

Original Research Article

Mid-parent and better parent heterosis study on highland quality protein maize hybrids in Ethiopia

Abstract

Determination of heterosis in maize hybrids is necessary for the identification of superior F1 hybrids for breeding programs. Therefore, this study was conducted to estimate the amount of mid parent (MPH) and better parent heterosis (BPH) for grain yield, yield-related, agronomic, and morphological traits. Hybrid development from fixed inbred lines is one of the strategies for the improvement of maize production. The national average maize yield in Ethiopia is low and thus, selection of promising germplasm, knowledge of combining ability, and heterotic grouping are prerequisites to developing high-yielding maize varieties. Forty-two Quality Protein Maize (QPM) crosses (21 inbred lines each crossed with two testers) along with three popular standard hybrids were evaluated in two replications using alpha lattice during the 2017 cropping season at Ambo, Arsi-Negele, and Kulumsa. ~~The other set of parental~~ Parental line trials ~~consisted~~ ~~consisting~~ of 21 lines, two testers, and one ~~Conventional~~ ~~conventional~~ Maize maize (CM) parent check (FS67) ~~was~~ ~~were~~ ~~evaluated~~ ~~established~~ in two replications laid out using RCBD side by side with the hybrid ~~trial~~ ~~trials~~ at Ambo and Arsi-Negele. ~~The objectives of this study were to estimate mid and better parent heterosis for grain yield and other agronomic and morphological characteristics.~~ At Ambo, almost all crosses showed positive and significant BPH except three crosses (L1xT1, L4xT1, and L13xT1). The maximum BPH (276.2%) was obtained from L17xT2. Similarly, at Arsi-Negele, most of the crosses had positive and significant BPH except for five crosses for BPH which are showing negative heterosis. The highest BPH was obtained from L10xT2 at Arsi-Negele. Generally, the high ~~yielder~~ ~~yielding~~ crosses had reasonable BPH. Based on the result promising crosses and lines were identified. Some of the crosses showed good performance in terms of heterosis against the mid parent and better parent: L17xT2 (329.88% MPH, 276.18% BPH), L3xT2 (320.05% MPH, 273.91% BPH), and L19xT2 (2802.57% MPH, 247.31% BPH) at Ambo, whereas at Arsi-Negele L10xT2 (128.38% MPH, 111.27% BPH) and L11xT2 (115.33% MPH, 98.00% BPH) showed the higher heterosis compared with the mid ~~of the~~ parent and better parent. ~~Some other crosses~~ ~~Crosses that showed better best yield performance considering the selection method these were:~~ L8xT2, L7xT1, L8xT1, L19xT1, L6xT2, and L18xT1. These crosses should be reconsidered ~~in~~ ~~breeding materials~~ for further evaluation ~~in the maize breeding program for further work~~ and possible release.

Keywords: Better parent heterosis, mid parent heterosis, quality protein maize

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Introduction

Maize breeders need to determine the genetic diversity of inbreeds because it facilitates the identification of those that would produce crosses possessing high levels of heterosis (Badu-Apraku et al., 2013). The information facilitates the development of high-yielding hybrids without testing all possible hybrid combinations among the potential parents available in a hybrid program. The phenomenon of heterosis was defined by Shull (1952) as “the interpretation of increased vigor, size, fruitfulness, speed of development, resistance to disease and insect pests, or climatic vigor of any kind manifested by crossbred organisms as compared with corresponding inbreeds, as the specific results of unlikeness in the constitution of the uniting parental gametes”. Falconer and Mackay (1996) defined it as the difference between the hybrid value for one trait and the mean value of the two parents for the same trait. According to Miranda (1999), heterosis is the genetic expression of the superiority of a hybrid over its parents. Three types of estimation of heterosis are reported in the literature; namely, mid-parent or average heterosis, which is the increased vigor of the F1 over the mean of two parents; and high-parent or better-parent heterosis, which is the increased vigor of F1 over the better-parent (Jinks, 1983) and standard heterosis (Birhanu, 2009; Beyene, 2016 and Abiy, 2017). Heterosis is usually considered synonymous with hybrid vigor (Stuber, 1994). Heterosis, or hybrid vigor, refers to the phenomenon in which the offspring of two inbred parents exhibit phenotypic performance beyond the mid-parent or better parent used to generate the hybrid (Li *et al.*, 2018). Grain yield in maize is expected to exhibit heterosis as a consequence of partial to complete dominance of genes controlling the trait (Miranda, 1999). Three major ~~dominance~~ theories, ~~such as viz.~~ dominance, overdominance, and epistasis, ~~as the main theories~~ have been put forward to explain the mechanisms underlying the phenomena of heterosis. However, it is generally accepted that heterosis, to a large extent, is due to overdominance gene action (Singh, 2005). On the other hand, the expression of heterosis also depends on the level of genetic divergence between parents; i.e., differences in allele frequencies are necessary for the expression of heterosis. For that reason, the expression of heterosis is expected to be lower in crosses between broad base open-pollinated populations (Miranda, 1999).

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Heterosis is important in maize breeding and depends on the level of dominance and differences in gene frequency (Falconer & Mackay, 1996). The manifestation of heterosis depends on the genetic divergence of the two parental varieties (Hallauer; Miranda, 1988). Low grain yield heterosis were observed for crosses among genetically similar germplasms and for crosses among broad genetic base germplasms (Vasal *et al.*, 1993b). Higher levels of heterosis were seen with increased divergence within a certain range, but that heterosis declined in extremely divergent crosses (Prasad and Singh, 1986). Genetic divergence of the parents is inferred from the heterotic patterns manifested in a series of crosses (Hallauer and Miranda, 1988; Miranda, 1999).

Heterosis in maize has been investigated extensively. Hallauer and Miranda (1988) reported that mid-parent heterosis ranged from -3.6% to 72.0%, while high-parent heterosis ranged from -9.9% to 43.0% for maize. Maize has attained the highest levels of production in the temperate areas of the world employing modern agricultural techniques. Surprisingly, the magnitude of heterosis has not been changed during the hybrid era in tropical areas compared to temperate because, in most tropical countries, maize is grown as a rainfed crop in the hot season, under varying conditions of moisture, generally subject to periodic and erratic drought and/or excess of water at different stages of the growth cycle, without effective weed and pest control, and usually under low-fertility conditions. In general, it is grown as a subsistence crop, with very low levels of management and little input (Duvick, 1999), even though mean commercial maize grain yield has substantially increased during this time (Troyer, 1990). Birhanu (2009) reported an estimate of heterosis ~~ranged~~ ranging from 28.95 to 202.34% over mid-parent and 16.97 to 175.46 % over the better parent grain yield from crosses generated from LxT mating design.

The development of hybrid varieties has played a great role in improving food and feed supplies. Food and feed supplies would unquestionably be greatly reduced if only nonhybrids were available to the producer (Stuber, 1994b). Hybrid varieties are the first filial generations (F1) from crosses between two or more pure lines, inbreds, open-pollinated varieties, clones, or other populations that are genetically dissimilar (Singh, 2005). The development of the maize ~~hybrid~~ hybrids began in the early 1900s (Shull, 1908; East, 1908; Hallauer *et al.*, 1988; Smith *et al.*, 2017). According to Singh (2005), most of the

commercial hybrid varieties are F1's from two or more inbreds. The success of hybrid maize development depends on the capacity of the breeding program to rapidly develop lines that combine well and identify superior heterotic combinations to maximize the vigor of the hybrid (Kim and Ajala, 1996). An inbred [line](#) is a nearly homozygous line obtained through continuous inbreeding of cross-pollinated species with selection accompanying inbreeding (Singh, 2005).

Similar to the CM, QPM hybrids proved to yield more grains than open-pollinated QPM cultivars, but the mean grain yield does not differ for a single, three-way, and double-cross QPM hybrid (Pixley and Bjarnason, 2002). The broader genetic constitution of three-way and double-cross hybrids might have helped them to buffer the extreme environmental diversity of the environment better than single crosses (Pixley and Bjarnason, 2002). In a different trial, Pixley and Bjarnason (1993) also observed a QPM hybrid exceeding a normal endosperm hybrid check by an average of 14% for grain yield, and 48% for [Trp](#) concentration in grains, and 60% for Trp concentration in protein. Birhanu (2009) evaluated tester crosses of white QPM and CM inbred lines and reported higher grain yield, heterosis overall, mid and better parents, and some of the crosses over the standard checks. Similarly, Beyene (2016) reported higher heterosis in diallel crosses evaluated at Bako, Ethiopia. In this study, the aim was to estimate better parent and mid-parent heterosis of the crosses.

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2. Materials and methods

2.1. Study sites

The study was conducted at [two locations](#) in the highland agroecology of Ethiopia, including; Ambo and Arsi-Negele Agriculture Research Centers during the 2017 main cropping season.

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Table 1. Latitude, longitude, altitude ([masl](#)), long-term annual rainfall (mm), maximum temperature (MaxT) (°C), minimum temperature (MinT) (°C), soil type, and soil pH of the study sites.

Site	Latitude	Longitude	Altitude (m)	Annual rainfall (mm)	MaxT °C	MinT °C	Soil type	pH
Ambo	8° 57' N	38° 7' E	2225	1115	25.5	11.7	Heavy clay	7.8
A.Negele	7° 19' N	38° 39' E	1960	886	26.0	9.1	clay loam	6.5-7.5

2.2. Experimental materials

From the 21 inbred lines and two testers, 42 F1 hybrids were generated at Ambo Highland Maize Breeding Program (AHMBP). The 42 F1 hybrids along with three standard checks: one QPM (AMH852Q) and two CM (Jibat and AMH853), designated as hybrid checks, were tested.

2.3. Experimental Design and Crop Husbandry

The hybrid trial was laid out using an alpha lattice design consisting of one-row plots replicated twice. RCBD was used for testing the performance of the parental lines. For the hybrid trial, each plot consisted of a 5.25 m long row with 0.75 and 0.25 cm interrow, and intra-row spacing. For the inbred line trial, each plot consisted of a 3.75 m long row with 0.75 and 0.25 cm interrow, and intra-row spacing. The plot was hand-planted with two seeds per hill and later was thinned to one plant per hill to attain the final plant density of 53,333 plants per hectare. Diammonium phosphate (DAP) fertilizer was applied at planting at the rate of 150 kg ha⁻¹ while 200 kg ha⁻¹ of urea was applied in partition 1/3 at planting, 1/3 at knee height, and 1/3 at flowering at Ambo. At Arsi-Negele, 100 kg ha⁻¹ DAP and 150 kg ha⁻¹ urea fertilizer were applied based on the site recommendation following the same time of application mentioned for Ambo above. The rest of the field management practices are applied based on recommendations for each site.

