HARVEST INDEX IN WINTER WHEAT:

BREEDING AND GENETIC STUDIES

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INTRODUCTION

The four parts of this dissertation are separate and complete manuscripts to be submitted to _Crop Science_ for publication. The format of each manuscript conforms to the style of _Crop Science_.

PART I

STABILITY OF HARVEST INDEX AND GRAIN YIELD IN WINTER WHEAT

STABILITY OF HARVEST INDEX AND GRAIN YIELD IN WINTER WHEAT

ABSTRACT [1]

Ten winter wheat (Triticum aestivum L.) genotypes were grown in replicated tests at six sites in Oklahoma in each of two years to determine the stability of harvest index and grain yield. Two stability parameters were obtained as linear regression coefficient of an entry mean on the average of all entries in each environment and mean square for deviation from linear regression. Genotypes differed significantly for harvest index and grain yield. Mean values ranged from 33.0 to 41.1% for harvest index and 316 to 437 g m^{-2} for grain yield. Significant genotype x environment interactions occurred for both traits, indicating that there were differences in environmental responses among the ten genotypes for harvest index and grain yield. Regression coefficients ranged from 0.65 to 1.46 and 0.75 to 1.17 for harvest index and grain yield, respectively. Mean squares for deviation from regression were significant for most genotypes for both traits. Linear regression accounted for 50 to 89% and 85 to 99% for the variation in harvest index and grain yield, respectively. On the basis of the estimates of stability parameters, most of the ten genotypes were unstable for both traits. Average stability in terms of linear regression coefficients and high grain yield was observed for one genotype. Correlation coefficients between harvest index and grain yield changed from more favorable environments (r=-0.17) to less

[1]To be submitted for publication in Crop Science.

favorable environments (r=0.62). Harvest index was negatively correlated with plant height. This study suggested that both harvest index and grain yield are significantly affected by environmental changes. Consequently, selection for yield *per se* could be just as effective as selection for harvest index for improving wheat grain yields in the highly diverse environments of the Southern Great Plains.

Additional index words: *Triticum aestivum* L., harvest index, grain yield, stability, genotype x environment interaction.

INTRODUCTION

Genotype x environment (GE) interactions are of major concern to plant breeders in developing improved cultivars. In order for a cultivar to be commercially successful it must perform well over the range of environments in which the cultivar may be grown. Stability of a cultivar refers to its consistency in performance over environments and is affected by the presence of GE interactions. The presence of GE interactions reduces the correlation between phenotype and genotype and makes it difficult to judge the genetic potential of a genotype. Plant breeders grow performance tests at different sites (locations) in different years in the target area. The data obtained from these tests are used to determine the magnitude of GE interactions. In the presence of significant GE interactions, stability parameters need to be estimated to determine the superiority of individual genotypes over the range of environments.

There are two general methods available for estimating the magnitude of GE interactions. One method (Sprague and Federer, 1951; Comstock and Robinson, 1952; Hanson et al., 1956; Comstock and Moll, 1963) involves an analysis of variance approach to estimate GE interactions. The other method involves regression analysis. This method was first proposed by Yates and Cochran (1938) and later modified by Finlay and Wilkinson (1963), Eberhart and Russell (1966) and Perkins and Jinks (1968). It involves the regression of each genotype on the environmental index. The environmental index is determined by the mean performance of all genotypes grown in each environment. Stability parameters are estimated from this regression analysis. Finlay and

Wilkinson (1963) used mean yield of a genotype and slope of its regression line to determine the stability of the genotype over the environments. This method was modified by Eberhart and Russell (1966). They added an extra parameter which measures the deviation from linear regression.

The present experiment involved a study of stability of harvest index (HI) and grain yield in a set of hard red winter wheat (*Triticum aestivum* L.) cultivars. Harvest index is the ratio of grain yield to total biomass yield (Donald, 1962). Cereal breeders have considered the use of harvest index as a potential criterion in selecting indirectly for increased grain yield (Rosielle and Frey, 1975; Nass, 1980). Stability of harvest index under diverse environmental conditions would be an important factor in the use of harvest index as a selection criterion. At present, little information is available on the stability of harvest index in hard red winter wheats. Outlining ideal traits for a plant architectural model of wheat breeding, Smith (1976) emphasized the importance of environmental influences on yield related traits. He suggested that modifications in plant type to obtain higher grain yield might reduce the inherent stability of yield. Since harvest index is a ratio, it might be influenced to a lesser extent than grain yield by diverse environmental conditions. Hence, a study of the stability of harvest index across a series of environments and comparing it to the stability of grain yield was undertaken.

The major objectives of this study were: i) to determine the range of variability for harvest index and grain yield in a set of representative wheat cultivars grown in the Southern Great Plains, ii) to estimate the stability parameters for harvest index and grain yield, iii) to identify superior wheat cultivars based on the stability parameters, and iv) to determine the association of harvest index with grain yield and plant height.

MATERIALS AND METHODS

The ten winter wheat genotypes included in this study were: 'Bounty Hybrid 100', 'Bounty Hybrid 203', and 'Bounty Hybrid 310', all three from Cargill, Inc.; 'Newton' from Kansas; 'TAM 105' from Texas; 'Vona' from Colorado; and 'Chisholm', 'Concho', 'Payne' and 'Triumph 64', all four from Oklahoma. These genotypes were chosen because they represented a range in plant type, grain yield potential, and genetic background. Three of these ten genotypes were hybrids, five of the remaining seven genotypes were semi-dwarf cultivars grown commercially in the region, and the two remaining (Concho and Triumph 64) were standard height, long term check cultivars.

The ten genotypes were grown at six sites in Oklahoma in the 1982-83 and 1983-84 growing seasons. These six sites were: Stillwater, Lahoma, Altus, Goodwell (irrigated), Goodwell (dryland), and Woodward. The field plot design was a randomized complete block with four replications. Each plot (1.2 x 3.1 m) was sown with 30 g seed which represents the commercially recommended seeding rate. The two sites at Goodwell in both growing seasons and the Stillwater site in 1982-83 only, were planted as four row plots. The plots at the remaining sites were planted as five row plots. Cultural practices consistent with good crop husbandry were applied at each site. Only one site indicated in this report as Goodwell (irrigated), received irrigation during the growing season. The plots were seeded between October 15 and December 15 in 1982 and between October 18 and December 6 in 1983. The plots were harvested between June 22 and July 7 in 1983 and between June 11 and July 2 in 1984.

At maturity, one sample consisting of a 60 cm segment of row was harvested from the middle of each plot. These samples were cut with a hand sickle (1.8 cm above ground level). The rest of each plot was harvested by a plot combine harvester to obtain grain yield. The sickle-harvested samples were air-dried in a glasshouse and biomass yield (weight of above ground plant parts harvested) of each sample was recorded. After threshing, grain weight of individual samples was recorded. The harvest index value for each sample was calculated by the following formula:

Harvest index = (grain weight/biomass weight) x 100.

Mean grain yield was reported in g m^{-2} on a per plot basis. Prior to harvest, plant height in each plot was measured in centimeters from ground level to the tip of the spikes.

The analysis of variance procedure of Comstock and Moll (1963) was adopted. This analysis was done by years and locations. Significance of GE interactions was tested using the procedure outlined by Perkins and Jinks (1968). This method partitions GE interactions into a component due to heterogeneity between regressions and a remainder component. If either of the two components or both components are significant, GE interactions are present. If the heterogeneity component alone is significant, all the GE interactions for individual genotype can be predicted from the linear regressions on the environmental values. If the remainder component alone is significant there is no simple relationship between the GE interactions and the environmental values and hence no predictions can be made by this approach.

Stability parameters suggested by Eberhart and Russell (1966) were estimated. As contrasted to Comstock-Moll (1963) analysis, each location in a particular year was treated as an environment. One "stability" parameter was estimated as the linear regression coefficient (b) of an entry mean on the average of all entries in the particular environment. The other "stability" parameter was the mean square of deviation from regression (s^2d) for each entry.

For the regression analysis of variance the residuals from the combined analysis of variance were used as the pooled errors. These pooled errors were used to test the s^2d values. A significant 'F' value would mean that the s^2d value were significantly different from zero. The hypothesis that each regression coefficient did not differ from unity was tested by the 't' test using appropriate standard errors. Coefficients of determination were obtained from the linear regression analysis. Simple correlation coefficients were calculated based on the mean values over four replications.

RESULTS AND DISCUSSION

According to the Comstock-Moll (1963) analysis, differences among genotypes for harvest index and grain yield were highly significant (Table 1). Year, location, as well as first and second order interactions were significant for both traits. The presence of significant year and location effects suggested that environmental conditions were different throughout the experiments. The presence of significant first order interactions indicated that differences among genotypes were inconsistent over locations and years. The presence of significant second order interactions indicated that there were changes in genotype x year effects among locations. The two components of GE interactions, heterogeneity between regressions and the remainder component, were statistically significant which indicated the presence of GE interactions (Perkins and Jinks, 1968). The heterogeneity mean squares when tested against remainder mean squares, were significant for both traits. This suggested that there were differences in regression coefficient values among the ten genotypes.

Harvest index for the ten genotypes ranged from 33.0 to 41.1%, while grain yield ranged from 316 to 437 g m^{-2} (Table 2). Chisholm had the highest harvest index, while Bounty Hybrid 203 (B.H. 203) showed the highest grain yield.

Stability parameters were estimated by the method described by Eberhart and Russell (1966). This method defines a stable cultivar as one which has a regression coefficient of 1.0 and no deviation from regression mean square. However, according to Eberhart and Russell (1966) an ideal cultivar should also have high average performance over a wide range of environments, besides being a stable one. Becker et al. (1982) regarded mean square for deviation from regression to be the most appropriate criterion for measuring phenotypic stability in an agronomic sense because this parameter measures the predictabilty of genotypic reaction to environments. Langer et al. (1979) suggested that the regression coefficient is a measure of response to varying environments. The regression coefficient (b) values of the ten genotypes ranged from 0.65 to 1.46 and 0.75 to 1.17 for harvest index and grain yield, respectively (Table 2). These variations in b values suggested that the ten genotypes responded differently to the different environments. Variability among environments is an important factor and in large part determines the usefulness of b values (Pfahler and Linskens, 1979). Statistically significant environmental effects (Table 1) indicated that variability across environments was large enough for a proper estimation of b values.

