Evaluation of cytoplasmic male sterile hybrid barley in hill plots
by Mohammad Anwar Khan

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Agronomy
Montana State University
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Abstract:
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APPROVAL

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This thesis has been read by each member of the author's graduate committee and has been found satisfactory after reading contents, English usage, format, citations, bibliographic style, and consistency. Therefore, the thesis is ready for submission to the College of Graduate Studies.

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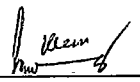
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Date 1 March 1991

Dedicated to my beloved wife, Mrs. Fakhira Anwar Khan, our two sons (Raheel Anwar Khan, and Saad Anwar Khan), our parents, my uncle (Late Hafiz Ali Mohammad), my major professor (Dr. Eugene A. Hockett) whose best wishes were all the time with me.

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ABSTRACT

Research was initiated in 1987-1988 in the greenhouse where crosses were made between five parents (Klages, Harrington, Menuet, Piroline, and Morex) which have different malting traits. All the parents that were used as females had 94.0 to 100.0% cytoplasmic male sterility, which was used as a crossing tool for making different hybrids. Reciprocal crosses were also made except in the case of Klages. The objective of this study was to evaluate hybrid barley for its agronomic and malting quality traits in hill plots. Therefore, a hybrid yield trial was planted at Post Research Farm of Montana State University, Bozeman, USA, using randomized complete block design with six replications. The trial was conducted in 1989. After recording agronomic data, the samples were analyzed for malting quality traits by using NIR (near infra-red reflectance) procedures. Statistical analysis has revealed that hybrids in general have shown significant heterosis compared to their "best" parent for important agronomic traits, and NIR determinations. Gains obtained for individual characteristics were bundle weight (10.2 to 27.6%), grain yield (-29.2 to 36.1%), harvest index (-25.0 to 11.4%), seeds/spike (-3.3 to 6.6%), 1000 kernel weight (-4.3 to 31.0%), tillers/unit area (-30.4 to 33.4%), plant height (6.73 to 11.16%), heading date (-1.7 to -0.61%), shattering percent (-600.0 to 0.0%), malt extract (-1.94 to 2.12%), hardness (-25.81 to 51.97%), lysine (-6.00 to -4.00%), moisture (-3.17 to 4.76%), fat (-14.8 to -1.66%), protein (-8.69 to 12.10%), and viscosity (-8.61 to 10.22%). In two-rowed/six-rowed crosses shattering of the F1 hybrid was a problem due to complementary genes coming together from the two types of parents. It was also revealed that general combining ability (GCA) is important for all characteristics except lysine but specific combining ability (SCA) was only important for kernel weight and malt extract. NIR was shown to be a reliable technique for estimating protein content and for malt extract except for the Harrington and Klages comparison. Some hybrids showed a significant decrease in protein content which is a welcome phenomenon for the production of hybrid barley meant for malting quality.

INTRODUCTION

The cereal grain crops are the world's most important source of food and can truly be called the "staff of life." One of the most important crops is barley. It has a wider ecological adaptation than wheat. It is a more dependable crop under extreme environmental conditions and is considered to be a poor soil and a poor man's crop. In fact, the majority of barley is produced under moisture stress conditions because in these areas barley is the best option left to farmers and is mostly grown for animal feed either as winter grazing or for grain and straw. At present the brewing industry is mainly dependent on barley for its raw material (11). It is also being used as a food crop for human beings especially in developing countries. Barley lowers cholesterol level in chickens and humans (30). It is a good source of starch and protein when it is used as a food crop. It is also used as a poultry feed. Barley originated in the Eastern Mediterranean. It has persisted as a major cereal crop because of broad ecological adaptation (11,13,and 14).

The primary objective of this research was to evaluate hybrid barley for its agronomic and malting quality traits in hill plots.

LITERATURE REVIEW

What Hybrid Barley Is

"The first generation offspring of a cross between two individuals differing in one or more genes is called a hybrid" (44). So, hybrid barley can be defined as the first generation offspring of a cross between two barley cultivars differing in one or more genes. Hybrids are often developed to increase grain yield, biomass production and other desirable traits i.e. better malting quality, adaptability to less favorable environment including disease and climate resistance, etc. Another advantage for breeding companies from producing hybrid barley is that by doing so, they do not need to worry about cultivar protection (28). The first commercial hybrid barley cultivar, Hembar, was developed in the USA in Arizona in the winter of 1960. It was a cross between a genetic recessive male-sterile diploid and 'Arivat'. Hembar produced 15-20% more grain yield than Arivat when grown under high yield conditions (46 and 47).

Heterosis

"Condition in which a hybrid exceeds the performance of its parents for one or more characters. Mid-parent heterosis represents performance of the hybrid that exceeds the average performance of the parents per se. High parent heterosis occurs when the hybrid performance exceeds that of the best parent" (19). Heterosis can also be defined as "the behavior of the hybrid compared to the mid-parent, the best parent, or the best commercial cultivar" (28). With hybrid barley higher grain yield, increased forage production, and other desirable traits, e.g. higher grain quality, better malting quality and lower protein content is expected. Hybrid barley should be desirable because it capitalizes on heterosis (28).

There is general agreement among scientists that high-yielding barley parents produce higher-yielding hybrids than those of low-yielding ones (48). Another investigator says that specific combining ability is very important and perhaps direct selection should be done for combining ability in lines which are used as parents in order to exploit heterosis completely (33). This specific study also shows that the highest yielding male parent did not produce the highest yielding hybrid (33). Another study showed that the highest yielding hybrids came either from parents from F_2 populations of hybrids with significant heterosis or from composite crosses, and not from the crosses of conventional pure line cultivars (23).

Production of Hybrid Barley

The idea of producing the cereal hybrids has been considered by scientists since the early 1920's and maize was the pioneer crop in this respect. Hybrid maize became popular in the U.S. in 1930's when the hybrids performed much better than the open pollinated cultivars under the then prevailing drought conditions (34). Before evaluating hybrid barley, it is a pre-requisite to find an appropriate system for the production of F_1 or hybrid seed. Most of the systems proposed involve genetic male-sterility (22 and 28).

The successful use of hybrid cultivars depends on the existence of an economically significant level of heterosis, sufficient cross pollination and an efficient as well as reliable system of producing the female parent of the hybrid. The use of cytoplasmic male sterility is perhaps the most viable and widely used system in producing commercial hybrid barley at present. Cytoplasmic male sterility has advantages in commercial production of hybrid barley, e.g. using cytoplasmic male sterility it is much easier to develop female parents than with the gametocidic system (28). The use of cytoplasmic male sterile system was first described for maize, sorghum, etc. hybrids (2). Cytoplasmic male

sterility was first found in vulgare in 1968, by crossing H. vulgare and H. jubatum (51). But this female parent was not proven to be successful because there were many side effects, e.g. extreme lateness of hybrids, etc. In 1978 a breakthrough was made in this field; cytoplasmic male sterility was obtained from crosses of H. vulgare and H. spontaneum which did not have the side effects found in the cross between H. vulgare and H. jubatum (1). In this system, the sterile female plant contains msm cytoplasm and rfm rfm recessive restorer genes. The fertile male parent has the Rfm Rfm or Rfm rfm genotype. The source of msm cytoplasm and Rfm restorer is from H. spontaneum (28). A problem with the cytoplasmic male sterility obtained from H. spontaneum is that some cultivars with the msm rfm rfm genotype are not completely sterile (3). In order to obtain parents for hybrid barley, female plant containing msm and male plant containing Rfm are backcrossed into selected cultivars of H. vulgare (28). Some workers are using the cytoplasmic male-sterile system to obtain hybrid barley (34).

Drilled Row Plots vs Hill Plots

Several scientists have utilized multiple row drilled yield trials for the evaluation of hybrid barley (23, 32, and 35). In one study barley hybrids were compared at four seeding rates where they found that average performance of hybrids and cultivars was the same for grain yield and its components at the different rates (52). But in multiple row plots, the performance of lines was significantly different from their performance in hill plots for agronomic and quality traits (53). Hill plots have an advantage over conventional drilled plots in requiring smaller quantities of seeds as compared to multiple row plots (36). Moreover, while performing hill plot experiment one can reduce the number of years for cultivar development (25). Hill plots also allow the evaluation of a greater number of genotypes per unit of area as compared to the larger drilled plots (12). The lesser the number of plants per hill, the greater

the heterosis in bean yield and its components (7). Another study has shown that 15 cm hill spacing is ideal for producing higher grain yield and number of fertile tillers per unit area in barley. But number of seeds per spike, 1000 kernel weight, harvest index, and weight of kernels per spike were the highest at 45 cm hill spacings (50). Two recent studies have shown that hill plots are useful for evaluating most agronomic and malting quality traits in spring barley (18 and 54).