2.4. Data Collected

Data on morphological, phenological, yield and related yield traits were recorded and presented as follows. Days to tasseling (DT), Days to silking (DS), Anthesis, silking interval (ASI), Days to maturity (MD), Plant aspect (PAS), Disease score: turcicum leaf blight (TLB), and common leaf rust (CLR), Ear aspect (EAS), Number of ears per plant (EPP), Kernel Modification (MOD) Grain yield (GY), Number of leaves per plant (LFPP), Number

Comment [CM5]: Do not start a sentence with an abbreviation

Comment [CM6]: For the following traits; CLR = Common Leaf Rust (1-5 scoring), TLB = Turcicum Leaf Blight (1-5 scoring), EAS = Ear Aspect (1-5 scoring), PAS = Plant Aspect (1-5 scoring), you should inform the readers what 1 and 5 mean. This is important since the scoring scale affects the direction of desirable heterosis

of leaves above upper most ear per plant (LFAE), Number of leaves bellow upper most ear per plant (LFBE), Leaf angle (LANG), Leaf length (LL), Leaf width (LW), Leaf area (LFAR), Plant height (PH), ear height (EH), ear length (EL), Ear diameter (ED), Number of kernel rows (NKR), Number of kernels per row (KPR), Thousand seed weight (TSW), Biomass (BIOM) and Harvest index (HI) and Grain Yield (GY).

Table 2. List of QPM parental inbred lines used to generate single-cross hybrids using line x tester mating design and standard checks.

Code	Pedigree	Tryptophan (%)
L1	[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5-1-B-B-B-#	0.056
L2	[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5-2-6-B-B-#	0.062
L3	(CLQRCWQ50/CML312SR)-2-2-1-BB-1-B-B-B-#	0.077
L4	[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5-1-B-B-B-#	0.077
L5	([NAW5867/P49SR(S2#)/NAW5867] F#-48-2-2-B*/CML511) F2)-B-B-39-1-B-#	0.066
L6	(CML197/(CML197/[(CLQRCWQ50/CML312SR)-2-2-1-BB/CML197]-BB) F2)-B-B-9-1-B-#	0.063
L7	(CML197/(CML197/[(CLQRCWQ50/CML312SR)-2-2-1-BB/CML197]-BB) F2)-B-B-35-2-B-#	0.063
L8	(CML197/(CML197/[(CLQRCWQ50/CML312SR)-2-2-1-BB/CML197]-BB) F2)-B-B-44-2-B-#	0.069
L9	(CML197/(CML197/(CLQRCWQ50/CML312SR)-2-2-1-BBB) F2)-B-B-18-2-B-#	0.086
L10	(CML197/(CML197/(CLQRCWQ50/CML312SR)-2-2-1-BBB) F2)-B-B-30-1-B-#	0.080
L11	(CML197/(CML197/(CLQRCWQ50/CML312SR)-2-2-1-BBB) F2)-B-B-35-2-B-#	0.109
L12	(CML395/(CML395/[NAW5867/P49SR(S2#)/NAW5867] F#-48-2-2-B*4) F2)-B-B-30-1-B-#	0.076
L13	[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5-2-6-B-B-#	0.060
L14	(CML395/(CML395/[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5) F2)-B-B-46-1-B-#	0.063
L15	(CML395/(CML395/[CML144/[CML144/CML395] F2-8sx]-1-2-3-2-B*5) F2)-B-B-50-1-B-#	0.062
L16	(CML395/(CML395/S99TLWQ-B-8-1-B*4-1-B) F2)-B-B-10-3-B-#	0.061
L17	(CML395/(CML395/S99TLWQ-B-8-1-B*4-1-B) F2)-B-B-14-1-B-#	0.073
L18	(CML395/(CML395/S99TLWQ-B-8-1-B*4-1-B) F2)-B-B-29-1-B-#	0.060
L19	(CML395/(CML395/CML511) F2)-B-B-7-2-B-#	0.060
L20	(CML395/(CML395/CML511) F2)-B-B-11-2-B-#	0.066
L21	(CML395/(CML395/CML511) F2)-B-B-37-1-B-#	0.061
T1	CML144	
T2	CML159	

Better-parent heterosis (BPH), mid-parent heterosis (MPH), and standard heterosis in percent were calculated for those parameters that showed significant differences among crosses following the method suggested by Falconer and Mackay (1996).

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In addition, MPH and BPH were done only for those traits that had significant MS for cross vs parents and significant MS between crosses as criteria of selection. To consider traits for combined analysis for MPH and BPH, the cross \times location for interaction should be nonsignificant as an additional criterion. For traits that had significant cross \times location interaction, the traits were considered for MPH and BPH for each location.

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$$\text{Mid-parent heterosis (MPH)} = \frac{F1 - MPV}{MPV} \times 100$$

$$\text{Better parent heterosis (BPH)} = \frac{F1 - BPV}{BPV} \times 100$$

Where $F1$ = mean value of the cross, MPV = the mean value of the two parents (lines and tester), BPV = the mean value of the better parent

The test of significance of heterosis (the numerator in each equation before multiplying by 100) was determined using the t-test. The critical differences (CD) for testing the significance of MPH, BPH, and SH were calculated using the following formulas:

Critical differences for heterosis over MPH:

$$CD (\text{MPH}) = \sqrt{3MSe/2r} \times t$$

Critical difference for heterosis over better parent or standard heterosis (SH)

$$CD (\text{BPH}) = \sqrt{2MSe/r} \times t$$

Where MSe is the error MS, r is the number of replications, and t is the table value at 0.05, 0.01 and 0.001, CD is Critical Difference, MP is mid-parent, BP is the better parent, t -value in the formula is not included in the square root. The absolute values of the relevant heterosis were tested against this critical difference.

3. Result and discussion

3.1. Analysis of Variance

The combined analysis of ~~Variance~~ variance (ANOVA) for the hybrid showed ~~a~~ highly significant ~~difference~~ differences among crosses for Grain Yield (GY), Days to Tasseling (DT), Day to Silking, (DS) Plant Height (PH), Anthesis Silking Interval (ASI), Days to Maturity (DM), Plant Height (PH, Ear Height (EH), Ear Aspect (EA). Plant Aspect (PA), Ear Per Plant (EPP), Ear Length (EL), Kernel Per Row (KPR), Number of Kernel Row per plant (NKR), Ear Diameter (ED), Thousand Seed Weight (TSW), Biomass yield (BIOM), Number of Leaves Per Plant (LFPP), and Number of Leaf Bellow Ear (LFBE) in combined analysis ~~Whereas~~ whereas, the difference between ~~cross~~ crosses was non-significant ~~for~~ Kernel modification (MOD), Common Leaf Rust (CLR), Turcicum Leaf Blight (TLB), Harvest Index (HI), Leaf Angle (LANG), Leaf Length (LL), Leaf Width (LW), Leaf Area (LEAR), and Number of Leaf above Ear (LFAE) (Table 4). A similar result was also reported by (Birhanu, 2009). The ~~cross~~ mean ~~square~~ squares ~~showed~~ were highly significant ($P < 0.01$) ~~difference~~ among locations for all traits except GY and LFPP (Table 4). ~~For~~ The cross*location ~~effect~~ the difference was highly significant for GY, MD, PH, EH, TLB, and PAS, also significant at $p < 0.05$ level for LFPP and LFBE ~~whereas~~ but non- significant for the rest of the traits ~~the~~ mean square difference was non- significant (Table 4).

At both locations the mean square of the cross was significant for GY, DT, ASI, MD, PH, EH, EPP, EL, KPR, ED, TSW, and BIOM but again at both locations the difference was nonsignificant for CLR, NKR, LANG, LW, and LEAR (Table 3). The mean square was significant for DS, MOD, EAS, PAS, LL, LFPP, LFAE, and LFBE whereas, the difference was nonsignificant for TLB and HI only at Ambo. The mean square of the cross for TLB and HI, the difference among crosses was significant only for Arsi-Negele and nonsignificant for DS, MOD, EAS, PAS, LL, LFPP, LFAE, and LFBE (Table 3).

Table 3. Mean square of a table for crosses tested at each location in 2017.

Location	Mean Square											
Ambo	SV	DF	GY	DT	DS	ASI	MD	PH	EH	Mod	CLR	
	rep	1	7.72**	0.43	0.19	0.05	3.86	786.29**	340.01**	1.86**	0.00	
	Cross	41	4.90***	22.97***	15.98***	4.94***	3.60*	1276.53***	606.06***	0.48*	0.00	
	Error	41	0.71	2.92	3.17	1.44	1.83	72.40	40.84	0.24	0.00	
				TLB	EAS	PAS	EPP	EL	NKR	KPR	ED	TSW
	rep	1	0.00	1.31**	0.76**	0.31*	9.56	1.19	26.86	0.03	8893.28**	
	Cross	41	0.05	0.40***	0.34***	0.16***	9.59***	2.19	35.77**	0.24***	6373.16***	
	Error	41	0.05	0.11	0.07	0.07	3.20	1.39	13.33	0.04	1168.31	
				BIOM	HI	LANG	LL	LW	LFAR	LFPP	LFAE	LFBE
	rep	1	73.90*	2682.96***	28.58	10.71	1.11	12033.58	31.77***	0.11	38.67***	
	Cross	41	21.75**	209.51	12.73	71.28***	0.59	9848.86	2.92***	0.47*	1.84***	
	Error Cross	41	14.17	192.14	10.98	41.54	0.72	11302.14	1.01	0.37	0.59	
Arsi-Negele	SV	GY	DT	DS	ASI	MD	PH	EH	Mod	CLR		
	rep	1	9.51**	36.01*	33.44	0.05	20.01***	2690.53***	762.01***	0.19	1.44*	
	Cross	41	3.53***	27.13***	17.12*	4.88	3.49***	542.65***	308.64***	0.80	0.38	
	Error	41	0.95	7.52	9.49	2.93	1.26	71.92	41.99	1.15	0.29	
				TLB	EAS	PAS	EPP	EL	NKR	KPR	ED	TSW
	rep	1	2.67***	3.44**	0.05	0.07*	14.58**	40.04***	14.86	1.66***	133.21	
	Cross	41	0.32*	0.43	0.30	0.04***	5.42***	2.78	29.31***	0.20***	5928.86***	
	Error	41	0.17	0.28	0.22	0.02	1.70	2.19	11.67	0.06	1912.74	
				BIOM	HI	LANG	LL	LW	LFAR	LFPP	LFAE	LFBE
	rep	1	9.51*	70.59	16.01	838.11**	9.33**	114635.53**	1.81	0.08	2.56	
	Cross	41	3.84*	208.77*	31.37	67.88	0.47	6518.12	0.80	0.20	0.52	
	Error Cross	41	1.70	105.09	59.64	85.94	0.86	9657.96	1.01	0.20	0.64	

*= significant at 0.05 probability level, **= significant at 0.01 probability level and *** = significant at 0.001 probability level, DF = Degree of freedom, GY = Grain yield (t/ha), DT = Days to tasseling (days), DS = Days to silking (days), ASI = Anthesis Silking Interval (days), MD = Days to Maturity (days), PH = Plant Height (cm), EH = Ear Height (cm), MOD = Kernel Modification (1-5 scoring), CLR = Common Leaf Rust (1-5 scoring), TLB = Turicum Leaf Blight (1-5 scoring), EAS = Ear Aspect (1-5 scoring), PAS = Plant Aspect (1-5 scoring), EPP = Ear Per Plant (number), EL = Ear Length (cm), NKR = Number of Kernel Rows (number), KPR = Kernel Per Row (number), ED = Ear Diameter (cm), TSW = Thousand Seed Weight (gram), BIOM = Biomass yield (t/ha), HI = Harvest Index (%), LFANG = Leaf Angle (degree), LL = Leaf Length (cm), LW = Leaf Width (cm), LFAR = Leaf Area (cm²), LFPP = Leaf Per Plant (number), LFAE = Leaf above upper most ear (number), LFBE = Leaf below upper most ear (number).