The coefficients of determination (r^2) were very high for grain yield (0.85 to 0.99) which indicated that linear regression accounted for most of the variation in grain yields of individual genotypes. The coefficients of determination ranged from 0.50 to 0.89 for harvest index. Joarder et al. (1978) reported that linear regressions were responsible for most of the variation in grain yield of genotypes over environments for *Brassica campestris* L. Langer et al. (1979) found that linear regression accounted for 70 to 99% of the variation in grain yields of three sets of *Avena sativa* L. genotype. On the basis of regression coefficient values, there were not detectable trends for stability among genotypes with high and low values for harvest index and grain yields. Chisholm, with the highest harvest index of all entries, had a regression coefficient that was not significantly different from unity. Also, Chisholm was the highest grain yielding genotype among pure line, semi-dwarf cultivars. B.H. 203 showed the highest grain yield among the ten genotypes and it also had a regression coefficient not significantly different from one. Concho, a long term check cultivar had the lowest values for both harvest index and grain yield. However, the regression coefficient values for this cultivar differed for the two traits. For harvest index its regression coefficient was equal to one, while for grain yield its regression coefficient was significantly less than one.

Deviation from the linear regression component was significant for harvest index in all ten genotypes and for grain yield in nine of the ten genotypes. Hence, based on the estimates of the two stability parameters none of the ten genotypes reported herein appeared to be ideal. However, based on linear regression coefficient and highest average grain yield, one genotype appeared desirable. Smith (1982) considered a desirable genotype with an average stability and above average grain yield should follow a regression line with a positive intercept and a slope equal to one. The three genotypes shown in the Fig. 1 represent the stability trends for grain yield observed in the ten genotypes in this study. Grain yield of B.H. 203 was above average in all twelve environments in which this study was conducted. Johnson et al. (1968) identified a hard red winter wheat cultivar that was superior both in stability of yield and actual yield potential when compared with a long term check cultivar. Tai (1979) reported that high yielding potato (Solanum tubersoum L.) genotypes tended toward instability. Cammack (1982) reported that higher grain yield in wheat appeared to be associated with a trend toward instability. Three genotypes (Fig. 2) have been used to show the stability trends for harvest index for the ten genotypes. Harvest index changed with the environmental index for most of the ten genotypes. The harvest index of Vona appeared to be least affected by the environmental changes as compared to the other nine genotypes.

Pairwise correlation coefficients (r), presented in Table 3, showed that grain yield was not significantly correlated with harvest index ($r = 0.08$). This indicated that differences in grain yield of sets of genotypes relative to the differences in respective harvest index were not consistent across the environments. Grain yields were drastically reduced in poor environments as compared to good environments without a proportionate reduction in harvest index. Plant height showed significant negative correlation with harvest index ($r = -0.43$) which was as expected because semi-dwarf wheats show higher grain yields and higher harvest index as compared to the standard height old cultivars. The correlation coefficient of grain yield with plant height was positive and significant ($r = 0.64$). The three hybrids that possessed high grain yield, were relatively taller than high grain yielding pure line cultivars.

The response of the 12 environments (Table 4) showed that the highest grain producing environments had lower values for harvest index as compared to intermediate productive environments. The highest grain producing environments also produced taller plants. The decrease in harvest index values in better environments could be attributed to environmental stress (moisture and temperature) during the grain filling period as compared to somewhat optimum environments during vegetative growth. Such environmental fluctuations are frequently found in the Southern Great Plains. As a consequence, there were two apparent trends in environmental response. In the six more favorable environments, environment 1 through 6 (Table 4), harvest index tended to increase with decreasing grain yield, while in the six less favorable environments (environment 7 through 12) harvest index decreased as grain yields decreased. The genotypic response in these two groups of environments were examined in terms of associations of harvest index with other traits (Table 3). Correlation between harvest index and grain yield was nonsignificant in high productive environments (Group 1), while a significant positive correlation was found between harvest index and grain yield in low productive environments (Group 2). The correlation between grain yield and plant height changed only slightly in the two groups of environments.

The result of this study indicated that both harvest index and grain yield are significantly influenced by the changes in the environmental conditions. For the ten genotypes reported herein, instability in terms of deviation from regression slope of 1.0, was observed for both traits. Consequently, from the environmental considerations selection for grain yield <u>per se</u> could be just as effecteive as selection for harvest index in the highly diverse environments of the Southern Great Plains. Also, the magnitude of the generally accepted positive relationship between harvest index and grain yield changed under diverse environments.

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Table 1. Analysis of variance for harvest index and grain yield for ten winter wheat genotypes based on two years data from six locations.

Source of variation	df	Mean Squares Harvest index %	Grain yield (x1000) $g\ m^{-2}$
Year	1	51.4**	432.7**
Location	5	244.6**	1,558.8**
Yr x Loc	5	635.6**	32.0**
Replication (Yr Loc) †	36	4.4	3.1
Gentoype	9	267.7**	54.8**
Geno x Yr	9	20.9**	2.9*
Geno x Loc	45	18.1**	7.3**
Geno x Yr x Loc	45	11.7**	4.1**
Environment	(11)	404.8**	893.5**
Geno x Env	(99)	15.4**	5.5**
Heterogeneity between regression	9	30.4*	18.4**
Remainder ‡	90	13.9**	4.2**
Error	324	2.9	1.2

*, ** Significant at the 0.05 and 0.01 levels, respectively.

†Mean square used to test Year, Location and Yr x Loc interaction.

‡Mean square used to test heterogeneity between regression.

Table 2. Mean harvest index, grain yield and plant height and estimates of stability parameters in ten winter wheat genotypes based on 12 environments.

	Harvest index				Grain Yield				Plant height
Genotypes	$\bar{x}$ %	b	s^2d	r^2	$\bar{x}$ g m^{-2}	b	s^2d	r^2	(cm)
Bounty Hybrid 203	37.2	0.92	2.28**	0.72	437	1.10	1120**	0.95	87
Bounty Hybrid 100	38.6	1.01	2.18**	0.80	404	1.05	601**	0.97	82
Bounty Hybrid 310	34.8	1.13	3.28**	0.76	389	1.17**	21	0.99	85
Chisholm	41.1	0.91	0.88*	0.85	383	1.08	392**	0.98	76
Vona	39.8	0.65*	2.18**	0.62	376	1.05	373**	0.98	75
TAM 105	37.5	1.37*	2.18**	0.88	370	1.04	1092**	0.95	78
Payne	36.4	0.82	0.98**	0.82	363	0.91	864**	0.95	79
Newton	36.0	1.46**	2.18**	0.89	355	1.06	642**	0.97	81
Triumph 64	36.8	0.72	4.98**	0.50	337	0.78**	396**	0.85	89
Concho	33.0	1.00	1.78**	0.82	316	0.75**	784**	0.86	97
LSD (0.05)	0.7				14.1				1.2
(0.01)	0.9				18.6				1.6

*,** Significant at the 0.05 and 0.01 levels, respectively.

Table 3. Simple correlation coefficients (r) between harvest index, grain yield, and plant height.

Traits	Correlation coefficient 12 environments	Group 1¶	Group 2
Harvest index vs grain yield	0.08	-0.17	0.62**
Harvest index vs plant height	-0.43**	-0.80**	-0.40**
Grain yield vs plant height	0.64**	0.17	0.15

*,** Significant at the 0.05 and 0.01 levels, respectively.

¶Group 1 = Environments 1 through 6 (high productive)
Group 2 = Environments 7 through 12 (low productive)

Table 4. Mean values of the 12 environments for harvest index grain yield and plant height.

Environments	Harvest Index (%)	Grain yield ($g\ m^{-2}$)	Plant height (cm)
1 (GDIRR, 1983)†	33.9	586	102
2 (WD, 1984)	34.1	560	109
3 (GDIRR, 1984)	37.9	534	83
4 (WD, 1983)	38.8	520	89
5 (LA, 1983)	37.4	428	93
6 (ST, 1984)	40.2	371	88
7 (GDDRY, 1983)	42.4	326	72
8 (AL, 1983)	40.7	324	70
9 (ST, 1983)	31.9	239	84
10 (LA, 1984)	35.7	227	83
11 (GDDRY, 1984)	36.8	196	66
12 (AL, 1984)	34.6	174	60
LSD (0.05)	0.8	16	1.4
(0.01)	1.0	20	1.8

†GDIRR = Goodwell (Irrigated), WD = Woodward, LA = Lahoma, ST = Stillwater, GDDRY = Goodwell (Dryland), AL = Altus.

