GENOTYPE X ENVIRONMENT INTERACTIONS OF KERNEL HARDNESS IN HARD RED WINTER WHEATS

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CHAPTER I

INTRODUCTION

Wheat kernel hardness has recently become an important issue because the Federal Grain Inspection Service (FGIS) has proposed using it as a classification factor in the USA. In general, wheats are classified according to kernel texture, protein content of endosperm (Kent, 1975), and color. Kernel texture affects the way the grain breaks down during milling. The quantity and chemical structure of endosperm protein is a most important characteristic in determining baking quality (Kent, 1975). The traditional wheat market classes in the USA are based primarily on milling and baking quality (Smith, 1991). The FGIS has emphasized the need to preserve the integrity of the traditional wheat classes. However, the changes in grain classification standards in the new system may have a great effect on wheat market classes, wheat breeding and quality evaluation.

Hard red winter (HRW) wheat, grown mainly in the central Great Plains, is used primarily for breadmaking. It is apparent that kernel hardness has great potential significance in classifying wheats in the markets in light

of changes in grain classification standards. It follows that the development of HRW wheat varieties with acceptable kernel hardness values appears to be an important objective for the Oklahoma wheat breeding program in the future.

It is known that genotype x environment (G x E) interactions occur for grain yield and end-use quality traits in wheat. It is assumed that kernel hardness would also show G x E ınteractions. The presence of G x E interactıons reduces the correlation between phenotype and genotype (Comstock and Moll, 1963), which in turn reduces selection efficiency in a breeding program. Therefore, precise information on the interactions helps wheat breeders to design more effective breeding programs.

The objectives of this study were to (i) examine the presence of G x E interactions for kernel hardness in a set of HRW wheat genotypes utilized commercially in the Southern Great Plains, (ii) estimate stability parameters for individual genotypes, and (iii) examine the usefulness of genotype grouping techniques based on mean values and stability parameters of kernel hardness.

CHAPTER II

LITERATURE REVIEW

Wheat Kernel Hardness

Wheat kernel hardness has been equated with kernel vitreosity, kernel texture, or amount of force necessary to crush the kernel (Wu et al., 1990). According to Pomeranz and Williams (1990), hardness is simply the state of being hard; "hard" is defined as "difficult to penetrate or separate into fragments", and "soft" is defined as "easily disintegratıng under stress." They considered that texture is "the arrangement of the constituents or particles of any material", which can be used to imply the degree of any hardness and softness. It is easy to determine the difference between hard and soft wheats by biting the kernels, but difficult to make the determination on a quantitative basis (Hoseney, 1987).

The major factor involved in kernel hardness has remained unclear. Barlow et al. (1973) showed that the binding between the protein and the starch appeared to be stronger in hard wheat than in soft wheat. They suggested that binding strength was responsible for the difference in kernel hardness. However, no further findings in support of

this view have been published (Malouf et al., 1992).

There is some relationship between kernel hardness and milling and baking quality; this relationship tends to be stronger with milling quality than with baking quality. Generally, of all quality characteristics, flour yield has the strongest relationships to kernel hardness (Smith, 1991). Pomeranz and Williams (1990) pointed out that there is no strong genetic linkage between kernel hardness and breadmaking potential. They concluded that significant correlations between hardness and breadmaking absorption, mixing time, or loaf properties, if any, are primarily due to selection pressures applied by wheat breeders and geneticists.

Measurement of Kernel Hardness

In wheat classification, kernel hardness is usually judged on the basis of appearance of the kernel rather than actual measurement. Theoretically, kernel hardness of wheats should be measurable. Ten methods have been used for evaluating kernel hardness (Wu et al., 1990). These methods involve measuring: 1) the force to crush or shear kernels, 2) abrasion, 3) work to grind kernels, 4) starch damage or diastatic activity, 5) flour yield or surface area, 6) speed reduction of a mill during grinding, 7) grinding time, 8) vibrations produced by grinding grain, 9) Near-infrared reflectance (NIR) analysis after grinding, 10) particle size

of ground wheat kernels. Among these methods, approved hardness method 39-70 based on NIR (American Association of Cereal Chemists, 1986), shows great potential to be used in the new classification system and in breeding programs.

The NIR hardness method is based on the following assumption. Near-infrared absorption increases with particle size of ground wheat kernels, which is in turn, related to kernel hardness. According to the assumption, Norris et al. (1989) developed an equation to estimate kernel hardness:

$$\text{Hardness value} = a + b_{1680} \times L_{1680} + b_{2230} \times L_{2230}$$

where a, b_{1680} and b_{2230} are standardization constants, and L_{1680} and L_{2230} are the log(1/reflectance) values at 1680 and 2230 nm. The kernel hardness value is scaled such that the five reference soft wheats average 25 and the five reference hard wheats average 75 units in the range of 0 to 100 units. The equation needs to be adjusted for each instrument, grinder, and operator configuration. It seems that this method is preferred by the FGIS to determine kernel hardness of bulk samples.

Genetics of Kernel Hardness

Wheat kernel hardness can be considered as a varietal character and may be modified by environmental factors (Symes, 1965). The inheritance of kernel hardness has been investigated by several workers.

Symes (1965) employed a particle size index (PSI) test to study kernel hardness in Australian wheats. He found that one major gene controlled the difference between a hard and a soft wheat with modification by minor genes.

Based on grinding time, Baker (1977) also showed a single-major-gene difference ın kernel hardness between "Glenlea", a very hard wheat, and "Neepawa", a hard wheat. But he detected two major genes for the difference between "Pitic 62" (soft) and "Neepawa".

Lukow et al. (1989) studied the genetics of medium hardness defined by grinding time. They demonstrated that there was no single major gene conferring medium kernel hardness, which most frequently is the result of kernel hardness mixture. However, they suggested that medium hardness wheats can be developed by an accumulation of one or more minor genes. These minor genes either soften the effect of the major genes for hardness or conversely harden the effect of the major genes for softness.

Recently, Baker and Sutherland (1991) studied kernel hardness as measured by grinding time. They indicated a two-major-gene difference in kernel hardness between a very hard and a soft wheat and a single gene difference between a hard and a soft wheat. However, genetic differences were also detected between a very soft and a soft wheat, a very hard and a hard wheat, and two very hard wheats. Therefore, they concluded that the genetıcs of kernel hardness is more

complex than described in previous work.

Genotype and Environment Effects on Kernel Hardness

Wheat kernel hardness has been investigated with other quality traits by several researchers. However, various results have been reported in terms of the effects of genotype, environment, and their interactions on kernel hardness.