Table 4. Mean square of a table for combined across three locations for tested crosses in 2017.

Source of variation	Mean Square									
	DF	GY	DT	DS	ASI	MD	PH	EH	MOD	CLR
Rep(location)	2	8.62***	18.22*	16.82	0.05	11.94***	1736.16***	551.01***	1.03	0.72**
Location	1	1.35	4190.01***	2251.34***	298.67***	21240.0***	219170.38***	109140.03***	6.29**	63.15***
Cross	41	6.37***	43.74***	27.34***	7.28***	4.34***	1647.61***	837.71***	0.84	0.19
Cross*location	41	2.07***	6.36	5.77	2.54	2.76**	171.59***	76.99**	0.45	0.19
Error	82	0.83	5.22	6.33	2.18	1.54	72.26	41.41	0.69	0.14
	DF	TLB	EAS	PAS	EPP	EL	NKR	KPR	ED	TSW
Rep (location)	2	1.34***	2.38***	0.40	0.19*	12.07**	20.62***	20.86	0.85***	4513.25
Location	1	73.34***	11.79***	14.88***	2.00***	181.60***	168.00***	517.44***	2.16***	395968.30***
Cross	41	0.16	0.58***	0.33***	0.17***	12.57***	3.71**	49.26***	0.39***	10680.30***
Cross*location	41	0.21**	0.25	0.32***	0.04	2.44	1.27	15.82	0.07	1621.71
Error	82	0.11	0.19	0.15	0.041	2.45	1.79	12.50	0.05	1540.52
	DF	BIOM	HI	LANG	LL	LW	LFAR	LFPP	LFAE	LFBE
Rep (location)	2	41.71**	1376.78***	22.29	424.41***	5.22**	63334.47**	16.79***	0.10	20.62***
Location	1	1184.13***	23457.31***	1904.60***	66853.73***	509.85***	11163485.64***	0.001	63.96***	66.88***
Cross	41	15.65**	208.82	20.82	78.29	0.69	10073.23	2.15**	0.35	1.28**
Cross*location	41	9.95	209.48	23.27	60.86	0.38	6293.77	1.58*	0.33	1.08*
Error	82	7.94	148.61	35.31	63.74	0.79	10480.04	1.01	0.29	0.61

*= significant at 0.05 probability level, **= significant at 0.01 probability level and *** = significant at 0.001 probability level, DF = Degree of freedom, GY = Grain yield (t/ha), DT = Days to tasseling (days), DS = Days to silking (days), ASI = Anthesis Silking Interval (days), MD = Days to Maturity (days), PH = Plant Height (cm), EH = Ear Height (cm), MOD = Kernel Modification (1-5 scoring), CLR = Common Leaf Rust (1-5 scoring), TLB = Turicum Leaf Blight (1-5 scoring), EAS = Ear Aspect (1-5 scoring), PAS = Plant Aspect (1-5 scoring), EPP = Ear Per Plant (number), EL = Ear Length (cm), NKR = Number of Kernel Rows (number), KPR = Kernel Per Row (number), ED = Ear Diameter (cm), TSW = Thousand Seed Weight (gram), BIOM = Biomass yield (t/ha), HI = Harvest Index (%), LFANG = Leaf Angle (degree), LL = Leaf Length (cm), LW = Leaf Width (cm), LFAR = Leaf Area (cm²), LFPP = Leaf Per Plant (number), LFAE = Leaf above upper most ear (number), LFBE = Leaf below upper most ear (number).

3.2. Mid-parent and better-parent heterosis

The mid-parent and better-parent heterosis were computed for individual locations for traits showing significant mean square between crosses. Values of mid-parent heterosis (MPH) and better-parent heterosis (BPH) were estimated for 18 traits at Ambo and 14 traits at Arsi-Negele. The results of MPH and BPH is presented in Tables 5 and 6 for individual locations.

At Ambo, for GY, MPH and BPH ranged from -34.13% (L1xT1) to 329.89% (L17xT2) and -41.26% (L1xT1) to 276.18% (L17xT2), respectively. Most of the crosses except L2xT2 had a positive and significant difference for MPH. Similarly, for BPH, most of the crosses except L2xT1, L2xT2, L3xT1, and L14xT1 had positive values and significant differences for GY. Some crosses had negative heterosis for both MPH and BPH (Table 5). At Arsi-Negele, from 42 crosses, 39 of them had positive heterosis. Out of the 39 crosses that had positive MPH, 25 of them showed significant differences. For BPH, 37 crosses had a positive value of heterosis and out of these crosses, the difference was significant for 17 crosses. The magnitude ranged from -10.36% (L15xT1) to 128.38% (L10xT2) and from -25.87% (L11xT1) to 111.27% (L10xT2) respectively for MPH and BPH. This result is in line with the findings of Birhanu (2009) and Beyene (2016). They reported positive MPH and BPH with significant differences in grain yield in most of the crosses. However, the maximum MPH and HPH heterosis with a respective magnitude of 329.89% and 276.18% recorded in this study was lower than that of 508% and 473% reported by Beyene (2016) for crosses formed from fixed line of different origins mated using the diallel mating design. Whereas the maximum value obtained in the current experiment was higher than the maximum magnitude of MPH and BPH reported (MPH, 202.34% and BPH, 175.46%) by (Birhanu, 2009) from test crosses. The high level of heterosis observed in the study is mainly due to the use of inbred parents when crossed to recover their vigor and yield ability lost during inbreeding.

The difference in the magnitude of heterosis in different reports involving inbred parents is mainly attributed to the stage of inbreeding of the parents, the environmental conditions to which they were exposed, and the performance of the parental inbred lines (Birhanu, 2009). According to Reif *et al.* (2005), heterosis expression is in the range between 100% to 200%

of grain yield over the parents, but in this study, there were crosses with high heterosis values in both MPH and BPH as compared with the range suggested by (Reif *et al.*, 2005). The crosses which had higher heterosis were: L6xT2 (222.07%), L7x T2 (243.58%), (L9XT2 (221.52), L10xT2 (208.31%), L11xT2 (249.27%), L14xT2 (240.52%), L17xT2 (329.89%), L19xT2 (282.57%) and L21xT2 (200.06%) over the mid-parent. L3xT2 (273.91%), L11xT2 (210.87%), L14xT2 (203.17%), L17xT2 (276.18%) and L19xT (2247.31%) over better-parent (Appendix 1). Other crosses had a value of heterosis between the minimum (100%) and maximum (200%). At Arsi-Negele, the following crosses had a value of heterosis between the range value of heterosis (100% to 200%) suggested by Reif *et al.* (2005). These crosses are: L7xT2 (104.15%), L8xT2 (102.56%) L10xT2 (128.38%), L11xT2 (115.53%), L18xT2 (102.20%) and L19xT2 (109.20%) over mid-parent and L10xT2 (11.27%) over the better-parent (Table 6).

At Ambo for DT, 10 crosses showed negative MPH and from these crosses, only one cross (L16xT2) showed a significant difference. Of the remaining crosses which had positive MPH, nine of them showed significant differences over the mid parent. The value of MPH for DT ranged from -3.12% (L16xT2) to 5.41% (L12xT1). For BPH, all crosses showed significant differences in the negative direction except three crosses which are showing nonsignificant variation. A similar result like DT was shown by crosses for both MPH and BPH by DS. The value for DS ranged from -12.19% (17 x T2) to 0.23% (L1xT1) for MPH and from -14.66% (L18xT1) to -2.75% (L13xT1) for BPH (Table 5). This indicates parents were delayed in flowering compared to their offspring for DS and DT. At Arsi-Negele, a similar trend was observed for DT and DS for MPH and BPH with a slight difference in the magnitude of heterosis and level of variation (Table 6). The magnitude of MPH and BPH was smaller compared to the difference in Ambo. This indicates that parents were late in flowering at Ambo compared to crosses, whereas, at Arsi-Negele, crosses and parents were flowered relatively nearly on the same day compared with the result from Ambo. Similar to this study finding, Birhanu (2009) and Beyene (2016) observed significant negative heterosis in most of the crosses for MPH.

At Ambo, all crosses showed positive and significant MPH and BPH for both PH and EH. Similarly, most of the crosses showed positive and significant MPH and BPH with some

exception of crosses showing negative MPH and BPH against their parents with nonsignificant variation in Arsi-Negele (Tables 5 and 6). The MPH for PH ranged from 21.29% (L1xT1) to 91.61% (L8xT2) whereas for BPH the value ranged between 10.76% (L1xT1) to 84.72% (L7xT1). MPH ranged from 47.85% (L3xT1) to 130.30 % (L10xT2) and for BPH, the value ranged from 30.0% (L4xT1) to 115.71% (L7xT1) for EH, respectively (Table 5). At Arsi-Negele, MPH and BPH values ranged from 8.86% (L15xT1) to 61.43% (L7xT1) and from -3.91% to 59.09% for the same crosses respectively for PH. These crosses also showed the lowest and highest MPH and BPH with the magnitude ranging from -2.68% to 93.49% and from -21.12% to 80.87% for EH, respectively (Appendix 2). The positive and significant heterosis observed for PH is evidence of the increase in plant vigor upon crossing. This result is in agreement with the previous report (Birhanu, 2009; Beyene, 2016; Patil *et al.*, 2017). Beyene reported the range value from 36.0% to 115.0% for EH and from 25.7% to 95.2% for PH against mid-parents, he also reported the value of BPH ranged from 22.8% to 97.5% and 13.5 to 74.9% for EH and PH, respectively.