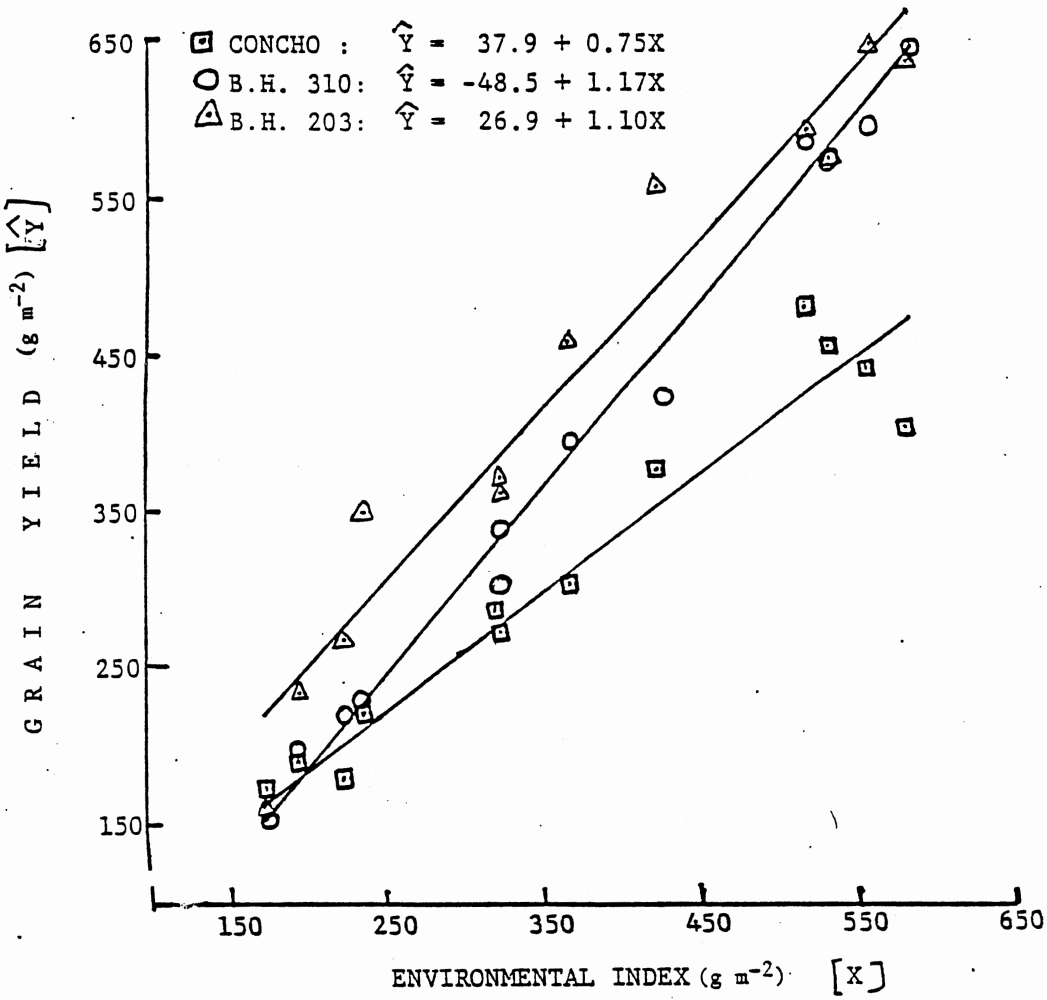

Fig 1. Patterns of stability for grain yield in three wheat genotypes in 12 environments.

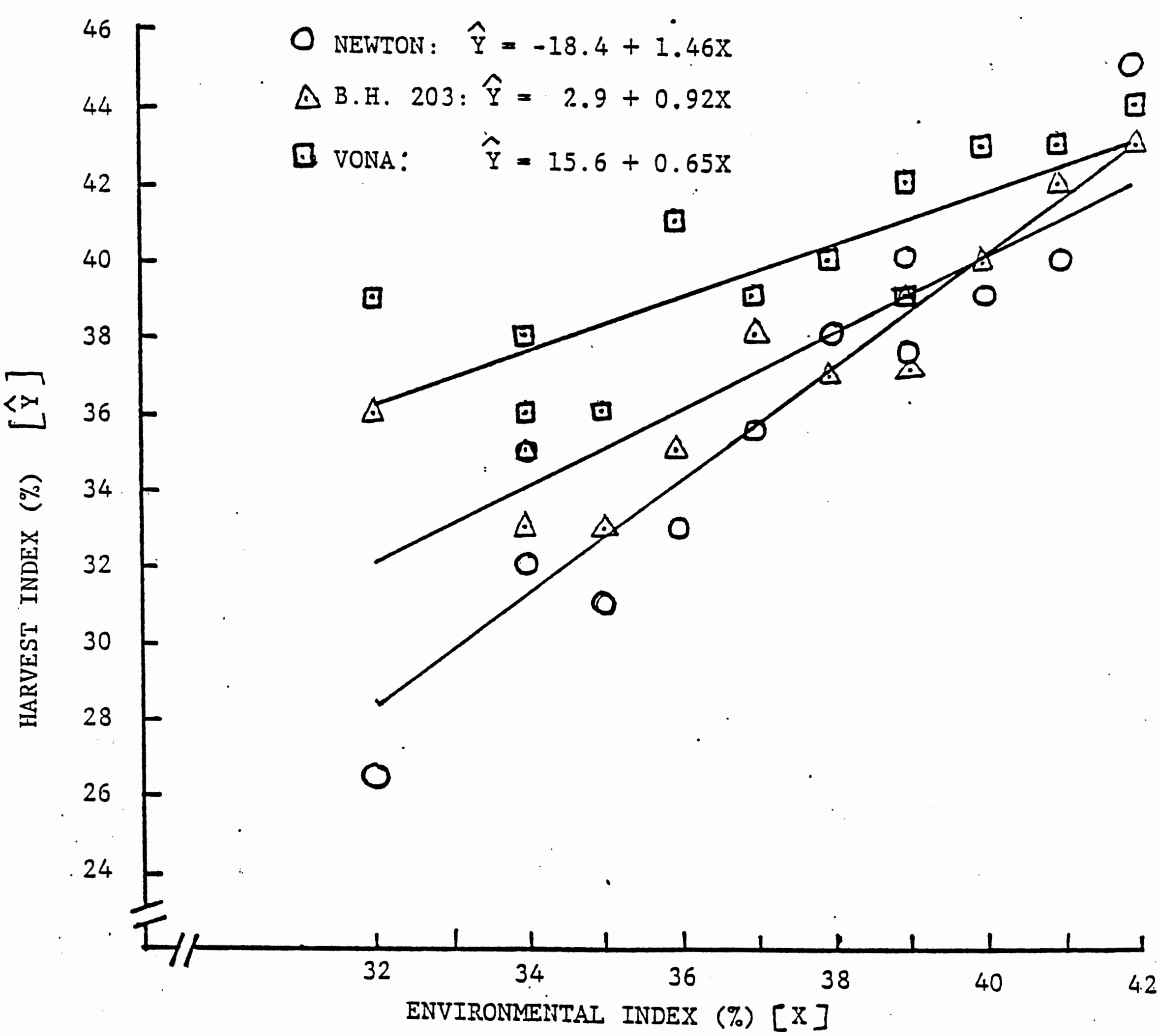

Fig 2. Patterns of stability for harvest index in three wheat genotypes in 12 environments.

PART II

SELECTION FOR HIGH AND LOW HARVEST INDEX IN THREE WINTER WHEAT POPULATIONS

SELECTION FOR HIGH AND LOW HARVEST INDEX IN THREE WINTER WHEAT POPULATIONS

ABSTRACT[1]

Low heritability of grain yield in wheat (_Triticum aestivum_ L.) often results in a slow response to selection. Selection criteria other than grain yield _per se_ are being sought by wheat breeders. Harvest index, the ratio of grain yield to total biomass yield, may be a useful selection trait for yield improvement. A study was undertaken to estimate the heritability of harvest index and to determine the response to selection for high and low harvest index in three genetically diverse populations of winter wheat. Selections were made in the F3 generation and selected progenies were evaluated in replicated tests in the F4 generation. Realized heritability estimates for harvest index were intermediate in magnitude (0.44 to 0.60). Selections for high and low harvest index were effective in identifying lines with high and low harvest index, respectively. Correlations between harvest index and grain yield were inconsistent in F3 and F4 generations. Harvest index was negatively correlated with plant height and days to heading. Correlations between harvest index and biomass yield were mostly nonsignificant. Simple correlation coefficients between F3 and F4 means were higher for harvest index as compared to grain yield. Results indicated that harvest index in the F3 generation was a good predictor of harvest index in the F4 generation, but a poor predictor of grain yields in F4 generation.

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Additional index words: <u>Triticum aestivum</u> L., harvest index Realized heritability, selection response.

INTRODUCTION

Harvest index can be defined as the ratio of economic yield to total biomass yield. Roots are not generally included, because of the difficulty in recovering roots in the field. Harvest index measures the efficiency with which a plant genotype diverts its total assimilates into economically important plant parts. Since the introduction of the term 'Harvest Index' by Donald (1962), it has been considered an important trait for yield improvement in cereals. Donald and Hamblin (1976) summarized the findings of studies related to harvest index and outlined a logical approach of using harvest index in plant improvement. The plant ideotype (Donald, 1968) or plant architectural (Smith, 1976) approach of plant breeding is primarily based on the concept of maximizing grain yield per unit of dry matter produced. Grain yields in cereals can be improved either by increasing biomass yield without changing harvest index or by improving harvest index keeping biomass unchanged or by increasing both biomass and harvest index. In general, the modern semi-dwarf wheat cultivars show improvement in harvest index over old standard height cultivars. For heat and drought tolerant wheats of the future Smith (1982) considered harvest index amenable to genetic improvement. Attempts should be made to find a combination of biomass yield and harvest index that will also maximize grain yield.

In general cereal breeders have selected directly for yield *per se* to improve grain yield. In the past two decades, however, there has been renewed interest in selecting indirectly for yield improvement. Breeding for yield components has produced mixed results (Grafius, 1978;

Sidwell et al., 1976; Abdelkader et al., 1984). The presence of component compensation has posed problems in breeding for yield components. Breeding for ideal plant traits to maximize grain yield has faced problems because of both genotype-environment interactions and the presence of allometric relationships (Grafius et al., 1976) in cereals. As it appears, harvest index is the end product cereal breeders should be interested in as long as yield levels are sufficiently high.

Any or all combinations of morpho-physiological traits of plants that also offer high harvest index and high grain yield should be considered in plant breeding programs. It is considered that there would be a limit to which harvest index can be increased and this value is considered to be around 60%. Hence, a cultivar with a low harvest index would indicate that further improvements in partitioning of biomass into economic yield would be possible. On the other hand, a cultivar with a harvest index value between 50 and 60% would indicate very little scope for increasing the harvest index and may necessitate the inclusion of new sources of germplasm in the breeding program for increasing biomass.

Harvest index has been shown to be positively related to grain yield in wheat (Singh and Stoskopf, 1971; Kulshrestha and Jain, 1982). Donald and Hamblin (1976) suggested the use of biomass and harvest index as early generation selection criterion in cereal breeding programs. Harvest index along with grain yield has been considered as a selection criterion in improving yields of cereals (Syme, 1972; Rosielle and Frey, 1975; Fisher and Kertsez, 1976; Bhatt, 1977; Nass 1980). Syme (1972) studied 49 spring wheat genotypes and found that 72% of the grain yield variability in field could be estimated on the basis of harvest index values from single plants grown in a greenhouse. Indirect selection for grain yield through harvest index in oats (Avena sativa L.) was 43% as efficient as direct selection (Rosielle and Frey, 1975). Harvest index of spaced plants was superior to grain yield of spaced plants for prediction of wheat grain yield in large plots (Fisher and Kertesz, 1976). Bhatt (1977) reported that harvest index as a selection criterion was useful for improving grain yield of two wheat crosses in early segregating generations. Harvest index was found to have merit as a selection criterion for grain yield in two crosses of spring wheat and was considered more reliable at high population densities (Nass, 1980).