Baenziger et al. (1985) studied kernel hardness based on particle size index in a set of soft red winter (SRW) wheat genotypes grown in 12 southeastern environments in the USA. They found that genotypic effect was much larger than the environmental effect. Genotype x environment interactions were relatively small and mainly caused by changes in magnitude rather than reversals of rank order. Significant differences in regression coefficients were observed. However, most genotypes showed significant ($P < 0.05$) or highly significant ($P < 0.01$) deviations from regression, which indicated that these genotypes would be classified as unstable.

Bassett et al. (1989) determined NIR kernel hardness in four soft white winter (SWW) wheat genotypes grown at 21 trials over 3 years in Washington and Idaho. Relatively large year x location and G x E interactions were found, suggesting a need for multiple environmental evaluation.

Pomeranz et al. (1985) examined NIR kernel hardness in

15 hard red winter (HRW) wheat genotypes from the International Wheat Performance Nursery grown at 11 locations in the USA, Europe, and Asia. They indicated that genotype had a much larger effect on kernel hardness than location. In a subsequent study, Pomeranz and Mattern (1989) investigated NIR kernel hardness in six HRW wheat genotypes from four locations in Nebraska, and ten HRW wheat as well as four SRW wheat genotypes from three locations in Kansas. Genotypic effect was found to be greater than environmental effect based on the analysis for all the test genotypes. But for HRW wheat genotypes, genotypic and environmental effects were similar in magnitude.

Recently, Peterson et al. (1992) determined kernel hardness by microscopic evaluation of individual kernels for 18 HRW wheat genotypes grown at six locations in Nebraska and one site in Arizona for two years. They detected that environmental effect on kernel hardness was greater than genotypic effect that was found to be similar in magnitude to G x E interaction effect. Regression analysis showed that there were significant differences in regression coefficients among the genotypes. Deviations from regression were nonsignificant for all the genotypes, which suggested that estimates of that statistic were of lesser value in differentiation of stability.

It appears that the estimates of genotypic and environmental effects, as well as the effect of G x E

interactions on kernel hardness are influenced by evaluation method. Therefore, further research on kernel hardness as measured by NIR is needed due to proposed changes in grain classification standards in the USA.

Genotype x Environment Interactions and Stability Analyses

According to Simmonds (1979), G x E interactions occur when two or more genotypes are compared in different environments, and are found to differ in their responses to environmental changes. Statistically, an interaction is described as the failure of the two response curves to be parallel (Baker, 1987).

Allard and Bradshaw (1964) divided environmental variation into two groups: predictable and unpredictable. The first category includes all permanent characters of the environment, such as general features of the climate, soil type, etc. The second category includes fluctuations in weather, such as annual precipitation and its distribution, disease infection and other factors that are unpredictable. When the environmental variations are due to predictable factors, the stratification of a region into homogeneous subregions can reduce the interactions within a sub-region (Horner and Frey, 1957; Allard and Bradshaw, 1964; Liang et al., 1966). However, it is common to find large genotype x year and large genotype x year x location interactions in

varietal trials. In such cases, tests should be conducted in a series of locations over several years (Allard and Bradshaw, 1964).

The magnitude of G x E interactions can be estimated by an analysis of variance (Sprague and Federer, 1951; Miller, et al., 1959; Comstock and Moll, 1963). Comparisons of variance components of variables are employed to determine the relative importance of different sources of environmental and G x E variation, which can be used to determine the optimum allocation of resources in testing.

Stuber et al. (1973) proposed another measure of G x E interactions. This method involves the correlation of performance of an array of genotypes in one environment with their performance in other environments, which has some appeal to empirical plant breeders (Moll and Stuber, 1974). Large positive correlation coefficients indicate little effect of G x E interactions, whereas the converse is true when evaluating the magnitudes of variance components attributed to such interactions (Stuber et al., 1973). A similar approach was also used to estimate the similarities among the test locations (Campbell and Lafever, 1977), and to determine if data from a single environment predict regional values of genotypes (Baenziger et al., 1985).

In discussing the implication of G x E interactions to plant breeding, Gregorius and Namkoong (1986) and Baker (1988) emphasized that interactions become important in

selection only when genotypes change in rank from one environment to another. In the absence of significant change in rank, data from one environment is sufficient for ranking genotypes in all other environments for breeding purpose. However, statistical methods available for detecting significant change in rank are not well developed (Baker, 1987).

The presence of significant G x E interactions in the analysis of variance does not provide information regarding the relative interaction of individual genotype with a series of environments. Thus, stability estimates are usually calculated for each genotype to characterize its performance in a series of environments. The relative differences among genotypes can then be compared.

A number of parametric statistics have been developed to enhance understanding of G x E interactions. Lin et al. (1986) studied the basic structures of nine statistics and found that they are related to three concepts as the following. "A genotype may be considered to be stable (i) if its among environment variance is small, (ii) if its response to environments is parallel to the mean response of all genotypes in the trial, or (iii) if the residual mean square from a regression model on the environmental index is small." Since these three concepts represent different aspects of stability, they may not lead to the same conclusions. Thus, the selection of stability statistics are

largely dependent on research objectives.

The most widely used stability analysis has been linear regression. It was first proposed by Yates and Cochran (1938), and later modified by several authors (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966; Perkins and Jinks, 1968). In general, this method involves the regression of each genotype on an environmental index derived from the mean of all or a subset of genotypes in tested environments. Although serious criticisms can be made on the interpretation of results, the method has been applied to a number of different crops and traits. As Hill (1975) concluded, it has the twin merits of simplicity and biological relevance.

In many cases, the linear regression method can be used successfully to describe the relationships between genotypes and environments. But like every other approach, this method fails sometimes (Hill, 1975). Perkins and Jinks (1968) recommended a variance analysis method to test the overall usefulness of the linear regression approach in an experiment. The method partitions significant G x E interactions into a part due to heterogeneity of regressions and a remainder due to pooled deviations from regression. If the heterogeneity of regressions alone is significant, all of the G x E interactions for each genotype can be predicted from the linear regressions on the environmental values within the limits of sampling error. If the remainder

component alone is significant, the usefulness of the approach for interpretation of data is doubtful. If both components are significant, and the heterogeneity of regression component is significant when compared with the remainder, the linear regression method would still have considerable practical value in the predictions of G x E interactions.

The method described by Eberhart and Russell (1966) has been used extensively in plant improvement. This method produces two parameters for each genotype, the linear regression coefficient (bi) and the deviation from regression (s^2di). A stable genotype is defined as one with a regression coefficient of 1.0 and zero deviation from regression.

