# PERFORMANCE OF WHEAT GERMPLASM IN COMPETITIVE VERSUS NON-COMPETITIVE CONDITIONS

by

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# APPROVAL

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# ABSTRACT

Selection of high yielding spring wheat (*Triticum aestivum*) genotypes, is the goal for most classical breeding programs in the United States. In a single seed descent breeding program intense selection is practiced in space planted nurseries, although the ultimate goal is to have high yields in a densely seeded situation. The first objective of this study was to determine the correlations between physiological traits and yield influencing traits to final crop yield. The second objective was to determine if there are correlations between physiological and yield influencing traits in space versus dense seeded spring wheat. A replicated field trial was grown in Bozeman, Montana over two successive years. The trial was done to correlate physiological traits and yield components to the plot weight of 20 different spring wheat varieties. Space and dense seeded conditions were used to determine if physiological and yield trait data from a space seeded plot correlated to a densely seeded plot. The data shows that many of the physiological and yield influencing traits are correlated to spring wheat yields. Also, many of these traits correlate between space and densely seeded plots. This experiment also shows that screening for key traits, such as grain fill period, harvest index, and leaf width, could significantly aid selection of space planted breeding material for yield potential in a single seed descent breeding program.

# CHAPTER 1

# INTRODUCTION

Conventional wheat breeding will always be a way to produce superior wheat varieties for the world. One of the main objectives of any breeding program is to produce high yielding wheat lines for release to farmers. Approximately one-sixth of the world's total arable land is in wheat production; this is the largest amount of land cultivated for any crop (Slafer and Satorre 1999). Wheat accounts for more than one-quarter of the total world cereal output and also constitutes the main source of calories for more than 1.5 billion people (Reynolds et al. 1999). Since 1955 wheat production increased substantially due to improvements in yield from 0.5-2.0% annually (Evans and Fischer 1999). Recently wheat yields have been leveling off, so a more comprehensive understanding of increased yield must be gained. Increased yields will then be seen through better breeding and management practices (Slafer et al 1994). This understanding of increased yields is urgent because the world's population is estimated to reach 8 to10 billion people in the early decades of the 21st century, and the demand for wheat is expected to grow by about 1.3% per year worldwide (Reynolds et al. 1999).

Donald (1968) proposed the use of crop ideotype breeding as a way to increase crop yields. Ideotype breeding is early generation selection of characteristics that will result in a genotype that will act in a predictable fashion in any given environment. This breeding method offered the framework for applying recent concepts of light interception and plant competition in development of high-yielding cultivars. It offered hope that selection for specific characteristics that effect photosynthesis in a plant may contribute to higher yields, such as leaf size and posture, plant height and a larger tillering capacity (Sedgley 1991). Ideotype breeding did not take a strong hold in the crop breeding community however, it did cause thoughts that specific characteristics could affect the final yield, or yield potential, of a crop. Ideotype breeding also gave rise to the idea that a breeder could select for specific traits that would confer high yields. Some of the traits that have been selected for include: maturity, height, kernel number, kernel weight, ear number, leaf area, leaf angle, and leaf-area duration (Rasmusson 1991). Yield potential of a plant is defined as the yield of a cultivar when it is grown in environments to which it is adapted, with stresses effectively controlled (Evans and Fischer 1999).

## Morphological and Physiological Traits Associated with Wheat Yields

Many studies have been conducted to look at the yield increase over time by comparing old and new varieties of wheat. The outlying message of these studies is that breeding progress toward greater yields could be greatly increased if physiological, morphological and biochemical characteristics were used as selection criteria, because many of these traits have a probable link to yield (Feil 1992). Breeders also need to keep in mind that environment, management practices, and genotypes react together to determine the final yield (mass) of a crop at harvest (Perry and D'Antuono 1989).

One study in Australia was done to identify yield increases due to selection over many years. It included 28 genotypes of wheat grown in 20 trials over a period of four years throughout Australia. The study showed that with few exceptions the yields of wheat genotypes in the study increased by about 0.50% per year. This increase was due to selection over time. Grain yields increased while straw yields remained the same, resulting in higher harvest indices. Also, the number of ears, grains per ear, and total grain number increased, resulting in larger yields. This data shows that number of ears, grains per ear, total grain number, and harvest index are important in achieving high grain yields (Perry and D’Antuono 1989). An equally important study was completed in Canada that looked at how yield-determining traits have changed. The experiment was conducted over a two-year period in three different environments with 12 different wheat genotypes. The data shows that large grain yields per spike is important; and is obtained by having many kernels per spike or by having heavy kernels within a spike. There was a high correlation shown between grain yield and kernels per spike (Hucl and Baker 1987).

A high harvest index is very important in conferring high yielding plants. It is associated with the development of more distal florets reaching anthesis, thus resulting in more grains per square meter or more kernels per spikelet or spike. It has been speculated that harvest indices could reach at least 60%; this would cause out-yielding of the best genotypes by as much as 20% if the biomass remained unaltered (Feil 1992). With unaltered biomass, harvest indices are being increased by the number of grains per ear or per unit of area (Siddique et al. 1989). Another study was done in Australia to determine the relationship of pre-anthesis development, floret production and survival, to the number of grains per ear and grain yield. This study was conducted in three environments for one year. Data shows that harvest index, grains per ear, grains per spikelet, and improvement in the ear to stem ratio (plants with few, big ears will have larger ear to stem ratios) affects yield (Siddique et al. 1989).

A study was conducted in Canada to determine which characteristics are correlated with yield components. Six cultivars of hard red spring wheat were included in the experiment that took place over a three-year period at one location in Saskatchewan. Harvest index, kernel weight, grain-filling period, kernels per spike, grain protein content, and spike-filling rate (yield per spike divided by grain-fill period) were determined. The data suggests that both high kernel weights, and an increase in the number of kernels per square meter can influence yields. Cultivars that had low kernel weights also had the greatest number of kernels per square meter; and there was no significant difference in the yield of the most recently released wheat cultivars in the trial. Yield in this study was determined by kernel weight and kernel number. Kernel number per plant, determined by multiplying the spikes per plant by kernels per plant, suggests that if a genotype produces abundant tillers that complete maturity and carry many, heavy kernels, it will be a superior high yielding variety. The most recently released cultivars of wheat in the trial had high harvest indices, slightly heavier kernels, larger yields per spike, more kernels per spike, and a larger spike-filling rate compared to the two older varieties in the study giving them larger yields. There was no change in protein content and the grain fill period was less than that of the older varieties in the trial suggesting that these characteristics are not important in the increased yield of the new cultivars. Final results of the experiment shows that there is an association between grain yield and yield per spike, and number of kernels per spike. Longer grain-filling periods may be an avenue for future yield gains as well (Wang et al. 2002).

An experiment in the United States that included 14 wheat genotypes of hard red winter wheat was conducted to determine gain in yield attributes in the Great Plains. The study was conducted at two locations for two field seasons. Increased yields were found in the newer varieties due to increased aboveground biomass, larger harvest indices, increased numbers of spikes per square meter, increased kernels per square meter, and greater spike lengths due to shorter stature of the genotypes (Donmez et al. 2001).

Studies were conducted at the international maize and wheat improvement center (CIMMYT), in Mexico, on the yield and yield components of many different bread wheats grown at one location over many field seasons. These studies showed high correlations of harvest index and kernels per square meter to yield, with anthesis, biomass, and kernel weight not highly correlated with yield. Also, having high grain numbers, grains per spike, large spike numbers, heavy kernel weights, high harvest indices, and long grain fill periods alone did not confer yield. Rather, the high yielding varieties had different combinations of these characteristics. The highest yielding variety in this study had an average number of spikes that included a lot of grains per spike and average kernel weights. CIMMYT's studies showed that yield isn't necessarily associated with improved partition of assimilates to the spike during growth; however, competition by alternate sinks, (root and tiller growth), may be reducing the partition of assimilates for grain yield (Reynolds et al. 1999).

In another experiment conducted by CIMMYT, the goal was to determine physiological and morphological traits that are associated with heat tolerance and high yields in wheat. Sixteen genotypes were selected based upon broad adaptation and high yields in irrigated conditions, and were grown in six different environments over a period of two years. When comparing the three highest yielding cultivars to the two lowest yielding cultivars at one of the locations harvest index, grains per spike and kernel weight seemed to have marginal effects on final yield. The cultivars that had many spikes per square meter and high numbers of grains per square meter were the highest yielding in a hot environment. When comparing the means of the traits of all environments with grain yield of the two cropping cycles grown in Mexico, the data shows that biomass, harvest index, number of grains per square meter, and days to anthesis were highly correlated with grain yield at most locations. Conversely, kernel weight, number of spikes per square meter, number of grains per spike, and days to maturity were not highly correlated to grain yield at the growing locations. Other traits that were highly correlated with yield in heat stressed locations included membrane thermostability of flag leaves, post-anthesis photosynthetic activity, chlorophyll loss and chlorophyll post-anthesis, stomatal conductance, and canopy temperature depression throughout the growing season (Reynolds et al. 1994).