Near-Infrared Reflectance (NIR)

A preliminary screening technique for malt quality characteristics such as grain protein, malt extract, hardness and viscosity, is required for efficient use of hill plots in breeding for the assessment of malt quality. Two independent studies have recently reported that the Near Infra Red (NIR) screening technique for spring oats and spring barley, in hill plots evaluation, was a useful preliminary screening technique for malt quality traits (24 and 54). The NIR screening technique was originally developed for the measurement of moisture content in grains (41). Later, it was found to be a useful, rapid and inexpensive technique for the prediction of grain quality and other traits in a number of crops (31, 37, 42 and 54). NIR is reported to successfully predict grain protein (45). For the improvement of malt quality in barley, focus is required on malt extract, enzymatic activity, % plump, and grain protein in breeding programs. NIR successfully predicted grain protein (51) and malt extract in two studies (37 and 40). However, a third study found that NIR did not estimate malt extract accurately (54).

MATERIALS AND METHODS

Five parents i.e. Klages (CI 15478); Harrington (SK 76333); Menuet (VD 3); Piroline (CI 9558); and Morex (CI 15773), were used to make reciprocal crosses (no reciprocal crosses for Klages). Harrington, Klages, Piroline, and Menuet are two-rowed barley, whereas Morex is six-rowed (4, 5, 6, 49, and 56). All the parents except Menuet are classified in the U.S. as malting cultivars of barley and the ranking of two-rowed parents for malting quality is as follows (30):

1. Harrington
2. Klages
3. Piroline
4. Menuet

All these parents produce cytoplasmic male sterile female stocks with the following percentage of sterility in the msm1 rfm1 rfm1 stocks: Klages - 94.1%; Harrington - 98.8%; Menuet - 100.0%; Piroline - 100%; and Morex - 99.4%. (29).

Cytoplasmic male sterility was used for making crosses in 1987-88 in the green-house by crossing the msm1 rfm1 rfm1 female with the Rfm1 Rfm1 male. The F1 seeds obtained from these crosses are the basis of this experiment. Before planting the average seed weight of 150 seeds of each entry was determined. In 1989 the hybrid yield trial was conducted at the Post Research Farm, Bozeman in hill plots; each plot having five hills. Each hill was 60.96 cm apart from the other hill of the same plot. Five seeds/hill were planted. A randomized complete block design was used with six replications. Each replication had 36 entries (10 F1's and 6 reciprocals F1's plus 5 parents repeated 4 times per replication), and two treatments per cross (parents and F1's). The trial was bordered by Bearpaw (PI531228) and the experiment was conducted under irrigated conditions (two irrigations). Planting and harvesting were performed by hand using

hoes and sickles, respectively.

Heading date (days from January 1), kernel shattering (%), plant height (cm), tiller breakage (%), and seeds/spike (no.) were recorded before harvest. Plant materials harvested from the hills were dried by putting them in a drier overnight to remove excessive moisture. Bundle weight, and grain yield (gm), and 1000 kernel weight (mg) were then taken by using a computer program written by Mr. Allen Cook, USDA Technician, for Radio Shack computer, connected to an electronic balance. All data was taken on a hill basis except heading date, kernel shattering, tiller breakage, and plant height; these data were taken on a plot basis. The grain samples from each hill (10 gm) were sent to the quality laboratory of Dr. C. F. McGuire at MSU to take/record NIR readings to estimate grain protein (%) on hill basis along with malt extract (%), viscosity (cp-centipoise units), kernel hardness (no.), lysine (% of grain), moisture (%), and fat (%). The near infrared analyzer was used to obtain protein content by AACC Method 39-10, 1983 (39), whereas malt extract was obtained by NIR curves derived by McGuire (37). An NIR technique, derived by McGuire in 1985, was used to estimate lysine content, moisture, and kernel hardness (38). Number of tillers/unit area and harvest index (%) were calculated using the following formulae:

$$\text{No of fertile tillers/hill} = \frac{\text{Grain yield/hill}}{\text{No. of kernels/spike} \times \frac{\text{1000 kernel wt.}}{1000}}$$

$$\text{Harvest index/hill} = \frac{\text{Grain yield}}{\text{Bundle Wt.}}$$

The data obtained on both a hill and plot basis was analyzed using MSUSTAT programs "COMPARE" and "AVFT". A SAS program, written by Dr. Jack Martin, was used for additional analysis of the data obtained on a hill basis. While analyzing data on hill basis means of the hills were used. ANOVAS obtained from this procedure were comprised of following sources of variation:

Sources Of Variation	df
Replications	5
Entries	15
Parents	3
Heterosis	1
Crosses	11
General Combining Ability (GCA)	3
Specific Combining Ability (SCA)	2
Maternal Effects	3
Reciprocal Effects	3
Error	147

No agronomic data or NIR estimates were obtained on border rows of Bearpaw.

RESULTS AND DISCUSSION

Comparison Between Parents

The following summary is deduced from Table 1 and Table 27 (separate listings are significantly different):

Parent/parents	Bundle weight (grams/hill)
Klages	168.1
Harrington = Piroline	153.7 = 141.9
Menuet = Morex	122.0 = 119.9
Parent/parents	**Grain yield (grams/hill)**
Klages	59.30
Harrington = Piroline	53.50 = 52.80
Menuet = Morex	39.80 = 41.30
Parent/parents	**Harvest index**
Piroline	0.37
Klages	0.35
Harrington = Morex	0.34 = 0.34
Menuet	0.32
Parent/parents	**Seeds/spike (no.)**
Morex	60.50
Harrington = Piroline = Menuet	24.90 = 24.90 = 24.70
Klages	24.10
Parent/parents	**1000 kernel weight (grams)**
Klages	44.20
Harrington	40.80
Menuet	39.00
Piroline	37.20
Morex	33.60

Table 1. Treatment mean difference for comparisons between parents 1/.

	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Plant height cm	Heading date days fr 1/1	Tiller breakage %
Morex vs Klages	-48.1**	-18.0**	-0.0	36.4**	-10.6**	-35.0**	5.7**	-4.0**	12.4**
Morex vs Harrington	-33.7**	-12.2**	-0.0	35.6**	-7.2**	-32.3**	6.0**	-3.1**	12.8**
Morex vs Menuet	-2.1	1.5	0.0	35.8**	-5.4**	-20.6**	5.9**	-2.5**	12.6**
Morex vs Piroline	-21.9**	-11.5**	-0.03**	35.6**	-3.6**	-36.6**	2.2	-2.7**	12.7**
Harrington vs Menuet	31.6**	13.7**	0.03**	0.2	1.8**	11.7**	0.0	0.6	-0.2
Harrington vs Piroline	11.8	0.7	-0.02*	0.1	3.7**	-4.3	-3.8*	0.4	0.0
Menuet vs Klages	-46.0**	-19.5**	-0.03**	0.6*	-5.2**	-14.3**	-0.3	-1.5**	-0.2
Menuet vs Piroline	-19.28**	-13.0**	-0.1**	-0.2	1.9**	-16.0**	-3.8*	-0.2	0.1
Piroline vs Klages	-26.2**	-6.5*	0.0	0.8**	-7.1**	1.7	3.5*	-1.3**	-0.3

	Grain NIR Measurements						
	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
Morex vs Klages	0.1	-12.7**	-0.1**	0.1*	-0.3**	-0.5**	2.3**
Morex vs Harrington	0.8**	-3.2*	-0.03**	0.1*	-0.2**	-0.7**	1.3**
Morex vs Menuet	1.6**	-1.5	-0.03**	0.1*	-0.5**	-1.3**	1.3**
Morex vs Piroline	1.7**	-2.7	-0.03**	0.0	-0.4**	-1.4**	2.4**
Harrington vs Klages	-0.6**	-9.5**	-0.0	0.0	-0.0	0.2*	1.0**
Harrington vs Menuet	0.8**	1.7	-0.0	0.0	-0.2**	-0.6**	-0.1
Harrington vs Piroline	0.9**	0.6	0.0	-0.0	-0.2**	-0.7**	1.1**
Menuet vs Klages	-1.4**	-11.2**	-0.0	0.0	0.2**	0.8**	1.0**
Menuet vs Piroline	0.1	-1.2	0.0	-0.1*	0.0	-0.1	1.1**
Piroline vs Klages	-1.6**	-10.0**	-0.02*	0.1*	0.2**	0.9**	-0.1

1/ Shattering data for six-rowed parent only.
*,** Significant at the P < 0.05, 0.01, respectively.