Heritability of a trait is important in determining its response to selection. Grain yield is known to have low heritability and is highly influenced by the environment. This has resulted in low response from selection for yield per se. The effect of genotype-environment interactions on harvest index needs to be investigated. Heritability of harvest index has been reported from intermediate to high (Rosielle and Frey, 1975; Bhatt, 1977). Rosielle and Frey (1975) reported that the estimates of heritability were intermediate in magnitude (0.36 to 0.66) in oat lines derived from a bulk population. Bhatt (1976) reported that heritability estimates for harvest index were intermediate and high in magnitude (0.70 and 0.88) in two crosses of wheat.

The objectives of this study were to determine the response to high and low selections for harvest index, to estimate the heritability of harvest index and to determine the correlation of harvest index with other plant traits in winter wheat.

MATERIALS AND METHODS

Three F3 populations were chosen for this study on the basis of their wide inter- and intra-population diversity for plant type, maturity, and genetic background. The pedigrees of the three populations (Pop) were as follows.

Pop 1 = Newton/Chisholm//Plainsman V/Chisholm.

Pop 2 = OK 78002/FV 2410, where OK 78002 = TAM W-101/Amigo, and

FV 2410 = Favorit/5/Cirpiz/4/Jung Kwang/2/At166/Cmn/3/Velvet

Pop 3 = OK 79257/3/Pyn//T-101/Amigo, where OK 79257 = Aurora/2*T 101. These three populations were chosen from the F3 head rows grown at Stillwater in 1982-83 growing season. Each of these three populations had been generated from an F2 population in 1981-82 growing season. Within an F2 population 96 plants were selected randomly to produce F3 progeny rows. One head from each of the selected F2 plants was threshed and seeds were used to plant one F3 head row. Each F3 population consisted of 96 rows with individual rows being 1.2 m long. A standard nursery management and fertilization were employed.

At maturity, plant height of each row was measured from ground level to the tip of spikes. A 60 cm segment of row was harvested from the center of each row. These samples were harvested 1.8 cm above ground level and heads were protected by paper bags. The samples were air dried in a glasshouse and the weight of each individual sample was recorded as biomass yield. After threshing, grain weight was recorded and harvest index was calculated by the following formula:

Harvest index = (grain yield/biomass yield) x 100.

Harvest index was calculated for each of the 96 rows in each population. On the basis of harvest index value, 15 high and 15 low selections were made in each population. Each set of 30 selections was grown as F4's in replicated tests at two locations (Stillwater and Lahoma) in Oklahoma, in 1983-84 growing season. Crop management and fertilizer applications were consistent with good crop husbandry.

Each population was planted in a randomized complete block with three replicates. The selected lines were planted in single 3.3 m long rows at the rate of 7.5 g seed per row. Heading date was recorded when approximately half of the plant in a row had spikes emerged from the boot. At maturity, plant height was measured in each row.

The entire row was harvested in each population close to the ground surface and bundles from individual rows were air dried. The dried bundles were weighed to record biomass yield and after threshing grain yield of individual bundles were recorded. Harvest index was calculated for each line by the formula given earlier. Harvest index was determined in percent. Grain yield and biomass yield per plot are reported in g m^{-2}.

An analysis of variance was conducted on each population to determine differences between the high and the low harvest index selections for harvest index, grain yield and biomass yield. Response from selection was estimated in the F4 generation for each population at each location as the difference between the means of the 15 lines with high harvest index and the 15 lines with low harvest index. Falconer (1956) has given the formula for calculating realized heritability which was later used for high and low selection study in wheat by Alexander et al. (1984). Realized heritability (RH) estimates for harvest index were calculated by the following formula:

$$RH = \overline{High} - \overline{Low}\ F4,/\overline{High} - \overline{Low}\ F3.$$

Phenotypic correlation coefficients of harvest index with grain yield, biomass yield, plant height and heading date were calculated in each population. Correlations between F3 and F4 generations were determined for harvest index and grain yield.

RESULTS AND DISCUSSION

The F3 frequency distributions for harvest index of the three populations are shown in Fig. 1. Population 1 and Pop 3 had a greater number of lines with higher harvest index than Pop 2. The combined two locations analysis of F4 lines indicated significant differences in harvest index, grain yield, and biomass yield for the populations (Table 1). Significant interactions occurred between selection type and location only for biomass yield. Interactions among population and selection type were significant for all three traits. The means utilized to calculate realized heritability came from separate analyses of variance for each population at each location.

The F4 means for harvest index, grain yield and biomass yield for high and low harvest index groups are given in Table 2. For harvest index, expressed in percent, the high and low selection groups differed in each population at each location with actual differences ranging from 4.4 to 7.1. This indicated that selection for higher or lower harvest index was effective from one generation to another. Bhatt (1977) reported that high and low selection for harvest index in two wheat crosses was effective from the F2 to the F3 generation, while random selection for harvest index was not effective. For grain yield, the high and low harvest index selection groups differed only for Pop 3 at the Lahoma site. The high harvest index selection group usually produced lower biomass than low harvest index group. In the F3 generation, the lines were selected on the basis of high harvest index were not necessarily high in grain yield, and those selected for low harvest index were not always low in grain yield. This trend continued in the F4 generation where several of the lines in the high harvest index selection group produced low grain yields and vice versa. Thus, selection for high and low harvest index in the F3 generation was not efficient in identifying high and low grain yielding lines in the F4 generation. The response to selection as the percent of the mean of the high harvest index selection group ranged from 10.5 to 16.5 for harvest index and was somewhat lower for grain yield (0.5 to 6.4).

The realized heritability estimates calculated for harvest index are given in Table 3. These values were similar for the same population at the two locations for Pop 1 and 2, but not for Pop 3. The values for realized heritability ranged from 0.44 to 0.60 and are considered intermediate in magnitude. Bhatt (1977) reported that realized heritability estimates for harvest index were 0.70 and 0.88 in two wheat crosses. Population 2 had higher realized heritability values (0.59 and 0.60) of the three populations.

Phenotypic correlation coefficients among various plant traits were calculated for each generation, location and population (Table 4). Correlations between harvest index and grain yield were inconsistent in F3 to F4 generations. Also, these correlations differed from one site to another in the same generation. Bhatt (1977) reported variations in correlations between harvest index and grain yield in F2 and F3 generations in two wheat crosses. The correlation coefficient between harvest index and grain yield was lower in the F4 generation as compared to the values in the F3 generation. The single row plots with taller plants in low harvest index group than in high harvest index group might have biased the correlation between harvest index and grain yield.

Correlations between harvest index and biomass yield were mostly nonsignificant in both F3 and F4 generations. This was in agreement with the previous findings (Rosielle and Frey, 1975; Bhatt, 1977). Harvest index was negatively correlated with plant height and days to heading. Correlation coefficients of grain yield with biomass yield were very high in both generations. Rosielle and Frey (1975) and Bhatt (1977) also reported high correlations between grain yield and biomass yield in oats and wheat, respectively. Correlations of grain yield with plant height and heading date were mostly nonsignificant.

Simple correlation coefficients between F3 and F4 means are presented in Table 5. Correlation coefficients were high ($r = 0.77$ to 0.91) for harvest index. Correlations for grain yield between the two generations were significant only for Pop 3. Mean F3 harvest index showed low correlation with F4 grain yield. These correlation coefficient values indicated that harvest index in the F3 generation could be a good predictor of harvest index, but a poor predictor of grain yields, in the F4 generation.

The results of this study indicated that selections for high and low harvest index were effective in identifying lines with high and low harvest index, respectively. However, grain yield and biomass yield usually showed no significant response to selection for high and low harvest index. There were lines with high harvest index and high grain yield and lines with low harvest index and high grain yield. The heritability estimates for harvest index reported in this study were intermediate in magnitude (0.44 to 0.60), which suggested that progress could be made in a breeding program emphasizing increased harvest index, assuming proper parental germplasms were utilized. Donald and Hamblin (1976) suggested the use of parental material of high biomass yield or high harvest index in the breeding programs for increasing grain yield.

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Table 1. Analysis of variance for harvest index, grain yield and biomass yield over two locations, three populations, two selection types (high vs. low) and selections.

Source of variation	df	Mean squares Harvest index (%)	Grain yield ($g\ m^{-2}$)	Biomass yield ($g\ m^{-2}$)
Location (Loc)	1	2.4	117325**	6839431**
Population (Pop)	2	1874.8**	119949**	1421495**
Loc x Pop	2	403.4**	8485	121295
Replication (Loc Pop)	12	9.2	6260	40856
Selection type	1	4637.3**	16132**	183704**
Sel type x Loc	1	2.0	138	36580*
Sel type x Pop	2	49.7**	6185*	49941**
Selection (Sel type pop) x Pop	84	16.6**	4516**	27533**
Sel type x Loc x Pop	2	4.6	1097	1098
Selection (Sel type pop) x Loc x Pop	84	6.6**	1712	10230*
Error	348	4.0	1332	7448

*,** Significant at the 0.05 and 0.01 levels, respectively.

Table 2. Response of harvest index (HI), grain yield and biomass yield in F4's to high and low selections for harvest index in F3's of three winter wheat populations.

	Harvest index			Percent of	Grain yield			Percent of	Biomass yield			Percent of
	Mean of HI selection group			mean of high	Mean of HI selection group			mean of high	Mean of HI selection group			mean of high
Population	High	Low	Difference	HI group	High	Low	Difference	HI group	High	Low	Difference	HI group
	%				$g\ m^{-2}$				$g\ m^{-2}$			
1 (ST)	45.8	39.9	5.9**	12.9	230	216	14	6.1	505	541	-36	6.7
(LA)	49.0	43.4	5.6**	11.4	124	116	8	6.4	253	267	-14	5.2
2 (ST)	43.5	36.6	6.9**	15.6	220	219	1	0.5	508	600	-92**	15.3
(LA)	43.0	35.9	7.1**	16.5	121	120	1	0.8	280	336	-56**	16.6
3 (ST)	41.8	37.4	4.4**	10.5	262	246	16	6.1	628	660	-32	4.8
(LA)	39.8	34.5	5.3**	13.3	191	162	31**	6.2	483	474	9	1.9

**Significant at the 0.01 level.

ST = Stillwater. LA = Lahoma.

