowest mid and better parent heterosis values of -16% and -4% respectively were recorded in Abola × Dure. Similar results were also reported by Singh *et al.* (2004).

The number of fertile tillers/ plant is an important yield component and its positive heterosis is useful in wheat breeding program. In this study, however, 19 and 22 crosses exhibited negative mid and better parent heterosis, respectively (Table 3). Wabe × Mitike (-28%) and Galema × Dure (-32%) gave significant and lowest heterosis over mid and better parent, respectively, while highest but not significant mid and better parent heterosis values were in that order recorded in Dashen × Abola (16%) and Dashen × Sofumer (3%). Thus, this result indicated that hybrids failed to produce superior productive tillers than their respective parents and the result is in agreement with that of Farooq and Khaliq (2004), who reported negative and highly significant heterosis over better and mid-parent ranging from -33% to -6% and from -31% to -8%, respectively. However, the results obtained for this trait are not in conformity to that of Khan and Khan (1996) and Hussian *et al.* (2004), who reported fairly high number of hybrids that had positive and significant mid and better parent heterosis ranging from 4% to 62% and 1% to 46%, respectively.

Significantly negative heterosis for spike length over mid and better parent was exhibited by one and seven crosses, respectively (Table 3). Of the 28 hybrids, thirteen and three crosses recorded positive but not significant mid and better parent heterosis. Of these, Sofumer × Meda-Welabu and Mitike × Dashen recorded maximum mid and better parent heterosis of 6% and 2%, respectively. For spike length, Wabe × Galema and Galema × Dure exhibited the lowest mid and better parent heterosis of -7% and -13%, respectively. Similarly, Prasad *et al.* (1998) reported over mid and better parent heterosis of -24% to 13% and -25% to 17%, respectively.

Number of seeds/spike is an essential component of grain yield. However, all, except five of the hybrids showed negative heterosis over better parent, and out of these 8 crosses manifested highly significant heterosis (Table 3). None of the positive crosses showed significant heterosis over the better parent for number of seeds/ spike. Wabe × Dure cross recorded the highest and significant mid and better parent heterosis of 16% and 15%, respectively, while the lowest significant heterosis of -12% and -21% were found in Dashen × Sofumer and Mitike × Abola crosses, respectively. Farooq and Khaliq (2004) also reported negative heterosis in most of the crosses for tillers per plant. Contrary to these findings, however, Singh *et al.* (2004) reported positive and highly significant mid and better parent heterosis ranging from 1 to 31% and 1.00 to 28%, respectively. Larik *et al.* (1995) also reported the presence of considerable hybrid vigor in number of seeds/spike.

For number of spikelets/spike, none of the crosses displayed significant positive mid and better parent heterosis, whereas three crosses (Abola × Dure, Wabe × Abola and Dashen × Abola) exhibited significant negative over better parent heterosis with lowest heterotic values of -10%, -7% and -7% in that order (Table 3). Negative over mid and better parent heterosis for number of spikelets/spike was recorded in 15and 21 one crosses, respectively. The results obtained for spikelets/spike in this study are in agreement with the findings of Hussian *et al.* (2004), who reported negative and significant better parent heterosis in most of the hybrids they studied.

Similarly only two crosses, Mitike × Abola (-16.67%) and Galema × Dure (-18%) exhibited significant negative heterosis over better parent, while none of the crosses showed significant mid parent heterosis for number of seeds/spikelet (Table 3). Positive heterosis over better parent was recorded only in Wabe × Mitike, Wabe × Dashen, Wabe × Sofumer and Wabe × Dure with the heterotic value of 11%. For seed weight/spike, positive heterosis over mid and better parent was observed in twenty six and twenty one crosses, respectively. Of these, nine and four crosses exhibited significant heterotic values in that order for seed weight/spike. For this trait, Mitike × Meda-Welabu manifested the highest and significant mid and better parent heterosis of 28% and 25%, respectively. Generally, most of the hybrids failed to produce significant heterosis over better parents for the improvement of spike traits, which had direct impact on grain yield improvement.