In a study conducted at the University of Buenos Aires during two field seasons, seven genotypes of wheat were grown to observe genetic changes in yield associated traits over a 70 breeding year period. The results show that grain yield has increased over the 70 year breeding period, which suggests that there was selection for high yielding varieties. Harvest index and number of grains per square meter were highly correlated with yield.

The data also showed that grain weight and number of spikes per square meter remained fairly unchanged over the selection period suggesting that these characteristics may not have a significant relationship with final grain yields. However, the number of grains per spike did increase substantially over the selection period, showing that more grains per spike could aid in conferring high yields of newer germplasm (Calderini et al. 1995).

A two-year study was conducted in Canada during 1971 and 1972 with 22 spring wheat cultivars that were released from areas around the world. The germplasm varied in their ability to mature, their yield, and also their height. Twenty variables were measured for each cultivar both years. The data showed that there was statistical evidence to suggest that the yield per ear, kernels per ear, and harvest index were significantly correlated to yield in both years of the experiment. However, traits that are commonly correlated with yield, such as ears per plant and spikelets per ear were not highly correlated with yield in either year. A stepwise regression analysis was performed to derive the best equation for conferring high yields from the data collected for the two separate years. The equation derived to calculate final grain yield changed from one year to the next, but the equations for both years contain the same traits and variables in the equation. This experiment also measured photosynthetic ability above the flag leaf node and, contrary to past data, found that it is not as important to final grain yield as are other traits. However, the data did suggest that one could select for a genotype with large, well-filled ears and there is a good probability that the flag leaves in that genotype will have a high photosynthetic capability and the variety will have high yields (Nass 1973). Harvest index was not included in the stepwise regression model in this study, however it has been shown that harvest index accounts for up to 72% of the variation in the total plot yield (Syme 1972). The result of this study suggests that good selection criteria in a breeding program would include selection for ears per plant, yield per ear and harvest index, resulting in a high yielding variety (Nass 1973).

F.H. McNeal spent several years of his spring wheat breeding career at Montana State University studying traits that could be selected for to confer high yielding plants. Two major studies were performed, one between 1955 and 1956, and one from1964 to 1974. The findings of these studies concluded that there are traits that can be correlated to yield. In one study two generations of a parental cross between economically important wheat varieties of the time, Thatcher and Lemhi were used. It was concluded that the traits that corresponded with yield were; heads per plant, kernels per head, spikelets per head, grams per kernel, and kernels per plant. However, McNeal noted that heritability values of these traits were not very high when they were selected for in the F2 generation (McNeal 1960). Another study was conducted to determine grain yield and its components in a spring wheat cross between an experimental line and Thatcher. Final analysis on the grain yield and its components was conducted in 1970 when the F4 through F8 progeny from the cross were evaluated at 3 locations. Selection of kernel weight and kernels per spike gave increased yield performance in the progeny over the mid-parent. Conversely selection for grain yield per plant, spikes per plant, and spikelets per spike produced lower yields in the progeny than the mid-parent. This study indicated that there is merit in selection of certain yield components to confer high grain yield in a final population of the crop. Based upon these findings a breeder could select for both kernel weight and kernels per spike and have a good reason to believe that a high yielding variety will be the end product (McNeal et al. 1978).

All of the above mentioned experiments suggest that there are plant characteristics, both physiological and morphological, that are correlated with the final grain yield of wheat germplasm. Much of the data shows that the traits that are correlated with the final grain yield are directly related to the grain traits such as kernel weight and grains per head. Some traits are related to the spike of the plant, such as spikelet number and the number of spikes per plant. Yet other physiological characteristics like photosynthesis and stomatal conductance could also be considered. However, the trait that stands out in all of the experimental trials as being important to the final crop yield of a cultivar is harvest index. The most important concept in the results of these experiments is that one trait doesn’t act alone in producing high grain yields, instead many traits work together to produce a high yielding variety of wheat.

## Single-Plant Breeding Selection

Measurements of characteristics are made on early generation material, and in many breeding programs on single plants. This occurs so the evaluation of the plants can be done individually, and each plant has the same opportunity for development without competition by neighboring plants (Woodworth 1931). The hope is, when selections in space plantings are made, plants showing superior qualities under the space planted condition will be chosen. These plants will then have good qualities to the field in full measure (Bull 1909).

Syme (1971) conducted a study to determine the correlation between single-plant characteristics and field performance of 49 spring wheat cultivars released by 16 countries. The cultivars were grown in pots in an unheated glasshouse, and 16 characteristics were selected, and measured, for their possible correlation with yield. The measurements of the characteristics were then correlated with the mean yields of the varieties when they were grown under field plot conditions. This study found that days to heading, height, and 100-grain weight are highly correlated between single plants and field plots; but found no correlation between single plants and field plots with grain yields. A stepwise regression was performed to determine the mean yields of the field plots based upon single plant variables. Harvest index was the most important characteristic to enter into the regression explaining 71.7% of the variation in cultivar mean yields. Days to emergence of leaf 7 and 100-grain weight were also in the equation with a final 78.5% of the variation in cultivar final mean yields being explained by the regression. This data indicates that there can be confidence in selection for final yield, with space planted characteristics (Syme 1972).

Two adjacent experiments were performed in Mexico from 1973 to1974. The experiments contained both spaced plants and large plots. One of the experiments contained 34 genotypes and the other contained ten; four genotypes were common in both trials. All of the genotypes used were the highest yielding varieties of the time. When the spaced plant traits were correlated to the final adjusted grain weight of the large plots, there were characteristics that were moderately or weakly correlated; including shoot harvest index (r = 0.66), adjusted plant harvest index (r = 0.56), spikes per plant (r = 0.59), spikelets per spike (r = 0.86), grains per spikelet (r = 0.59), kernel weight (r = 0.92), and grains per square meter (r = 0.45) (Fischer and Kertesz 1976).

Selection is often done in a single-plant condition and does not represent a commercial seeding rate; thus the selection of characteristics in space-plants may not confer the favorable genotype in the final product. Although the generation of selection in such breeding programs may differ, the final goal is the same; select early generation germplasm that will confer high yielding varieties. Yield has many complex characters; however, if there are characters that have high associations with yield, then selection for these characters may result in high yields (Bhatt 1980). Thus, selection for yield components in a breeding program may be very effective in producing high yielding varieties as end products. There are many yield components that data suggests have high associations with the final yield of a crop. Many of these yield components are those that have been mentioned before; spikelet number per spike, spikes per plant, kernel weight, and kernels per spike. It is important to note that these characteristics alone can slightly affect yield, but all of them acting together will confer the best yielding genotypes. Many breeding programs do not use yield component breeding because the relationship between yield and yield components may not always be linear; and there are too many environmental effects in the relationship between yield and yield components. There may be a more extensive time commitment in collection of yield component data as opposed to simply collecting final grain yield data. Other characteristics are also associated in the improvement of yield; besides yield components. There has been data shown to favor selection for characters such as short stature, lodging resistance, awns on the florets, erect foliage, and high leaf area ratios. High photosynthetic rates, harvest index, and seedling vigor are other morpho-physiological traits that may also influence yields. Selection for any of the individual criteria may not be the best way to improve crop yields; but selection for a number of the characteristics, in conjunction with each other, may improve selection of early generation plant materials that will confer high yields (Bhatt 1980).

The lack of seed in early generation selection forces a breeder to plant into space-plant situations in hopes that their selections will confer high yield and desirable agronomic traits in a field cropping environment. To allow breeders to easily and efficiently select for yield influencing traits in early generation germplasm the methods need to be quick and easy to measure, reliable, low cost, and applicable. Also notable is the genetic variability of the character, its heritability, and their relationship with final grain crop yields (Bhatt 1980, Fischer and Kertesz 1976).

Yield is highly correlated with several measurable agronomic traits. All of the past experimental data shows correlations between yield and measurable agronomic traits, including: harvest index (Calderini et al 1995, Donmez et al 2001, Feil 1992, Hucl and Baker 1987, Nass 1973, Perry and D’Antuono 1989, Reynolds et al 1994, Reynolds et al 1999,Siddique et al 1989, Wang et al 2002), number of grains/$m^2$ (Calderini et al 1995, Feil 1992, Reynolds et al 1994, 1999, Wang et al 2002), long grain fill periods (Reynolds et al 1994, 1999, Wang et al 2002), number of grains/head (Calderini et al 1995, Feil 1992, Hucl and Baker 1987, McNeal 1960, Nass 1973, Perry and D’Antuono 1989, Siddique et al 1989, Wang et al 2002), number of grains/spikelet (Feil 1992, McNeal 1960, Siddique et al 1989), number of tillers (Reynolds et al 1999, Sedgley 1991, Wang et al 2002), kernel weight (Hucl and Baker 1987, McNeal 1960, McNeal et al 1978, Wang et al 2002), leaf size and posture (Sedgley 1991), and photosynthetic ability (Nass 1973). Data from these experiments suggests that characteristics acting together, not alone, confer high yields. Correlations between plot weights and agronomic traits are important, because if there are traits that can be easily measured, and confer high yields, they could aid in the selection phase of a wheat-breeding program.