Parent/parents	Tillers/hill (no.)
Piroline	57.00
Klages = Harrington	53.70 = 52.60
Menuet	41.00
Morex	20.30
Parent/parents	**Plant height (cm)**
Morex = Piroline	73.50 = 71.30
Klages = Harrington = Menuet	67.80 = 67.50 = 67.50
Parent/parents	**Heading date (days from January 1)**
Klages	198.30
Harrington = Menuet = Piroline	197.40 = 196.8 = 197.0
Morex	194.30
Parent/parents	**Tiller breakage (%)**
Klages = Harrington	
Menuet = Piroline	0.5 = 0.1 = 0.3 = 0.1
Morex	12.9
Parent/parents	**Malt extract (%)**
Morex = Klages	77.30 = 77.20
Harrington	76.50
Piroline = Menuet	75.60 = 75.60
Parent/parents	**Hardness (no.)**
Klages	27.90
Harrington	18.50
Piroline = Menuet = Morex	17.90 = 13.90 = 15.20
Parent/parents	**Lysine (%)**
Klages = Harrington = Menuet = Piroline	0.50 = 0.50 = 0.50 = 0.50
Morex	0.40
Parent/parents	**Grain moisture (%)**
Morex = Piroline	6.40 = 6.40
Klages = Harrington = Menuet	6.30 = 6.30 = 6.30

Parent/parents	Fat (%)
Menuet = Piroline	2.50 = 2.50
Klages = Harrington	2.40 = 2.30
Morex	2.10
Parent/parents	Protein (%)
Piroline = Menuet	13.80 = 13.70
Harrington	13.10
Klages	12.90
Morex	12.40
Parent/parents	Viscosity (cp)
Morex	20.90
Harrington = Menuet	19.40 = 19.60
Klages = Piroline	18.60 = 18.60

A comparison between the six-rowed parent (Morex) and the two-rowed parents (Klages, Harrington, Menuet, and Piroline) showed that the two-rowed parents were significantly higher in bundle weight and grain yield with the exception of Menuet whereas Morex and Menuet did not differ for these traits (Table 1). There was no significant difference between the six-rowed parent and the two-rowed parents in terms of harvest index with the exception of Piroline which had higher harvest index than the six-rowed parent. For grain yield the higher number of seeds/spike of Morex was compensated for by the higher 1000 kernel weight and greater number of tillers/unit area of the two-rowed parents. Morex and Menuet have the same grain yield because higher number of seeds/spike of Morex are compensated for by the higher 1000 kernel weight and greater number of tillers/unit area of Menuet (Table 1). Morex had significantly higher seeds/spike, plant height, malt extract (no difference between Morex and Klages), moisture (no difference between Morex and Piroline), and viscosity than the two-rowed parents. Morex had significantly less 1000 kernel weight, tillers/unit area, days to heading, hardness (only Klages and Harrington had significantly more hardness), lysine, fat and protein than the two-

rowed parents (Table 1). The six-rowed parent also had significantly higher tiller breakage than the two-rowed parents (Table 1).

Comparisons between the two-rowed parents indicated that Klages is higher than Harrington, Menuet and Piroline in terms of bundle weight and grain yield because it has greater 1000 kernel weight which outweighs the rest of the yield components of the later cultivars. Harrington had significantly greater grain yield than Menuet where 1000 kernel weight and tillers/hill contributed significantly in the increased grain yield of Harrington. Harrington and Piroline had similar grain yield because the higher 1000 kernel weight of Harrington is not enough to increase its grain yield significantly over Piroline (Table 1). Piroline has higher bundle weight and grain yield than Menuet, because the former has significantly greater tillers per unit area which compensates for the superiority of Menuet in 1000 kernel weight. Harrington has less malt extract and hardness but higher protein and viscosity than Klages (Table 1). The NIR does not always accurately separate two cultivars for malt extract because results obtained here from NIR determinations indicated that Klages has higher malt extract than Harrington. This result is contrary to the results obtained from multiple row solid-seeded plots evaluated with laboratory malting analysis (30). But the NIR results here are in agreement with results obtained from multiple row plot samples evaluated by laboratory malting analysis of extract for Piroline and Menuet. Therefore, NIR is probably not completely accurate when evaluating hill plots, because similar doubts were also raised in a study in Oregon in which hill plots were used (54).

Comparison Between Reciprocal F1's

No significant difference was observed between reciprocals when Morex was crossed with two-rowed parents except for grain protein and viscosity (Table 2). The reciprocals for Morex over all crosses had significantly lower protein content and higher viscosity when Morex was

Table 2. Treatment mean differences between F_1's and their reciprocal crosses (See Table 26).

	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Plant height cm	Heading date days fr 1/1	Tiller breakage %
Morex/? vs ?/Morex	-10.7	-2.2	0.0	-0.2	-0.1	-1.5	-2.1	-0.6	0.2
Harrington/? vs ?/Harrington	22.5**	8.5*	0.0	-0.3	-0.4	8.7**	-2.1	-0.7	-0.5*
Menuet/? vs ?/Menuet	0.6	-1.2	0.0	0.5	0.5	-2.8	3.6	-0.6	0.3
Piroline/? vs ?/Piroline	-12.3	-5.1	0.0	-0.1	0.1	-4.4	-1.0	0.7	0.0

	Grain NIR Measurements							
	Shattering percent %	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
Morex/? vs ?/Morex	0.1	-0.1	3.3	-0.1	0.1	0.0	0.2*	-0.5*
Harrington/? vs ?/Harrington	-0.2	0.1	2.5	0.0	0.1	0.0	-0.2*	-0.6**
Mnuet/? vs ?/Menuet	-0.4	0.5	0.6	0.0	-0.1	0.0	-0.1	0.9**
Piroline/? vs ?/Piroline	0.0	-0.1	-1.4	0.0	-0.14*	0.0	0.1	0.2

*,** Significant at the P < 0.05, 0.01 respectively.

used as the male parent (Table 2). With further statistical analysis of individual reciprocal crosses, Harrington/Morex, and Morex/Menuet, had significantly higher shattering than their reciprocals (Table 3). Individual crosses and their reciprocals showed that Menuet/Morex had a significantly higher bundle weight, plant height, malt extract and viscosity but lower protein content than its reciprocal. Difference between reciprocals for harvest index, seeds/spike, kernel weight, heading, tiller breakage, hardness, moisture, and fat was not detected in individual crosses (Table 3).

Reciprocal differences in two-rowed/two-rowed crosses were found mainly with the Harrington crosses. When Harrington was used as the female parent, bundle weight, grain yield and tillers/unit area were higher, but tiller breakage, protein and viscosity were lower (Table 2). Most of these reciprocal differences were due to the individual crosses of Harrington with Piroline (Table 3). The only other reciprocal differences found for the two-rowed parents were for Piroline as female when moisture was lower and for Menuet as female when viscosity was higher (Table 2). In general reciprocal differences are not found in barley crosses (27). However, in Fejer and Fedak's study (21) reciprocal differences were found for grain yield and yield components/plant in 16 hybrid combinations.

Comparison Between Hybrids and the "Best" Parents

The following summary is deduced from Tables 4 through 11:

Traits	Significant Heterosis (%)
I. Biomass	
i. bundle weight	10.2 to 27.6
ii. harvest index	-25.0 to -8.1, and 11.4
iii. grain yield	-29.2, and 14.2 to 36.1

Table 3. Treatment mean differences between individual crosses and reciprocals (See Table 26).