Nine and twelve crosses showed significant plant height heterosis over mid-parent and over better parent, respectively (Table 3). Of these, only one cross exhibited significant reduced plant height. For this trait, Abola × Dure and Abola × Galema revealed the highest mid and better parent heterosis of 9% and 12%, respectively, while Wabe × Dashen exhibited the lowest and equivalent mid and better parent heterosis of -7%. This indicates that dwarfness, which is a desiered character in bread wheat improvement, was favored in the latter hybrid. The negative estimates of mid and better parent heterosis for plant height are preferred in wheat breeding in view of tolerance to lodging and response to fertilizer. These results are in agreement with earlier research findings in which positive significant heterosis for plant height were reported in most of the hybrids, and this contardicts with the general breeding objective of reducing the straw length of wheat (Khan and Khan, 1996; Necdet, 2001; Oettler *et al.,* 2003). Contrary to these results, Desphande and Nayeem (1999) reported negative and significant mid and better parent heterosis for plant height in most of the hybrids they studied.

For days to head, twenty two and twelve crosses showed negative and highly significant mid and better parent heterosis, respectively (Table 3). This indicates that heterosis resulted in early heading which is the desired character in bread wheat improvement. The mid and better parent days to head heterosis ranged from -15% (Abola × Galema) to -1% (Dure × Meda-Welabu) and -14% (Abola × Dure) to 9% (Sofumer × Dure and Galema x Dure), respectively. The tendency of a negative heterosis for days to heading may be a favorable trait for breeding, since earlier heading and thus earlier maturity with acceptable yield is a desirable aim in applied breeding. Necdet (2001), Oettler *et al.* (2003) and Singh *et al.* (2004) also reported similar results.

For grain filling, eight and twenty crosses exhibited positive and significant over mid and better parent heterosis, respectively (Table 3). The maximum significant heterosis of 23% and 3% over mid and better parent were obtained from Abola × Galema, respectively. Generally, 82% and 100% of the hybrids manifested positive mid and better parent heterosis, respectively, indicating early heading may not result into early grain filling and also hybrids failed to improve this trait in the present study. Thus, early heading and maturity may not considered as desirable characters in plant breeding unless resulting early grain filling and high grain yield. These results are in disagreement with Singh *et al.* (2004), who reported negative and significant mid and better parent heterosis for days to grain filling in most of the hybrids they studied.

For days to mature, even thought twenty four and nineteen crosses manifested negative heterosis, only eight and two crosses revealed significant mid and better parent heterosis in the desired negative direction for the improvement of the trait (Table 3). Accordingly, the lowest and highly significant negative mid and better parent heterotic values of -5% and -4% were obtained from Abola × Dure and Wabe × Abola crosses, respectively, indicating earliness was favored in these hybrids than their respective parents. This result is in agreement with Khan and Khan (1996) and Akhter *et al.* (2003), who reported negative and significant mid-parent heterosis for maturity in some crosses they studied.

Table 3. Percentage heterosis over mid parent (MPH) and better parent (BPH) for yield and yield related traits in 8 × 8 half-diallel cross of bread wheat at Sinana Agricultural Research Center in 2005