Table 3. Realized heritability (h^2) estimates for harvest index in three winter wheat populations.

Population	Location	Realized h^2
1	Stillwater	0.46
	Lahoma	0.45
	Average	0.46
2	Stillwater	0.59
	Lahoma	0.60
	Average	0.60
3	Stillwater	0.44
	Lahoma	0.54
	Average	0.49

Table 4. Phenotypic correlation coefficients among harvest index and several other plant traits.

Traits	Population	F3 (ST)	F4 (ST)	F4 (LA)
Harvest index vs grain yield	1	0.78**	0.21	0.39*
	2	0.57**	0.07	0.16
	3	0.74**	0.46**	0.26
Harvest index vs biomass yield	1	0.06	-0.26	0.14
	2	-0.22	-0.38*	-0.18
	3	0.06	-0.17	-0.22
Harvest index vs plant height	1	-0.46**	-0.54**	-0.63**
	2	-0.56**	-0.78**	-0.62**
	3	-0.48**	-0.78**	-0.57**
Harvest index vs heading date	1	---	-0.84**	-0.43**
	2	---	-0.82**	-0.84**
	3	---	-0.72**	-0.74**
Grain yield vs biomass yield	1	0.68**	0.88**	0.96**
	2	0.66**	0.89**	0.94**
	3	0.70**	0.79**	0.88**
Grain yield vs plant height	1	-0.12	-0.27	-0.21
	2	0.01	-0.06	0.38*
	3	-0.28	-0.20	0.18
Grain yield vs heading date	1	---	-0.28	-0.34*
	2	---	-0.18	-0.12
	3	---	-0.31	-0.63**

*, ** Significant at the 0.05 and 0.01 levels, respectively.

ST = Stillwater LA = Lahoma.

---Data not available.

Table 5. Correlation coefficients between the F3 and F4 generations for harvest index and grain yield.

Traits		Population I	II	III
Harvest index (F3 vs F4)	ST	0.89**	0.89**	0.82**
	LA	0.77**	0.91**	0.84**
Grain yield (F3 vs F4)	ST	0.32	0.01	0.42*
	LA	0.06	0.14	0.67**
Harvest index (F3) vs grain yield (F4)	ST	0.25	0.00	0.30
	LA	0.09	0.08	0.52**

*,**Significant at the 0.05 and 0.01 levels, respectively.

ST = Stillwater. LA = Lahoma.

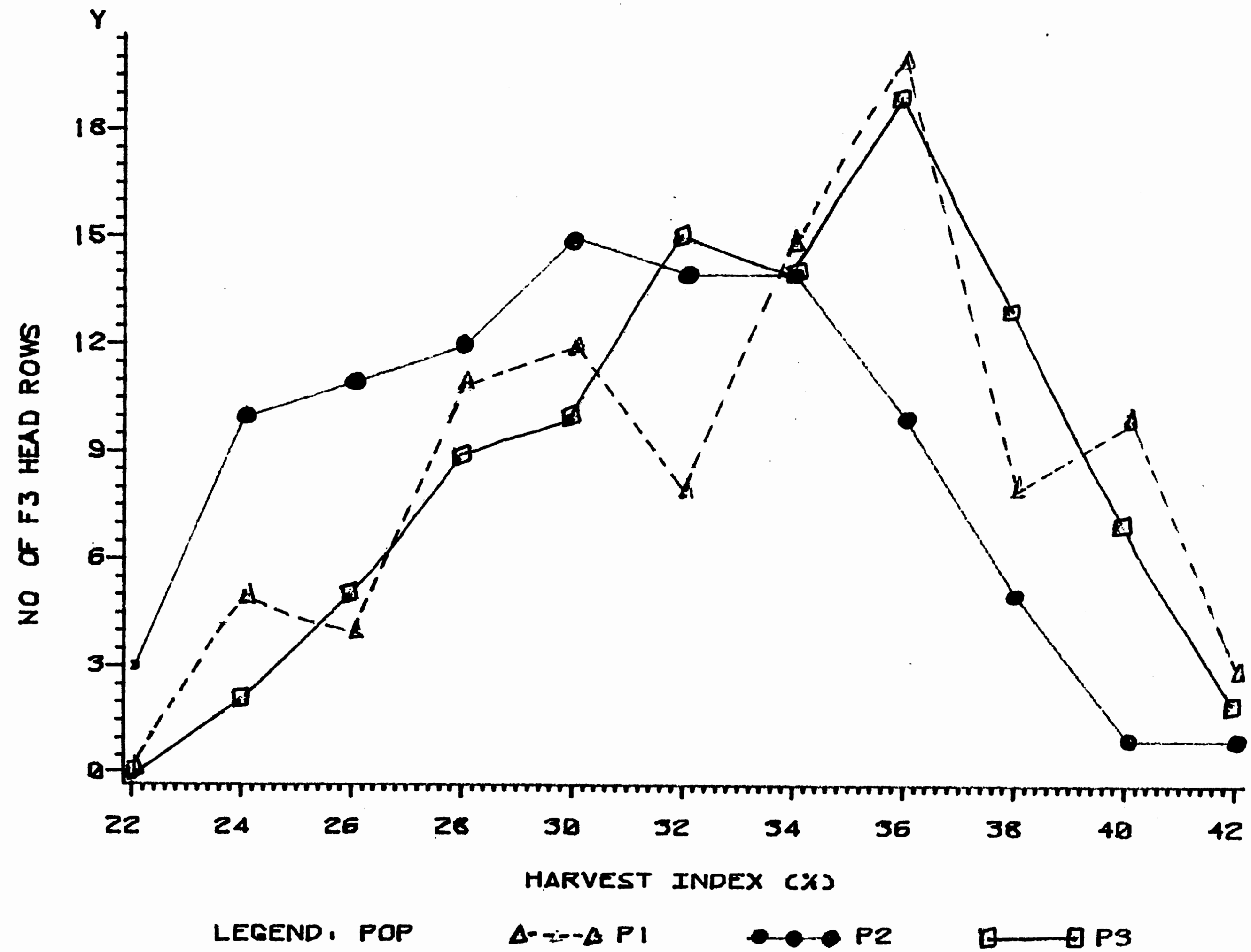

Fig 1. F_3 frequency distribution for three winter wheat populations for harvest index.

PART III

EFFECTS OF SEEDING RATE ON HARVEST INDEX AND OTHER AGRONOMIC TRAITS IN WINTER WHEAT

EFFECTS OF SEEDING RATE ON HARVEST INDEX AND OTHER AGRONOMIC TRAITS IN WINTER WHEAT [1]

ABSTRACT

Harvest index is considered as a potential selection criterion for improving grain yield in cereals. Since selection is made in early segregating generations in thinly seeded populations, expression of the traits under selection must be consistent in variable crop stands. This study was conducted to examine the effects of two seeding rates, standard (67.2 kg/ha) and low (16.8 kg/ha), on harvest index and seven other agronomic traits in winter wheat (Triticum aestivum L.). A set of ten hard red winter wheat genotypes, adapted to the Southern Great Plains, were evaluated in replicated tests at two locations in Oklahoma in the 1983-84 growing season. The field plot design was a split plot with genotypes as main plots and seeding rates as sub-plots. Results indicated that all eight traits were influenced by the low seeding rate as compared to the standard seeding rate. The degree to which these traits were influenced differed from one trait to another. Harvest index, kernel weight, days to heading, and plant height were influenced to a lesser extent than other traits by the change in seeding rate. There were genotypic differences in the response to seeding rates for all eight traits. However, all genotypes produced lower grain yield, lower biomass yield, fewer tillers per unit area, and more kernels per spike at the low seeding rate. Heading was usually delayed by a day or

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two and plants were a few centimeters shorter at the low seeding rate. The simple correlation coefficient between the two seeding rates was higher for harvest index (r = 0.957) as compared to grain yield (r = 0.683), which suggested that harvest index could have merit over grain yield as a selection criterion in variable stands.

Additional index words: *Triticum aestivum* L., harvest index, grain yield, biomass yield, seeding rate.

INTRODUCTION

In the past two decades, harvest index, the ratio of grain yield to total biomass yield, has been advocated and used as a selection criterion for improving grain yield of cereals. In small grain crops, selection for grain yield is usually made in early generations in thinly seeded stands. In order for the selection in sparse population densities to be of practical use, a high positive correlation must exist between grain yield and yield components of spaced plants and solid-seeded plants. Harvest index measures the physiological efficiency of plants in terms of partitioning total assimilates into economic plant parts. There might be a possibility that harvest index of spaced plants may show higher correlation with harvest index of solid-seeded plants as compared to the correlation for grain yield. Effects of different seeding rates on yield and other agronomic traits have been investigated to study the change in expression of these plant traits in small grain cereals.

Guitard et al. (1961) studied the effects of five different seeding rates on yield and yield components in wheat (*Triticum aestivum* L.) for three years. The increase in seeding rates caused a linear increase in the number of plants per unit area, reduced number of kernels per head and lower average kernel weight. In a study on the effect of plant density on the yield components of barley (*Hordeum vulgare* L.), Kirby (1967) found that higher seeding rates resulted in a greater number of tillers per unit area but a lower 1000 grain weight. Pelton (1969) studied the influence of low seeding rates on wheat yield components for eight years. Low seeding rates produced longer heads and heavier kernels. Briggs (1975) examined the effects of seeding rate on agronomic traits of three wheat genotypes at two locations in two years. In that study, higher seeding rates resulted in higher grain yields and somewhat earlier maturity without any marked effect on plant height, kernel weight or test weight.

Effects of plant population on harvest index have been the subject of a few studies. Donald and Hamblin (1976) summarized studies on the influence of plant population density on harvest index in cereals. In wheat, both biomass and grain yield approached maximum levels at the same plant population (15400 per hectare) and then started declining. Harvest index, however, was maximum in magnitude at a significantly lower population (14000 per hectare) and started declining at higher plant populations. McVetty and Evans (1980) studied seven tall and seven semi-dwarf wheat cultivars in spaced planted and solid-seeded trials. They concluded that potentially high grain yielding tall cultivars could be selected from spaced planted populations using biomass yield. In contrast, the high grain yielding semi-dwarf cultivars could be selected from spaced planted populations using harvest index as a selection criterion. Baker (1982) examined the effect of three seeding rates on grain yield, biomass yield and harvest index of eight spring wheat cultivars under several experimental conditions. Harvest index changed with seeding rate under certain experimental conditions, but remained unchanged over three seeding rates under other experimental conditions.