At Ambo, most of the crosses had negative MPH and most of these were also manifested by significant differences for ASI. Eight crosses showed positive and highly significant heterosis. This indicates that these crosses had a wide-substantially higher number of days between than the average value of parents and their offspring. The values ranged from -700% to 400% obtained from L13xT1 and L13xT2, respectively. For BPH, most of the crosses had a negative value of heterosis and these crosses showed significant differences. The range value -116.67% to 200.0% BPH was recorded in L9xT1 and L13xT1 (Table 5). At Arsi-Negele, most of the crosses had positive MPH and five of them showed significant differences. Three crosses showed zero MPH heterosis, indicating that the average value of the parents showed an was equal to the average value for crosses equal number of days for ASI. Whereas some crosses showed negative heterosis but none of the crosses showed significant difference over the mid-parent value, this means the mid parent average number of days with-ASI values of the mid parents was were higher than that of their offspring values. Regarding BPH, 24 crosses showed negative BPH and from these crosses, only one cross (L14xT1) showed significant BPH, indicating that the crosses had shorter showed less in number of-ASI relative to better parent ASI. There were three crosses (L8xT1, L10xT1,

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and L12xT1) that showed zero heteroses-heterosis over better parent. The remaining crosses showed positive BPH, but the differences were not significant. The lowest (-55.56%) and highest (85.71%) were showed by L17xT1 and L2xT1, respectively (Table 6). In line with this study, Beyene (2016) and Bitew (2016) also reported significant positive and negative MPH and BPH in some of the crosses tested for mid-altitude materials.

For MD, MPH and BPH had negative magnitude for all crosses except L13xT1 for both MPH and BPH and L10xT2 for MPH which had positive magnitude heterosis but were not significantly different. Most of the crosses showed negative and significant heterosis for both MPH and BPH consistently. This indicates that most of the offspring/crosses were earlier in maturity than the mean value of the parents and the better parent of each cross. At Ambo, the lowest and highest value of heterosis was -2.58% and 0.92% for MPH and -4.31% and 0.79% for BPH, respectively (Table 5) which is in line with the report of Beyene (2016) and Bitew (2016) they reported negative heterosis whereas the result of this study in contrast to positive MPH and BPH reported by (Birhanu, 2009). At Arsi-Negele, the heterosis for MD was the reverse result obtained at Ambo because of the environment in which maturity of parents was more forced at Arsi-Negele as compared with the crosses. In reality, parents are weaker than the hybrids/offspring of the parents to resist harsh conditions in maize. The results also confirmed that the parents were more forced to maturity than their offspring in Arsi-Negele, which is manifested by the positive magnitude of both MPH and BPH for all crosses. For MPH, from a total of 42 crosses, six of them showed positive and nonsignificant differences and 22 crosses had positive and significant BPH (Table 6). This positive magnitude of heterosis in crosses over the mid-parents and better parent indicates that parents were earlier than crosses for maturity. However, this value may not indicate the reality due to the existence of environmental pressure at Arsi-Negele. Based on this, it is better to rely on the results obtained at Ambo for this specific trait.

At Ambo, most of the crosses showed positive values for MPH and BPH for MOD except L2x xT1, and L17xT1 for both MPH and BPH and L11xT2 and L14xT1 for BPH. L11xT2, L14xT2, and L16xT1 showed zero heteroses for MPH and L3xT1, L19xT1, and L21xT1 for BPH. The crosses with negative heterosis values indicate that crosses showed good improvement for this trait than mid-parents or the better parent. Most of the crosses showed

positive value and significant MPH, whereas, for BPH, few numbers of crosses showed significant heterosis. For crosses that had negative values, none of them showed a significant difference. The lowest (-25.0%) and highest (200.0%) values were recorded by L2xT1 for MPH and -30.0% and 150.0% by L17xT1 and L20xT2 for BPH, respectively (Table 5).

Regarding CLR, all crosses had negative BPH, and most of the crosses except L4xT1 and L14xT1 for MPH. There were also some crosses which are explaining the difference significantly. The lowest (-55.56%) and the highest (10.0%) were obtained from (L7xT1) and L14xT1, respectively, for MPH. At Arsi-Negele, the lowest (-57.14%) and the highest (-7.69%) values of BPH were recorded by L7xT1 and L12xT1, respectively (Table 6). In contrast to the current study, Birhanu (2009) reported both negative and positive MPH and BPH with a ranging value of -30.77 to 38.89 % and from -42.86 to 31.58%, respectively.

At Ambo, for EAS, most of the crosses showed negative values for both MPH and BPH. Twelve for MPH and 19 for BPH recorded negative values and showed significant heterosis over the mid-parent and better parent, respectively. This indicates that the ~~parents contributed more to their offspring for the improvement of EAS~~ crosses had better EAS scores (better looking ears) than their parents. Some crosses had zero heterosis, meaning that each cross was equal in magnitude to that of the value of mid-parent and better parent. There were also a few crosses that had positive and significant heterosis over the mid-parent and better parent. This indicates crosses were poor for EAS compared to the mid and better parents. The lowest and highest heterosis was -33.33% and 52.38% for MPH and -37.50% and 45.45% for BPH, and these records were obtained from L3xT2 and L13xT1, respectively (Table 5).

At Ambo, for PAS, only two crosses (L6xT1 and LL1xT2) had negative values for both MPH and BPH with a nonsignificant difference. L8xT2 and L3xT2 had zero heteroses for MPH. Cross: L3xT2, L8xT2 and L17xT1, and L20xT2 manifested by negative BPH. Generally, most of the crosses with a positive and significant difference for MPH and BPH implies hybrids fully fill the criteria of PAS poorly compared to parents with Ambo (Table 5). Beyene (2016), in contrast, reported a higher number of crosses with positive and significant MPH and BPH.

At Ambo, all crosses had positive MPH except L1xT1 which showed negative MPH for EL. Out of the 41 crosses that had positive MPH, 25 of them showed significant differences. The value was ranged from -10.40% (L1xT1) to 61.80% (L8xT2). For BPH, most of the crosses had positive heterosis except for two crosses. Seventeen crosses had a positive magnitude and significant difference over the better parents. The magnitude of BPH ranged from -15.15% (L1xT1) to 54.55% (L6xT1) (Table 5). At Arsi-Negele, 28 crosses showed positive MPH and out of these, four of them showed significant differences with the mid-parent value. Twenty-one crosses had positive heterosis and out of these, two crosses showed significant differences for BPH. The MPH and BPH ranged from -20.27 (L15xT1) to 32.85% (L7xT1) and from -26.25% to 31.89% in the same crosses, respectively (Table 6). For ED, the majority of crosses had positive and significant heterosis over mid-parent and better parent. However, there were two crosses for MPH and three crosses for BPH that had negative heterosis for Ambo. The value of MPH and BPH ranged from -2.55% (L13xT1) to 36.37% (L3xT1) and from -5.14% (L1xT1) to 31.94% (L8xT2) (Table 5). At Arsi-Negele, positive heterosis was obtained from 34 crosses and 29 crosses for MPH and BPH, respectively. Twelve crosses for MPH and five crosses for BPH positive heterosis showed a significant difference. Some crosses showed negative heterosis over the mid-parent and better parent. For ED, the magnitude of MPH and BPH ranged from -7.85% (L11xT1) to 22.47% (L5xT2), and from -11.36% (L9xT1) to 20.98% (L5 T2), respectively (Table 6). Even though there were some crosses with a negative magnitude over mid-parent and better parent, the result of this study is more similar to the previous report made by Birhanu (2009) and Beyene (2016). These two authors observed positive and significant MPH and BPH in all crosses for EL and ED except for two crosses which are showing negative heterosis over better parent (2009) for ED.

For KPR, positive MPH was obtained from all crosses and most of the crosses showed significant differences. Similarly, most of the crosses had positive and significant BPH except for two crosses (L4xT1 and L13xT1). At Ambo, the magnitude of MPH and BPH ranged from 3.23% (L13xT1) to 99.07% (L17xT2) for MPH and from -5.96% (L4xT1) to 78.34% (L17xT2) for BPH (Table 5). In Arsi-Negele, out of 42 crosses, 38 crosses had positive heterosis over the mid-parent, again from these 38 crosses 20 of them showed a

significant difference in mid-parent performance. For BPH, 31 crosses had positive heterosis and from these crosses, six of them had significantly different BPH. The magnitude of MPH and BPH ranged from -18.52% (L15xT1) to 53.51% (L14xT1) for MPH and from -25.13% (L15xT1) to 40.62% (L8xT2) for BPH (Table 6). The result obtained for MPH and BPH from Ambo, a place where high rainfall was recorded, is in line with the result reported by Birhanu (2009), Beyene (2016), and Patil *et al.* (2017). They reported positive and significant heterosis over the mid-parent and better parent. The magnitude of MPH and BPH in this study was lower compared with the findings reported by Birhanu (2009). He reported a higher value of MPH (ranging from 3.96 to 77.18 %) and MPH (ranging from 18.36 to 80.85%).

At Ambo, positive heterosis was obtained from 36 crosses for MPH and 26 crosses for BPH. Out of 36 crosses with a positive value of MPH, 18 of them showed significant differences and for BPH out of the 26 traits, nine of them showed significant differences. The value of the MPH ranged from -40.56% (L2xT2) to 78.46% (L11xT2) and for BPH it ranged from -51.65% (L1xT1) to 75.37% (L11xT2) for TSW (Table 5). At Arsi-Negele, most of the crosses had positive values for both MPH and BPH for TSW. Twenty crosses showed a significant difference for MPH and 10 crosses for BPH. The lowest (-5.54%) and the highest (94.68%) MPH were obtained from L4xT1 and L7xT2, respectively. BPH is the lowest -13.93% and the highest (63.49%) obtained from the same crosses for BPH. However, there were also crosses with inferior performance than the mid-parent and better parent values. This is manifested by the negative MPH and BPH. The 2nd high yielder cross (L8xT2) had positive and showed significant MPH and BPH for this trait at Arsi-Negele (Table 6). Most of the crosses showed significant differences which are made from most of the lines crossed with T2, indicating that T2 had a good combining ability for TSW at Ambo and Arsi-Negele (Tables 5 and 6). Birhanu (2009) and Beyene (2016) reported positive magnitude and significant MPH and BPH which is similar to this study finding for TSW.

For BIOM, all crosses had positive MPH and BPH except one cross (L1xT1) which had negative heterosis, and the significant difference indicates that this cross manifested by lower BIOM performance than the mid-parent and better parent. Based on this, we can say the interaction between the male and female parents was weak to get the minimum possible

heterosis. At Ambo, out of the crosses with positive values of heterosis, most of them showed significant MPH and BPH. The highest MPH (241.15%) and lowest BPH (183.05%) were obtained from L20xT2 and L11xT2, respectively (Table 5). Out of the crosses which had positive and significant MPH for BIOM, five of them were included in the top five crosses (L3xT2, L8xT2, L9xT1, L17xT2, and L18xT1) for GY at Ambo. At Arsi-Negele for BIOM, most of the crosses had positive MPH and 16 crosses had positive BPH. For MPH L7xT1 and L18xT1 showed significant differences with a positive magnitude, but for BPH none of the crosses showed significant differences. L1xT1, L9xT1, and L15xT1 showed significant differences with negative values for both MPH and BPH. The crosses: L2xT1, L4xT1, L11xT1, L13xT1, L16xT1, and L17xT1 also had significant differences with negative magnitude for BPH. Crosses with negative MPH and BPH indicated that the hybrids are lower in BIOM than their mid-parent and better parent. The value of MPH ranged from -32.93% (L9xT1) to 50.77% (L18xT1) and BPH value ranged from -42.54% (L1xT1) to 19.67% (L2xT2) (Table 6). In line with the results obtained from Ambo, Birhanu (2009) and Beyene (2016) reported positive and highly significant MPH and BPH in all crosses tested. However, compare the results from Arsi-Negele, there was variation based on the direction of heterosis and magnitude as well due to the presence of random stress.