Breese (1969) considered that the variation of any genotype can be divided into a predictable part corresponding to regression and an unpredictable part corresponding to deviation from regression. This work defined stability as the measurement of unpredictable irregularities in the response to environment as provided by the deviation from regression. Several authors (Becker, 1981; Yue et al., 1990; Kang and Pham, 1991) also ındicated that deviation from regression could be used to measure stability.

Lin et al. (1986) pointed out that regression analysis is a descriptive model, not a predictive model. Deviation

from regression represents no more than how good is the fit to a linear model. Lin et al. (1986) suggested that when deviations from regression are large, or heterogeneous, Wricke's ecovalence (W^2i) or Shukla's stability variance (σ^2i) should be used for the determination of stability. However, empirical comparisons of several methods indicated that W^2i, σ^2i and s^2di generally give similar information, so that with careful interpretation either one would be sufficient to obtain stability estimates (Kang and Miller, 1984; Pham and Kang, 1988; Yue et al., 1990).

Becker and Leon (1988) concluded that linear regression should be used only when there is interest in estimating and interpreting the value of regression coefficient, otherwise, W^2i or σ^2i is preferable to s^2di as a more direct measure of G x E interactions. Lin et al. (1986) indicated that unless the concept of stability and the kinds of environments are clearly understood, parametric statistics are of little use and may be misleading.

The genotype grouping technique characterizes genotypes on a group basis, and is particularly important in simultaneous selection. Francis and Kannenberg (1978) proposed a technique based on mean yields and their corresponding coefficients of variation (CVi). This method groups genotypes in four categories:

Group I-- Genotypes with high (above average) mean yield and low (below average) CVi

Group II-- Genotypes with high mean yield and high CVi

Group III-- Genotypes with low mean yield and low CVi

Group IV-- Genotypes with low mean yield and high CVi.

It is apparent that this method could be used for traits other than yield. Theoretically, the CVi statistic has a sufficiently broad inferential base for general assessment, but it does not provide information on the response pattern over environments which is vital for genotype recommendation (Lin et al., 1986). However, this method is particularly useful in screening a large number of entries in a breeding program (Funnah and Mak, 1980; Ntare and Aken'Ova, 1985).

A number of multivariate methods also have been proposed to allow a more detailed analysis of G x E interactions. As Becker and Leon (1988) indicated, these methods are too cumbersome to give any simple measure of stability that allows a ranking of genotypes. In general, there is a common agreement that the mean performance of a genotype is more reliable and important than any other stability estimates. It seems that the linear regression method described by Eberhart and Russell (1966), despite statistical imperfections, will continue to be used by breeders to deal with stability problems.

CHAPTER III

MATERIALS AND METHODS

Fifteen HRW wheat genotypes utilized commercially in the Southern Great Plains were used in this study. The genotypes were a part of the Oklahoma State University Wheat Variety Test System. These genotypes consisted of 7846, 2157, Abilene, Arkan, Century, Chisholm, Cody, Mesa, Siouxland, Stallion, TAM 200, TAM W-101, Thunderbird, Victory and Wrangler. The origins of the genotypes are given in Table I.

The genotypes were grown in randomized complete block designs with three replications at eight locations in Oklahoma in 1988 and 1989 (Fig. 1). The soil type at each location is given in Table II. Accepted cultural practices for use on a continuous wheat system were applied at all locatıons. Plots were 5 rows, 11.2 m long with 25 cm row spacing. Tests were planted after September 1 as soon as moisture was available, at the rate of 246 seed/m^2 (equivalent to 60 1b/A). Nitrogen, based on soil test, was applied in the proper amounts at planting to obtain grain yield of ca. 3360 kg/ha. All plots were harvested by a plot combine harvester between 8 and 17 June in 1988 and between

17 and 21 June in 1989.

Four 13-gram samples from the harvested grain of each plot were taken and analyzed separately. The individual sample was ground on a Udy cyclone grinder, and then the flour was mechanically mixed for 30 minutes. A Technicon InfraAlyzer 400 was used to determine kernel hardness values according to approved hardness method 39-70 at wavelengths of 1680 and 2230 nm (American Association of Cereal Chemists, 1986).

All data analyses were performed by using the procedures of the Statistical Analysis System (SAS Institute, 1987). Sample standard deviations of kernel hardness for individual genotypes were calculated on the basis of all sample values in the experiment. The mean of four samples from each plot was used for variance analyses.

A combined analysis of variance, following the outline presented by Comstock and Moll (1963) was adopted to test the significance of variables. The year and location effects were assumed to be random while the genotypic effect was assumed to be fixed. Significant G x E interactions were further partitioned into heterogeneity among regressions and a remainder source using the procedure outlined by Perkins and Jinks (1968).

For the examination of stability for individual genotypes, each location in each year was considered as a separate environment. Stability parameters discussed by

Eberhart and Russell (1966) were obtained from a linear regression analysis. This analysis produces two parameters: a regression coefficient (bi) estimated by regression of the genotype mean on the average of all genotypes in the particular environment, and a deviation from regression (s^2di). A t-test was used to test each regression coefficient under the hypothesis that bi = 1.0. The pooled error from the combined analysis of variance was used to test whether the deviations from regression were statistically significant.

The stability variances (σ^2i and s^2i) of Shukla (1972) were obtained with a computer program developed by Kang (1989). From this approach, the G x E interactions were divided into components, one corresponding to each genotype. According to theory, σ^2i is an unbiased estimate of the G x E interaction for genotype i, whereas s^2i is an adjusted stability variance after taking a covariate into consideration. The approximate test suggested by Shukla (1972) was used to test the significance of σ^2i and s^2i.

Spearman's rank correlations (Snedecor and Cochran, 1980) were calculated to measure the agreement of genotype ranks between one environment and the means of all the environments, and to determine the relationships among genotype means and their stability statistics.

The 15 genotypes were also divided on the basis of means vs. regression coefficients (mean-bi), and means vs.

standard deviations (mean-SD), respectively. These are the modification of grouping methods proposed by Eberhart and Russell (1966) and Francis and Kannenberg (1978). The two methods grouped genotypes into four categories:

Group I: Genotypes with high (above average) mean and low (below average) bi or SD;

Group II: Genotypes with high mean and high bi or SD;

Group III: Genotypes with low mean and low bi or SD;

Group IV: Genotypes with low mean and high bi or SD.

CHAPTER IV

RESULTS AND DISCUSSION

Kernel hardness values of the 15 genotypes tested at 8 locations in 2 years ranged from 38.7 to 84.4 units (Table III). Based on the pooled analysis of variance for kernel hardness (Table IV), differences among genotypes were highly significant ($P < 0.01$). Year and location mean squares were not significant, whereas their interaction was highly significant. Among the first order interactions, the G x Y mean square was also highly significant, but the G x L mean square was nonsignificant. This indicated that unpredictable yearly factors had more influence on kernel hardness than location factors. The presence of highly significant G x Y x L interaction suggested that the genotypes tended to respond differently to certain year - location combinations.