Cross	DH		DGF		DM		PH		TPP	
	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH
$P_1 \times P_2$	-5.73*	-8.73**	8.53*	7.00*	-0.94	-2.21	5.61	1.89	-28.30	-28.30*
$P_1 \times P_3$	-5.86**	-6.59**	5.43	2.05	-1.43	-3.15*	-6.80*	-7.42**	-10.00	-4.42
$P_1 \times P_4$	-9.62**	-9.96**	10.32*	5.04	-2.14	-4.07**	1.40	1.01	-9.09	-7.41
$P_1 \times P_5$	-8.47**	-10.69**	9.82*	5.60	-4.36**	-4.36**	3.44	-0.04	-7.55	5.38
$P_1 \times P_6$	-5.77*	-8.41**	17.25**	5.92	-1.19	-3.04*	1.40	-0.48	-18.18	-9.24
$P_1 \times P_7$	-5.71*	-5.53*	5.12	-4.15	-3.09	-4.91**	5.24	3.32	-11.32	-4.08
$P_1 \times P_8$	0.42	-3.39	0.00	-0.28	0	-2.11	5.58	3.78	0.00	7.07
$P_2 \times P_3$	-4.97*	-7.20**	7.27	2.31	-2.85	-3.31*	-2.01	-4.81*	-16.67	-11.50
$P_2 \times P_4$	-5.32*	-8.70**	12.42**	5.85	-2.60	-2.83	5.50*	2.53	-10.98	-9.26
$P_2 \times P_5$	-2.86	-8.32**	16.56**	10.47**	0.47	-0.81	7.35*	-0.03	-28.79*	-5.38
$P_2 \times P_6$	2.04	-7.90**	22.06**	8.59*	-0.95	-1.54	5.27	3.52	-26.42	-21.01
$P_2 \times P_7$	2.85	-4.85*	7.74*	-0.26	-2.14	-2.72	10.26*	4.37	-15.09	-20.41
$P_2 \times P_8$	-4.98*	-5.57**	13.00**	11.73**	2.63	1.78	11.03*	5.23*	3.33	-9.09
$P_3 \times P_4$	-3.12	-4.25*	6.21	4.91	-0.47	-0.71	4.90	-5.20*	3.33	7.83
$P_3 \times P_5$	3.12	-6.24**	7.36	6.71	0.47	-1.28	5.55	1.30	-3.33	16.00
$P_3 \times P_6$	-5.46*	-8.85**	15.86**	8.39*	-2.38	-2.50	4.46	-6.60**	-12.12	-7.94
$P_3 \times P_7$	5.71*	-3.86	11.51**	-1.87	-2.85	-2.97*	7.64*	4.96	-11.67	0.95
$P_3 \times P_8$	0	-3.02	5.45	1.75	-0.75	-1.07	-.021	-2.59	1.67	15.09
$P_4 \times P_5$	-6.11**	-8.04**	6.83	6.17	-1.18	-2.68	3.67	-0.22	-9.09	5.26
$P_4 \times P_6$	0.38	-2.05	11.04*	5.23	0.95	0.59	4.07	2.50	1.52	10.74
$P_4 \times P_7$	8.57**	-3.39	13.66**	-1.35	-2.14	-2.49	11.41*	8.96**	-12.73	-4.00
$P_4 \times P_8$	-3.3	-7.36**	10.55*	5.33	-0.96	-2.26	5.85	3.59	1.82	10.89
$P_5 \times P_6$	-14.29**	-14.60**	30.55**	22.73**	0.71	-1.17	12.16*	6.15*	-22.73	-3.77
$P_5 \times P_7$	3.81	-9.73**	15.34**	0.80	-3.33*	-5.14**	10.7**	9.01**	-13.33	-8.24
$P_5 \times P_8$	-2.07	-8.17**	12.27**	7.65*	0.24	-1.87	3.75	2.03	-8.70	-2.33
$P_6 \times P_7$	8.57**	-5.98**	28.27**	4.79	-1.43	-1.43	7.42**	3.47	-31.82*	-18.92
$P_6 \times P_8$	2.08	-4.65**	21.39**	9.32*	0.96	0.72	7.71*	3.64	-24.24	-10.71
$P_7 \times P_8$	6.67*	-0.67	13**	3.36	1.43	1.19	6.6*	6.50*	-23.91	-23.08
Mean heterosis	**-6.75**		**4.91**		**-2.02**		**1.76**		**-4.72**	
SE	**1.94**	**1.68**	**2.24**	**1.94**	**2.34**	**2.02**	**2.73**	**2.37**	**2.72**	**2.35**