	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Plant height cm	Heading date days fr 1/1	Tiller breakage %
Morex/Hrn vs Hrn/Morex 1/	-15.4	-5.1	0.0	0.6	0.1	-5.8	2.2	1.2	0.7
Morex/Menuet vs Menuet/Morex	-24.2*	-6.0	0.0	-0.5	-0.9	-3.4	-8.3**	1.0	-0.3
Morex/Pon vs Pon/Morex	7.4	4.4	0.0	-0.6	0.5	4.6	-0.2	-0.2	0.3
Hrn/Menuet vs Menuet/Hrn	22.0	7.4	0.0	-0.5	-0.8	8.4	-1.8	-0.1	-0.3
Hrn/Pon vs Pon/Hrn	30.0**	13.1*	0.0	0.2	-0.4	11.9*	2.5	-0.7	-0.3
Menuet/Pon vs Pon/Menuet	-0.5	-2.2	0.0	0.6	-0.3	-3.4	0.7	-1.0	0.0

	Grain NIR measurements							
	Shattering percent %	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
Morex/Hrn vs Hrn/Morex	-1.0**	-0.2	4.0	0.0	0.1	0.0	0.3	-0.2
Morex/Menuet vs Menuet/Morex	1.0**	-0.5*	2.1	0.0	0.1	0.1	0.5*	-1.1**
Morex/Pon vs Pon/Morex	0.3	0.2	3.9	0.0	0.2	0.1	0.1	0.0
Hrn/Menuet vs Menuet/Hrn	0.0	-0.3	-4.8	-0.1**	0.2	0.1	0.1	-0.3
Hrn/Pon vs Pon/Hrn	-0.3	0.3	1.3	0.0	0.2	0.0	0.3	-1.1**
Menuet/Pon vs Pon/Menuet	-0.2	-0.2	-1.0	0.0	0.1	0.0	0.1	0.7

1/ Hrn - Harrington; Pon - Piroline.
*,** Significant at the P < 0.05, 0.01 respectively.

Table 4. Treatment mean difference between hybrid and the "best" parent.

F1 (1/) vs "best" parent (2/)	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Shattering percent %	Tiller breakage %
Morex/Klages vs Klages	-14.3	-13.4**	-0.1**	-0.4	6.3**	-16.8**	-3.5**	0.6
Morex/Harrington vs Harrington	6.2	2.8	0.0	-0.7*	8.9**	-5.6	-1.7**	1.3
Morex/Menuet vs Menuet	30.3**	9.4**	0.0	-0.6	11.8**	-0.6	-3.0**	0.9
Morex/Piroline vs Piroline	25.0**	3.5	-0.03*	-0.8**	11.6**	-8.5**	-1.8**	0.2
Harrington/Klages vs Klages	22.2*	5.5	0.0	1.0**	0.0	2.8	0.0	0.3
Harrington/Menuet vs Menuet	16.9*	8.1*	0.0	1.3**	3.4**	0.5	0.0	0.1
Harrington/Piroline vs Piroline	41.5**	21.7**	0.04*	0.7*	1.0*	17.6**	-0.2	0.2
Menuet/Klages vs Klages	14.4	12.9**	0.04*	1.6**	1.0*	7.0	0.0	0.2
Menuet/Piroline vs Piroline	33.2**	15.9**	0.0	0.9**	4.3**	7.6*	0.1	-0.1
Piroline/Klages vs Klages	36.6**	20.9**	0.04*	1.5**	-1.8**	18.5**	0.0	-0.3

1/ Reciprocals are averaged except for Klages crosses.
2/ Parents are averaged.
*, ** Significant at $P < 0.05$, 0.01, respectively.

Table 5. Treatment mean difference for plant height and heading date between hybrid and the tallest parent and earliest parent, respectively.

F1 (1/) vs "tallest" parent (2/)	Plant height cm	F1 (1/) vs "earliest" parent (2/)	Heading date day fr 1/1
Morex/Klages vs Morex	8.2**	Morex/Klages vs Morex	-0.3
Morex/Harrington vs Morex	6.9**	Morex/Harrington vs Morex	-0.7
Morex/Menuet vs Morex	0.0	Morex/Menuet vs Morex	-0.8
Morex/Piroline vs Morex	8.9**	Morex/Piroline vs Morex	-0.3
Harrington/Klages vs Klages	0.7	Harrington/Klages vs Harrington	-0.9
Harrington/Menuet vs Menuet	3.4	Harrington/Menuet vs Menuet	-2.1**
Harrington/Piroline vs Piroline	4.8**	Harrington/Piroline vs Piroline	-1.2*
Menuet/Klages vs Klages	2.6	Menuet/Klages vs Menuet	-1.3*
Menuet/Piroline vs Piroline	2.7	Menuet/Piroline vs Menuet	-0.8
Piroline/Klages vs Piroline	1.4	Piroline/Klages vs Piroline	-1.8*

1/ Reciprocals are averaged except for Klages crosses.
2/ Parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Table 6. Treatment mean difference for malting characteristics between hybrid and the "best" parent.

	Grain NIR Measurements			
F1 (1/) vs "best" parent (2/)	Malt extract %	Hardness no.	Protein %	Viscosity cp
Morex/Klages vs Morex	-1.0**	7.5**	1.1**	-1.1**
Morex/Harrington vs Morex	-0.8**	4.4*	0.7**	-0.6
Morex/Menuet vs Morex	-1.5**	6.2**	1.5**	-0.8**
Morex/Piroline vs Morex	-1.4**	7.9**	1.4**	-1.8**
Harrington/Klages vs Klages	-0.2	-7.2**	-0.1	0.7*
Harrington/Menuet vs Harrington	0.8**	-3.7	-0.1	0.4
Harrington/Piroline vs Harrington	1.4**	0.8	-0.4**	-0.4
Menuet/Klages vs Klages	-0.1	-3.8	-0.1	1.9**
Menuet/Piroline vs Piroline	0.3*	-3.0	-0.4**	0.8**
Piroline/Klages vs Piroline	1.6**	4.7**	-1.2	1.0**

1/ Reciprocals are averaged except for Klages crosses.
2/ Parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Table 7. Treatment mean difference for quality characteristics between hybrid and the "best" parent.

	Grain NIR Measurements		
F1 (1/) vs "best" parent (2/)	Lysine %	Moisture %	Fat %
Morex/Klages vs Klages	-0.01	0.2**	-0.24**
Morex/Harrington vs Harrington	-0.03*	0.3**	-0.22**
Morex/Menuet vs Menuet	0.0	0.1*	-0.27**
Morex/Piroline vs Piroline	0.01	0.0	-0.37**
Harrington/Klages vs Klages	-0.03*	0.0	-0.04*
Harrington/Menuet vs Menuet	-0.03*	0.0	-0.10**
Harrington/Piroline vs Piroline	-0.03*	0.0	-0.21**
Menuet/Klages vs Klages	-0.02*	-0.2**	-0.15**
Menuet/Piroline vs Piroline	-0.02*	-0.1*	-0.06**
Proline/Klages vs Klages	0.0	-0.1*	-0.22**

1/ Reciprocals are averaged except for Klages.
2/ parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Table 8. Percent difference between hybrid and the "best" parent.

F1 (1/) vs "best" parent (2/)	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Shattering percent %
Morex/Klages vs Klages	-8.5	-29.2**	-25.0**	-1.7	14.3**	-30.4**	-100.0**
Morex/Harrington vs Harrington	3.9	5.5	0.0	-2.8*	21.8**	-11.3	-300.0**
Morex/Menuet vs Menuet	27.6**	25.5**	0.0	-2.5	30.6**	-1.5	-600.0**
Morex/Piroline vs Piroline	17.2**	6.4	-8.1*	-3.3*	31.0**	-14.3**	-257.0**
Harrington/Klages vs Klages	13.2*	9.3	0.0	4.1**	0.0	5.1	0.0
Harrington/Menuet vs Menuet	10.2*	14.2*	0.0	5.3**	8.4**	0.9	0.0
Harrington/Piroline vs Piroline	24.6**	36.1**	11.4*	2.8*	2.5*	30.0**	0.0
Menuet/Klages vs Klages	8.6	21.8**	11.4*	6.6**	2.3*	12.6	0.0
Menuet/Piroline vs Piroline	23.4**	30.7**	0.0	3.6**	11.6**	13.8*	0.0
Piroline/Klages vs Klages	21.8**	35.2**	11.4*	6.2**	-4.3**	33.4**	0.0

1/ Reciprocals are averaged except for Klages.
2/ parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Table 9. Percent difference for plant height and heading date between hybrid and the tallest parent and earliest parent, respectively.