Joint regression analysis (Perkins and Jinks, 1968) was used for further partitioning of the total G x E interaction sum of squares into two components: the heterogeneity among regressions and the remainder (Table V). This was a test to determine the overall usefulness of the linear regression approach for examining kernel hardness. The analysis showed that both components were highly significant (Table V). The

heterogeneity component was also highly significant ($F=2.89$, $P < 0.01$) when compared with the remainder (Table V). These results indicated that there were significant differences in regression coefficients among genotypes. The linear model would still be expected to retain considerable predictive value although it would not be entirely satisfactory because of significant nonlinear response of genotypes to varying environments.

Spearman's rank correlations of kernel hardness between the ranks of the 15 genotypes in one environment and the ranks of genotype means averaged over all the environments are given in Table VI. All environments except Purcell in 1989 showed highly significant rank correlations ($P < 0.01$) with overall environmental values. These results indicated that rank data of kernel hardness from a single environment were sufficient for predicting regional ranking values of genotypes in Oklahoma. For breeding purposes, the kernel hardness of early generation materials could be evaluated in one location. However, because of highly significant G x Y, G x Y x L, and Y x L interactions, multiple environmental testing, specially more than one year, is needed to accurately determine the kernel hardness value of a genotype.

A characterization of individual genotypes is given in Table VII. Mean kernel hardness values of genotypes ranged from 46.4 to 73.6 units. Thunderbird showed the highest mean

kernel hardness value (73.6), whereas Chisholm showed the lowest mean value (46.4). Standard deviations of samples for individual genotypes ranged from 5.53 to 8.41 units. Unlike yield, disease resistance and other quality traits, kernel hardness as such has not been considered as a breeding objective in wheat improvement programs. Results reported by Baker and Sutherland (1991) indicated a two-gene difference between a very hard and soft genotype and a one-gene difference between a hard and soft genotype. Lukow et al. (1989) found that there was no evidence of a major gene conferring medium kernel hardness, which is caused most frequently by kernel hardness mixtures. However, they suggested that medium hardness wheats can be developed by an accumulation of one or more minor genes that can weaken the function of major genes for hardness. Thus, the variation of kernel hardness in the 15 HRW wheat genotypes was probably caused by the different combinations of the major and minor genes and modified by environments.

Stability of kernel hardness can be examined from estimates of stability statistics. The regression analysis (Eberhart and Russell, 1966) resulted in regression coefficients (bi) ranging from 0.29 to 1.50 (Table VII). This indicated that there were large differences in response to environmental changes among the 15 genotypes. Three genotypes, Cody, Stallion and Siouxland, had regression coefficients significantly greater than 1.0 ($P < 0.05$) which

indicated that they were highly responsive to changes in environmental conditions. Chisholm and Century, with regression coefficients significantly less than one unit, showed less responsiveness to the environmental changes.

A stable genotype is defined by Eberhart and Russell (1966) as one with a regression coefficient of 1.0 and zero deviation from regression (s^2di). According to Becker (1981), s^2di can be used as a measure of the agronomic concept of stability. Small values should be desirable in an agronomic sense. Since deviations from regression for kernel hardness were significantly different from zero (Table VII), none of the genotypes can be considered to be stable. A quadratic model was also used to fit the data. However, this did not result in reduced deviations for most of the genotypes, which suggested that the large deviations of kernel hardness were not caused by quadratic response of genotypes.

Shukla's method provides an unbiased estimate of G x E interaction variance for each genotype (Shukla, 1972). This method also allows the use of a covariate(s) to remove the linear effects from G x E interactions. Consequently, the method has been recommended when the data show poor fit to a linear model, or when the deviations from regression are heterogenous (Lin et al., 1986). Since none of the genotypes was stable for kernel hardness based on the estimates of s^2di, the Shukla statistics (σ^2i and s^2i) were calculated

(Table VII). Both stability variance (σ^2i) and adjusted stability variance (s^2i) were significant or highly significant, indicating that instability of genotypes was not caused by a linear effect of the covariate. The results confirmed that NIR kernel hardness was an unstable character in the set of genotypes tested.

Interrelationships among stability statistics SD, bi, s^2di, σ^2i and s^2i were studied by Spearman's rank correlation (Table VIII). The rank coefficients between s^2di and Shukla statistics (σ^2i and s^2i) were highly significant, with r_s = 0.86 and r_s = 1.00, respectively. These indicated that both s^2di and Shukla statistics (σ^2i and s^2i) could provide useful stability estimates for kernel hardness. Similar results for yield in maize, wheat and sorghum were reported by other investigators (Yue et al., 1990; Pham and Kang, 1988). The Shukla statistics, σ^2i and s^2i were highly correlated with each other (r_s = 0.86, $P < 0.01$).

Regression coefficients (bi) and standard deviations (SD) were not rank correlated with s^2di, σ^2i, or s^2i (Table VIII). However, regression coefficients showed a highly significant rank correlation with standard deviations (r_s = 0.88, $P < 0.01$). These results showed that the standard deviation was approximately equivalent to the regression coefficient as a measure of genotype response to environmental changes.

Since Eberhart and Russell's method (1966) gives information on both regression coefficients and deviations from regression, it would be more preferable than Shukla's method (1972) in this case. However, variability among environments should be large enough for a proper estimation of regression coefficients (Sharma et al., 1987). Caution should also be used in the interpretation of regression coefficients for kernel hardness because of large unexplained variation, due, no doubt, to climatic variability.

For wheat quality traits, Peterson et al.(1992) emphasized the importance of optimal mean values and consistency of performance when measured across environments. Busch et al. (1969) suggested that a genotype with desirable stability parameters for flour ash concentration should have a regression coefficient as close to zero as possible, and the smallest possible deviation from regression. In terms of kernel hardness of HRW wheat, a desirable genotype should have acceptable values at all target environments to meet the future classification requirement set by the FGIS, a low regression coefficient ($b < 1$) with relatively small deviation from regression.