At Arsi-Negele, for HI, all crosses showed a positive value for MPH except L11xT1 which had a negative magnitude for both MPH and BPH, in addition, L10xT1, L21 xT1, and L21xT2 had a negative magnitude for BPH. For crosses with positive magnitude, 25 crosses showed significant MPH, whereas for BPH fifteen crosses explained the difference with significant variation. The MPH value ranged from - 0.79 % (L11xT1) to 106.44% (L5xT1). All of the five top crosses showed significant differences for MPH and three of the top five crosses (L5xT1, L8xT2, and L9xT1) had positive and significant heterosis for both MPH and BPH (Appendix 2). In line with this study's results for MPH and BPH, Birhanu (2009) and Bitew (2016) reported positive and significant MPH and BPH for most of the crosses tested for HI whereas Beyene (2016) reported a highly significant difference in the positive side for both MPH and BPH in all crosses.

For LL, most of the crosses had positive and highly significant MPH except three crosses (L1xT1, L2xT2, and L6xT1) which had positive and nonsignificant MPH. Mostly the same

trend was observed in crosses for BPH except for two crosses (L5xT2) which had a negative value and L6xT1 had zero heterosis. The highest MPH values (44.40%) and BPH (37.61%) were recorded by L18xT1 at Ambo (Table 5).

For MPH, most of the crosses had positive values of heterosis for LFPP, while eight crosses had a positive value of heterosis significant difference and there was one cross (L2xT1) with zero heterosis for MPH. Cross (L4xT1) also has shown zero heteroses over a better parent. Out of the crosses with positive values, only three crosses (L10xT2, L13xT2, and L17xT2) had significant BPH. There were also crosses with negative for both MPH and BPH. Some of the crosses showed significant differences in the negative direction at Ambo (Table 6). Similarly, Birhanu also reported a significant difference in the positive and negative direction for MPH and BPH (Birhanu, 2009). The lowest (-14.10%) and highest (22.29%) heterosis values were recorded by L4xT2 and L10xT2, respectively, for MPH, whereas for BPH was -the lowest (19.57%) and highest (21.52%) for L5xT2 and L10xT2, respectively (Table 5).

At Ambo for LFBE, most of the crosses had negative and significant heterosis over both mid-parent and better parent. Some crosses had negative and positive values of heterosis for MPH and BPH with a nonsignificant difference. The negative heterosis value indicates that the parents had a greater number of leaves below the uppermost ear compared to their offspring. The MPH values ranged from -43.96 % (L5xT2) to 14.81% (L19xT2), whereas for BPH the values ranged from -50.0% to 13.42% in the same crosses (Table 5).

Table 5. Better-parent heterosis for trait heterosis determination of the 42 F1hybrids obtained by LxT and evaluated at Ambo in 2017.

Code	GY		DT		DS		ASI		MD		PH	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L1xT1	-34.13	-41.26	3.66**	-2.65	0.23	-3.50*	-100.0***	-100.00	-2.22***	-2.85***	21.29***	10.76
L1xT2	192.09***	138.34**	2.49	-10.61***	-7.82**	-9.64***	33.33	0.00	-1.82**	-2.33**	79.91***	79.16***
L2xT1	70.25*	35.68	3.00*	-10.31***	-6.39**	-9.69***	100.0***	25.00	-0.92	-1.31	59.45***	42.01***
L2xT2	37.55	26.11	1.83	-5.82***	-4.48**	-6.16***	-25.00	-25.00	-2.35***	-2.61***	41.50***	37.08***
L3xT1	79.61**	46.78	1.41	-5.09**	-4.40**	-6.36***	-60.00***	-75.00	-1.57*	-1.83*	43.77***	39.54***
L3xT2	320.05***	273.91***	0.23	-7.40***	-7.97**	-8.18***	-50.00***	-50.00	-1.18	-1.31	65.93***	48.03***
L4xT1	-6.46	-21.47	3.22*	-5.80***	-2.05	-5.70***	60.00***	0.00	-1.44*	-1.82*	29.20***	15.97**
L4xT2	148.24***	114.59**	2.05	-11.16***	-8.72**	-10.52***	25.00	25.00	-1.30*	-1.56*	79.95***	75.83***
L5xT1	71.62**	71.50**	4.32**	-8.73***	-5.54**	-11.25***	-33.33***	-63.63**	-1.96**	-2.59***	67.14***	62.5.0***
L5xT2	156.09***	91.35***	3.15*	-13.10***	-10.23**	-14.16***	-6.67	-36.36	-0.52	-1.04	67.96***	58.08***
L6xT1	112.15***	97.45***	1.18	-6.04***	-5.77**	-8.10***	-50.00***	-71.42*	-1.18	-1.31	73.67***	71.04***
L6xT2	222.07***	153.58***	0.00	-7.44***	-7.02**	-7.65***	9.09	-14.29	-0.26	-0.26	80.63***	63.29***
L7xT1	133.96***	106.54***	-0.72	-2.86	-3.52*	-4.20*	-75.00***	-85.71*	-1.44*	-1.57*	86.33***	84.72***
L7xT2	243.58***	182.87***	-1.90	-9.76***	-8.54**	-9.58***	-27.27***	-42.86	-1.57*	-1.83*	82.02***	68.19***
L8xT1	82.15***	61.48**	0.94	-7.00***	-6.29**	-7.79***	-20.00	-50.00	-1.57*	-2.08**	79.19***	73.37***
L8xT2	190.70***	100.98**	-0.23	-8.83***	-8.00**	-8.21**	25.00	25.00	-0.39	-0.78	91.61***	70.45***
L9xT1	161.59***	135.54***	1.41	-6.48***	-7.15**	-9.45***	-128.57***	-116.67**	-1.18	-1.81*	59.86***	57.96***
L9xT2	221.52***	160.14***	0.23	-8.33***	-7.93**	-8.55***	0.00	-16.67	-0.78	-1.30	79.81***	63.05***
L10xT1	89.06***	70.94**	-0.48	-3.80*	-4.24**	-4.69**	-66.66***	-80.00	-0.66	-1.05	71.27***	63.54***
L10xT2	208.31***	148.57***	-1.65	-8.37***	-7.87**	-9.13***	-55.55***	-60.00	0.26	-0.26	90.03***	82.06***
L11xT1	99.36***	62.94*	-0.48	-5.23**	-5.16**	-6.04***	-25.00	-57.14	-0.79	-1.05	60.99***	57.63***
L11xT2	249.27***	210.87***	-1.65	-8.83***	-7.83**	-8.67***	-27.27***	-42.86	-0.13	-0.52	78.29***	66.66***
L12xT1	81.52***	75.85**	5.41***	-7.69***	-3.78**	-9.24***	-100.00***	-100.00	-2.58***	-4.31***	57.30***	49.22***
L12xT2	124.38***	71.43*	4.23**	-10.25***	-7.22**	-10.92***	-50.00***	-50.00	-1.41*	-3.04***	65.77***	44.85***

Table 5 (Continued)

Code	GY		DT		DS		ASI		MD		PH	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L13xT1	-24.34	-37.15	2.33	-5.00**	-1.17	-2.75	-700.00***	200.00	-1.83**	-2.09**	39.79***	20.13**
L13xT2	136.95***	107.16**	1.15	-9.54***	-6.63**	-6.84***	400.00***	25.00	0.92	0.79	78.52***	66.25***
L14xT1	81.57**	48.36	2.77*	-5.85***	-4.71**	-9.40***	-53.84***	-75.00***	-1.56*	-2.33**	56.82***	52.45***
L14xT2	240.52***	203.17***	1.60	-9.90***	-8.60**	-11.53***	-12.50	-41.66*	-0.65	-1.30	76.51***	57.70***
L15xT1	144.02***	101.33***	2.33	-7.72***	-5.28**	-8.03***	20.00	-25.00	-1.44*	-1.82*	50.82***	43.71***
L15xT2	174.36***	141.64***	1.15	-10.45***	-8.35**	-9.37***	50.00***	50.00	-1.57*	-1.82*	72.04***	50.94***
L16xT1	65.47**	59.07*	-1.94	-5.71**	-3.54*	-3.77*	9.09	-40.00	-1.71**	-1.84*	60.28***	54.16***
L16xT2	135.83***	81.18**	-3.12*	-14.41***	-8.12**	-9.58***	100.00***	40.00	-0.26	-0.52	66.79***	58.64***
L17xT1	138.08***	97.60***	3.22*	-8.48***	-6.09**	-10.34***	-33.33***	-62.50*	-0.65	-1.30	75.08***3	70.83***
L17xT2	329.89***	276.18***	2.05	-14.28***	-12.19**	-14.66***	0.00	-25.00	-1.82**	-2.33**	80.15***	68.97***
L18xT1	165.19***	131.10***	1.87	-10.09***	-8.54**	-10.81***	-20.00	-50.00	-1.44*	-1.82*	74.07***	68.95***
L18xT2	126.09***	88.37*	0.69	-8.71***	-6.57**	-7.20***	75.00***	75.00	-2.35***	-2.61***	71.79***	53.26***
L19xT1	117.13***	52.40*	0.47	-4.71**	-4.67**	-5.99***	-33.33	-60.00	-0.92	-1.05	63.26***	60.00***
L19xT2	282.57***	247.31***	-0.70	-10.23***	-9.174**	-9.58***	11.11	0.00	-1.05	-1.05	74.44***	57.00***
L20xT1	110.29***	71.74**	2.55	-7.23***	-2.48	-6.89***	83.33***	0.00	-1.30*	-1.82*	75.21***	74.30***
L20xT2	194.94***	162.72***	1.38	-10.40***	-7.31**	-9.91***	46.66***	0.00	-1.18	-1.56*	74.85***	61.05***
L21xT1	101.30***	78.38**	1.64	-1.84	-2.07	-4.91**	-100.00***	-100.00**	-1.70**	-1.83*	74.26***	64.58***
L21xT2	200.06***	146.20***	0.46	-8.29***	-6.09**	-7.14***	63.63***	28.57	-0.79	-0.79	89.51***	83.59***
Minimum	-34.13	-41.26	-3.12	-14.42	-12.19	-14.66	-700.00	-116.67	-2.58	-4.31	21.29	10.76
Maximum	329.89	276.18	5.41	-1.84	0.23	-2.75	400.00	200.00	0.92	0.79	91.61	84.72
CD,0.05	1.48	1.70	2.99	3.45	3.11	3.59	2.10	2.42	2.37	2.73	14.88	17.18
CD,0.01	1.97	2.28	3.99	4.61	4.16	4.81	2.81	3.24	3.17	3.66	19.90	22.98
CD,0.001	2.59	2.99	5.24	6.05	5.46	6.31	3.68	4.25	4.16	4.80	26.12	30.16