F1 (1/) vs "tallest" parent (2/)	Plant Height cm	F1 (1/) vs "earliest" parent (2/)	Heading date days fr 1/1
Morex/Klages vs Morex	11.6**	Morex/Klages vs Morex	-0.15
Morex/Harrington vs Morex	9.4**	Morex/Harrington vs Morex	-0.36
Morex/Menuet vs Morex	0.0	Morex/Menuet vs Morex	-0.41
Morex/Piroline vs Morex	12.1**	Morex/Piroline vs Morex	-0.15
Harrington/Klages vs Klages	1.0	Harrington/Klages vs Harrington	-0.45
Harrington/Menuet vs Menuet	5.0	Harrington/Menuet vs Menuet	-1.07**
Harrington/Piroline vs Piroline	6.7**	Harrington/Piroline vs Piroline	-0.61*
Menuet/Klages vs Klages	3.8	Menuet/Klages vs Menuet	-0.66*
Menuet/Piroline vs Piroline	3.8	Menuet/Piroline vs Menuet	-0.40
Piroline/Klages vs Piroline	2.0	Piroline/Klages vs Piroline	-0.91*

1/ Reciprocals are averaged except for Klages crosses.
2/ Parents are averaged.
*, ** Significant at $P < 0.05$, 0.01, respectively.

Table 10. Percent difference for malting characteristics between hybrid and the "best" parent.

	Grain NIR Measurements			
F1 (1/) vs "best" parent (2/)	Malt extract %	Hardness no.	Protein %	Viscosity cp
Morex/Klages vs Morex	-1.42**	49.34**	8.87**	-5.26**
Morex/Harrington vs Morex	-1.04**	28.95*	5.65**	-2.87
Morex/Menuet vs Morex	-1.94**	40.79**	12.10**	-3.83**
Morex/Piroline vs Morex	-1.81**	51.97**	11.29**	-8.61**
Harrington/Klages vs Klages	-0.26	-25.81**	-0.78	3.76*
Harrington/Menuet vs Harrington	1.05**	-20.00	-0.76	2.06
Harrington/Piroline vs Harrington	1.83**	4.32	-3.05**	-2.06
Menuet/Klages vs Klages	-0.13	-13.62	-0.78	10.22**
Menuet/Piroline vs Piroline	0.40*	-16.76	-2.90**	4.30**
Piroline/Klages vs Piroline	2.12**	26.26**	-8.69**	5.38*

1/ Reciprocals are averaged except for Klages crosses.
2/ Parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Table 11. Percent difference for quality characteristics between hybrid and the "best" parent.

	Grain NIR Measurements		
F1 (1/) vs "best" parent (2/)	Lysine %	Moisture %	Fat %
Morex/Klages vs Klages	-2.00	3.17**	-10.00**
Morex/Harrington vs Harrington	-6.00*	4.76**	-9.56**
Morex/Menuet vs Menuet	0.0	1.58*	-10.80**
Morex/Piroline vs Piroline	-2.00	0.0	-14.80**
Harrington/Klages vs Klages	-6.00*	0.0	-1.66*
Harrington/Menuet vs Menuet	-6.00*	0.0	-4.00**
Harrington/Piroline vs Piroline	-6.00*	0.0	-8.40**
Menuet/Klages vs Klages	-4.00*	-3.17**	-6.00**
Menuet/Piroline vs Piroline	-4.00*	-1.58*	-2.40**
Proline/Klages vs Klages	0.0	-1.56*	-8.80**

1/ Reciprocals are averaged except for Klages.
2/ parents are averaged.
*, ** Significant at P < 0.05, 0.01, respectively.

Traits	Significant heterosis (%)
II. Yield Components	
i. seeds/spike	-3.3 to -1.7, and 2.2 to 6.6
ii. 1000 kernel weight	-4.3, and 2.3 to 31.0
iii. tillers/unit area	-30.4 to -14.3, and 13.8 to 33.4
III. Agronomic Characteristics	
i. plant height	6.73 to 11.16
ii. heading date	-1.7 to -0.61
iii. shattering percent	-600.0
IV. Malting Traits	
i. malt extract	-1.94 to -1.04, and 0.40 to 2.12
ii. protein	-8.69 to -3.5, and 5.65 to 12.10
V. Other Quality Traits	
i. hardness	-25.81 and 26.26 to 51.97
ii. lysine	-6.00 to -4.00
iii. grain moisture	-3.17 to -1.56, and 1.58 to 4.76
iv. fat	-14.80 to -1.66
v. viscosity	-8.61 to -3.83 and 3.76 to 10.22

In the present study seven out of ten comparisons showed increased bundle weight and grain yield of hybrids over the best parent. Pawlisch (43) also showed increased biomass for F1 hybrids. An increase in bundle weight leads to an increase in grain yield (9 and 10). The present study also shows the same relationship between bundle weight and the grain yield in five out of ten comparisons.

Six-rowed/Two-rowed Crosses

Studies in the past, using genetic male sterility as a crossing tool have shown increases up to 30.0 to 40.0% in grain yield of barley hybrids over the best parents (47). In 1989 Eckhoff and Ramage (18) showed that 16 of 22 hybrids outyielded their respective "high" parents when the cytoplasmic male sterile system was used in crossing. An increase in grain production was found in this study in six of ten cases (14.2 to 36.1%),one

of the exceptions i.e., Morex/Klages, showed a significant decline of about 29.0% in grain yield as compared to Klages (Table 4). Two-rowed parents typically have a higher number of tillers than six-rowed cultivars (30). Klages being two-rowed has a high number of tillers per hill (53.7) whereas the hybrid in this case has a reduced number of tillers (38.5) due to its six-rowed parent, Morex (Table 27). In this instance Klages has a significantly higher number of tillers/unit area than the hybrid which outweighed the hybrid's significantly higher kernel weight (Table 4). For positive yield heterosis a favorable combination of yield components must be present. Previous studies indicated a positive relationship between the grain yield and number of tillers (7), and the same phenomenon was observed in the present study. The Morex/Menuet cross has significantly higher grain yield than its best parent, Menuet, because the 1000 kernel weight of the hybrid was very high and no compensating effects were found for seeds/spike or tillers (Table 4). The Morex/Piroline hybrid does not have significant heterosis for grain yield because its high 1000 kernel weight is compensated for by significantly lower tillers/unit area and seeds/spike when compared to Piroline (Table 4).

Six-rowed/two-rowed combinations showed significantly higher shattering than the two-rowed parent in all four comparisons for the F1 (Table 4). In crosses of two-rowed/six-rowed barley the complementary genes for brittle rachis Bt1 and Bt2 often come together in the F1 hybrid causing severe shattering. Apparently Morex has one of the Bt genes and the two-rowed parents the other (30). One study showed that heading date is controlled by a polygenic system with additive effects (55).

Two-rowed/Two-rowed Crosses

In two-rowed/two-rowed crosses the hybrid seed/spike was significantly higher than the best parent in all six comparisons, for kernel weight in five of six comparisons and tiller numbers in three of six comparisons. the two-rowed/two-rowed hybrids also have higher bundle weight than their respective best parents in five of six cases (Table 4).

Harrington/Klages has higher grain yield than Klages because of its higher seed no./spike. Harrington/Menuet, and Menuet/Klages have significantly higher grain yield than Menuet and Klages due to the hybrid's higher no. of seeds/spike and 1000 kernel weight (Table 4). The Harrington/Piroline and Menuet/Piroline hybrid is higher in grain yield than its best parent because the former has significantly higher yield components. Piroline/Klages also has higher grain yield than its best parent because the hybrid has more seeds/spike and tillers/unit area which outweighed the higher 1000 kernel weight of the parent. A previous study has shown that there is a negative correlation between kernel/spike and kernel weight as well as between kernel weight and grain yield (26). Spikes/plant and kernels/spike are significantly correlated with grain yield (8,16, 20, and 57). The greatest effect on grain yield is caused by kernels/spike (17) and spikes/plant (16). In contrast to Grafius's study (26), literature indicates that the effect of kernel weight on yield is mostly positive but not as effective as the rest of the yield components (27). In a hill study by Eckhoff and Ramage (18) only two of 22 hybrids had greater 1000 kernel weight than their high parents but in this study eight of ten hybrids have significantly higher kernel weight than their best parents (Table 4).