Kernel hardness values of 40 or 50 units (on a scale of 0 to 100) have been considered as the break point between HRW and SRW wheats (Smith, 1991). In this experiment, mean kernel hardness of a genotype was calculated on the basis of

192 sample values. According to the Empirical Rule (Dowdy, 1983), approximately 95% of the kernel hardness data for a genotype lies within the interval between mean - 2 x SD and Mean + 2 x SD. On the basis of calculations for kernel hardness interval, all the genotypes with mean kernel hardness below the grand mean (63.3 units) showed the lower bounds of the 95% of sample values (mean - 2 x SD) less than 50. These genotypes include Arkan, TAM W-101, 2157, 7846, TAM 200 and Chisholm. If the value of 50 is to be the break point, these genotypes may occasionally be classified as SRW or mixed wheats.

For many of the test environments in Oklahoma, Chisholm was lower in kernel hardness value compared with the other genotypes in the study. TAM 200, with b = 1.31, showed a high response to environmental changes (Table VII). If 40 is the minimum kernel hardness value set for HRW wheats, Chisholm, and possibly TAM 200 could be classified as SRW or mixed wheats. But according to the traditional classification system, both Chisholm and TAM 200 are defined as HRW wheats. Cox et al. (1989) studied milling and baking quality traits of a number of HRW wheat genotypes that represented varieties grown during the past 70 years. They found that TAM 200 and Chisholm have excellent overall baking quality, ranking 2nd, and 7th out of 40 genotypes, respectively. These results indicate that further research is required for making necessary refinements of the

classification system based on kernel hardness as measured by NIR to maintain the integrity of traditional classes in terms of end-use quality.

Spearman's rank correlations between mean kernel hardness and stability statistics (SD, bi, s^2di, σ^2i and s^2i) were not significant (Table VIII). This suggested that ranks in kernel hardness of genotypes relative to ranks in respective stability statistics were not consistent across the environments. Therefore, the selection of genotypes with both acceptable mean kernel hardness and desirable stability parameters appears to be possible.

The 15 genotypes were grouped according to the mean-bi and mean-SD methods, respectively. Based on the two methods, these genotypes were divided into four categories (Fig. 2 and Fig. 3). The mean kernel hardness and regression coefficients (bi) of the genotypes are presented in Fig. 2. The genotypes, Abilene, Wrangler, Victory and Century were located in Group I, showing higher mean kernel hardness values with less responses to environment changes ($b < 1$). Century and Victory, with small estimates of s^2di (less than average), were most desirable in the group in terms of stability. Five genotypes in Group II, Thunderbird, Cody, Mesa, Siouxland and Stallion had high mean kernel hardness values and high responses to environments. Four of the five genotypes (Cody excepted) also had relatively stable performance in the agronomic sense, as demonstrated by the

small estimates of s^2di. The six remaining genotypes were located in Groups III and IV with low (below average) mean kernel hardness values. Incidentally, three of the genotypes in Groups III and IV, Chisholm, 2157 and TAM W-101 were the most widely grown genotypes in Oklahoma during the years the study were conducted (Smith, 1991).

The mean-SD method showed similar results in grouping genotypes for kernel hardness as the mean-bi method (Fig. 3). Of the 15 genotypes, 13 were located in the identical groups by using the two methods. However, the mean-bi method provides additional information on deviations from regression for kernel hardness, which is useful to assess stability in the agronomic sense.

It is apparent that integration of desirable stability parameters with acceptable mean kernel hardness is essential in the selection or recommendation of HRW wheat genotypes in the future. Therefore, wheat breeders in the Southern Great Plains will be forced to pay more attention to kernel hardness in their breeding programs. The results of this study suggested that the mean-bi approach could be employed as an additional step following linear regression analysis (Eberhart and Russell, 1966) to characterize genotypes on a group basis. This method is best used in the later generations of the breeding programs when multiple environment data are available. The mean-SD method could be applied in the early generation selection programs to deal

with large numbers of materials.

CHAPTER IV

SUMMARY AND CONCLUSIONS

Research on kernel hardness has important implications in wheat breeding and quality evaluation because the FGIS has proposed the use of kernel hardness as a grain classification factor in the USA. The objectives of this study were to determine: (i) G x E interactions on kernel hardness in a set of HRW wheat genotypes grown in Oklahoma, (ii) stability parameters for individual genotypes, (iii) the usefulness of genotype grouping techniques based on mean values and stability parameters of kernel hardness.

Fifteen HRW wheat genotypes adapted to the Southern Great Plains were used in this study. All genotypes were grown in randomized complete block designs with three replications on a continuous wheat system at eight locations in Oklahoma in 1988 and again in 1989. Four samples were taken from the harvested grain of each plot to obtain a more accurate assessment of kernel hardness value. The individual grain sample was ground and the flour was used to determine a kernel hardness value according to the AACC method 39-70 (American Association of Cereal Chemists, 1986).

A combined analysis of variance was applied to the data

set based on the means of four samples from each plot. Highly significant differences among genotypes were found for kernel hardness (Table IV). The mean kernel hardness values over 16 environments ranged from Chisholm 46.4 to Thunderbird 73.6 units on a scale of 0 to 100 units. The sample standard deviations for individual genotypes ranged from 5.53 to 8.41 units (Table VII). The presence of G x Y and G x Y x L interactions suggested that genotypes tended to respond differently to yearly factors, especially to certain year-location combinations (Table IV). A linear regression analysis based on Perkins and Jinks method (1968) showed that the linear approach would be of considerable predictive value for kernel hardness.

Under the test environments, rank data of kernel hardness for the genotypes from a single environment were sufficient for predicting regional ranking values of the genotypes. For breeding purposes, the early generation materials could be evaluated in one location. But multiple environment testing, especially in more than one year, would be needed to accurately determine the kernel hardness of a genotype.

Stability statistics of kernel hardness were calculated for each genotype. The regression coefficients ranged from 0.29 to 1.50 (Table VII), indicating that there were large differences in response to environmental changes among the genotypes. However, all genotypes were unstable in kernel

hardness on the basis of deviations from regression (Eberhart and Russell, 1966) and stability variances (Shukla, 1972). Since the Eberhart and Russell approach gave information on both regression coefficient and deviation from regression, it would be preferable to Shukla's statistics in this case.

A HRW wheat genotype with desirable NIR kernel hardness should have acceptable values at all target environments and a low regression coefficient with relatively small deviation from regression.

If the kernel hardness value of 50 units is used as a break point between HRW and SRW wheats, six out of the 15 tested genotypes may occasionally be classified as SRW or mixed wheats. Even if 40 units were set as the minimum value for HRW wheats, Chisholm and TAM 200, with excellent breakmaking quality, would be classed as SRW or mixed wheats under certain circumstances. Therefore, further research is required for making necessary refinements in the wheat classification system based on kernel hardness in order to maintain the integrity of traditional market classes in terms of end-use quality.