Single plant breeding selection is also important in single seed descent wheat-breeding programs. The data shows that characters can be selected for under space planted conditions, and that these characters will act the same in a densely planted field. Past data shows that there are some traits that are correlated between the spacings. These traits have also been shown to confer high yields; harvest index (Fischer and Kertesz 1976, Syme 1972), spikes/plant (Bhatt 1980, Fischer and Kertesz 1976), spikelets/spike (Bhatt 1980, Fischer and Kertesz 1976), kernel weight (Bhatt 1980, Fischer and Kertesz 1976), and grains/square meter (Fischer and Kertesz 1976).

This report details some characteristics that are associated with final grain yield of a wheat genotype and how well these traits might correlate between a space-planted and a densely planted field.

# CHAPTER 2

# MATERIALS AND METHODS

## Planting Materials

Two farm trials of this experiment were grown in 2002 and 2003 at the Arthur H. Post Research Farm, located west of Bozeman Montana. The elevation of the site is 1,439 m above sea level and the soil is Amsterdam silt loam. The entries consisted of 20 varieties of spring wheat from Canada, North Dakota, Montana, Minnesota, and Western Plant Breeders that were released during the 20th century (Table 1). The varieties were grown in two environments, irrigated and dryland, in a randomized block split plot design. Within these plots the varieties were randomized within three densities: spaced, mid-dense and dense; which were then randomized within each of three blocks. Each plot consisted of four rows that were ten feet long. The spaced plots were seeded at a rate of two seed/foot, and were thinned back to one plant/foot after plant emergence. In the dryland trial the mid-dense plots were seeded at a rate of ten seed/foot and the dense at a rate of 20 seed/foot; while in the irrigated trial the mid-dense plots were seeded at a rate of 15 seeds/foot and the dense at a rate of 30 seed/foot.

Table 1. Varieties with their respective origin and year of release.

| Entry | Variety | Origin | Year of release |
|---|---|---|---|
| 1 | MARQUIS | CANADA | 1911 |
| 2 | CERES | ND | 1926 |
| 3 | THATCHER | MN | 1934 |
| 4 | PILOT | ND | 1939 |
| 5 | NEWTHATCH | MN | 1944 |
| 6 | RESCUE | CANADA | 1946 |
| 7 | CHINOOK | CANADA | 1952 |
| 8 | CENTANA | MT | 1958 |
| 9 | SAWTANA | CANADA | 1961 |
| 12 | FORTUNA | ND | 1967 |
| 10 | ERA | MN | 1970 |
| 11 | SHORTANA | MT | 1971 |
| 13 | LEW | MT/ND | 1977 |
| 14 | NEWANA | MT | 1977 |
| 16 | WESTBRED 926 | WPB | 1987 |
| 17 | AMIDON | ND | 1988 |
| 15 | HI-LINE | MT | 1991 |
| 18 | MCNEAL | MT | 1995 |
| 19 | SCHOLAR | MT | 1998 |
| 20 | REEDER | ND | 1999 |

In 2002 the mid-dense and dense plots of the irrigated trial were planted on April 24th; the dryland plots of mid-dense and dense were planted on April 25th. Both the irrigated and dryland spaced plots were planted on April 26th. On August 27th one meter was sickled out of each row of the dryland mid-dense and dense plots, and five plants were taken from the spaced plots for a biomass study. These plants were bundled and set aside to dry. The remainder of the spaced plots were also sickled down and bundled. Harvest took place on August 30th, when the mid-dense and dense dryland plots were harvested with a combine and the space planted plots and the bundles from each plot for the biomass study were threshed (Vogel, St. Louis, MO). On September 5th one meter was sickled out of each row of the irrigated mid-dense and dense plots, and five plants were taken from the spaced plots, for a biomass study. These plants were then bundled and set aside to dry. The remainder of the spaced plots were also sickled down and bundled. Harvest took place on September 9th, when the mid-dense and dense irrigated plots were combined. On September 10th the space planted plots and the bundles from each plot for the biomass study were threshed (Vogel, St. Louis, MO)

Average precipitation for May through July from 1958-2002 was 6.76 inches and the actual precipitation from May through July in 2002 was 7.89 inches. An additional 6 inches of water was applied to the irrigated plots during June and July. The available soil nitrogen for 2002 was 135 LB/AC, and N-P-K 75/40/0 LB/AC was applied and tilled into the soil before planting.

In 2003 all of the plots were planted on May 12th. Harvest took place on August 19th; when one meter was sickled out of each row of the mid-dense and dense plots, and five plants were taken from the spaced plots, for a biomass study. The bundles from the dryland and the mid-dense and dense irrigated plots were bundled and threshed (Vogel, St. Louis, MO); the irrigated spaced bundles were set aside to dry. The dryland plots were combined August 19th. On August 23rd the irrigated plots were combined and the spaced biomass bundles were threshed (Vogel, St. Louis, MO).

Average precipitation for May through July from 1958-2003 was 6.71 inches and the actual precipitation from May through July in 2003 was 4.75 inches. An additional 6.25 inches of water was applied to the irrigated plots during June and July. The available soil nitrogen for 2003 was 130 LB/AC, and N-P-K 95/40/40 LB/AC was applied and tilled into the soil before planting.

## Characteristics evaluated

Traits that were evaluated on the plots were: leaf length, leaf width, tillers/meter and tillers/plant, stem solidness, plant height, days to heading, days to maturity, grain fill period, harvest index, plot length and number of plants, plot weight, weight/square foot and plant, test weight, single kernel hardness, single kernel weight, single kernel diameter, grain protein, spikelets/head, and seeds/head.

### Leaf Length and Width

Leaf lengths and widths were measured on three random flag leaves in each plot using a clear ruler placed over the leaves. Measurements were taken in centimeters. Lengths were measured from the collar to the tip of the leaf and were averaged. Leaf width was measured across the center (widest part) of the flag leaves; the measurements were then averaged.

### Tillers

The total number of tillers was counted on ten plants in each of the space planted plots. The measurements were averaged to arrive at the average number of tillers per plant. Also the total number of tillers were counted in one meter of a row in each of the mid-dense and dense seeded plots.

### Stem Solidness

Three stems were randomly selected and removed from each plot. The stems were cross sectionally cut at each of the five internodes. Each internode was scored on a scale of 1-5 (1-hollow, 5-solid) for the amount of pith contained in the stem. The scores of the five internodes were then added together, to obtain a final score of 5-25, and an average was then calculated for each plot.

### Plant Height

Plant height measurements were taken by holding a centimeter marked measuring stick in each of the plots. The wheat in a small area around the stick was held up to it and a measurement was taken. Height was recorded as the average height where the tips of the heads landed on the stick. Two plant height measurements were taken in each plot.

### Days to Heading

Heading dates were taken on each of the plots by assigning a Julian date when 75% of the heads were completely emerged. A Julian date was assigned to the planting date and was subtracted from the Julian date of heading to obtain the number of days to heading.

### Days to Maturity

Physiological maturity was rated on each of the plots by assigning a Julian date to the plot when 75% of the plot exhibited heads having glumes showing complete loss of green color (Hanft and Wych 1982, Singh et al. 1984). The Julian date that was assigned to the planting date was then subtracted from the Julian date of physiological maturity to obtain the number of days to maturity.

### Grain Fill Period

The duration of the grain fill period was determined by subtracting the Julian date for physiological maturity, and the Julian date for heading, to arrive at the number of days each plot obtained grain fill.

### Harvest Index

Before harvest, one meter was sickled out of one row in each mid-dense and dense seeded plot and five plants were taken from each of the spaced plots and bundled. Each bundle was weighed and then threshed (Vogel, St. Louis, MO). The threshed material was cleaned, so that only the seed remained, and the seed was weighed. From the bundle weights and seed weights a ratio of final harvest index was determined by dividing grain weight by straw weight.

### Plot Length and Number of Plants

Plot lengths were taken by measuring the length of each of the four rows of the mid-dense and dense seeded plots. Lengths of gaps in the rows were subtracted from the total length; and 3.3 ft was subtracted from the final length, due to the one meter section sickled out of each plot for the harvest index measurement, to arrive at a final plot length. Also the number of plants were counted in each of the spaced seeded plots, five plants were subtracted from this total due to the harvest index measurement, to arrive at the final number of plants harvested.

### Plot Weight

After each plot was combined, the seed was weighed to determine the raw grain weight of each plot.

### Weight/Sqft and Weight/Plant

A calculation was made by dividing the final plot weight and final plot length, or the final plot weight and the number of plants in the spaced seeded plots to determine the final weight/sqft and the weight/plant of each plot respectively.

### Test Weight

After the seed was weighed for plot weight, the seed from each plot was cleaned and reweighed on a Seedburo (Chicago, IL) test weight scale to determine the test weight of each plot.

### Single Kernel Hardness, Weight and Diameter

A sub-sample of seed was taken from each plot and was analyzed in the Single Kernel Characterization System 4100 (Perten, Huddinge, Sweden), to determine single kernel hardness, weight, and diameter.

### Grain Protein

Grain protein contents were obtained from the Infratec 1225 Whole Grain Analyzer (Tecator, Höganäs, Sweden).

### Spikelets/Head and Seeds/Head

Before harvest 10 heads were randomly removed from each plot. Each head was individually counted for the number of spikelets it contained. The heads were then threshed and seed from each individual head was counted. The measurements of each of the ten heads per plot were then averaged.