Table 3. Continued…

Cross	FLA		SL		SPS		SPPS		SPSP	
	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH	BPH	MPH
$P_1 \times P_2$	-7.59	5.73	-2.05	2.27	7.21	10.95	-2.99	-2.26	11.11	17.65
$P_1 \times P_3$	-8.30	-1.03	-4.35	1.91	1.32	9.26	0.00	1.49	11.11	17.65
$P_1 \times P_4$	-10.78	3.10	-8.18*	-2.71	0.00	5.37	-4.29	-1.47	11.11	17.65
$P_1 \times P_5$	-0.13	0.64	-3.58	-2.71	-20.13**	-1.99	-6.76*	-1.43	-8.33	10.00
$P_1 \times P_6$	3.57	5.15	-9.07*	-7.13*	-0.41	10.34	-2.94	-1.49	0.00	15.79
$P_1 \times P_7$	-5.62	8.27	-7.16	1.40	15.38	15.68*	-1.52.	0.78	11.11	17.65
$P_1 \times P_8$	-3.77	2.27	-6.91	-6.55	-0.43	8.02	0.00	0.76	0.00	11.11
$P_2 \times P_3$	-4.19	2.11	1.68	3.85	3.08	7.59	1.47	2.22	0.00	0.00
$P_2 \times P_4$	6.57	7.81	-1.40	0.14	-1.85	-0.00	-2.86	-0.73	0.00	0.00
$P_2 \times P_5$	-7.58	5.05	-2.60	0.81	-20.45**	-5.04	-5.41	-0.71	-16.67*	-4.76
$P_2 \times P_6$	-10.46	1.11	-11.03**	-5.22	-4.15	2.90	-1.47	-0.74	-9.09	0.00
$P_2 \times P_7$	5.97	6.29	-1.40	3.37	6.73	10.17	-2.99	0.00	11.11	11.11
$P_2 \times P_8$	6.51	15.27*	-0.77	3.22	-0.87	4.11	1.49	3.03	-10.00	-5.26
$P_3 \times P_4$	1.80	9.67	-2.88	-2.32	-14.10*	-11.96*	-4.76	-2.90	0.00	0.00
$P_3 \times P_5$	1.17	8.40	-3.91	1.51	-19.16**	-6.92	-6.76*	-2.82	-8.33	4.76
$P_3 \times P_6$	3.75	10.40	-9.07*	-1.20	-4.56	-1.71	-1.47	-1.47	-9.09	0.00
$P_3 \times P_7$	0.30	7.19	-3.21	-0.60	-3.96	3.32	-5.88	-2.29	0.00	0.00
$P_3 \times P_8$	10.35	12.17*	-5.15	0.68	-2.17	-1.53	-1.47	0.75	0.00	5.26
$P_4 \times P_5$	-6.87	6.92	-7.81	-3.15	-20.13**	-6.11	-4.05	-1.39	-8.33	4.76
$P_4 \times P_6$	-3.55	10.02	-8.33*	-0.93	-4.15	1.09	0.00	1.45	-9.09	0.00
$P_4 \times P_7$	15.71*	16.71*	0.29	3.57	-6.9	4-.19	-5.71	-0.75	0.00	0.00
$P_4 \times P_8$	4.12	13.89*	0.26	5.85	-2.17	0.90	1.43	5.19	-10.00	-5.26
$P_5 \times P_6$	5.83	6.63	-6.37	-3.54	-16.56**	-6.38	-4.05	0.00	0.00	4.35
$P_5 \times P_7$	-15.88**	-4.14	-8.33*	-0.71	-20.13**	-2.19	-9.46**	-2.19	-8.33	4.76
$P_5 \times P_8$	7.13	13.03*	-0.77	-0.26	-14.94**	-2.60	-4.05	2.16	-8.33	0.00
$P_6 \times P_7$	-1.32	11.73*	-12.99**	-3.14	-8.30	1.30	-2.94	0.76	-18.18**	-10.00
$P_6 \times P_8$	6.58	11.6*	-6.86	-4.52	-2.90	-0.64	-4.41	-2.26	9.09	14.29
$P_7 \times P_8$	-0.07	8.44	-6.96	1.26	-3.04	4.94	3.08	4.69	-10.00	-5.26
Mean heterosis	**7.18**		**-0.62**		**1.22**		**-0.08**		**4.27**	
SE	**2.91**	**2.52**	**0.51**	**0.44**	**5.04**	**4.37**	**0.69**	**0.60**	**0.32**	**0.28**