Spearman's rank correlations between mean kernel hardness and stability statistics were nonsignificant. This lack of correlations would permit simultaneous selection for genotypes with both acceptable mean values and relatively desirable stability parameters in a breeding program.

According to the mean-bi method (Fig. 2), four out of the 15 genotypes, Abilene, Wrangler, Victory and Century showed high mean kernel hardness values and less responses to environments. Century and Victory, with relatively small deviations from regression, were most desirable in the group in terms of stability. Four genotypes, Thunderbird, Mesa, Siouxland and Stallion showed high mean kernel hardness values, high responses to environments with small deviations from regression. Incidentally, three most widely grown genotypes in Oklahoma, Chisholm, 2157 and TAM W-101, were located in the groups with relatively lower mean kernel hardness.

Wheat breeders will need to pay more attention to kernel hardness in their breeding programs because of proposed changes in the wheat classification standards. The results of this study suggested that the mean-bi method could be best used as an additional step following the Eberhart and Russell regression approach (1966) to characterize genotypes on a group basis. The mean-SD method would also be useful particularly in grouping early generation material for simultaneously selection for kernel hardness.

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APPENDIXES

APPENDIX A

TABLES

TABLE I

FIFTEEN HARD RED WINTER WHEAT GENOTYPES ANALYZED FOR KERNEL HARDNESS FROM 1988 AND 1989 CROP SEASONS

Genotype	Originating Institution
1. 7846	AGSECO
2. 2157	Formerly Pioneer Hi-Bred Int'l, Inc.
3. Abilene	Agripro
4. Arkan	Kansas State University
5. Century	Oklahoma State University
6. Chisholm	Oklahoma State University
7. Cody	University of Nebraska
8. Mesa	Agripro
9. Siouxland	University of Nebraska
10. Stallion	Agripro
11. TAM 200	Texas A & M University
12. TAM W-101	Texas A & M University
13. Thunderbird	Agripro
14. Victory	Agripro
15. Wrangler	Agripro

TABLE II

SOIL TYPES FOR THE EIGHT LOCATIONS IN OKLAHOMA, 1988 AND 1989

Location	Soil Series and Texture
Altus (AT)	Hollister clay loam
Apache (AP)	Hollister silt loam
Haskell (HK)	Taloka silt loam
Kingfisher (KF)	Kirkland silt loam
Lahoma (LH)	Pond Creek silt loam
Perkins (PK)	Teller loam
Purcell (PC)	Bethany silt loam
Tonkawa (TK)	Bethany silt loam

TABLE III

KERNEL HARDNESS VALUES OF 15 GENOTYPES TESTED AT 8 LOCATIONS IN EACH OF 2 YEARS

Genotype	1988								1989							
	LH	HK	TK	AP	PC	AT	PK	KF	LH	HK	TK	AP	PC	AT	PK	KF
7846	62.2	62.1	61.8	63.9	59.7	66.9	59.4	60.8	59.9	62.8	55.2	59.5	47.7	55.0	56.1	56.5
2157	51.4	61.8	57.2	73.1	60.4	72.4	53.3	63.8	59.3	62.5	57.9	58.8	55.3	53.0	52.4	58.4
Abilene	63.0	72.6	67.0	77.2	61.9	71.0	66.9	64.8	72.3	74.7	66.1	65.5	61.5	72.8	61.5	65.6
Arkan	63.8	63.1	61.7	70.2	63.6	74.7	62.3	62.2	68.8	64.9	63.2	64.2	49.5	56.2	60.7	60.4
Century	62.0	61.7	64.2	67.5	61.3	70.8	61.2	63.1	72.7	63.1	65.9	63.4	58.9	64.2	59.0	61.5
Chisholm	48.0	52.0	45.9	42.8	41.2	45.7	46.9	47.9	50.1	50.5	50.0	50.4	38.7	40.7	47.0	44.2
Cody	68.1	83.3	70.8	81.1	71.2	78.9	70.9	70.7	74.6	70.8	69.8	66.9	49.7	70.6	61.1	66.7
Mesa	66.3	68.9	65.9	75.9	63.1	77.9	62.2	64.9	75.1	68.8	65.9	71.6	55.2	68.7	64.1	61.8
Siouxland	56.6	68.4	66.8	76.5	68.4	76.0	63.6	67.2	66.4	71.3	63.2	65.2	50.7	63.4	59.3	60.8
Stallion	59.3	71.3	63.5	75.9	63.5	76.1	58.2	64.5	71.6	61.9	61.5	64.7	49.8	63.8	63.5	60.3
TAM 200	57.6	64.6	60.0	67.6	60.1	68.3	61.6	62.2	57.4	52.9	53.1	53.7	45.3	50.8	44.9	46.6
TAM W-101	50.4	61.8	59.1	69.3	59.6	69.7	56.2	61.2	59.0	59.2	57.4	67.5	60.5	67.6	55.2	50.0
Thunderbird	71.2	76.9	74.6	84.4	71.0	82.4	70.2	70.8	76.4	78.3	72.8	75.7	58.3	77.6	70.3	66.7
Victory	61.6	69.2	68.3	76.7	62.1	70.7	66.1	63.1	66.0	62.4	62.4	65.6	55.5	66.7	56.2	61.8
Wrangler	70.2	69.5	71.4	76.0	67.9	73.5	65.1	68.1	71.1	66.9	68.4	62.8	57.4	52.7	61.1	63.5

TABLE IV

ANALYSIS OF VARIANCE FOR KERNEL HARDNESS OF 15 GENOTYPES OVER 8 LOCATIONS IN 2 YEARS

Source	df	MS
Years (Y)	1	3248.17
Locations (L)	7	1106.33
Y x L	7	601.03**
Reps/Y/L	32	27.00
Genotypes (G)	14	1988.55**
G x Y	14	132.10**
G x L	98	37.01
G x Y x L	98	30.12**
Pooled error	448	9.27

**: Significant at the 0.01 probability level.

TABLE V

JOINT REGRESSION ANALYSIS FOR PARTITIONING THE G x E INTERACTIONS OF KERNEL HARDNESS

Source	df	MS
G x E Interactions	210	40.14**
Heterogeneity of regressions	14	103.02**
Remainder	196	35.64**
Pooled error	448	9.27

**: Significant at the 0.01 probability level.

TABLE VI

SPEARMAN'S RANK CORRELATIONS OF KERNEL HARDNESS BETWEEN ONE ENVIRONMENT[¶] AND THE MEANS OF ALL ENVIRONMENTS

Location	1988	1989
Altus	0.80**	0.79**
Apache	0.90**	0.78**
Haskell	0.84**	0.85**
Kingfisher	0.90**	0.96**
Lahoma	0.74**	0.87**
Perkins	0.84**	0.86**
Purcell	0.82**	0.52*
Tonkawa	0.90**	0.91**

¶: Each location within a year is considered as one environment.
*, **: Significant at the 0.05 and 0.01 probability levels, respectively.