## Statistical Analysis

The data was combined over the four locations and an analysis of variance was computed using a model appropriate for the original block split plot design. Means were obtained for the measured traits in relation to the year, water category, planting density, and genotype; an LSD was also calculated for the means of the planting densities and genotypes by using a PROC GLM statement in SAS (SAS Institute Inc. 1999,2000). The significance of interactions between year, water, planting density, and variety was also determined with the PROC GLM statement in SAS (SAS Institute Inc. 1999,2000). Correlations were computed in Minitab (Minitab Inc. 2000) from the means of the traits among the planting densities obtained from the SAS analysis.

# CHAPTER 3

# RESULTS AND DISCUSSION

## Experimental Interactions

Wheat breeding techniques in a single seed descent program involve selection of plant materials that have been put through several generations of selfing, with no plant selection, to produce progeny lines that have only a small percentage of heterozygosity at the time of plant selection. This type of program produces tens of thousands of plants by the selection phase. Only a small percentage of those plants will be taken from the field for further testing in the development of a new variety.

Selection in a single seed descent wheat breeding programs is often done on space planted fields so that the breeder can evaluate each plant individually. No replication is practiced in single plant selection processes; however plants may be selected within families to allow for some comparison of the single plants to other family units, to help identify superior lines.

One worry for breeders is that yield influencing traits may or may not correlate from the selected plant and a densely planted field. This experiment was designed to determine if there are traits that do correlate with yield, as past experimental data has suggested, and if those traits will correlate between space and dense plantings.

Due to the large nature of this experiment and its many factors many interactions between the factors were exhibited (Table 2). There were significant differences among the planting densities and all of the traits measured. Year by density interactions were exhibited at significant levels for all traits except test weight, plot weight, harvest index, seed diameter, spikelets/head, and leaf width. Water by density interactions occurred at significant levels for weight/plant and weight/sqft, plot weight, grain fill period, days to maturity, tillers/meter, plant height, leaf width, and grain protein content. Significant effects were shown for all of the traits in the categories of genotype and year by genotype. This indicates that there were differences in the genotypes and that differences in weather patterns from year to year interacted with the genotypes to produce significant year by genotype interaction. Water by genotype interaction was significant for most traits. Those traits that weren’t significant were harvest index, spikelets/head, days to heading, tillers/meter, stem solidness, lead width, and leaf length. Density by genotype interactions occurred among all of the traits that were measured except harvest index and leaf width. Harvest index, spikelets/head, and leaf width were the measured traits that exhibited the least amount of significant interactions suggesting that these traits may be stable and predictable in most environments.

Table 2. Sources of variation[1] for the traits from combined data of all locations.

| Traits | Density | Year * Density | Water * Density | Genotype | Year * Genotype | Water * Genotype | Density * Genotype |
|---|---|---|---|---|---|---|---|
| **Wt/Plant and Wt/SqFt** | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 |
| **Test Weight** | 0.0005 | 0.4537 | 0.5597 | <.0001 | <.0001 | 0.0044 | <.0001 |
| **Plot Weight** | <.0001 | 0.6434 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 |
| **Harvest Index** | 0.0008 | 0.6800 | 0.2603 | <.0001 | 0.0002 | 0.5402 | 0.1403 |
| **Seed Hardness** | <.0001 | <.0001 | 0.1169 | <.0001 | <.0001 | <.0001 | 0.0094 |
| **Seed Weight** | <.0001 | 0.0083 | 0.4711 | <.0001 | <.0001 | <.0001 | <.0001 |
| **Seed Diameter** | <.0001 | 0.7010 | 0.1348 | <.0001 | <.0001 | 0.0001 | 0.0015 |
| **Seeds/Head** | <.0001 | <.0001 | 0.0858 | <.0001 | <.0001 | 0.0006 | <.0001 |
| **Spikelets/Head** | <.0001 | 0.2727 | 0.7090 | <.0001 | <.0001 | 0.1047 | 0.0122 |
| **Grain Fill** | <.0001 | 0.0001 | 0.0008 | <.0001 | <.0001 | <.0001 | 0.0147 |
| **Days to Maturity** | <.0001 | 0.0018 | 0.0026 | <.0001 | <.0001 | <.0001 | 0.0002 |
| **Days to Heading** | <.0001 | 0.0008 | 0.5453 | <.0001 | <.0001 | 0.2050 | 0.0008 |
| **Tillers/Meter** | <.0001 | 0.0011 | <.0001 | <.0001 | <.0001 | 0.1358 | <.0001 |
| **Plant Height** | <.0001 | 0.0097 | 0.0003 | <.0001 | <.0001 | <.0001 | <.0001 |
| **Stem Solid** | <.0001 | <.0001 | 0.0973 | <.0001 | <.0001 | 0.4316 | <.0001 |
| **Leaf Width** | 0.0002 | 0.3647 | 0.0109 | <.0001 | 0.0070 | 0.6933 | 0.7620 |
| **Leaf Length** | 0.0032 | 0.0035 | 0.2180 | <.0001 | <.0001 | 0.1275 | 0.0009 |
| **Protein** | 0.0002 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 | <.0001 |

[1] sources of variation are represented by p-values

## Means of Yield Influencing and Physiological Traits

Yield influencing traits were measured on the 20 genotypes of wheat over the four locations and three planting densities and were compiled into a table of means. This was done to exhibit differences among the factors within the study (Table 3). There were differences among means of the yield influencing traits averaged over the years, location, and planting densities.

There were notable differences found between the years due to climatic conditions. 2003 was extremely hot and dry for many weeks during the growing season. Due to the harsh climatic conditions, there were large differences between the year for yield influencing traits; plot weight, test weight, weight/sqft or plant, harvest index, single kernel hardness, seed weight, and seeds/head (Table 3). Differences were also found between the dryland and irrigated environments. Plot weight, weight/sqft or plant, and seed weight were noticeably greater in the irrigated plots. Test weight and harvest index were greater in the dryland plots (Table 3).

The mid-dense and dense treatments exhibited differences in four of the nine yield influencing traits that were measured, as shown by the LSD ($p<0.05$) of the traits within the density category. Differences between dense and mid-dense treatments were exhibited for harvest index, single seed hardness, single seed diameter, and spikelets/head. Differences were not shown between the means of the mid-dense and dense treatments in plot weight, test weight, weight/sqft or plant, single seed weight, and seeds/head. There were differences in the means of the space and dense seeded treatments for all of the yield influencing traits measured.

Table 3 also shows that there were differences among variety means for the yield influencing traits. The varieties of spring wheat in this trial were very diverse due to the large time period of selection. This diversity leads to large differences in the means of the traits that were measured.

Table 3. Means associated with yield influencing traits combined over the four locations.

| Year | Location | Density | Genotype | Plot Weight (g) | Test Weight | Wt/sqft or Plant (g) | Harvest Index |
|---|---|---|---|---|---|---|---|
| **2002** | | | | 1250.67 | 59.24 | 38.13 | 0.33 |
| **2003** | | | | 755.74 | 56.93 | 24.26 | 0.37 |
| | **Dryland** | | | 877.28 | 58.50 | 27.93 | 0.36 |
| | **Irrigated** | | | 1129.14 | 57.68 | 34.46 | 0.34 |
| | | **Space** | | 654.83 | 57.52 | 22.11 | 0.37 |
| | | **Mid-dense** | | 1150.40 | 58.47 | 36.09 | 0.35 |
| | | **Dense** | | 1204.39 | 58.26 | 35.37 | 0.33 |
| | | **LSD 0.05** | | **56.983** | **0.318** | **1.120** | **0.020** |
| | | | **Marquis** | 693.73 | 57.96 | 21.82 | 0.35 |
| | | | **Ceres** | 848.98 | 57.77 | 26.28 | 0.32 |
| | | | **Thatcher** | 986.44 | 57.03 | 29.78 | 0.33 |
| | | | **Pilot** | 762.39 | 56.07 | 24.67 | 0.32 |
| | | | **Newthatch** | 710.98 | 56.61 | 22.64 | 0.32 |
| | | | **Rescue** | 817.27 | 57.80 | 25.26 | 0.30 |
| | | | **Chinook** | 717.86 | 59.09 | 22.17 | 0.29 |
| | | | **Centana** | 875.39 | 57.81 | 27.41 | 0.30 |
| | | | **Sawtana** | 717.93 | 58.90 | 23.44 | 0.28 |
| | | | **Fortuna** | 998.06 | 59.24 | 30.58 | 0.35 |
| | | | **Era** | 1160.84 | 58.13 | 38.17 | 0.41 |
| | | | **Shortana** | 1145.07 | 56.94 | 35.31 | 0.36 |
| | | | **Lew** | 1032.59 | 59.83 | 31.59 | 0.35 |
| | | | **Newana** | 1154.02 | 57.64 | 35.98 | 0.39 |
| | | | **Westbred 926** | 1266.38 | 58.07 | 38.06 | 0.43 |
| | | | **Amidon** | 1196.94 | 58.07 | 37.19 | 0.35 |
| | | | **HiLine** | 1185.98 | 58.73 | 36.95 | 0.43 |
| | | | **McNeal** | 1263.02 | 58.29 | 39.05 | 0.41 |
| | | | **Scholar** | 1214.84 | 58.68 | 37.28 | 0.33 |
| | | | **Reeder** | 1315.49 | 59.06 | 40.27 | 0.39 |
| | | | **LSD 0.05** | **169.310** | **0.922** | **4.759** | **0.047** |