This study was conducted to examine the effects of two seeding rates on harvest index, grain yield and several other agronomic traits in a set of ten hard red winter wheat genotypes adapted to the Southern Great Plains.

MATERIALS AND METHODS

The ten winter wheat genotypes included in this study were 'Bounty Hybrid 100', 'Bounty Hybrid 203', 'Bounty Hybrid 310', 'TAM 105', 'Newton', 'Vona', 'Chisholm', 'Payne', 'Triumph 64', and 'Concho'. Their origin and year of release are given in Table 1. These ten genotypes were chosen for this study because they represented a range in plant type, grain yield potential and genetic background.

The ten selected genotypes were grown at two sites (Stillwater and Lahoma) in Oklahoma in the 1983-84 growing season. The field plot design used was a split plot with genotypes as main plots and seeding rates as subplots. The nursery was planted in a randomized complete block arrangement for main plots. There were four replications at both locations. Each main plot was 2.4 x 3.1 m. The two seeding rates were 30.0 g and 7.5 g per sub-plot. The 30.0 g seed per sub-plot represented the commercially recommended seeding rate and is referred to as the standard seeding rate in this report. The 7.5 g per sub-plot seeding rate was used to simulate spaced planted populations, and is referred to as low seeding rate in this report. The nursery was planted on November 11, 1983, at both locations and harvested on June 29 and July 11, 1985, at Lahoma and Stillwater, respectively. Cultural practices consistent with a good crop husbandry were applied at each site.

Agronomic data were recorded for each sub-plot at each location as follows:

Days to Heading: Number of days to heading was recorded when half of the total number of tillers in a sub-plot had spikes completely out of boot. The number of days to heading was reported starting April 1.

Plant Height: Plant height (cm) was measured in each sub-plot at maturity from the base of the plant to the tip of the spikes.

Tiller Number: The number of head bearing tillers in the middle two rows of each sub-plot was counted. This trait was reported as tiller number per square meter.

Kernel per Spike: Ten spikes were selected at random from the middle two rows of each sub-plot. These ten spikes were threshed together and the total number of kernels was counted. Then, the average number of kernels per spike was determined.

Biomass Yield: At maturity, the middle two rows of each sub-plot was harvested with a 'Suzu Binder' close to the ground level. The bundles from each sub-plot were air-dried in a glasshouse and weighed individually to record biomass yield (g m^{-2}).

Grain Yield: Bundles used for biomass determination were threshed and grain yield (g m^{-2}) was recorded for each sub-plot.

Harvest Index: Harvest index was calculated according to the following formula: (grain yield/biomass yield) x 100. It was expressed as percent.

Hundred Kernel Weight: One hundred randomly chosen seeds from each sub-plot grain sample were counted and weighed (g). This trait was expressed as 100 kernel weight.

A combined split plot analysis of variance over two locations was conducted. Phenotypic correlation coefficients among various agronomic traits were determined.

RESULTS AND DISCUSSION

The analysis of variance for the eight agronomic traits studied is presented in Table 2. Mean squares for location were significant for grain yield, biomass yield, tiller number, kernels per spike, days to heading, and plant height. Location effect was nonsignificant for harvest index and 100 kernel weight. Mean squares for genotype were significant for all eight traits, which indicated the presence of genotypic differences for these traits among the ten genotypes included in this study. Genotype x location interaction was significant for harvest index, tiller number, kernels per spike, 100 kernel weight, and days to heading, but was nonsignificant for grain yield, biomass yield, and plant height. The presence of a significant genotype x location interaction indicates that relative rankings of the genotypes have changed over locations. Seeding rate showed a significant effect on all eight traits. Seeding rate x location interaction was significant for harvest index, grain yield, tiller number, and 100 kernel weight, but was nonsignificant for the other four traits. Genotype x seeding rate interaction was significant for five out of eight traits. It was nonsignificant for harvest index, kernels per spike, and plant height. The second order interaction was significant only for tiller number and kernels per spike.

Mean values for the eight traits at two seeding rates are given in Table 3. The mean harvest index values ranged from 32.9 to 46.9% and from 33.0 to 45.5% at the standard and low seeding rates, respectively. Chisholm showed the highest harvest index of all ten genotypes at both seeding rates, while Concho had the lowest harvest index value at both seeding rates. However, the rankings of certain genotypes for harvest index changed over the two seeding rates. All genotypes except Triumph 64, Payne, and Concho had a somewhat lower harvest index values at the low seeding rate as compared to harvest index values at the standard seeding rate. The harvest index of Triumph 64 and Payne was higher at low seeding rate than at the standard seeding rate.

Grain yield, biomass yield, and tiller number of all genotypes were lower at the low seeding rate than at the standard seeding rate. At the standard seeding rate, Bounty Hybrid 203 had the highest grain yield and highest biomass yield, but not the highest tiller number. For all genotypes, kernels per spike was lower at the standard seeding rate than at low seeding rate. This was in agreement with the results of the previous studies (Guitard et al., 1961; Pelton, 1969). Kernel weight was higher at the low seeding rate for certain genotypes, but was lower for the other genotypes. Seeding rate showed some effect on the number of days to heading. Most genotypes headed 1 or 2 days later at low seeding rate as compared to heading at the standard seeding rate. This result was in agreement with a previous finding (Briggs, 1975). Seeding rate influenced plant height to a certain extent as plants were 1 to 4 cm shorter at the low seeding rate as compared to plant height at the standard seeding rate.

Phenotypic correlation coefficients (r) among the eight agronomic traits are given in Table 4. Harvest index was significantly positively correlated with grain yield (r = 0.453) and 100 kernel weight (r = 0.646) and significantly negatively correlated with days to heading (r = -0.781) and plant height (r = -0.642). Other significant positive correlations were found between grain yield and biomass yield (r = 0.823), grain yield and tiller number (r = 0.788), biomass yield and tiller number (r = 0.861), and biomass yield and days to heading (r = 0.447). Significant negative correlations were found between grain yield and kernels per spike (r = -0.455), grain yield and plant height (r = -0.696), tiller number and kernels per head (r = -0.488), tiller number and plant height (r = -0.488), and 100 kernel weight and days to heading (r = -0.690).

Phenotypic correlation coefficients of the same trait at two seeding rates are presented in Table 5. All traits showed positive correlation over the two seeding rates, however, the magnitude of the correlations ranged from 0.629 to 0.991. Biomass yield was the only trait with a nonsignificant correlation coefficient over the two seeding rates. Harvest index had a correlation coefficient of 0.957 as compared to 0.683 for grain yield. Thus, harvest index appeared to be more consistent than grain yield over seeding rates. Consequently, selection for harvest index could have merit over selection for grain yield in thinly seeded populations, assuming a high positive correlation exists between harvest index and grain yield in the reference population.

The results of this study indicated that all eight agronomic traits, reported herein, were influenced to a greater degree by low seeding rate as compared to the standard seeding rate. The extent to which these traits were influenced differed from trait to trait. Harvest index, kernel weight, heading date, and plant height were influenced to a lesser extent than the other traits by the change in seeding rate. There were genotypic differences in the response to all eight traits. However, all genotypes produced lower grain yield, lower biomass yield, fewer tillers per unit areas, and more kernels per spike at low seeding rate. Heading was usually delayed by a day or two and plants were a few centimeters shorter at the low seeding rate. Yield component compensation was present and number of tillers appeared to be closely related to grain yield in this set of ten genotypes. Harvest index showed merit over grain yield as selection criterion in variable stand densities. However, correlation between harvest index and grain yield must be high and positive before harvest index could be used as a selection criterion for improving grain yield.

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Table 1. Ten winter wheat genotypes, their origin and year of release.

Genotype	Type of cultivar	Origin	Year of release
Bounty Hybrid 100	Hybrid	Cargill	1984
Bounty Hybrid 203	Hybrid	Cargill	1984
Bounty Hybrid 310	Hybrid	Cargill	1984
TAM 105	Pure-line, semi-dwarf	Texas	1979
Newton	Pure-line, semi-dwarf	Kansas	1977
Vona	Pure-line semi-dwarf	Colorado	1976
Chisholm	Pure-line semi-dwarf	Oklahoma	1983
Payne	Pure-line semi-dwarf	Oklahoma	1977
Triumph 64*	Pure-line tall	Oklahoma	1964
Concho*	Pure-line tall	Oklahoma	1954

*Long term check cultivars.

Table 2. Analysis of variance for ten winter wheat genotypes over two locations and two seeding rates.

Source	df	Mean Squares							
		Harvest index	Grain yield	Biomass yield	Tiller number	Kernels per spike	100 Kernel weight	Days to heading	Plant height
		---%---	---- g m^{-2}----		--m^{-2}--		---g----		--cm--
Location	1	ns	**	**	**	**	ns	**	**
Error (a)	6	14.8	2203	18202	3978	3.1	0.05	2.00	16.0
Genotype	9	**	**	**	**	**	**	**	**
Geno x Loc	9	**	ns	ns	**	*	**	**	ns
Error (b)	54	4.3	909	6334	1312	11.6	0.03	0.63	9.7
Seed rate	1	**	**	**	**	**	**	**	**
Seed rate x Loc	1	**	**	ns	**	ns	*	ns	ns
Geno x Seed rate	9	ns	**	*	**	ns	**	**	ns
Geno x Loc x Seed rate	9	ns	ns	ns	**	*	ns	ns	ns
Error (c)	60	2.8	356	2221	513	13.9	0.02	0.23	4.0

*,**Significant at the 0.05 and 0.01 levels, respectively.

Table 3. Mean values for eight agronomic traits of ten winter wheat genotypes at standard (S)* and low (L) seeding rates over two locations.