Table 3. *Continued…*

Cross	SWS		GYP			HI		TKW	
	BPH	MPH	BPH	MPH	SH	BPH	MPH	BPH	MPH
$P_1 \times P_2$	1.05	7.26	-4.48	-1.46	-17.60	5.86	13.12*	-6.29	1.08
$P_1 \times P_3$	-5.26	-2.70	-4.65	-0.04	-9.39	1.94	9.23	-11.81*	-3.36
$P_1 \times P_4$	-1.03	0.00	-15.22	-8.98	-15.23	-5.36	5.32	-7.98	-6.69
$P_1 \times P_5$	-4.63	1.48	8.23	9.73	-6.62	-0.59	6.56	-13.04**	-3.24
$P_1 \times P_6$	3.09	4.17	13.86	15.85	1.73	22.11**	23.75**	-5.52	6.39
$P_1 \times P_7$	9.47	17.51	6.12	11.53	-8.45	-5.19	1.27	0.15	1.71
$P_1 \times P_8$	15.79	20.88*	24.77	28.05	7.64	2.36	13.20*	0.77	8.60*
$P_2 \times P_3$	13.33	17.24	1.08	9.14	-3.95	-2.11	-1.82	2.33	4.11
$P_2 \times P_4$	-4.12	2.76	-6.23	3.62	-6.25	0.70	5.19	-1.26	5.12
$P_2 \times P_5$	-4.63	7.29	9.87	11.81	-7.81	2.11	2.46	5.57	9.19
$P_2 \times P_6$	2.06	9.39	-1.24	3.61	-11.76	3.65	9.37	6.64	11.76*
$P_2 \times P_7$	22.62*	24.10*	6.33	8.39	-13.89	8.07	8.12	6.33	13.04**
$P_2 \times P_8$	25.29	27.49*	39.69	40.44	14.34	-3.70	-0.08	15.23**	5.34**
$P_3 \times P_4$	-8.25	-4.81	9.70	12.49	9.69	-0.39	3.76	-2.84	5.12
$P_3 \times P_5$	-0.93	8.08	28.30	36.27	21.90	10.63	10.68*	14.31*	16.26**
$P_3 \times P_6$	6.19	10.16	11.29	14.71	5.75	12.08	18.59**	18.40**	22.03**
$P_3 \times P_7$	15.56	20.93*	20.75	32.69	14.74	9.71	10.08	5.85	14.36**
$P_3 \times P_8$	23.33	25.42*	51.87**	63.17	44.31	8.51	12.27*	24.55**	26.82**
$P_4 \times P_5$	0.00	5.37	0.55	9.35	0.5	2.80	7.04	-2.21	7.45
$P_4 \times P_6$	8.25	8.25	28.39	35.61	28.38	3.11	13.37*	3.47	15.09**
$P_4 \times P_7$	1.03	9.50	-7.10	4.43	-7.09	-1.01	3.45	16.72**	16.90**
$P_4 \times P_8$	8.25	14.13	27.60	40.33	27.58	-0.31	0.39	7.41	14.26**
$P_5 \times P_6$	12.96	19.02*	36.10	40.37	21.59	1.01	6.92	21.54**	23.20**
$P_5 \times P_7$	2.78	16.84*	7.33	11.31	-9.94	28.19**	28.67**	1.90	11.81**
$P_5 \times P_8$	13.89	26.15*	31.95	33.59	10.72	7.64	11.33*	22.24**	27.27**
$P_6 \times P_7$	4.12	12.85	13.24	20.98	1.18	12.41*	18.57**	9.34*	21.44**
$P_6 \times P_8$	9.28	15.22	6.44	11.10	-4.89	-2.92	6.07	12.01*	17.48**
$P_7 \times P_8$	24.14	27.81*	-11.18	-8.98	-	-6.93	-3.39	5.85	12.44**
Mean heterosis	**12.31**		**17.52**			**8.53**		**10.93**	
SE	**0.31**	**0.27**	**6.91**	**5.98**	**6.91**	**2.44**	**2.11**	**1.96**	**1.69**