Hybrids also showed significant heterosis for increased plant height in four of ten comparisons, three of these hybrids are six-rowed/two-rowed crosses (Table 5). Days to heading were significantly reduced for hybrids in four of ten comparisons compared to the best parent all in two-rowed/two-rowed crosses (Table 5).

Malt extract was significantly lower in the hybrids for all the six-rowed/two-rowed crosses. However, in three of six of the two-rowed/two-rowed crosses the hybrids were significantly higher in NIR malt extract (Table 6). Hardness and grain protein were significantly higher in all six-rowed/two-rowed hybrids than Morex, while the two-rowed/two-rowed crosses varied for hardness and were lower than the parents in grain

protein in three of six cases (Table 6). Viscosity was significantly higher in the six-rowed parent than the hybrids in all 4 six-rowed/two-rowed crosses, while the reverse was true in four of six two-rowed/two-rowed crosses (Table 6).

Table 7 gives the results for other quality characteristics. Grain fat content as measured by the NIR was consistently lower in the hybrid than in the best parent for all crosses, while lysine content was lower in the hybrid in six of the ten comparisons.

Analysis of variance tables show that replications were significantly different from each other at 0.05 and 0.01 level of significance (Table 13 through 27). This was probably due to heterogeneity between replications because of the ground slope from west to east and some Canadian thistle in replication 5.

General and Specific Combining Ability

General combining ability (GCA) is defined as "The general combining ability of a particular inbred is determined by its average performance in a series of hybrid combinations" and specific combining ability (SCA) is defined as "the performance of two particular inbreds in a specific cross (44). Analysis of variance indicates that GCA is significant for all characteristics except lysine (Table 12). SCA is only significant for kernel weight (Table 12).

Hockett (27) has reviewed the importance of GCA and SCA for many of these traits and found that in 17 of 36 studies SCA was more important while GCA was important in only seven of 36 studies for grain yield. In five other studies both SCA and GCA were equally important for grain yield. Hockett (27) while reviewing for SCA and GCA for grain yield also found that in two studies both combining abilities were affected by the environment but SCA was more sensitive to environmental effects than GCA while another study showed that SCA and GCA are equally vulnerable to the environment. In 21 of 24, 19 of 26 and 15 of 17 studies GCA was more

important than SCA for spike-number, kernels/spike and kernel weight respectively. Hockett's review (27) has also shown that in 15 of 17 studies GCA was four times more important than SCA for plant height. In two studies on malt extract one study has indicated that both GCA and SCA are equally important whereas in the other study only GCA is important for malt extract (27). The present study has also shown that GCA is significant for all the traits (data on plant height, heading date, and shattering was not analyzed for GCA and SCA) except lysine whereas SCA is only significant for kernel weight (Table 12).

Hockett's literature review (27) shows that in 4 of 4 studies heterosis for bundle weight (plant weight) is due to additive gene action. In other three studies reported in this review (27) dominance and overdominance is involved in heterosis for bundle weight. Dominance was significantly important for grain yield heterosis in two studies (27). In another study reported in Hockett's review (27), gene action for malt extract was additive whereas two different studies showed that gene action was dominant and/or showed epistasis for heterosis in malt extract.

Table 12. Mean squares of General combining ability (GCA) and Specific combining ability (SCA) of parents.

	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.
General combining ability	3695.4**	1714.0**	0.02**	20.03**	338.1**	2447.5**
Specific combining ability	249.5	94.0	0.00	0.27	262.1**	180.5

	Grain NIR Measurements						
	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
General combining ability	4.2**	189.3**	0.0	0.2**	0.4**	4.2**	6.7**
Specific combining ability	0.5	57.5	0.0	0.0	0.0	0.2	0.7

*, ** Significant at P < 0.05, 0.01, respectively.

CONCLUSIONS

My results from this study show that heterosis for grain yield is from 14.2 to 36.1% whereas heterosis for bundle weight is from 10.2 to 27.6% in favorable hybrid combinations. Days to heading were significantly reduced in four of ten hybrid combinations which may be useful for the production of barley in arid and semi-arid areas where available water at the time of anthesis is the limiting factor. Protein contents were also lowered in some hybrid combinations. When the six-rowed cultivar (Morex) was crossed with a two-rowed parent, significant shattering occurred in individual crosses. Therefore, one has to be careful in making six-rowed/two-rowed crosses because the parents may have complementary genes for shattering. NIR is a reliable technique for estimating malting quality (most of the time) and other quality traits. GCA was more important than SCA for the biomass, agronomic, malting quality and other quality traits. SCA was important only for kernel weight. The cytoplasmic male sterile system is another alternative for producing hybrid barley. Reciprocal differences are present in some hybrid combinations but not in others. In this study all three yield components played an important role in increased grain yield production.

Some thoughts for future research are: (1) More sources of germplasm need to be explored to find out better parents in terms of grain yield, and malting quality. (2) F2 plants obtained from F1 hybrid barley need to be tested for heterosis of desirable traits. If we find enough heterosis, we can use F2 populations as an alternate and cheaper source for high yield and enough malting quality to satisfy both farmers and brewery industry.

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APPENDIX

Table 13. Analysis of variance for bundle weight.

Source	df	SS	MS	F-ratio	P-value
Reps	5	1470.96	2942.19	6.70*	0.00
Entries	15	96496.68	6433.11	14.66**	0.00
Parent	3	18888.39	6296.13	14.35**	0.00
Heterosis	1	59254.36	59254.36	135.03**	0.00
Crosses	11				
GCA	3	11086.32	3695.44	8.42**	0.00
SCA	2	498.98	249.49	0.57	0.57
Maternal	3	5193.75	1731.25	3.94**	0.01
Reciprocal	3	1574.90	524.97	1.19	0.31
Error	147	64508.27	438.83		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 14. Analysis of variance for grain yield.

Source	df	SS	MS	F-ratio	P-value
Reps	5	1173.00	234.60	2.36*	0.04
Entries	15	18581.00	1238.73	12.46**	0.00
Parent	3	3843.00	1281.00	12.88**	0.00
Heterosis	1	8465.00	8465.00	85.16**	0.00
Crosses	11				
GCA	3	5144.00	1714.00	17.24**	0.00
SCA	2	188.00	94.00	0.95	0.39
Maternal	3	712.00	237.00	2.38	0.07
Reciprocal	3	229.00	76.00	0.76	0.52
Error	147	14612.00	99.40		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 15. Analysis of variance for harvest index.

Source	df	SS	MS	F-ratio	P-value
Reps	5	0.0453	0.0091	6.15**	0.00
Entries	15	0.0840	0.0056	3.06**	0.00
Parent	3	0.0266	0.0089	6.03**	0.00
Heterosis	1	0.0060	0.0060	4.10*	0.04
Crosses	11				
GCA	3	0.0480	0.016	10.88**	0.00
SCA	2	0.00081	0.00041	0.28	0.76
Maternal	3	0.00189	0.00063	0.43	0.73
Reciprocal	3	0.00067	0.00022	0.15	0.93
Error	147	0.2163	0.00147		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 16. Analysis of variance for number of seeds/spike.

Source	df	SS	MS	F-ratio	P-value
Reps	5	13.50	2.70	2.39*	0.04
Entries	15	26101.82	1740.12	1542.93**	0.00
Parent	3	22876.60	7625.53	6761.41**	0.00
Heterosis	1	3159.71	3159.71	2801.65**	0.00
Crosses	11				
GCA	3	60.10	20.03	17.76**	0.00
SCA	2	0.54	0.27	0.24	0.79
Maternal	3	2.82	0.94	0.83	0.48
Reciprocal	3	2.07	0.69	0.61	0.61
Error	147	165.79	1.13		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 17. Analysis of variance for 1000 kernel weight.

Source	df	SS	MS	F-ratio	P-value
Reps	5	101.85	20.37	10.99**	0.00
Entries	15	4673.79	311.59	168.14**	0.00
Parent	3	687.68	229.23	123.70**	0.00
Heterosis	1	2955.03	2955.03	1594.61**	0.00
Crosses	11				
GCA	3	1014.42	338.14	182.47**	0.00
SCA	2	524.10	262.05	141.41**	0.00
Maternal	3	2.73	0.91	0.49	0.69
Reciprocal	3	2.99	0.99	0.54	0.66
Error	147	272.41	1.85		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 18. Analysis of variance for number of tillers/hill.