Table 3, continued.

| Year | Location | Density | Genotype | Seed Hardness | Seed Weight (mg) | Seed Diameter (mm) | Seeds/ Head | Spilelets/ Head |
|---|---|---|---|---|---|---|---|---|
| **2002** | | | | 71.70 | 38.96 | 2.78 | 25.30 | 15.99 |
| **2003** | | | | 83.11 | 27.22 | 2.21 | 41.37 | 16.13 |
| | **Dryland** | | | 77.73 | 32.14 | 2.44 | 33.27 | 16.19 |
| | **Irrigated** | | | 77.10 | 34.03 | 2.56 | 33.40 | 15.94 |
| | | **Space** | | 75.95 | 34.71 | 2.57 | 36.32 | 16.62 |
| | | **Mid-dense** | | 77.68 | 32.86 | 2.49 | 32.90 | 16.20 |
| | | **Dense** | | 78.61 | 31.69 | 2.43 | 30.79 | 15.38 |
| | | **LSD 0.05** | | **1.867** | **0.481** | **0.012** | **1.304** | **0.724** |
| | | | **Marquis** | 74.13 | 32.19 | 2.52 | 31.25 | 16.27 |
| | | | **Ceres** | 80.39 | 31.89 | 2.46 | 36.10 | 16.99 |
| | | | **Thatcher** | 78.29 | 29.53 | 2.34 | 35.59 | 16.90 |
| | | | **Pilot** | 79.55 | 30.85 | 2.43 | 33.41 | 15.54 |
| | | | **Newthatch** | 73.79 | 31.43 | 2.46 | 30.09 | 15.09 |
| | | | **Rescue** | 69.11 | 32.42 | 2.51 | 30.22 | 17.48 |
| | | | **Chinook** | 71.13 | 33.66 | 2.55 | 27.08 | 13.93 |
| | | | **Centana** | 74.71 | 31.54 | 2.48 | 33.90 | 16.10 |
| | | | **Sawtana** | 75.99 | 32.73 | 2.50 | 30.54 | 16.09 |
| | | | **Fortuna** | 67.63 | 41.06 | 2.68 | 26.04 | 14.28 |
| | | | **Era** | 83.57 | 31.13 | 2.44 | 37.61 | 16.53 |
| | | | **Shortana** | 85.35 | 29.50 | 2.34 | 35.62 | 16.76 |
| | | | **Lew** | 75.14 | 36.13 | 2.47 | 28.73 | 15.90 |
| | | | **Newana** | 80.97 | 31.21 | 2.38 | 36.99 | 17.16 |
| | | | **Westbred 926** | 72.02 | 37.37 | 2.69 | 35.79 | 16.78 |
| | | | **Amidon** | 83.17 | 32.90 | 2.55 | 34.63 | 15.88 |
| | | | **HiLine** | 78.35 | 34.17 | 2.54 | 36.70 | 16.92 |
| | | | **McNeal** | 89.34 | 34.39 | 2.61 | 37.34 | 16.34 |
| | | | **Scholar** | 80.23 | 34.80 | 2.56 | 34.43 | 16.53 |
| | | | **Reeder** | 75.34 | 32.82 | 2.46 | 34.67 | 13.84 |
| | | | **LSD 0.05** | **3.365** | **3.049** | **0.149** | **4.693** | **0.470** |

Physiological traits were measured on the 20 genotypes of wheat over the four locations and three planting densities and were compiled into a table of means (Table 4). There were differences between the means for physiological traits averaged over the year of growth, the location and the planting densities.

Climatic conditions caused large differences between the years of growth, due to a long period of hot, dry weather during the 2003 growing season. The plots matured earlier in 2003; heading, on average, occurred 10 days quicker than the plots in 2002. The plots also reached physiological maturity nearly 30 days earlier in 2003; this early maturity resulted in very short grain fill periods (Table 4). Differences were also found between the years with tillers/m or plant, plant heights, leaf widths, and leaf lengths (Table 4). Differences were also found between the dryland and irrigated environments. Grain fill periods and days to maturity were longer in the irrigated plots. The irrigated plots had more tillers/m or plant, greater heights, and longer leaves. The dryland plots had more solid stems and greater protein contents (Table 4).

The mid-dense and dense treatments exhibited a difference in tillers/meter based on LSD ($p<0.05$). The other physiological characteristics that were measured showed no significant differences between the mid-dense and dense treatments; thus suggesting that the seeding differences did not affect the physiological traits between the mid-dense and dense treatments. Significant differences were exhibited in four of the nine physiological traits that were measured between the space and dense seeding treatments as shown by LSD ($p<0.05$). Significant differences in means were found in stem solidness, tillers/meter or plant, plant height, and leaf width. There were no differences among grain fill periods, days to maturity, days to heading, leaf length, or grain protein content between the space and dense seeding treatments.

Since the traits that were measured in mid-dense and dense seed treatment were so similar to each other, the rest of this report will only detail differences within the space and dense seed treatments to express their importance in the crop breeding process of single seed descent breeding programs.

Table 4. Means associated with physiological traits combined over the four locations.

| Year | Location | Density | Genotype | Grain Fill | Days to Maturity | Days to Heading | Stem Solid |
|---|---|---|---|---|---|---|---|
| **2002** | | | | 48.40 | 118.71 | 70.31 | 10.20 |
| **2003** | | | | 33.17 | 92.49 | 59.33 | 11.44 |
| | **Dryland** | | | 38.39 | 103.23 | 64.84 | 11.32 |
| | **Irrigated** | | | 43.18 | 107.98 | 64.80 | 10.32 |
| | | **Space** | | 42.53 | 107.95 | 65.42 | 13.56 |
| | | **Mid-dense** | | 40.20 | 105.02 | 64.82 | 9.95 |
| | | **Dense** | | 39.63 | 103.85 | 64.22 | 8.95 |
| | | **LSD 0.05** | | **4.045** | **6.570** | **2.702** | **1.045** |
| | | | **Marquis** | 38.42 | 104.92 | 66.50 | 8.07 |
| | | | **Ceres** | 39.69 | 105.67 | 65.97 | 7.78 |
| | | | **Thatcher** | 38.72 | 105.17 | 66.44 | 7.59 |
| | | | **Pilot** | 40.44 | 105.92 | 65.47 | 7.98 |
| | | | **Newthatch** | 39.19 | 103.42 | 64.22 | 7.57 |
| | | | **Rescue** | 39.06 | 104.78 | 65.72 | 18.61 |
| | | | **Chinook** | 39.92 | 103.56 | 63.64 | 17.38 |
| | | | **Centana** | 41.67 | 108.56 | 66.89 | 7.86 |
| | | | **Sawtana** | 38.14 | 104.61 | 66.47 | 18.32 |
| | | | **Fortuna** | 39.94 | 102.81 | 62.86 | 17.52 |
| | | | **Era** | 41.06 | 108.58 | 67.53 | 7.50 |
| | | | **Shortana** | 41.97 | 109.14 | 67.17 | 8.20 |
| | | | **Lew** | 37.58 | 103.44 | 65.86 | 14.69 |
| | | | **Newana** | 41.97 | 107.25 | 65.28 | 8.10 |
| | | | **Westbred 926** | 45.00 | 104.75 | 59.75 | 8.75 |
| | | | **Amidon** | 42.11 | 105.44 | 63.33 | 14.43 |
| | | | **HiLine** | 41.19 | 103.22 | 62.03 | 7.00 |
| | | | **McNeal** | 41.94 | 106.00 | 64.06 | 7.35 |
| | | | **Scholar** | 42.64 | 107.08 | 64.44 | 14.63 |
| | | | **Reeder** | 45.02 | 107.81 | 62.78 | 7.05 |
| | | | **LSD 0.05** | **0.470** | **0.447** | **0.311** | **0.608** |

Table 4, continued.