Table 5 (Continued)

Code	EH		MOD		EAS		PAS		EL		KPR	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L1xT1	48.63***	36.42***	83.33**	37.50	45.45***	33.33**	100.0***	100.00***	-10.40	-15.15	27.80	9.60
L1xT2	109.13***	95.72***	80.00*	50.00	-30.76**	-35.71***	15.79	0.00	30.55	28.93	46.48**	39.16*
L2xT1	80.95***	49.28***	-25.00	-25.00	-4.76	-9.09	36.84***	18.18	31.62	16.66	60.98	31.12*
L2xT2	75.12***	65.68***	28.57	12.50	20.00	7.14	54.54***	54.54***	29.15	19.01	36.74*	22.50
L3xT1	47.85***	37.42***	33.33	0.00	0.00	-18.75*	33.33***	7.69	15.38	13.64	34.08	19.87
L3xT2	84.90***	50.30***	60.00	33.33	-33.33***	-37.50***	0.00	-7.69	51.00**	46.87**	75.73***	75.00***
L4xT1	49.79***	30.00**	57.14*	37.50	30.43**	15.38	66.66***	50.00***	1.61	-4.55	4.03	-5.96
L4xT2	103.90***	102.91***	50.00	50.00	-18.51*	-21.42*	23.80*	18.18	28.27	25.63	37.19*	36.07
L5xT1	91.57***	78.57***	57.14*	37.50	33.33**	27.27*	33.33**	20.00	21.48	18.84	52.25	45.69**
L5xT2	100.00***	84.29***	116.66***	116.66***	-12.00	-21.42*	23.80*	18.18	37.45*	28.98	44.96**	35.50*
L6xT1	98.67***	85.71***	66.66*	25.00	-4.35	-15.38	44.44***	30.00**	54.54***	54.55**	63.23	47.01**
L6xT2	112.92***	73.91***	120.00***	83.33*	-11.11	-14.29	-4.76	-9.09	42.29**	36.36*	69.29***	68.59***
L7xT1	118.84***	115.71***	66.67	25.00	4.00	-13.33	41.17***	33.33**	49.62**	46.37**	61.67	53.64***
L7xT2	115.12***	88.23***	80.00*	50.00	-24.13**	-26.66**	20.00*	9.09	43.63**	34.78*	71.09***	61.02***
L8xT1	92.47***	71.50***	116.66***	62.50*	26.31*	20.00	41.17***	33.33**	23.74	17.80	23.62	20.89
L8xT2	114.94***	68.71***	140.00***	100.00**	-4.35	-21.42*	0.00	-9.09	61.80***	47.94**	79.85***	58.23***
L9xT1	72.97***	64.10***	83.33**	37.50	-25.00*	-35.71***	11.11	0.00	42.46**	30.00*	51.46	48.10**
L9xT2	100.77***	66.02***	40.00	16.67	-21.42*	-21.42*	14.29	9.09	59.43**	40.00**	71.94***	51.26***
L10xT1	92.56***	85.00***	22.22	10.00	12.00	-6.67	52.94***	44.44***	28.37*	15.85	26.52	22.22
L10xT2	130.30***	106.20***	37.50	10.00	-10.34	-13.33	10.00	0.00	41.05**	22.56	49.64***	30.24*
L11xT1	89.47***	80.00***	22.22	10.00	16.67	0.00	44.44***	30.00**	30.30*	30.30	35.23	25.83
L11xT2	114.03***	93.65***	0.00	-20.00	-21.42*	-21.42*	-4.76	-9.09	58.10**	51.51**	67.19***	60.76***
L12xT1	89.86***	80.12***	12.50	12.50	0.00	0.00	41.17***	33.33**	14.87	5.30	31.43	21.85
L12xT2	75.96***	45.51***	28.57	12.50	-25.00*	-35.71***	40.00***	27.27**	39.39*	33.07	53.41**	48.06**

Table 5 (Continued)

Code	EH		MOD		EAS		PAS		EL		KPR	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L13xT1	66.81***	32.85***	57.14*	37.50	52.38***	45.45***	68.42***	45.45***	4.13	-4.55	3.23	-4.64
L13xT2	108.64***	89.21***	66.66*	66.66*	-20.00*	-28.57**	9.09	9.09	54.10**	47.10*	31.85*	27.74
L14xT1	73.28***	66.44***	0.00	-10.00	-9.09	-16.67	41.17***	33.33**	18.70	10.61	7.04	0.66
L14xT2	98.42***	65.78***	62.50**	30.00	-15.38	-21.42*	20.00*	9.09	32.76*	28.93	41.10**	34.20*
L15xT1	67.33***	56.87***	100.00***	50.0*	18.18	8.33	73.33***	62.50***	12.78	11.94	30.81*	26.49
L15xT2	87.78***	53.75***	140.00***	100.00**	-15.38	-21.42*	33.33***	9.09	23.92	17.91	46.35**	35.45*
L16xT1	85.24***	61.42***	0.00	0.00	4.76	0.00	50.00***	50.00***	30.43*	25.00	34.48*	29.14
L16xT2	87.37***	85.57***	28.57	12.50	-12.00	-21.42*	15.79	0.00	34.33*	23.61	59.07***	48.19**
L17xT1	123.80***	101.42***	-22.22	-30.00	4.35	-7.69	75.00***	75.00***	43.93**	43.93**	56.09***	27.15
L17xT2	123.36***	113.39***	50.00*	20.00	-25.92**	-28.57**	5.26	-9.09	48.62**	42.42*	99.07***	78.34***
L18xT1	98.64***	89.03***	83.33**	37.50	4.76	0.00	52.94***	44.44***	20.28	11.69	66.78***	49.66**
L18xT2	86.77***	54.83***	140.00***	100.00**	-12.00	-21.42*	40.00**	27.27**	13.46	1.30	63.33***	63.33**
L19xT1	92.06***	72.85***	33.33	0.00	4.00	-13.33	75.00***	75.00***	40.27**	29.48*	48.65***	37.08*
L19xT2	108.41***	99.10***	140.00***	100.00**	-24.13**	-26.66**	26.31*	9.09	53.07***	35.90*	67.27***	62.35***
L20xT1	100.72***	98.57***	116.66***	62.50*	0.00	-8.33	50.00***	50.00***	39.30**	35.60*	63.56***	39.73**
L20xT2	102.51***	76.64***	200.00***	150.00***	0.00	-7.14	5.26	-9.09	56.09***	53.59**	69.16***	60.00**
L21xT1	107.40***	100.00***	33.33	0.00	4.35	-7.69	55.55***	40.00***	10.45	8.82	31.00*	24.50
L21xT2	104.31***	82.30***	100.00**	66.66*	-18.51*	-21.42*	23.80*	18.18	52.53***	44.11**	53.90***	44.84**
Minimum	47.85	30.00	-25.00	-30.00	-33.33	-37.50	-4.76	-9.09	-10.40	-15.15	3.23	-5.96
Maximum	130.30	115.71	200.00	150.00	52.38	45.45	100.00	100.00	61.80	54.55	99.07	78.34
CD,0.05	11.18	12.91	0.85	0.99	0.58	0.67	0.47	0.55	3.13	3.61	6.39	7.37
CD,0.01	14.95	17.26	1.14	1.32	0.78	0.90	0.63	0.73	4.18	4.83	8.54	9.86
CD,0.001	19.62	22.65	1.50	1.73	1.02	1.18	0.83	0.96	5.49	6.34	11.21	12.94

Table 5 (Continued)

Code	ED		TSW		BIOM		LL		LFPP		LFBE	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L1xT1	-0.02	-5.14	-39.86**	-51.65***	-20.21	-23.15	10.78	3.63	2.30	-6.32	-11.95	-20.58*
L1xT2	22.03***	12.07*	34.91*	10.49	83.28	39.78	32.57***	29.64**	13.92*	13.92	-7.41	-8.54
L2xT1	24.44***	23.07***	20.83	0.37	58.60	34.41	25.64***	21.97**	9.20	0.00	-19.35*	-26.47**
L2xT2	7.10	4.60	-40.56**	-49.65***	66.92	51.56	34.49***	32.33***	2.53	2.53	-19.51	-21.43
L3xT1	13.36*	1.79	6.40	1.46	30.24	19.82	20.19**	15.91*	-13.81*	-17.89**	-27.47**	-35.29***
L3xT2	36.37***	26.39***	60.86***	56.98**	144.78*	80.69*	23.12**	13.67	7.88	3.49	-2.50	-2.50
L4xT1	4.76	1.02	-19.21	-28.06	15.23	6.71	30.05***	23.89**	0.00	-9.47	-28.26**	-35.29***
L4xT2	27.43***	18.87***	25.35	14.04	168.54*	123.63*	23.64**	23.23***	-14.10*	-15.19	-37.03***	-37.80**
L5xT1	21.72***	18.67***	-8.50	-29.46*	128.03**	126.68*	17.46**	7.94	-13.36*	-14.73*	-41.17***	-41.17***
L5xT2	35.63***	27.86***	22.10	-4.25	137.30*	85.13*	7.18	-5.49	-13.45*	-19.57**	-43.95***	-50.00***
L6xT1	19.41***	13.45*	37.98*	24.98	79.94	59.80	1.00	0.00	-6.29	-13.68*	-40.62***	-44.11***
L6xT2	21.80***	19.71**	57.92***	46.19**	72.25	24.04	30.48***	23.51**	9.43	8.75	-11.76	-16.67
L7xT1	13.69**	10.27	18.59	9.45	133.58**	130.11*	18.26**	15.85*	-2.89	-11.58	-24.21**	-29.41**
L7xT2	16.38**	15.91**	59.77**	44.27*	139.98*	86.01*	23.01**	15.27*	15.92*	15.19	-10.71	-14.77
L8xT1	10.56*	8.46	30.73	26.59	50.03	18.31	22.14**	19.55*	-8.70	-11.58	-33.65***	-34.90***
L8xT2	34.00***	31.94***	55.36**	54.03**	89.66*	25.86*	25.99***	22.94**	11.91	5.62	-9.68	-20.75*
L9xT1	14.47**	11.87*	36.16*	24.24	152.24**	148.15**	23.56**	21.57**	5.95	3.16	-11.76	-11.76
L9xT2	32.09***	30.55***	58.60***	47.94**	239.97***	163.25**	20.60**	17.08*	-2.96	-8.89	-27.47**	-35.29***
L10xT1	5.57	4.98	35.71	33.88	157.94**	156.92**	35.78***	30.03***	5.20	-4.21	-16.13	-23.52*
L10xT2	24.94***	20.06***	66.98***	60.91**	184.00**	121.89*	24.50**	24.22**	22.29**	21.52**	6.10	3.57
L11xT1	7.35	4.79	25.75	24.94	23.03	2.15	20.90**	18.95*	2.22	-3.16	-15.63	-20.58*
L11xT2	20.77***	14.00**	78.46***	75.37***	204.61*	183.05*	17.07*	12.94	5.88	0.00	5.88	0.00
L12xT1	7.39	-0.73	1.66	-20.87	27.14	1.02	2.13	1.05	-8.16	-11.76	-8.16	-11.76
L12xT2	27.80***	14.46**	21.86	-3.48	53.44	2.34	11.63	3.23	3.45	-4.25	3.45	-4.25