Source	df	SS	MS	F-ratio	P-value
Reps	5	849.99	169.99	2.26*	0.05
Entries	15	33102.96	2206.86	29.32**	0.00
Parent	3	19323.89	6441.30	85.58**	0.00
Heterosis	1	5206.42	5206.42	69.17**	0.00
Crosses	11				
GCA	3	7342.55	2447.52	32.52**	0.00
SCA	2	360.91	180.46	2.40	0.09
Maternal	3	706.01	235.34	3.13*	0.03
Reciprocal	3	163.18	54.39	0.72	0.54
Error	147	11064.08	75.27		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 19. Analysis of variance for malt extract.

Source	df	SS	MS	F-ratio	P-value
Reps	5	4.60	0.92	6.87**	0.00
Entries	15	59.59	3.97	29.68**	0.00
Parent	3	44.46	14.82	110.71**	0.00
Heterosis	1	0.07	0.07	0.54	0.46
Crosses	11				
GCA	3	12.65	4.22	31.50**	0.00
SCA	2	0.89	0.45	3.32*	0.04
Maternal	3	0.49	0.16	1.22	0.30
Reciprocal	3	1.02	0.34	2.54	0.06
Error	147	19.68	0.13		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 20. Analysis of variance for hardness.

Source	df	SS	MS	F-ratio	P-value
Reps	5	6225.84	1245.17	35.75**	0.00
Entries	15	1143.46	76.23	2.19*	0.01
Parent	3	147.73	49.24	1.41	0.24
Heterosis	1	129.14	129.14	3.71	0.06
Crosses	11				
GCA	3	567.89	189.30	5.43**	0.00
SCA	2	114.98	57.49	1.65	0.20
Maternal	3	132.68	44.23	1.27	0.29
Reciprocal	3	51.03	17.01	0.49	0.69
Error	147	5120.28	34.83		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 21. Analysis of variance for lysine.

Source	df	SS	MS	F-ratio	P-value
Reps	5	0.10	0.02	24.96**	0.00
Entries	15	0.04	0.003	3.33**	0.00
Parent	3	0.02	0.01	8.32**	0.00
Heterosis	1	0.004	0.004	4.99*	0.03
Crosses	11				
GCA	3	0.0058	0.0019	2.41	0.07
SCA	2	0.0015	0.00075	0.93	0.40
Maternal	3	0.0044	0.0015	1.83	0.14
Reciprocal	3	0.0026	0.00087	1.08	0.36
Error	147	0.1178	0.0008		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 22. Analysis of variance for moisture.

Source	df	SS	MS	F-ratio	P-value
Reps	5	3.63	0.73	21.78**	0.00
Entries	15	1.81	0.12	3.62**	0.00
Parent	3	0.27	0.09	2.70*	0.05
Heterosis	1	0.44	0.44	13.20**	0.00
Crosses	11				
GCA	3	0.72	0.24	7.20**	0.00
SCA	2	0.04	0.02	0.60	0.55
Maternal	3	0.28	0.09	2.80*	0.04
Reciprocal	3	0.06	0.02	0.60	0.62
Error	147	4.90	0.03		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 23. Analysis of variance for fat.

Source	df	SS	MS	F-ratio	P-value
Reps	5	0.96	0.192	27.54**	0.00
Entries	15	4.97	0.331	47.53**	0.00
Parent	3	3.21	1.07	153.48**	0.00
Heterosis	1	0.48	0.48	68.85**	0.00
Crosses	11				
GCA	3	1.23	0.41	58.81**	0.00
SCA	2	0.0002	0.0001	0.014	0.99
Maternal	3	0.02	0.007	0.96	0.41
Reciprocal	3	0.033	0.011	1.58	0.20
Error	147	1.02	0.007		

*,** Significant at the P < 0.05, 0.01, respectively.

Table 24. Analysis of variance for protein.

Source	df	SS	MS	F-ratio	P-value
Reps	5	8.03	1.61	13.71**	0.00
Entries	15	43.99	2.93	25.03**	0.00
Parent	3	29.60	9.87	84.21**	0.00
Heterosis	1	0.41	0.41	3.50	0.06
Crosses	11				
GCA	3	12.46	4.15	35.45**	0.00
SCA	2	0.29	0.15	1.24	0.29
Maternal	3	0.75	0.25	2.13	0.10
Reciprocal	3	0.48	0.16	1.37	0.25
Error	147	17.22	0.12		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 25. Analysis of variance for viscosity.

Source	df	SS	MS	F-ratio	P-value
Reps	5	59.65	11.93	21.48**	0.00
Entries	15	109.92	7.33	13.20**	0.00
Parent	3	67.27	22.44	40.38**	0.00
Heterosis	1	9.15	9.15	16.48**	0.00
Crosses	11				
GCA	3	20.13	6.71	12.08**	0.00
SCA	2	1.32	0.66	1.19	0.31
Maternal	3	10.80	3.60	6.48**	0.00
Reciprocal	3	1.26	0.42	0.76	0.52
Error	147	81.63	0.56		

*,** Significant at the P < 0.05, 0.01 respectively.

Table 26. Treatment means (5 hills/plot, 6 reps).

	Bundle weight gm	Grain yield gm	Harvest index	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Plant height 1/ cm	Heading date 1/ days fr 1/1	Shattering percent 1/ %
Morex/Klages	153.8	45.87	0.30	23.70	50.48	38.52	81.67	194.0	3.50
Morex/Harrington	166.5	53.73	0.32	24.55	49.74	44.16	81.50	194.2	1.17
Morex/Menuet	140.2	46.20	0.34	23.83	50.35	38.68	69.33	194.0	3.50
Morex/Piroline	170.5	58.46	0.34	23.59	48.99	50.79	82.33	193.8	2.00
Harrington/Morex	181.9	58.81	0.32	23.99	49.69	49.91	79.33	193.0	2.17
Harrington/Klages	190.2	64.80	0.34	25.13	44.22	58.08	68.50	196.5	0.00
Harrington/Menuet	181.5	65.29	0.36	25.99	43.82	57.35	70.00	194.7	0.00
Harrington/Piroline	210.1	81.73	0.39	25.71	41.62	76.25	77.33	195.5	0.00
Menuet/Morex	164.4	52.22	0.31	24.36	51.21	42.06	77.67	193.0	2.50
Menuet/Harrington	159.5	57.89	0.36	26.44	44.65	48.98	71.83	194.8	0.00
Menuet/Klages	182.4	72.15	0.39	25.73	45.24	62.35	71.17	195.5	0.00
Menuet/Piroline	174.8	67.64	0.38	26.11	41.30	62.84	74.33	195.5	0.00
Piroline/Morex	163.1	54.08	0.33	24.21	48.50	46.21	82.50	194.2	1.67
Piroline/Harrington	180.1	68.59	0.38	25.55	42.01	64.32	74.83	196.2	0.33
Piroline/Klages	204.6	80.22	0.39	25.56	42.46	73.84	72.67	195.2	0.00
Piroline/Menuet	175.3	69.85	0.39	25.47	41.61	66.28	73.67	196.5	0.17
Morex	107.6	35.70	0.32	60.35	33.61	17.79	73.83	194.8	0.00
Klages	170.5	60.27	0.35	23.88	44.12	57.04	67.00	197.7	0.00
Harrington	161.6	57.62	0.35	24.65	41.66	56.28	67.50	196.7	0.00
Menuet	127.6	42.58	0.33	25.44	38.47	43.32	69.67	196.3	0.00
Piroline	143.2	54.25	0.38	24.93	36.68	58.93	71.67	196.7	0.00
Harrington	157.8	55.61	0.35	24.93	40.77	54.86	66.00	197.5	0.00
Morex	125.1	44.90	0.35	61.83	33.62	21.65	71.17	194.5	0.00
Klages	166.0	58.77	0.35	24.28	44.22	54.34	66.17	198.5	0.00
Menuet	121.3	40.18	0.33	24.96	39.13	40.99	66.50	196.8	0.00
Piroline	141.2	52.41	0.36	25.14	36.82	56.26	71.50	196.7	0.00
Menuet	113.4	35.67	0.30	24.84	38.31	36.89	66.50	196.7	0.00
Morex	132.1	46.57	0.35	60.88	33.64	22.83	74.50	194.0	0.00
Harrington	150.4	51.99	0.34	24.75	40.84	51.68	67.50	197.8	0.00
Klages	172.3	60.32	0.35	24.13	44.68	55.84	69.83	198.8	0.00
Piroline	146.1	53.92	0.36	24.73	37.67	58.14	71.83	197.0	0.00
Piroline	136.9	50.72	0.36	24.67	37.43	54.55	70.17	197.7	0.00
Morex	115.1	37.98	0.32	58.87	33.53	19.11	74.50	194.0	0.00
Harrington	144.8	48.80	0.33	25.40	40.06	47.75	69.00	197.7	0.00
Klages	163.4	57.78	0.34	24.12	43.88	54.08	68.33	198.2	0.00
Menuet	125.8	40.89	0.31	23.55	40.14	42.75	67.50	197.5	0.00

Table 26. Continued.