| Year | Location | Density | Genotype | Tillers/m or Plant | Plant Height (cm) | Leaf Width (cm) | Leaf Length (cm) | Protein |
|---|---|---|---|---|---|---|---|---|
| **2002** | | | | 120.96 | 100.99 | 1.59 | 21.85 | 16.04 |
| **2003** | | | | 101.07 | 83.10 | 1.46 | 19.96 | 17.73 |
| | **Dryland** | | | 97.92 | 86.47 | 1.52 | 20.33 | 17.07 |
| | **Irrigated** | | | 124.11 | 97.61 | 1.53 | 21.48 | 16.71 |
| | | **Space** | | 25.42 | 82.64 | 1.55 | 20.44 | 16.86 |
| | | **Mid-dense** | | 142.12 | 95.71 | 1.54 | 21.13 | 17.03 |
| | | **Dense** | | 165.51 | 97.78 | 1.49 | 21.16 | 16.77 |
| | | **LSD 0.05** | | **13.979** | **5.892** | **0.057** | **1.021** | **0.439** |
| | | | **Marquis** | 106.61 | 107.29 | 1.47 | 22.46 | 17.47 |
| | | | **Ceres** | 103.31 | 105.85 | 1.48 | 21.53 | 17.01 |
| | | | **Thatcher** | 114.81 | 101.01 | 1.48 | 22.74 | 17.03 |
| | | | **Pilot** | 103.08 | 100.25 | 1.35 | 20.56 | 16.86 |
| | | | **Newthatch** | 113.22 | 99.10 | 1.48 | 19.01 | 17.78 |
| | | | **Rescue** | 113.47 | 102.60 | 1.39 | 23.31 | 17.00 |
| | | | **Chinook** | 120.56 | 101.42 | 1.43 | 21.72 | 17.49 |
| | | | **Centana** | 111.75 | 104.25 | 1.43 | 21.80 | 16.97 |
| | | | **Sawtana** | 101.30 | 102.57 | 1.43 | 19.68 | 17.20 |
| | | | **Fortuna** | 117.75 | 95.56 | 1.44 | 19.21 | 16.80 |
| | | | **Era** | 111.94 | 74.19 | 1.53 | 21.39 | 14.97 |
| | | | **Shortana** | 115.08 | 75.89 | 1.42 | 22.01 | 16.26 |
| | | | **Lew** | 132.53 | 95.36 | 1.47 | 21.26 | 16.73 |
| | | | **Newana** | 115.28 | 76.75 | 1.52 | 20.71 | 15.96 |
| | | | **Westbred 926** | 85.64 | 74.76 | 1.85 | 22.18 | 16.90 |
| | | | **Amidon** | 110.53 | 94.68 | 1.50 | 18.55 | 16.33 |
| | | | **HiLine** | 105.47 | 75.63 | 1.66 | 19.48 | 16.07 |
| | | | **McNeal** | 105.22 | 80.58 | 1.69 | 19.19 | 16.51 |
| | | | **Scholar** | 110.22 | 91.86 | 1.73 | 20.76 | 16.91 |
| | | | **Reeder** | 122.53 | 91.28 | 1.68 | 20.64 | 16.73 |
| | | | **LSD 0.05** | **6.807** | **2.314** | **0.035** | **0.431** | **0.114** |

The highest yielding varieties in the study were Reeder, Westbred 926, and McNeal (Table 3). All of these varieties exhibit high weights per sq/ft or plant, high harvest indicies, long grain fill periods, short time to heading and wide leaves (Table 3 and 4). McNeal excelled in single seed diameter, the number of seeds/head, and it had large seeds (Table 3). Westbred 926 had heavy single seed weights, as well as large seeds, exhibited by single seed diameter (Table 3). Reeder did not excel in any of the yield influencing 'seed' traits; and it had the least number of spikelets/head (Table 3). However, high yields in Reeder may be due to its ample tillering and its ability to "stay green" longer than the other varieties in the trial. Reeder was the last variety to physiologically mature, resulting in the longest grain-filling period in the trial (Table 4).

## Correlations Between Plot Weights and Agronomic Traits

Yield is highly correlated with several measurable agronomic traits. Past experiments have shown correlation between yield and measurable agronomic traits, including: harvest index (Calderini et al 1995, Donmez et al 2001, Feil 1992, Hucl and Baker 1987, Nass 1973, Perry and D'Antuono 1989, Reynolds et al 1994, Reynolds et al 1999,Siddique et al 1989, Wang et al 2002), number of grains/m$^2$ (Calderini et al 1995, Feil 1992, Reynolds et al 1994, 1999, Wang et al 2002), long grain fill periods (Reynolds et al 1994, 1999, Wang et al 2002), number of grains/head (Calderini et al 1995, Feil 1992, Hucl and Baker 1987, McNeal 1960, Nass 1973, Perry and D'Antuono 1989, Siddique et al 1989, Wang et al 2002), number of grains/spikelet (Feil 1992, McNeal 1960, Siddique et al 1989), number of tillers (Reynolds et al 1999, Sedgley 1991, Wang et al 2002), kernel weight (Hucl and Baker 1987, McNeal 1960, McNeal et al 1978, Wang et al 2002), leaf size and posture (Sedgley 1991), and photosynthetic ability (Nass 1973). All data from these experiments suggests that one characteristic acting alone may not influence yield; rather many characteristics acting together will confer high yields. Correlations between plot weights and agronomic traits are important, because if there are traits that can be easily measured, and confer high yields, they could aid in the selection phase of a wheat-breeding program.

A correlation analysis was conducted in Minitab (Minitab, Inc. 2000) using the means of the traits from each of the densities combined over locations. Results from the trait correlation analysis show high correlations of several characteristics with plot weight (Table 5). Highly significant correlations at the 99% confidence level were shown in the space seeded treatment with plot weight and weight/plant (r = 0.948), harvest index (r = 0.563), grain fill period (r = 0.597), leaf width (r = 0.666), and grain protein content (r = -0.569). Significant correlations at the 95% confidence level were shown in the space seeded treatment with plot weight and seeds/head (r = 0.529), and plant height (r = -0.508). In the dense seeding treatment highly significant correlations at the 99% confidence level were shown with plot weight and weight/sqft (r = 0.951), harvest index (r = 0.896), grain fill period ( r = 0.748), leaf width (r = 0.754), and grain protein content (r = -0.610). Moderately significant correlations at the 95% confidence level were shown in the dense seeded treatment with plot weight and single seed hardness (r = 0.496), seeds/head (r = 0.555), and spikelets/head (r = -0.478). There were traits that the data from this experiment suggests aren’t correlated with plot weight, contradicting the past experimental findings that single seed weight, single seed diameter, and tillers affect the yield of a variety (Hucl and Baker 1987, McNeal 1960, Reynolds et al 1999, Wang et al 2002).

Table 5. Correlations (r) between plot weight and other agronomic traits among the three densities.

| | **Space** | **Mid-dense** | **Dense** |
|---|---|---|---|
| **Test Weight** | 0.312 | 0.143 | -0.031 |
| **Wt/sqft or Plant** | **0.948 | **0.992 | **0.951 |
| **Harvest Index** | **0.563 | *0.545 | **0.896 |
| **Seed Hardness** | 0.295 | *0.520 | *0.496 |
| **Seed Weight** | 0.316 | 0.243 | 0.119 |
| **Seed Diameter** | 0.165 | 0.169 | 0.022 |
| **Seeds/Head** | *0.529 | *0.544 | *0.555 |
| **Spikelets/Head** | 0.240 | -0.025 | *-0.478 |
| | | | |
| **Grain Fill Period** | **0.597 | **0.625 | **0.748 |
| **Days to Maturity** | 0.329 | 0.401 | 0.371 |
| **Days to Heading** | -0.263 | -0.443 | -0.436 |
| **Tillers/m or Plant** | 0.022 | -0.006 | -0.086 |
| **Plant Height** | *-0.508 | **-0.799 | **-0.870 |
| **Stem Solidness** | -0.094 | -0.321 | -0.325 |
| **Leaf Width** | **0.666 | **0.743 | **0.754 |
| **Leaf Length** | -0.219 | -0.123 | -0.116 |
| **Protein** | **-0.569 | **-0.652 | **-0.610 |

*, ** p-values significant at the 0.05 and 0.01 confidence levels, respectively

## Correlation Between Space Seeded and Dense Seeded Treatments

It is important to know which traits can be selected for, in a space-seeded treatment, which will have the same characteristics in a dense seeded treatment. Measurement of the correlation of characteristics between space and dense seeded treatments is important because when selections are made on space planted materials, the characteristics that cause high yielding capabilities in the space seeded plants should also be exhibited in a dense seeded field. This knowledge could lead to better selection criteria offered to breeders.

Past experimental data suggests that there are traits that can be selected for in a space-seeded nursery that will carry over into a densely seeded field. Days to heading, 100-grain weight, height, harvest index, number of spikes/plant, number of spikelets/spike, kernel weight, and number of kernels/spike have all shown high correlations between space and dense seed treatments (Fischer and Kertesz 1976, Syme 1972).

Since selection in early generations of a breeding program takes place in one year and typically in only one environment, it is important to correlate traits from one space seeded environment to several combined dense environments. This is needed to know how consistently the trait will perform, in a dense seeded population, compared to a space seeded plot. Results from this experiment show that there are correlations of the measured traits between the means in each of the space seeded environments and the combined means of all the dense seeded environments (Table 6).