Genotype	Harvest index S	Harvest index L	Grain yield S	Grain yield L	Biomass yield S	Biomass yield L	Tiller number S	Tiller number L	Kernels per spike S	Kernels per spike L	100 kernel weight S	100 kernel weight L	Days to heading S	Days to heading L	Plant height S	Plant height L
	%		$g\ m^{-2}$				m^{-2}				g				cm	
Chisholm	46.9	45.5	229	126	489	277	242	118	31	38	3.56	3.38	40	41	72	68
Vona	45.4	43.8	244	129	537	294	331	152	36	44	2.72	2.68	43	43	70	69
B. Hybrid 100	42.9	41.4	227	110	529	266	216	99	31	41	3.99	3.50	43	43	80	76
Triumph 64	42.4	44.1	219	124	517	280	268	118	29	38	3.73	3.64	41	42	89	86
Payne	41.6	42.3	223	148	536	349	336	161	34	42	2.75	3.02	47	48	76	74
B. Hybrid 203	41.5	38.8	246	118	592	304	267	112	40	50	3.00	2.90	47	49	86	82
TAM 105	40.8	40.0	225	144	551	360	337	180	31	39	2.72	2.76	47	48	80	76
Newton	38.8	37.7	223	136	575	360	321	160	37	46	2.44	2.36	47	48	82	80
B. Hybrid 310	34.4	33.2	202	105	587	316	275	127	41	46	2.58	2.46	48	49	84	80
Concho	32.9	33.0	144	85	438	257	212	121	33	41	2.46	2.53	50	52	97	93
S.E.	0.8		12.7		35.7		16.8		1.1		0.06		0.4		1.1	

*S = 67.2 kg/ha, L = 16.8 kg/ha seeding rates.

S.E. is the standard error of the difference between seeding rate means of the same cultivar averaged over locations.

Table 4. Phenotypic correlation coefficients (r) among eight agronomic traits in ten winter wheat genotypes over seeding rates and locations.

Traits	Harvest index	Grain yield	Biomass yield	Tiller number	Kernels per spike	100 Kernels weight	Days to heading
Grain yield	0.453*						
Biomass yield	-0.146	0.823**					
Tiller number	-0.004	0.788**	0.861**				
Kernels per spike	-0.200	-0.455*	-0.384	-0.488*			
100 kernels weight	0.646**	0.159	-0.207	-0.339	-0.387		
Days to heading	-0.781**	-0.021	0.447*	0.385	0.036	-0.690**	
Plant height	-0.642**	-0.696**	-0.369	-0.488*	0.283	-0.163	0.316

*,**Significant at the 0.05 and 0.01 levels, respectively.

Table 5. Phenotypic correlation coefficients (r) between seeding rates for eight agronomic traits.

Traits	r
Harvest index	0.957**
Grain yield	0.683*
Biomass yield	0.629
Tiller number	0.897**
Kernels per spike	0.933**
100 kernels weight	0.949**
Days to heading	0.989**
Plant height	0.991**

*,**Significant at the 0.05 and 0.01 levels, respectively.

PART IV

COMBINING ABILITY ANALYSIS OF HARVEST INDEX AND ITS COMPONENTS IN WINTER WHEAT

COMBINING ABILITY ANALYSIS OF HARVEST INDEX AND ITS COMPONENTS IN WINTER WHEAT[1]

ABSTRACT

A set of seven winter wheat (Triticum aestivum L.) genotypes, representing a range in plant type, grain yield potential, and genetic background, were crossed in a diallel mating system to produce F1's. The 21 F1's and seven parents were evaluated in hill plots in the 1983-84 growing season. Combining ability analysis was conducted using Griffing's Method 4, Model 1. General (GCA) and specific (SCA) combining ability effects were calculated for parents and F1's. The results of this study indicated that both GCA and SCA effects were significant for harvest index, grain yield and biomass yield. Chisholm appeared to be a superior parent for harvest index with the highest GCA estimate of the seven parents. It was also a good parent in terms of GCA for grain yield and biomass yield. Combining ability estimates for grain yield and biomass yield showed a similar trend which was supported by highly significant positive correlation between grain yield and biomass yield. The most promising F1's for harvest index were Vona/Triumph 64, Chisholm/TAM 105, and Chisholm/Triumph 64.

Additional index words: Triticum aestivum L., harvest index, combining ability.

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INTRODUCTION

The diallel cross system refers to a mating system in which a set of 'p' genotypes is crossed in all possible single-cross including selfing. The method will produce p^2 combinations. When all such matings are performed, the system is referred to as a complete diallel system. A diallel mating design is used to estimate the combining ability of a parental genotype in terms of its ability to transmit desired traits to its offspring. Sprague and Tatum (1942) identified two types of combining ability, general combining ability (GCA) and specific combining ability (SCA). They defined GCA as the average performance of a line in hybrid combination, and SCA as those cases where certain combinations perform relatively better or worse than expected on the basis of GCA of the parents involved. It is generally accepted that GCA and SCA are a measure of additive and non-additive gene action, respectively. Simmonds (1979) reviewed the general features of combining ability. He considered combining ability estimates to be statistically robust because their calculations are based on means and totals. Moreover, they are genetically neutral and hence, equally applicable to both self- and cross-pollinated species. Further, he compared combining ability to offspring-parent regressions and stated that the proportion of the total variance taken up by GCA is near to a narrow sense heritability. Baker (1978) considered GCA as the main effect and SCA as the interaction, and pointed out that if the SCA mean square is not significant, the performance of the single-cross progeny can be adequately predicted on the basis of GCA. In that case, the best performing progeny may be produced by crossing the two parents with the highest general combining abilities. On the other hand, a significant SCA mean square would suggest that the interactions are important in determining the performance of single cross progenies.

Various modifications of the basic diallel system have been described in the literature (Hayman, 1954; Griffing, 1956; Gardner and Eberhart, 1966). Baker (1978) compared several modifications and pointed out similarities and differences among them. He also mentioned several problems associated with certain models. The use of a particular model of diallel analysis depends on various factors including the nature of the experiment, the number of parents and the manner in which the parents are chosen.

This study involved a diallel analysis of seven winter wheat (Triticum aestivum L.) genotypes for harvest index, grain yield and biomass yield. The diallel analysis procedure of Griffing (1956) was adopted. The seven parents included in this study were chosen on the basis of prior knowledge of differences in plant type, yield potential and genetic background. Griffing (1956) has suggested two models of diallel analysis based on the way the parents are chosen. Randomly selected parents from a population should be analyzed by a random model (Model 2), while for deliberatly chosen parents, a fixed model (Model 1) is appropriate. Further, Griffing has listed four possible methods of analyzing data from a diallel crossing system depending upon the inclusion or exclusion of the reciprocal F1's and/or parents. This study utilized method 4, where only one set of F1's and neither the reciprocals nor the parents are included in the analysis. Both Baker (1978) and Griffing (1956) have suggested that Method 4 gives less biased estimates of combining ability than Griffing's three other methods.

Harvest index (HI) is the ratio of economic yield to total biomass yield and appears to be an important trait to be considered in cereal yield improvement. The importance of harvest index in plant improvement comes from its possible use as a indirect selection criterion for improving grain yield. The genetic mechanism controlling the inheritance of harvest index is not clearly understood. Both additive and non-additive gene actions have been reported to be important in controlling the combining ability of harvest index in wheat (Mosad, 1981; Nanda et al., 1983). Mosad (1981) reported that genetic variation in harvest index and its components in spring wheat was mostly due to additive genetic effect and/or additive x additive interactions. Nanda et al. (1983) found that in an 11-parent diallel study of harvest index in spring wheat, both GCA and SCA mean squares were significant with greater magnitude for GCA.

Genetic information on harvest index for winter wheat cultivars of the Southern Great Plains is lacking. Information on combining ability is important to plant breeders as it aids in the selection of the parents to be included in the crossing program. Hence, a study of the combining ability for harvest index in a set of leading winter wheat genotypes in the Oklahoma State University (OSU) wheat breeding program was considered important.

The objectives of this study were to estimate combining ability for harvest index and its components in a set of seven selected winter wheat genotypes using a diallel mating design, and to determine the correlations between harvest index and several other plant traits.

MATERIALS AND METHODS

Seven winter wheat genotypes selected for this study were 'Triumph 64', 'Scout 66', 'Vona', 'TAM 105', 'Brule', 'Chisholm', and 'NR 391-76'. The above seven genotypes have been utilized in the OSU wheat breeding program. Triumph 64 is an early maturing tall wheat with high test weight. It exhibits a 'slow-rusting' response to leaf rust (*Puccinia recondita* Rob. ex. Desm. f. sp. *tritici*). It was developed by the late Joseph Danne, a private farmer, as Rust Resistant Triumph. It was released as Triumph 64 by the Oklahoma Agricultural Experiment Station (AES) in 1964. Scout 66 is medium in maturity and has tall weak straw with some resistance to leaf rust and stem rust (*P. graminis* Pers. f. sp. *tritici* Eriks) of wheat. It was released by the Nebraska AES in 1967. Vona is a semi-dwarf wheat with early maturity and has good straw strength with moderate resistance to most races of stem rust. It was released by the Colorado AES in 1976. TAM 105 is a semi-dwarf wheat with medium maturity, strong straw and some leaf rust resistance. It was released by the Texas AES in 1979. Brule is a medium tall wheat with medium maturity and has resistance to stem rust. It was released by Nebraska AES in 1981. Chisholm is an early maturing semi-dwarf wheat with strong straw, high test weight and moderate resistance to leaf rust. It was released by the Oklahoma AES in 1983. NR 391-76 is an Austrian semi-dwarf wheat cultivar with wide leaves and thick straw. It is relatively well adapted to the Southern Great Plains of the USA.

These seven genotypes were crossed in a diallel mating system, without reciprocals, to produce 21 F1's. The crosses were made in the greenhouse at Stillwater in the spring of 1983. The 21 F1's and 7 parents were planted in the field at Stillwater, Oklahoma on Nov. 11, 1984. The planting was done in hill plots with a corn jabber. Each hill was planted with ten seeds and the hills were 30 cm apart in each direction. The field plot design was a randomized complete block with four replications. Standard nursery management practices were adopted during the growing season. However, the general growing conditions were somewhat poorer than average. The plant stands were poor in the hill plots because of the low soil moisture in the fall, early snow during mid December and drought during the later part of the growing season.

Heading date was recorded when approximately half of the total number of tillers in a hill had spikes completely out of boot. At maturity, plant height from each hill was recorded in centimeters. The number of seed bearing tillers was also recorded prior to harvest. Individual hills were harvested with a hand sickle at 1.8 cm above ground level. Plants from each hill were placed in individual paper bags and air dried in a glasshouse. The weight of the air dried samples were recorded as the biomass yield (g/hill). The samples were threshed individually with a belt thresher and grain weight of each sample was recorded as g/hill. Harvest index was calculated by the following formula:

Harvest index = (grain yield/biomass yield) x 100.