TABLE VII

MEANS AND STABILITY STATISTICS OF KERNEL HARDNESS FOR 15 GENOTYPES OVER 16 ENVIRONMENTS

Genotype	Mean	SD	bi	s^2di	σ^2i	s^2i
Thunderbird	73.6	7.26	1.20	3.17**	20.41**	18.94**
Cody	70.3	8.41	1.50*	8.01**	52.58**	35.67**
Abilene	67.8	5.94	0.79	8.52**	37.94**	37.45**
Mesa	67.3	6.66	1.11	3.65**	19.68**	20.60**
Wrangler	66.6	6.87	0.94	14.40**	53.75**	57.81**
Siouxland	65.2	7.16	1.30*	3.07*	23.74**	18.60*
Victory	64.6	6.30	0.98	3.39**	17.89*	19.69**
Stallion	64.3	7.30	1.31*	3.73**	26.67**	20.85**
Century	63.8	5.53	0.60*	3.85**	31.76**	21.28**
Arkan	63.1	6.94	1.05	4.08**	20.27**	22.08**
TAM W-101	60.2	6.71	0.73	22.18**	84.08**	84.73**
2157	59.4	6.84	1.07	12.44**	47.51**	51.00**
7846	59.4	5.60	0.81	2.64*	18.13*	17.10*
TAM 200	56.7	8.00	1.31	15.21**	63.48**	60.62**
Chisholm	46.4	5.66	0.29**	11.62**	84.14**	48.19**

*, **: Significant at the 0.05 and 0.01 probability levels, respectively.
SD: Standard deviation of samples for individual genotype.
bi: Regression coefficient.
s^2di: Deviation from regression.
σ^2i: Stability variance.
s^2i: Adjusted stability variance.

TABLE VIII

SPEARMAN'S RANK CORRELATIONS OF MEAN KERNEL HARDNESS AND STABILITY STATISTICS FOR 15 GENOTYPES OVER 16 ENVIRONMENTS

	SD	bi	s^2di	σ^2i	s^2i
Mean	0.29	0.35	-0.34	-0.31	-0.34
SD		0.88**	0.13	0.16	0.13
bi			-0.20	-0.17	-0.20
s^2di				0.86**	1.00**
σ^2i					0.86**

**: Significant at the 0.01 probability level.

APPENDIX B

FIGURES

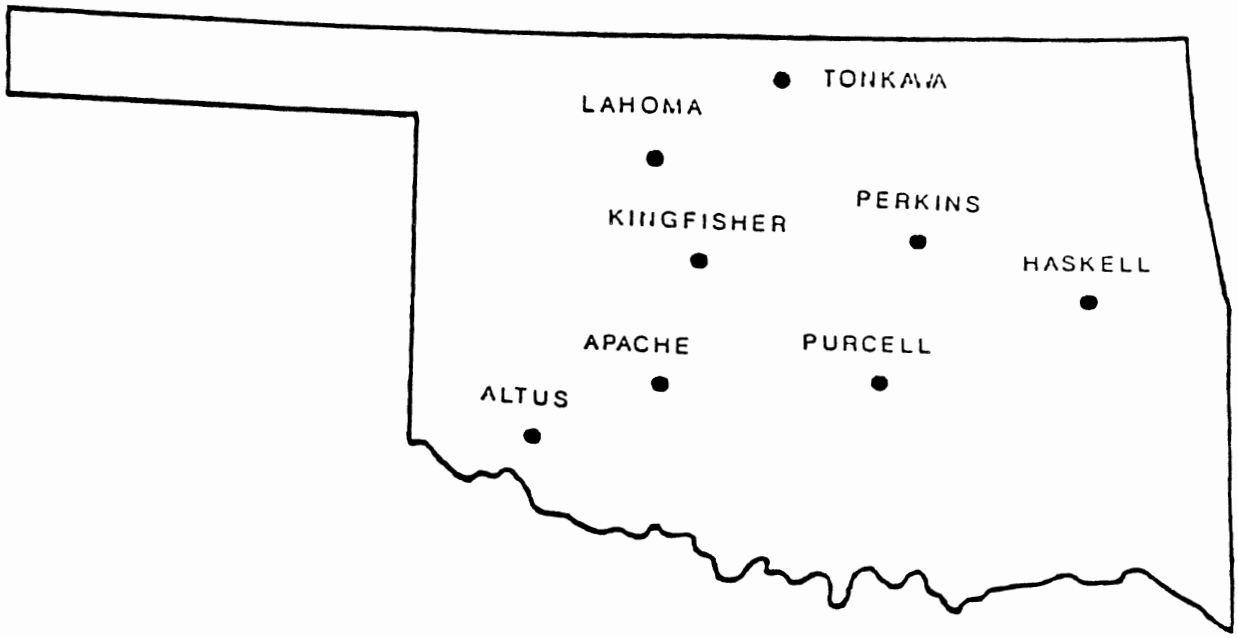

Figure 1. The eight locations used in analysis of kernel hardness for 15 genotypes in 1988 and 1989