Table 6. Correlations (r) of variety performance between agronomic traits and space planted and densely seeded treatments.

| | Combined Space[1] | Dry 2002[2] | Irrigated 2002[3] | Dry 2003[4] | Irrigated 2003[5] |
|---|---|---|---|---|---|
| **Plot Weight** | **0.830 | **0.839 | **0.764 | *0.522 | **0.680 |
| **Test Weight** | *0.546 | *0.470 | 0.295 | *0.538 | -0.205 |
| **Wt/sqft or Plant** | **0.775 | **0.711 | **0.616 | *0.465 | **0.716 |
| **Harvest Index** | **0.895 | **0.888 | **0.912 | 0.391 | **0.558 |
| **Seed Hardness** | **0.961 | **0.600 | 0.171 | 0.381 | 0.403 |
| **Seed Weight** | 0.330 | 0.009 | -0.152 | 0.087 | 0.164 |
| **Seed Diameter** | **0.889 | 0.254 | 0.178 | 0.406 | *0.466 |
| **Seeds/Head** | **0.941 | 0.417 | 0.430 | *0.450 | 0.364 |
| **Spikelets/Head** | **0.886 | **0.683 | 0.427 | *0.522 | *0.546 |
| **Grain Fill Period** | **0.886 | *0.488 | *0.473 | **0.634 | 0.331 |
| **Days to Maturity** | **0.844 | 0.348 | 0.142 | 0.198 | 0.105 |
| **Days to Heading** | **0.959 | **0.585 | *0.524 | 0.062 | 0.123 |
| **Tillers/m or Plant** | **0.604 | 0.213 | 0.195 | 0.172 | 0.275 |
| **Plant Height** | **0.894 | **0.949 | **0.967 | **0.732 | **0.745 |
| **Stem Solidness** | **0.961 | **0.946 | **0.961 | **0.582 | **0.590 |
| **Leaf Width** | **0.962 | **0.937 | **0.905 | 0.413 | **0.617 |
| **Leaf Length** | **0.735 | **0.721 | **0.633 | 0.067 | 0.416 |
| **Protein** | **0.908 | **0.819 | **0.774 | 0.328 | **0.560 |

*, ** p-values significant at the 0.05 and 0.01 confidence levels, respectively

[1] Correlation is between the combined means of the four locations of the space planted treatment to the combined means of the four locations of the dense planted treatment

[2] Correlation is between the means of the space planted treatment in the dryland environment in 2002 to the combined means of the four locations of the dense planted treatment

[3] Correlation is between the means of the space planted treatment in the irrigated environment in 2002 to the combined means of the four locations of the dense planted treatment

[4] Correlation is between the means of the space planted treatment in the dryland environment in 2003 to the combined means of the four locations of the dense planted treatment

[5] Correlation is between the means of the space planted treatment in the irrigated environment in 2003 to the combined means of the four locations of the dense planted treatment

Means of all locations were combined for a correlation analysis between the space and dense seeded treatments. Highly significant correlations at the 99% confidence level were found with all of the physiological traits, and with all of the yield influencing traits. The exceptions to this correlation were test weight, that was correlated at the 95% confidence level (r = 0.546), and single seed weight, which was not significantly correlated (Table 6).

When correlation analysis was performed with the means of one space seeded location to the combined means of all locations in the dense seeded treatments, significant correlations were found with traits in all of the space seeded locations and the dense seeded treatments. The correlation analysis of the means from the space seeded dryland location grown in 2002 showed highly significant correlations at the 99% confidence level for plot weight (r = 0.839), weight/sqft or plant (r = 0.711), harvest index (r = 0.888), single seed hardness (r = 0.600), spikelets/head (r = 0.683), days to maturity (r = 0.585), plant height (r = 0.949), stem solidness (r = 0.946), leaf width (r = 0.937, leaf length (r =0.721), and grain protein content (r = 0.819). Significant correlations at the 95% confidence level were found for test weight (r = 0.470) and grain fill period (r = 0.488) (Table 6).

Correlation analysis of the means from the irrigated space environment grown in 2002 showed highly significant correlations at the 99% confidence level for plot weight (r = 0.764), weight/sqft or plant (r = 0.616), harvest index (r = 0.912), plant height (r = 0.967), stem solidness (r = 0.961), leaf width (r = 0.905), leaf length (r = 0.633), and grain protein content (r = 0.774). Significant correlations at the 95 % confidence level were found for grain fill period (r = 0.473) and days to heading (r = 0.524) (Table 6).

The correlation analysis of means from the dryland 2003 spaced environment revealed highly significant correlations at the 99% confidence level for grain fill period (r = 0.634), plant height (r = 0.732) and stem solidness (r = 0.582). Significant correlations at the 95% confidence interval were shown for plot weight (r= 0.522), test weight (r = 0.538) weight/sqft or plant (r = 0.465), seeds/head (r = 0.450), and spikelets/head (r = 0.522) (Table 6).

Finally the correlation analysis of the irrigated 2003 spaced environment means showed highly significant correlations at the 99% confidence level for plot weight (r = 0.680), weight/sqft or plant (r = 0.716), harvest index (r = 0.558), plant height (r = 0.745), stem solidness (r = 0.590), leaf width (r = 0.617), and grain protein content (r = 0.560). Significant correlations at the 95% confidence level were shown for single seed diameter (r = 0.466) and spikelets/head (r = 0.546) (Table 6).

Significant correlations between all of the spaced environments and the dense seeded treatment were shown in plot weight, weight/sqft or plant, plant height, and stem solidness. This indicates that one could have confidence when selecting for these traits in a space seeded environment, and that the plants would exhibit the same level of the trait in a dense seeded environment. Significant correlations between three of the four spaced environments and the dense seeded treatments were shown with harvest index, spikelets/head, grain fill period, leaf width, and grain protein content. This suggests that a breeder could show some confidence when selecting for these traits in a space-seeded treatment that plants in a dense seeded environment would show the same level of the trait (Table 6).

The results of the correlation analysis are important to breeding programs because they show that there are traits that are highly correlated with plot weight in both the dense and space seeded treatments respectively; weight/sqft or plant (r = 0.948, r = 0.951), harvest index (r = 0.563, r = 0.896), seeds/head (r = 0.529, r = 0.555), grain fill period (r = 0.597, r = 0.748), plant height (r = -0.508, r = -0.870), leaf width (r = 0.666, r = 0.754), and grain protein content (r = -0.569, r = -0.610) (Table 5). These data agrees with prior experimental findings that found harvest index (Calderini et al 1995, Donmez et al 2001, Feil 1992, Hucl and Baker 1987, Nass 1973, Perry and D’Antuono 1989, Reynolds et al 1994, Reynolds et al 1999,Siddique et al 1989, Wang et al 2002), long grain fill periods (Reynolds et al 1994, 1999, Wang et al 2002), and number of grains/head (Calderini et al 1995, Feil 1992, Hucl and Baker 1987, McNeal 1960, Nass 1973, Perry and D’Antuono 1989, Siddique et al 1989, Wang et al 2002) were linked to final crop yield.

The data also suggests that all of the measured traits, except seed weight, are correlated with the combined space and dense seed treatments (Table 6). Also, many of the measured traits were correlated between one year and environment to the combined dense seed treatments as well (Table 6).

The results of this experiment show that there are some component traits that consistently influence yield (Table 5), and these yield influencing traits can be selected for with confidence in space plants (Table 6). Although extensive time was spent making careful measurements of many of the traits in the study, a breeder could use these yield influencing traits to make selections, that will in turn influence varietial improvement. The breeder will ultimately determine their own resource investment, versus the potential gains, with selection for the various traits.

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# APPENDIX A

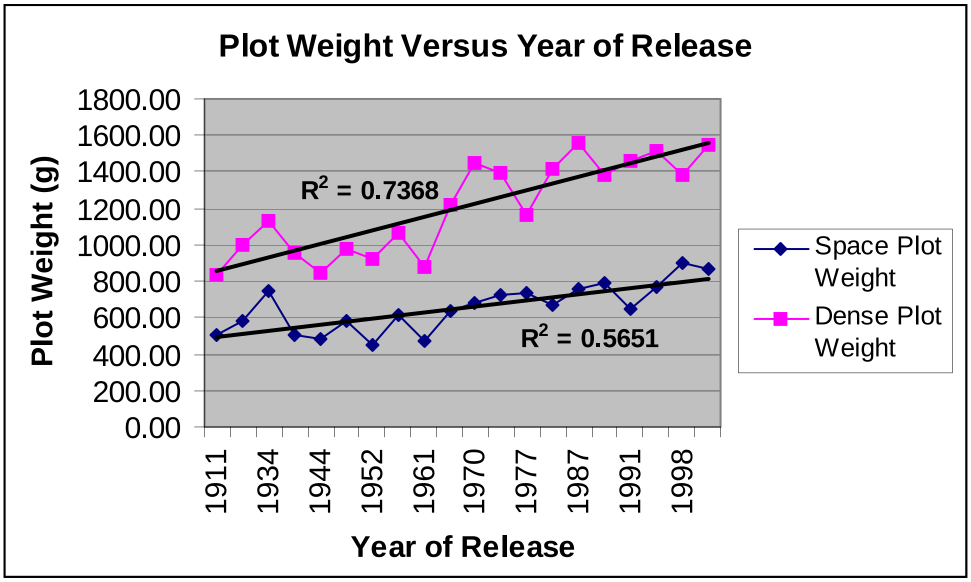
## Traits Versus Year of Release

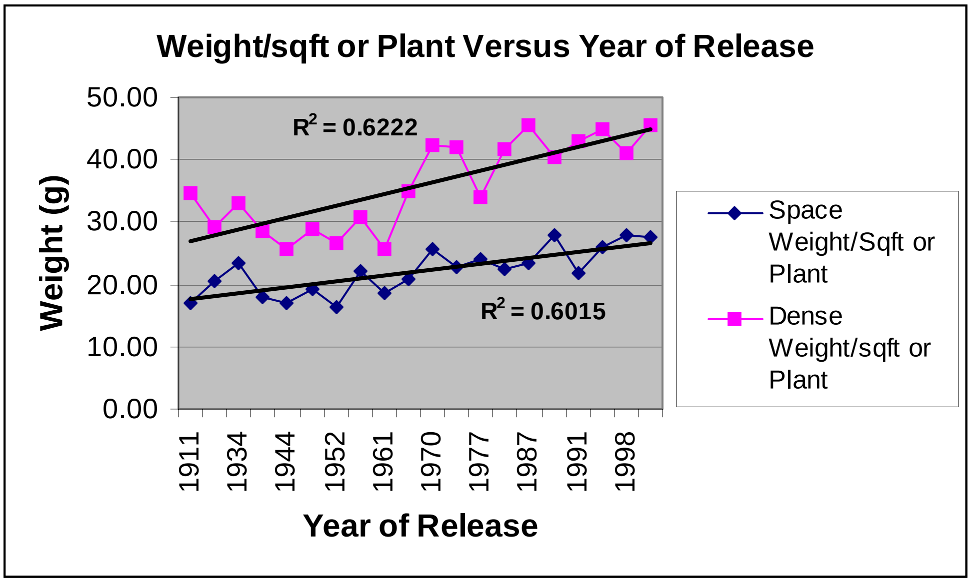
**Correlation of traits to year of release**