*, ** significant at P≤0.05 and P≤0.01,.respectively, SE = Standard error, BHP = Percent better parent heterosis, MPH = Percent mid-parent heterosis, SH = percent standard heterosis, DH = Days to head, DGF = Days to grain filling, DM = Days to mature, PH = Plant height (cm) TPP = Number of tillers per plant, FLA = Flag leaf area (cm^2), SL = Spike length (cm), SPS = Number of seeds per spike, SPPS = Number of spikelets per spike, SPSP = Number of seeds per spikelet, SWS = Seed weight per spikelet (g), GYP = Grain yield per plant (g), HI = Harvest index (%), TKW = 1000 kernel weight (g).The standard variety Sofumer was used as parent and to estimate standard heterosis.

Conclusions

In the present study, most of the crosses displayed significant and maximum mid and better parent heterotic effects for grain yield and important yield contributing traits. There were cross combinations having many desirable traits that could not be obtained from a best parent. This showed the possibility of exploiting the hybrid vigor for the improvement of grain yield and its components in bread wheat.

Both additive and non-additive gene actions played a role in the inheritance of grain yield per plant, 1000-kernal weight, harvest index, days to head and to mature, days to grain filling, and plant height. Only additive gene action plays important role in controlling the inheritance of the remaining traits. The presence of both additive and non-additive variances suggested the utilization of certain genotypes and promising crosses which can be utilized in future breeding work. These crosses might yield desirable transgressive segregants from which potential homozygous lines can be selected in subsequent generations, and also indicated the possibility of exploiting these crosses in commercial hybrid production.

Maximum over mid and better parent as well as economic heterosis for grain yield were recorded in Dashen × Meda-Welabu hybrid with corresponding values of 63%, 52% and 44%, respectively. This cross also had significant and positive mid and better parent heterosis for flag leaf area, seed weight per spike, harvest index and 1000-kernel weight followed by Abola × Meda-Welabu, Mitike × Meda-Welabu, Sofumer × Dure and Abola × Dure.

Furthermore, maximum percentage decrease in plant height over better and mid-parents was displayed by the cross Wabe × Dashen. The negative heterosis observed for plant height was in the desired direction as dwarfness is a desirable character for responsiveness to fertilizer and resistance to lodging. Even though, almost all crosses exhibited maximum negative heterosis for days to head and mature, they did not result in early grain filling. Highly significant negative mid and better parent heterosis was recorded in Abola × Galema for days to head and in Abola × Dure and Wabe × Abola for days to mature, respectively. However, crosses failed to be heterotic for tillers per plant, spike length, seeds per spike and spikelets per spike in the desirable direction as considerable number of crosses recorded negative mid and better parent heterosis for these traits.

The presence of remarkable heterosis in these crosses also reveals ample scope for exploitation of hybrid vigor for commercial production along with the availability of appropriate male sterility factors such as CHAs, and information on the transfer of pollen for advancement of grain yield in bread wheat.

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