The number of kernels per hill was counted and average kernel weight was determined as grain weight per hill divided by the number of kernels per hill. Seeds per head was calculated as: (number of kernels per hill/spikes per hill).

Analyses of variance were calculated on the 21 F1's for harvest index, grain yield and biomass yield. A combining ability analysis was conducted using Griffing's Method 4, Model 1 (1956). Phenotypic correlation coefficients were determined among eight plant traits on the basis of 21 F1's means over four replications.

RESULTS AND DISCUSSION

The mean squares for harvest index, grain yield and biomass yield are presented in Table 1. Mean squares for F1's were significant for all three traits. Mean squares for GCA and SCA were significant for the three traits (Table 2), which suggested that both additive and non-additive genetic effects were important for the three traits in these crosses. This finding was in agreement with the results reported by Nanda et al. (1983), but was different from the results reported by Mosad (1981).

The estimates of GCA effects and mean harvest index for the seven parents are presented in Table 3. In general, the parents with higher mean harvest index values showed positive GCA estimates, while the parents with lower values for harvest index showed negative GCA effects. Chisholm, with the highest mean harvest index also had the highest value for GCA estimate. This indicated that harvest index of the array of crosses involving Chisholm was usually higher than the average of the F1's. The lowest mean harvest index and the lowest GCA estimate for harvest index were associated with Scout 66, indicating that the series of crosses involving Scout 66 usually had lower harvest index values than the average of all F1 combinations.

Estimates of GCA effects for grain yield were high and positive for Triumph 64 and Chisholm and negative for Brule and Scout 66 (Table 3). Unlike harvest index, parents with high mean grain yields did not always show high GCA effects for grain yield. This suggested that a high mean grain yield of a parent with a low GCA effect could be due to high grain yield of one or more specific hybrid combination(s) involving that parent.

For biomass yield, the parents Triumph 64 and Chisholm had high GCA estimates (Table 3). Brule, Scout 66, and Vona had the lowest GCA estimates for biomass yield. The parent with the highest mean biomass yield (TAM 105) showed a negative GCA effect. This indicated that one or more crosses of the set of F1's involving TAM 105 as one parent differed significantly from others for mean biomass yield.

Estimates of the SCA effects and means for harvest index for the 21 F1's are given in Table 4. Several F1's had high positive SCA effects for harvest index. These F1's with high SCA effects involved some parents with high, as well as some with low, GCA effects. Since the SCA mean square was significant for harvest index, there may not be any valid prediction about SCA based on GCA effects. Hence, both the GCA of the parents and SCA of the F1 should be considered in order to find the best hybrid combinations. Considering both GCA and SCA effects, the hybrid combination of Chisholm/TAM 105 and Vona/Triumph 64 had the best specific combining ability for harvest index. The lowest value of SCA effect for harvest index was associated with TAM 105/Brule hybrid combination.

For grain yield, the highest positive SCA estimates were noted for Brule/Scout 66, Triumph 64/TAM 105, Vona/Brule, and TAM 105/Scout 66. These F1 combinations involved either one or both of the parents with low GCA estimates. Hence, considering both GCA and SCA effects, the best specific combination for grain yield was Triumph 64/TAM 105. The combination of the parents with the highest GCA estimates for grain yield (Chisholm/Triumph 64) showed negative SCA estimates for grain yield. This could be attributed to the significant SCA mean square for grain yield. The lowest SCA estimates for grain yield was associated with TAM 105/Brule and Vona/Scout 66 hybrid combinations.

Estimates of SCA effect for biomass yield showed a trend similar to that found for grain yield. The F1 combinations with the highest and lowest SCA estimates for biomass yield were those that had shown the highest and lowest SCA estimates for grain yield as well. Considering both GCA and SCA effect, the hybrid combination that resulted in the highest biomass yield was Triumph 64/TAM 105. The lowest SCA estimates for biomass yield were associated with TAM 105/Brule and Vona/Scout 66 hybrid combinations.

Phenotypic correlation coefficients (r) among eight different plant characters are given in Table 5. Harvest index showed significant positive correlations with grain yield (r = 0.731), biomass yield (r = 0.573), number of tiller (r = 0.558), and average number of kernels per head (r = 0.455) and significant negative correlation with days to heading (r = -0.833). Other significant positive correlations were found between grain yield and biomass yield (r = 0.976), grain yield and tiller number (r = 0.930) and biomass yield and tiller number (r = 0.937). Significant negative correlations were found between grain yield and days to heading (r = -0.751), biomass yield and days to heading (r = -0.630), tiller number and days to heading (r = -0.682) and between average number of kernels per head and average kernel weight (r = -0.493).

The results of the diallel study indicated that both GCA and SCA effects were significant for harvest index, grain yield and biomass yield. Chisholm appeared to be the best parent in terms of general combining ability for harvest index. It was also a good parent in terms of combining ability for grain yield and biomass yield. Combining ability estimates for grain yield biomass yield showed a similar trend which was supported by the highly significant positive correlation between grain yield and biomass yield. The most promising F1's for harvest index were Vona/Triumph 64 and Chisholm/TAM 105. This study should be repeated in other locations and/or year to obtain a more reliable result. The below normal growing season causing poor stands could have affected the results.

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LIST OF TABLES

Table 1. Mean squares of three traits for 21 F1's from a seven parent winter wheat diallel cross.

Source	df	Mean Squares Harvest index	Grain yield	Biomass yield
		-------%------	-----------g/hill----------	
Replication	3	32.53*	51.15	216.84
F1's	20	41.38**	170.72**	707.68**
Error	60	8.32	26.10	112.07

*,**Significant at the 0.05 and 0.01 levels, respectively.

Table 2. Mean squares for GCA and SCA for three traits from a seven parent diallel cross.

Traits	Mean squares GCA	SCA	Error
Harvest index	18.56**	6.92**	2.08
Grain yield	76.50**	28.18**	6.52
Biomass yield	198.33**	124.89**	28.02

**Significant at the 0.01 probability level. Degrees of freedom for GCA, SCA and error mean squares are 6, 14, and 60, respectively.

Table 3. Estimates of GCA effects and parental means for three characters from a 7 parent diallel cross.

Parent	Harvest index		Grain yield		Biomass yield	
	GCA	parental mean	GCA	parental mean	GCA	parental mean
	---------%-----------		-----------------------g/hill------------------			
Chisholm	2.83	46.9	4.69	41.4	7.39	88.5
Vona	1.71	43.3	-1.60	27.6	-6.26	63.5
Triumph 64	1.05	42.4	5.60	34.2	12.24	80.7
NR 391-76	-0.21	41.6	0.96	31.4	3.29	75.0
TAM 105	-1.21	39.7	-1.61	37.9	-2.91	96.2
Brule	-1.89	38.1	-4.08	29.1	-7.23	76.2
Scout 66	-2.27	34.1	-3.96	28.0	-6.51	82.0
Mean		41.0		32.8		80.3
LSD (0.05)		3.3		12.1		32.5
S.E.	0.91		1.61		3.35	

Table 4. Estimates of SCA effects and means for 21 Fl's from a 7-parent winter wheat diallel cross.

Cross	Harvest index		Grain yield		Biomass yield	
	SCA	Mean of Fl	SCA	Mean of Fl	SCA	Mean of Fl
	-------%-------		------------g/hill--------------			
Chisholm/Scout 66	2.30	45.0	3.10	29.9	4.40	66.5
Chisholm/Brule	0.50	43.6	-5.18	21.5	-11.60	49.8
Chisholm/TAM 105	2.24	46.0	1.40	30.6	0.80	66.5
Chisholm/NR 391-76	-1.86	42.9	-0.99	30.7	0.40	71.5
Chisholm/Triumph 64	-2.12	43.9	-1.79	34.6	2.20	78.8
Chisholm/Vona	-1.08	45.6	3.46	32.6	8.90	71.3
Vona/Scout 66	-3.58	38.0	-8.17	12.3	-16.20	32.3
Vona/Brule	1.44	43.4	4.90	25.3	10.55	58.3
Vona/TAM 105	0.96	43.6	0.90	23.8	2.20	54.3
Vona/NR 391-76	0.26	43.9	2.14	27.6	4.50	62.8
Vona/Triumph 64	2.00	46.9	-3.23	26.8	-9.15	57.3
Triumph 64/Scout 66	1.18	42.1	1.14	28.9	0.80	67.8
Triumph 64/Brule	0.90	42.2	2.20	29.8	3.80	70.0
Triumph 64/TAM 105	1.52	43.5	5.43	35.5	11.20	81.8
Triumph 64/NR 391-76	-3.48	39.5	-3.76	28.9	-3.75	73.0
NR 391-76/Scout 66	1.04	40.7	-1.82	21.3	-6.00	52.0
NR 391-76/Brule	1.86	41.9	0.22	23.2	-2.00	55.3
NR 391-76/TAM 105	2.18	42.9	4.20	29.6	7.65	69.3
TAM 105/Scout 66	-1.56	37.1	-2.03	18.5	-2.05	49.8
TAM 105/Brule	-5.34	33.7	-9.91	10.5	-19.80	31.3
Brule/Scout 66	0.62	38.6	7.77	25.8	19.05	66.5
Fl mean		42.1		26.1		61.2
LSD (0.05)		4.1		7.2		15.0
SE (common parent)	1.82		3.23		6.70	
SE (no common parent)	1.58		2.80		5.80	

Table 5. Phenotypic linear correlation coefficients among 8 traits of 21 F1's from a seven parent winter wheat diallel cross.

Traits	Grain yield	Biomass yield	Tiller number	Kernels per spike	Average kernel wt.	Plant height	Days to heading
Harvest index	0.731**	0.573**	0.558**	0.455*	0.205	-0.375	-0.833**
Grain yield		0.976**	0.930**	0.257	0.306	0.112	-0.751**
Biomass yield			0.937**	0.209	0.287	0.278	-0.630**
Tiller number				0.014	0.226	0.186	-0.682**
Kernels per spike					-0.493*	-0.200	-0.206
Average kernel wt.						0.245	-0.199
Plant height							0.036

*,**Significant at the 0.05 and 0.01 levels, respectively.

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