	Tiller breakage 1/ %	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
Morex/Klages	1.00	76.19	22.67	0.49	6.46	2.16	13.52	18.94
Morex/Harrington	1.67	76.43	21.62	0.47	6.63	2.06	13.27	19.34
Morex/Menuet	1.00	75.55	22.46	0.50	6.38	2.26	14.09	18.62
Morex/Piroline	0.50	76.00	25.03	0.48	6.61	2.09	13.75	18.03
Harrington/Morex	1.00	76.58	17.65	0.47	6.51	2.10	13.00	19.52
Harrington/Klages	0.67	76.95	20.68	0.47	6.24	2.34	12.78	19.29
Harrington/Menuet	0.17	76.29	12.41	0.45	6.40	2.42	13.00	19.47
Harrington/Piroline	0.17	77.16	19.96	0.46	6.51	2.27	12.53	18.61
Menuet/Morex	1.33	76.05	20.36	0.50	6.32	2.19	13.63	19.69
Menuet/Harrington	0.50	76.54	17.22	0.50	6.22	2.37	13.09	20.50
Menuet/Klages	0.67	77.08	24.14	0.48	6.47	2.35	12.82	20.46
Menuet/Piroline	0.00	75.84	14.43	0.47	6.35	2.45	13.49	19.72
Piroline/Morex	0.17	75.76	21.11	0.49	6.46	2.17	13.84	18.28
Piroline/Harrington	0.50	76.88	18.70	0.47	6.32	2.31	12.79	19.69
Piroline/Klages	0.17	77.25	22.64	0.50	6.28	2.28	12.65	19.58
Piroline/Menuet	0.00	76.02	15.42	0.48	6.27	2.43	13.36	18.98
Morex	21.33	77.09	15.02	0.45	6.40	2.07	12.55	21.03
Klages	0.17	77.19	28.96	0.48	6.30	2.28	12.85	18.48
Harrington	0.17	76.56	13.89	0.46	6.38	2.28	12.83	19.74
Menuet	0.17	75.61	13.23	0.46	6.32	2.56	13.64	20.11
Piroline	0.00	75.63	13.42	0.45	6.37	2.52	13.55	18.78
Harrington	0.00	76.69	19.57	0.47	6.33	2.27	12.96	19.68
Morex	6.67	77.60	12.96	0.43	6.41	2.11	12.01	20.65
Klages	0.50	77.30	25.02	0.47	6.35	2.37	12.61	18.64
Menuet	0.17	75.89	13.39	0.47	6.24	2.61	13.43	19.82
Piroline	0.17	75.51	15.38	0.46	6.42	2.57	13.70	18.25
Menuet	0.33	75.58	14.98	0.48	6.20	2.58	13.75	19.46
Morex	9.67	77.43	19.21	0.45	6.41	2.10	12.42	20.69
Harrington	0.00	76.49	19.67	0.48	6.18	2.35	13.17	19.45
Klages	0.50	77.24	29.74	0.51	6.16	2.37	12.89	18.65
Piroline	0.17	75.70	22.98	0.48	6.33	2.53	13.88	18.23
Piroline	0.17	75.58	19.85	0.49	6.32	2.48	13.87	18.93
Morex	13.83	77.11	13.72	0.44	6.27	2.09	12.52	21.27
Harrington	0.17	76.40	20.76	0.49	6.16	2.35	13.29	19.53
Klages	0.67	76.98	28.05	0.50	6.18	2.39	13.05	18.78
Menuet	0.33	75.92	25.43	0.50	6.25	2.42	13.91	19.19

1/ Data is on a plot basis only, hills were ignored.

Table 27. Treatment means (5 hills/plot, 6 reps), with reciprocals averaged and parents averaged over 4 treatments.

	Bundle weight gm	Grain yield gm	Harvest index %	Seeds/ spike no.	Kernel weight mg	Tillers/ hill no.	Plant height 1/ cm	Heading date 1/ days fr 1/1	Shattering percent 1/ %
Morex/Klages	153.8	45.87	0.30	23.70	50.48	38.52	81.67	194.0	3.50
Morex/Harrington	174.2	56.20	0.32	24.27	49.72	47.04	80.42	193.6	1.67
Morex/Menuet	152.3	49.21	0.33	24.10	50.78	40.37	73.50	193.5	3.00
Morex/Piroline	166.8	56.27	0.34	23.90	48.75	48.50	82.42	194.0	1.84
Harrington/Klages	190.2	64.80	0.34	25.13	44.22	58.08	68.50	196.5	0.00
Harrington/Menuet	170.5	61.60	0.36	26.22	44.24	53.20	70.92	194.7	0.00
Harrington/Piroline	195.1	75.16	0.39	25.63	41.82	70.30	76.10	195.9	0.16
Menuet/Klages	182.4	72.15	0.39	25.73	45.24	62.35	71.17	195.5	0.00
Menuet/Piroline	175.1	68.75	0.39	25.80	41.46	64.56	74.00	196.0	0.10
Piroline/Klages	204.6	80.22	0.39	25.56	42.46	73.84	72.67	195.2	0.00
Morex	119.9	41.30	0.34	60.50	33.60	20.30	73.50	194.3	0.00
Klages	168.1	59.30	0.35	24.10	44.20	53.70	67.80	198.3	0.00
Harrington	153.7	53.50	0.34	24.90	40.80	52.60	67.50	197.4	0.00
Menuet	122.0	39.80	0.32	24.70	39.00	41.00	67.50	196.8	0.00
Piroline	141.9	52.80	0.37	24.90	37.20	57.00	71.30	197.0	0.00

	Tiller breakage 1/ %	Malt extract %	Hardness no.	Lysine %	Moisture %	Fat %	Protein %	Viscosity cp
Morex/Klages	1.00	76.19	22.67	0.49	6.46	2.16	13.52	18.94
Morex/Harrington	1.34	76.51	19.64	0.47	6.57	2.08	13.14	19.43
Morex/Menuet	1.17	75.80	21.41	0.50	6.35	2.23	13.86	19.20
Morex/Piroline	0.34	75.88	23.07	0.49	6.54	2.13	13.80	18.16
Harrington/Klages	0.67	76.95	20.68	0.47	6.24	2.34	12.78	19.29
Harrington/Menuet	0.34	76.42	14.82	0.47	6.31	2.40	13.01	19.99
Harrington/Piroline	0.34	77.02	19.33	0.47	6.42	2.29	12.66	19.15
Menuet/Klages	0.67	77.08	24.14	0.48	6.47	2.35	12.82	20.46
Menuet/Piroline	0.00	75.93	14.93	0.48	6.31	2.44	13.43	19.35
Piroline/Klages	0.17	77.25	22.64	0.50	6.28	2.28	12.65	19.58
Morex	12.90	77.30	15.20	0.40	6.40	2.10	12.40	20.90
Klages	0.50	77.20	27.90	0.50	6.30	2.40	12.90	18.60
Harrington	0.10	76.50	18.50	0.50	6.30	2.30	13.10	19.40
Menuet	0.30	75.60	13.90	0.50	6.30	2.50	13.70	19.60
Piroline	0.10	75.60	17.90	0.50	6.40	2.50	13.80	18.60

1/ Data is on a plot basis only, hills were ignored.

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