Table 5 (Continued)

Code	ED		TSW		BIOM		LL		LFPP		LFBE	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L13xT1	-2.55	-3.21	-31.56*	-39.75*	24.04	10.83	30.65***	28.02***	5.14	-3.16	-6.67	-17.65
L13xT2	22.41***	17.48**	38.46*	24.49	184.31*	144.58*	30.38***	27.10**	20.75**	20.00*	13.92	12.50
L14xT1	8.02	-2.45	8.06	-10.24	44.08	34.29	23.40**	22.78**	-3.78	-6.32	-19.80*	-20.58*
L14xT2	21.40***	6.32	54.33***	30.72*	190.09**	140.23*	41.03***	35.43***	2.96	-3.33	-16.67	-24.99**
L15xT1	16.53***	10.70*	3.28	-21.30	143.80**	136.90*	30.34***	24.69**	0.55	-3.16	-13.86	-14.71
L15xT2	20.86***	11.13*	36.20**	5.55	116.38	73.22	31.27***	31.12***	-0.60	-5.68	-16.67	-24.99**
L16xT1	16.41***	8.79	27.30	11.08	82.83	71.91	39.80***	31.34***	1.18	-9.47	-14.77	-26.47**
L16xT2	22.86***	11.19*	57.72***	40.53*	187.39**	136.24*	24.55**	22.34*	14.29	11.39	1.30	-2.50
L17xT1	7.62	-0.52	5.66	-19.87	168.61**	141.10*	40.10***	30.64***	-3.30	-7.37	-17.34*	-20.58*
L17xT2	25.67***	12.54**	54.25***	18.95	172.27*	133.23	36.43***	32.96***	21.68**	16.09*	3.45	-4.25
L18xT1	21.14***	16.36**	17.15	-7.81	84.50*	63.75	19.71*	9.27	-5.82	-6.32	-22.11**	-23.58**
L18xT2	16.08**	7.88	16.77	-6.46	75.75	26.50	44.40***	37.61***	17.91**	8.51	0.00	-12.26
L19xT1	20.88***	17.21**	14.45	-10.94	42.52	36.91	26.78***	25.50**	-4.40	-8.42	-11.96	-20.58*
L19xT2	24.50***	24.03***	33.71*	5.89	105.01	56.06	33.04***	28.39***	13.25*	8.05	14.81	13.42
L20xT1	25.27***	18.31***	32.86*	4.03	125.94*	116.68*	24.50***	23.03**	9.19	6.32	2.00	0.00
L20xT2	28.85***	17.81***	17.45	-6.40	241.14***	175.94**	15.83*	9.45	12.43	5.56	-8.99	-17.35
L21xT1	14.03**	13.61*	-4.78	-20.20	40.66	31.12	26.84***	20.96*	5.03	-1.05	-7.22	-11.76
L21xT2	33.04***	28.99***	48.17**	26.64	199.98***	123.50*	35.47***	35.17***	15.33*	11.91	4.65	-2.17
Minimum	-2.55	-5.14	-40.56	-51.65	-20.21	-23.15	1.00	-5.49	-14.10	-19.57	-43.96	-50.00
Maximum	36.37	31.94	78.46	75.37	241.15	183.05	44.40	37.61	22.29	21.52	14.81	13.42
CD,0.05	0.35	0.40	59.78	69.03	6.58	7.60	11.27	13.02	1.76	2.03	1.34	1.55
CD,0.01	0.46	0.54	79.96	92.33	8.81	10.17	15.08	17.41	2.35	2.71	1.79	2.07
CD,0.001	0.61	0.70	104.91	121.14	11.55	13.34	19.78	22.84	3.08	3.56	2.35	2.72

Table 6. Better-parent heterosis for trait heterosis determination of the 42 F1hybrids obtained by LxT and evaluated by Arsi-Negele in 2017.

Code	GY		DT		DS		ASI		MD		PH		EH	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L1xT1	-4.74	-20.17	0.00	-0.52	0.76	0.51	27.27	16.67	0.91	0.30	10.36	4.26	9.28	6.00
L1xT2	74.13	70.05	-3.19	-5.70	-2.55	-3.54	12.50	-18.18	3.56***	0.91	31.09***	23.10**	33.33**	32.63*
L2xT1	24.78	3.57	-5.51*	-5.76*	-2.03	-2.03	100.0*	85.71	0.76	0.30	23.00**	11.49	19.32	5.00
L2xT2	5.06	1.40	2.41	0.53	2.81	2.03	11.11	-9.09	2.48***	0.00	12.82	1.68	25.15	12.63
L3xT1	43.00	18.39	-0.79	-1.05	0.51	0.51	38.46	28.57	1.39*	0.31	17.94**	9.93	15.65	2.31
L3xT2	65.88*	59.61	-5.63*	-7.36*	-5.37	-6.09	0.00	-18.18	5.36***	4.37***	23.92***	16.17*	28.00**	10.77
L4xT1	7.66	-8.87	0.53	0.00	0.00	0.00	-14.29	-25.00	1.52*	1.22	21.57**	11.49	24.73*	16.00
L4xT2	73.41**	71.37*	-5.37*	-6.87*	-4.86	-5.58	5.26	-9.09	3.57***	1.22	23.04**	12.18	14.92	9.47
L5xT1	84.99***	68.24**	-2.83	-4.55	0.76	0.51	233.33*	66.67	2.90***	2.75***	31.83***	26.66***	35.48**	25.64*
L5xT2	84.93**	72.57**	-4.46	-8.08**	-3.57	-4.55	27.27	-36.36	4.06***	2.14**	26.57***	22.35**	27.35*	15.38
L6xT1	12.08	8.86	1.33	-0.52	0.26	-0.51	-25.00	-40.00	0.91	0.61	43.03***	37.94***	42.97***	24.44*
L6xT2	64.60**	44.27	-3.54	-3.80	-2.06	-2.06	23.81	18.18	3.57***	1.22	29.12***	25.29***	39.13***	18.52
L7xT1	104.15***	78.92***	-1.86	-3.14	-1.02	-1.02	17.65	-9.09	2.61***	1.83*	61.42***	59.09***	93.49***	80.87***
L7xT2	85.53**	80.19**	-6.23*	-6.98*	-7.41**	-8.12*	-27.27	-27.27	3.77***	2.48***	33.33***	32.23***	41.90***	29.56*
L8xT1	81.32***	64.71***	-0.26	-0.52	-0.25	-0.51	0.00	0.00	1.67**	1.52*	40.44***	25.41***	34.05***	4.47
L8xT2	102.56***	59.97**	-5.63*	-7.36*	-4.62	-5.10	17.65	-9.09	4.36***	2.13**	29.60***	16.38**	29.19***	-1.12
L9xT1	34.74	11.80	0.52	0.52	-0.25	-0.51	-23.08	-28.57	1.99**	1.83*	28.93***	18.57**	33.87***	13.10
L9xT2	79.92**	73.58*	-6.95***	-8.90**	-3.06	-4.04	77.77*	45.45	3.75***	1.84*	25.86***	16.42**	26.66**	4.83
L10xT1	40.89	12.94	-0.53	-1.05	0.25	0.00	20.00	0.00	1.38*	0.61	28.51***	21.67**	22.27*	8.53
L10xT2	128.38***	111.27***	-6.98**	-8.46**	-5.10	-6.06	30.00	18.18	5.97***	4.65***	29.34***	23.19***	33.93	16.28
L11xT1	-7.07	-25.87	0.27	-2.09	0.00	-1.02	-5.88	-27.27	1.52*	1.52*	28.33***	25.71***	34.59**	27.92*
L11xT2	115.33***	98.00**	-9.04**	-9.28**	-7.49**	-7.73*	18.18	18.18	4.21***	2.14**	29.60***	27.75***	40.77***	30.63*
L12xT1	51.88*	28.73	0.52	0.52	0.76	0.51	7.69	0.00	1.984**	1.82*	25.28***	13.93*	51.56***	37.39***
L12xT2	63.96*	62.29*	-2.14	-4.19	-2.04	-3.03	0.00	-18.18	4.04***	1.82*	22.66***	12.19*	22.01*	8.13

Table 6 (Continued)

Code	GY		DT		DS		ASI		MD		PH		EH	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L13xT1	18.74	-9.34	1.31	1.04	1.01	0.50	-7.69	-14.29	0.46	0.00	18.24*	3.40	22.22	-1.00
L13xT2	79.22*	56.17	-4.53	-6.77*	-5.34	-6.53*	-22.22	-36.36	2.48***	0.00	34.29***	16.80*	35.03*	11.58
L14xT1	70.10**	36.37	-1.31	-1.57	-2.99	-4.88	-33.33	-53.33*	2.00**	1.22	39.04***	30.71***	51.35***	37.70***
L14xT2	56.00	44.33	-4.02	-5.79	-3.26	-5.85	7.69	-6.67	5.03***	3.72***	18.81**	12.36	28.11**	13.93
L15xT1	-10.36	-17.88	0.27	-1.57	1.55	0.00	38.46	28.57	0.46	0.31	8.86	-3.91	-2.68	-21.12*
L15xT2	38.31	9.99	-4.09	-4.35	-4.42	-5.15	-11.11	-27.27	2.81***	0.92	14.49*	1.63	8.59	-13.66
L16xT1	49.19*	36.35	-4.95	-9.42**	-3.17	-7.10*	42.86	25.00	1.84**	1.52*	45.77***	39.57***	59.59***	58.00***
L16xT2	38.42	28.53	-3.37	-6.01	-2.93	-6.19	5.26	-9.09	2.03**	0.31	16.55*	10.92	6.74	5.10
L17xT1	47.80*	19.46	-0.53	-2.09	-2.30	-3.05	-46.67	-55.56	1.67**	1.52*	40.96***	36.17***	61.38***	59.80***
L17xT2	72.59*	61.27*	-3.80	-4.32	-4.12	-4.12	-10.00	-18.18	1.55*	-0.61	23.85***	18.90*	30.96**	26.47*
L18xT1	92.38***	53.05*	-6.13*	-7.85**	-4.37	-5.58	42.86	25.00	0.92	0.31	41.40***	41.10***	48.38***	37.60**
L18xT2	102.06***	85.21**	-7.35**	-7.60*	-3.63	-4.12	68.42*	45.45	4.86***	3.40***	29.11***	28.57***	20.75	9.40
L19xT1	109.20***	69.00**	-6.35*	-7.32*	-5.82*	-6.06	5.88	-18.18	2.74***	2.43***	38.77***	33.33***	76.71***	67.00***
L19xT2	93.41**	80.62**	-6.48*	-7.48*	-4.59	-5.56	27.27	27.27	3.57***	1.22	36.30***	31.76***	58.69***	53.68***
L20xT1	87.22	40.98	-3.96	-4.71	-1.77	-2.02	50.00	20.00	2.29***	2.14**	44.88***	42.21***	60.93***	50.43***
L20xT2	68.11*	44.01	-4.58	-5.85	-1.02	-2.02	61.90*	54.55	4.37***	2.45***	28.38***	26.80***	27.61*	16.52
L21xT1	27.91	8.63	-1.06	-2.09	-2.54	-2.54	-37.50	-50.00	1.68**	1.22	39.51***	34.46***	44.49***	38.53**
L21xT2	61.53*	60.28*	-2.16	-3.21	-3.32	-4.06	-23.81	-27.27	5.01***	3.39***	36.40***	30.67***	34.31**	25.68*
Minimum	-10.36	-25.87	-9.04	-9.42	-7.49	-8.12	-46.67	-55.56	0.46	-0.61	8.86	-3.91	-2.68	-21.12
Maximum	128.38	111.27	2.41	1.04	2.81	2.03	233.33	85.71	5.97	4.66	61.43	59.09	93.49	80.87
CD,0.05	1.70	1.96	4.80	5.54	5.39	6.22	2.99	3.45	1.96	2.26	14.83	17.13	11.33	13.09
CD,0.01	2.27	2.63	6.42	7.41	7.21	8.32	4.00	4.62	2.62	3.03	19.84	22.91	15.16	17.50
CD,0.001	2.98	3.45	8.42	9.72	9.46	10.92	5.25	6.06	3.44	3.97	26.03	30.06	19.89	22.97