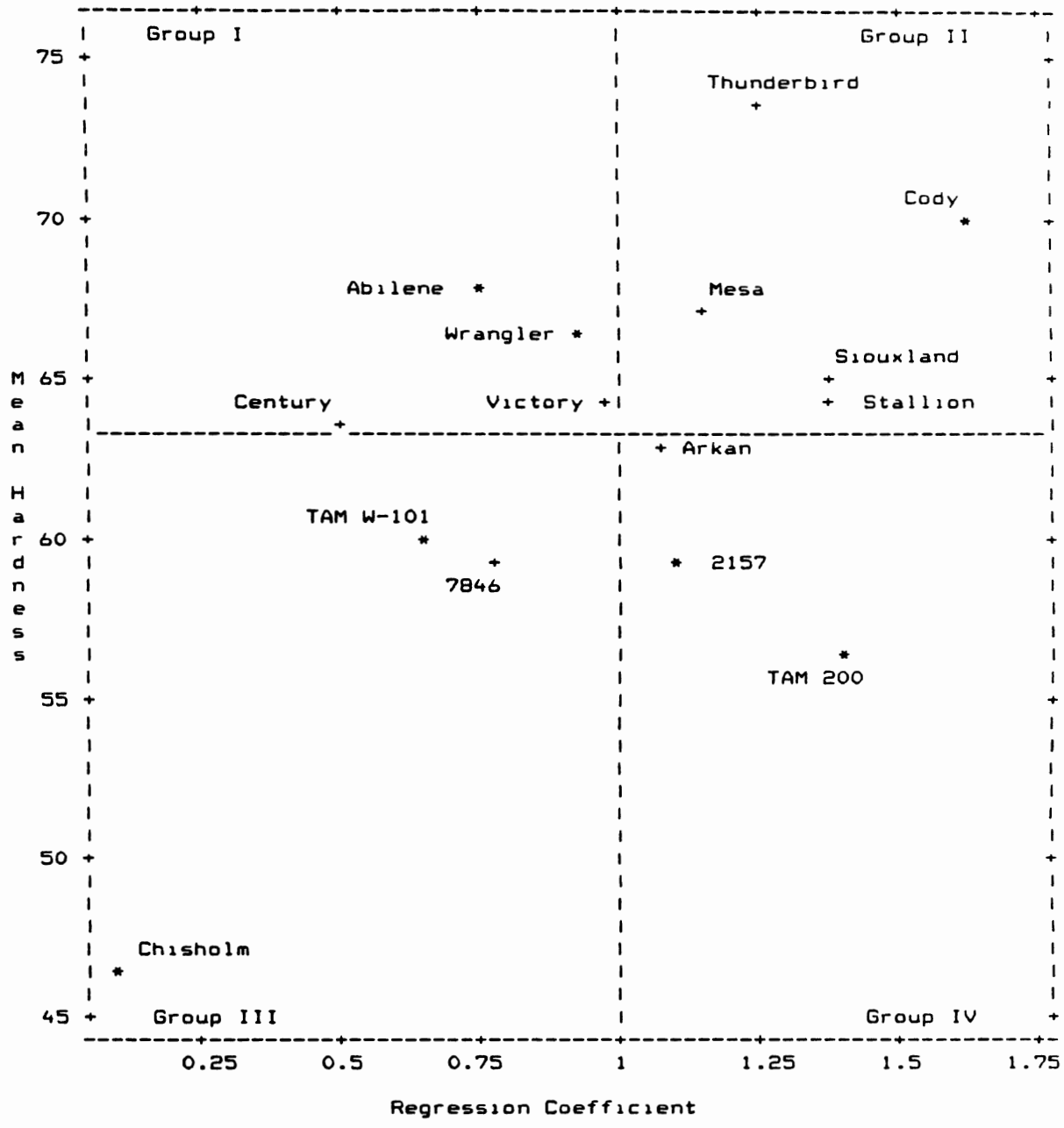

Figure 2. Means of kernel hardness plotted against regression coefficients for 15 genotypes. +: deviation less than average

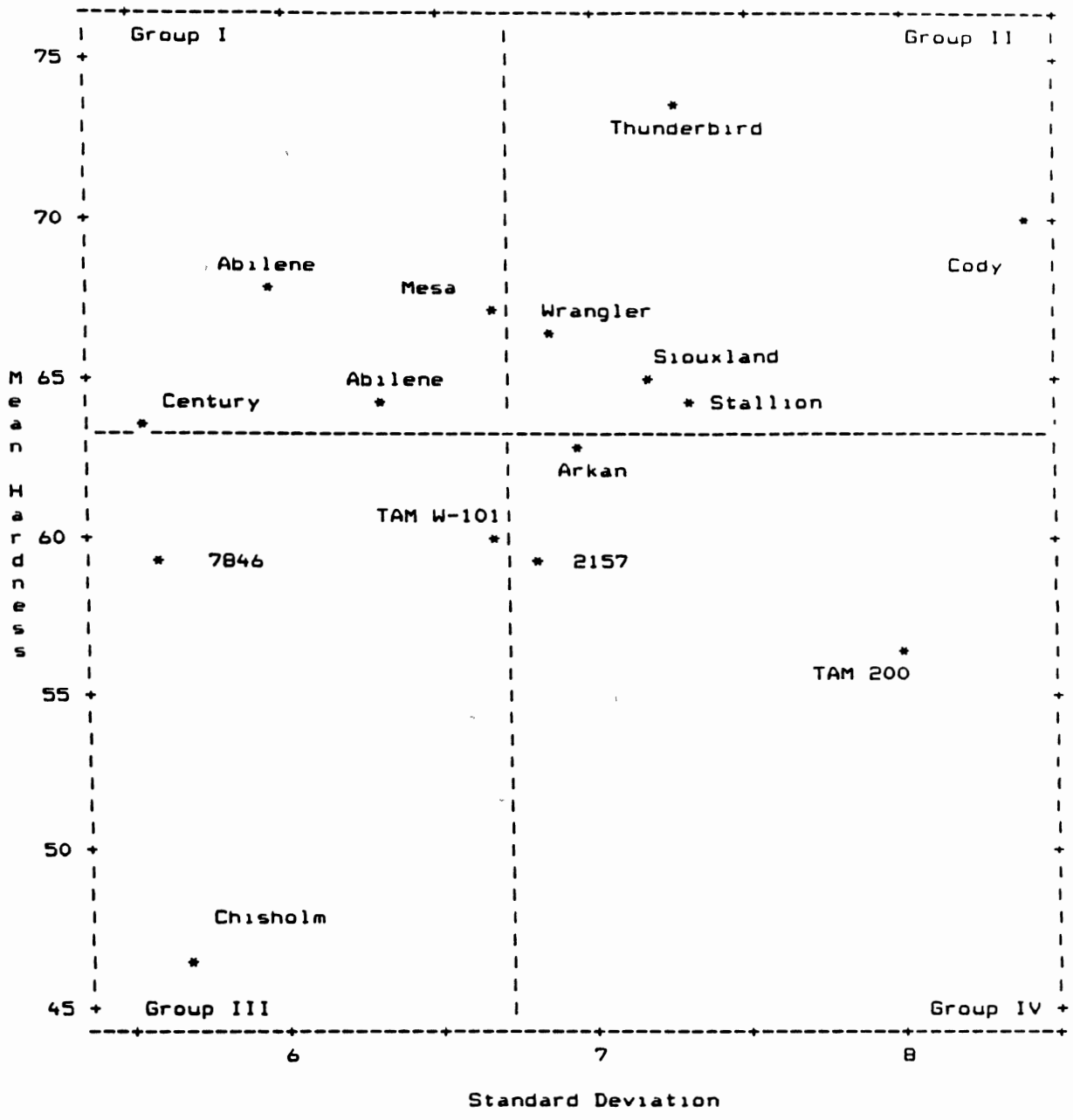

Figure 3. Means of kernel hardness plotted against standard deviations for 15 genotypes

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