Table 6 (Continued)

Code	CLR		EL		KPR		ED		TSW		BIOM		HI	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L1xT1	-4.35	-15.38	-11.59	-12.86	19.10	-0.63	-1.66	-1.83	-4.35	-11.13	-32.41*	-42.53**	34.94	31.67
L1xT2	-14.29	-18.18	-1.37	-5.27	37.96*	22.47	14.32*	12.38	23.74	16.89	19.99	19.67	38.12	31.22
L2xT1	-30.43	-38.46*	2.22	1.47	7.37	-4.38	5.04	4.05	35.73*	34.91*	-21.17	-36.29**	54.75*	49.96*
L2xT2	-4.76	-9.09	-16.78	-21.71*	12.55	7.25	-4.39	-5.29	-5.16	-6.26	-22.94	-27.74	28.38	27.85
L3xT1	-9.09	-23.08	12.41	11.59	40.92**	23.75	9.72	-5.06	-2.20	-13.39	-8.08	-19.28	59.12*	51.30*
L3xT2	-20.00	-27.27	8.27	3.28	49.80***	40.57**	16.25*	2.23	30.23	13.57	19.13	15.02	29.11	19.61
L4xT1	4.76	-15.38	-6.15	-10.29	10.00	-10.63	0.60	-0.68	-5.54	-13.93	-19.28	-35.93*	27.81	19.02
L4xT2	-5.26	-18.18	-4.35	-13.16	20.17	3.62	10.99	10.31	22.92	13.84	15.21	5.65	45.16*	38.77
L5xT1	-33.33	-46.15**	6.96	6.57	24.32*	19.65	13.87*	13.11*	9.62	-2.33	-15.68	-22.99	106.44***	104.26***
L5xT2	-15.79	-27.27	2.42	-2.64	26.04*	13.30	22.47***	20.98**	51.26**	32.70*	-10.53	-17.15	77.27**	70.71**
L6xT1	-28.00	-30.77	14.48	7.79	13.70	3.75	-4.96	-7.82	24.09	22.74	-22.09	-22.63	43.73	39.39
L6xT2	-30.43	-33.33	17.65	16.89	42.96**	39.85*	1.37	0.16	33.59*	29.84	-4.30	-17.99	67.12**	57.84*
L7xT1	-55.55***	-57.14***	32.85**	31.89**	22.68	20.00	4.88	0.66	56.14**	33.05	34.43*	3.20	44.89*	25.19
L7xT2	-36.00*	-42.85**	13.10	7.89	32.65	26.15	5.29	2.93	94.67***	63.48***	8.72	-4.30	62.86***	44.11*
L8xT1	-23.08	-23.08	4.11	-2.56	15.00	15.00	3.99	0.80	21.84	15.24	19.63	16.20	49.92*	33.72
L8xT2	-41.66*	-46.15**	11.68	10.25	51.00***	40.62**	15.03*	13.60*	40.74**	35.40*	21.49	6.13	64.96***	50.82*
L9xT1	-16.13	-27.77*	15.87	9.09	27.97*	24.37	-4.10	-11.36	8.47	1.52	-32.92*	-41.33**	100.04***	86.76**
L9xT2	-17.24	-33.33**	22.87*	22.08*	28.71*	23.18	2.18	-3.88	41.78**	30.53	16.42	12.91	49.58*	36.14
L10xT1	-18.52	-21.43	18.75*	3.26	32.88**	22.50	-0.61	-5.15	21.15	18.75	29.34	-2.36	3.14	-5.96
L10xT2	-36.00*	-42.85**	10.71	1.09	29.67*	28.26	9.54	6.45	32.40*	27.56	17.62	1.39	82.04***	70.27**
L11xT1	-46.15**	-46.15**	-0.74	-1.46	18.49	8.12	-7.85	-8.81	19.01	13.72	-13.20	-33.84*	-0.79	-10.59
L11xT2	-8.33	-15.38	13.28	6.58	29.63*	26.81	6.51	5.62	48.79**	39.80*	15.54	0.78	69.61***	56.74**
L12xT1	-4.00	-7.69	3.71	2.95	5.16	1.87	1.62	-4.11	12.41	10.58	3.86	-18.92	41.97*	28.84
L12xT2	-21.74	-25.00	0.70	-5.27	33.33**	28.00*	10.72*	2.65	26.63	26.47	32.67	19.22	18.02	9.84

Table 6 (Continued)

Code	CLR		EL		KPR		ED		TSW		BIOM		HI	
	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH	%MPH	%BPH
L13xT1	-4.35	-15.38	8.95	-1.46	15.67	-3.13	4.93	1.56	2.65	-0.96	-16.38	-38.54*	35.38	29.50
L13xT2	-4.76	-9.09	0.76	-13.16	16.26	3.62	7.84	6.33	28.04*	25.70	16.95	-2.52	47.64*	45.08
L14xT1	10.00	-15.38	26.82*	14.71	53.51***	29.99*	14.66**	10.58	35.59*	25.20	6.04	-12.16	53.76*	53.73*
L14xT2	-11.11	-27.27	-3.82	-17.11	-0.40	-10.14	12.45*	6.50	50.40**	36.64*	6.40	2.83	35.63	31.98
L15xT1	-25.00	-30.77	-20.27*	-26.25*	-18.52	-25.13*	1.26	-2.70	25.77	20.00	-29.79*	-32.11*	25.21	11.42
L15xT2	-45.45*	-45.45*	-6.41	-8.75	0.91	-13.09	9.36	3.20	46.83**	42.52**	-0.38	-12.63	41.13*	28.73
L16xT1	-23.81	-38.46*	14.29	11.77	11.92	5.62	8.70	5.71	27.86*	17.82	-18.74	-33.59*	76.96***	57.53**
L16xT2	-26.32	-36.36	-7.80	-14.48	-1.43	-2.82	5.29	0.54	36.73**	28.07*	-8.65	-13.18	49.18**	36.13
L17xT1	-20.00	-23.08	6.98	1.47	40.14**	24.37	-2.78	-5.23	17.57	5.61	-3.38	-27.35*	43.64	28.35
L17xT2	-21.74	-25.00	11.68	0.66	33.58*	26.81	15.54**	10.58	63.86***	49.56***	24.24	6.57	28.89	18.07
L18xT1	-14.29	-30.77	7.36	7.36	26.75*	12.50	12.60*	6.65	3.35	-9.32	50.76**	6.14	17.62	0.50
L18xT2	-26.32	-36.36	-2.78	-7.89	43.50**	36.23*	18.67**	14.46*	4.87	-6.55	27.80	0.93	51.31**	32.36
L19xT1	-23.81	-38.46*	5.41	-2.50	21.68	17.50	8.49	3.11	17.97	8.32	21.30	-4.11	70.41**	64.46**
L19xT2	-15.79	-27.27	6.41	3.75	31.70*	26.85	22.43***	18.50**	31.11*	22.38	10.32	0.67	68.83**	67.42**
L20xT1	-30.76*	-30.77	21.26	13.24	29.07*	13.75	9.31	7.74	28.89*	20.02	18.83	-14.00	52.30*	44.52
L20xT2	-41.66*	-46.15**	-4.44	-15.13	13.85	7.25	8.73	5.19	46.13***	38.36**	2.69	-16.03	57.80**	53.79*
L21xT1	-21.74	-30.77	-10.61	-13.24	-0.99	-6.25	-1.57	-2.10	17.85	5.58	9.06	-20.28	9.32	-8.78
L21xT2	-42.85*	-45.45*	-4.29	-11.84	10.32	8.39	6.91	4.36	37.48**	25.14	36.33	12.89	9.98	-6.12
Minimum	-55.56	-57.14	-20.27	-26.25	-18.52	-25.13	-7.85	-11.36	-5.54	-13.93	-32.93	-42.54	-0.79	-10.59
Maximum	10.00	-7.69	32.85	31.89	53.51	40.62	22.47	20.98	94.68	63.49	50.77	19.67	106.44	104.27
CD,0.05	0.94	1.08	2.28	2.64	5.97	6.90	0.44	0.51	76.49	88.32	2.28	2.63	17.93	20.70
CD,0.01	1.26	1.45	3.05	3.52	7.99	9.23	0.59	0.68	102.31	118.14	3.05	3.52	23.98	27.69
CD,0.001	1.65	1.90	4.00	4.62	10.48	12.11	0.77	0.89	134.24	155.00	4.00	4.62	31.46	36.33

4. Conclusion

The crosses that showed negative heterosis also showed negative GCA effect and SCA effects for DS and DT, highlighting the parents are late for flowering compared to their crosses. For quantitative traits (GY, PH, EH, EL, KPR, ED, TSW, and BIOM), the value of the mid-parent and better parent heterosis indicates the positive value by most of the crosses whereas for phenology traits (DS, DT, and DM) both mid-parent and better parent heterosis showed to the negative side under ideal location that is Ambo but under location, with some natural stress (Arsi-Negele) this conclusion is somehow contrasted. To be clearer, for such kinds of information about our germplasm, it is advisable to evaluate the new germplasms in different testing environments. In general, for-grain yield and yield related traits, both the MPH and BPH values were found in the positive direction for almost all crosses. This highlights that the crosses evaluated in the study were created from genetically diverse inbred parents.

Comment [CM9]: How? GCA is a property of the parents and not the crosses!

Comment [CM10]: For SCA, I agree but this has to be included in the discussion, and references should be cited in support

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