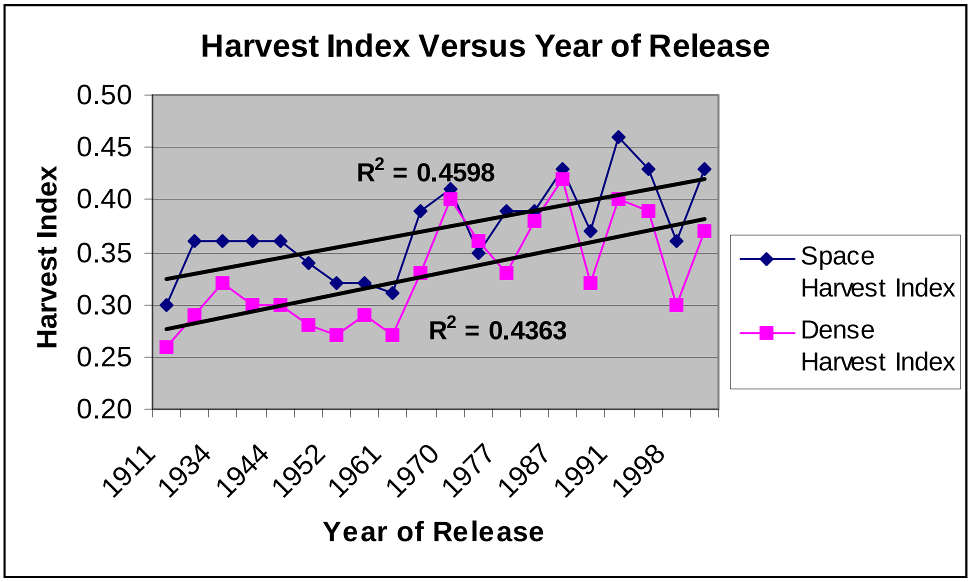
| | **Space** | **Middense** | **Dense** |
|---|---|---|---|
| **Plot Weight** | **0.723 | **0.857 | **0.846 |
| **Test Weight** | *0.497 | 0.364 | 0.297 |
| **Wt/sqft or Plant** | **0.759 | **0.849 | **0.736 |
| **Harvest Index** | **0.683 | 0.253 | **0.671 |
| **Seed Hardness** | 0.218 | 0.315 | 0.355 |
| **Seed Weight** | 0.375 | 0.411 | 0.303 |
| **Seed Diameter** | 0.409 | 0.346 | 0.191 |
| **Seeds/Head** | 0.351 | 0.311 | 0.237 |
| **Spikelets/Head** | -0.016 | -0.096 | -0.189 |
| | | | |
| **Grain Fill Period** | **0.615 | **0.584 | **0.677 |
| **Days to Maturity** | 0.131 | 0.260 | 0.198 |
| **Days to Heading** | *-0.502 | *-0.504 | *-0.522 |
| **Tillers/m or Plant** | -0.078 | 0.070 | 0.055 |
| **Plant Height** | **-0.694 | **-0.670 | **-0.686 |
| **Stem Solidness** | 0.064 | 0.041 | 0.011 |
| **Leaf Width** | **0.637 | **0.672 | **0.673 |
| **Leaf Length** | *-0.548 | -0.366 | -0.327 |
| **Protein** | *-0.528 | *-0.487 | -0.425 |

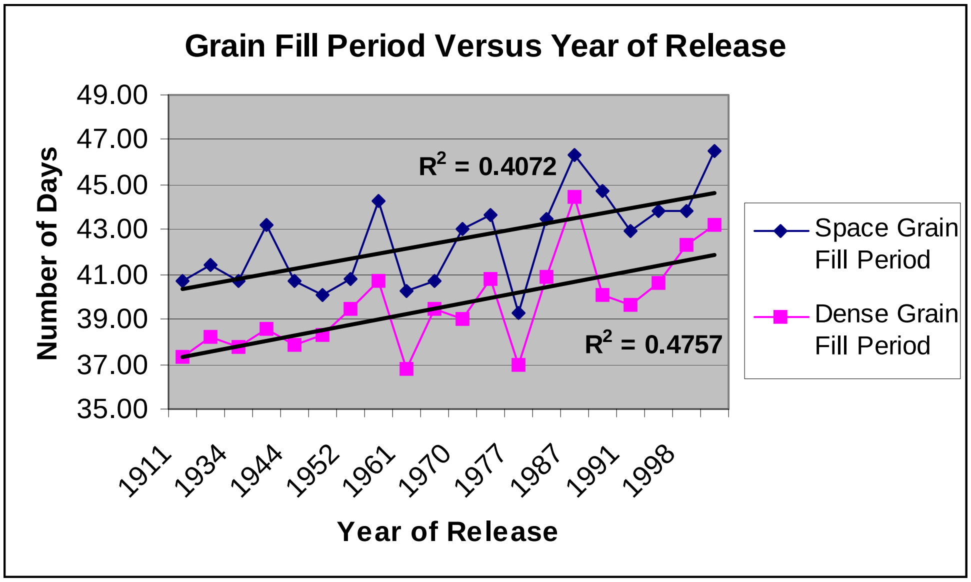
* p-value significant at the 95% confidence level
** p-value significant at the 99% confidence level

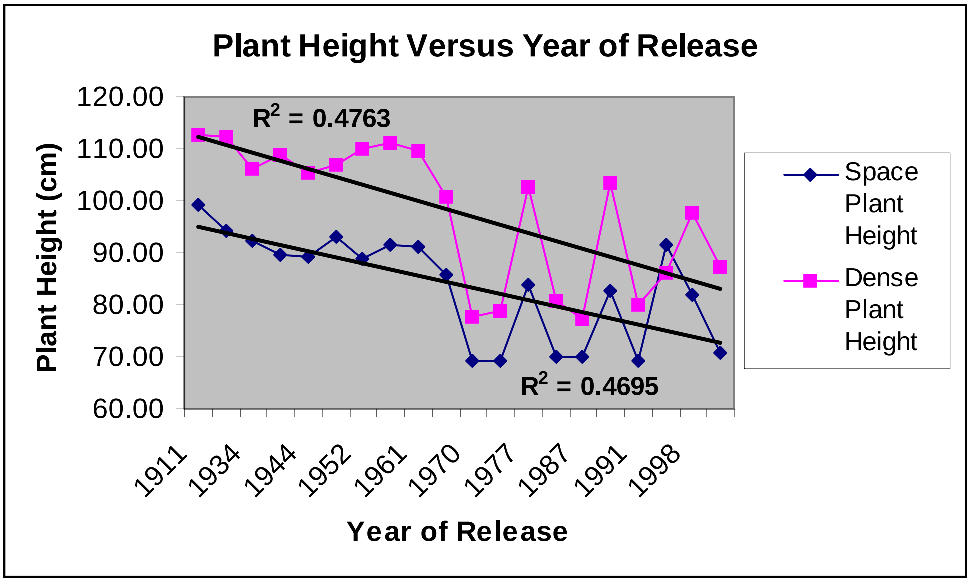
A correlation analysis was conducted in Minitab (Minitab, Inc. 2000) using the means of the traits from each of the densities combined over the locations. Results from the trait correlation analysis show high correlations of several characteristics with year of release. Highly significant correlations at the 99% confidence level were shown in the space seeded treatment with the year of release and plot weight (r = 0.723), weight/plant (r = 0.759), harvest index (r = 0.683), grain fill period (r = 0.615), plant height (r = -0.694), and leaf width (0.637). Significant correlations at the 95% confidence level were shown in the space seeded treatment with year of release and test weight (r = 0.497), days to heading (r = -0.502), leaf length (r = -0.548), and protein (r = -0.528). In the dense seeded treatment highly significant correlations at the 99% confidence level were shown with year of release and plot weight (r = 0.846), weight/sqft (r = 0.736), harvest index (r = 0.671), grain fill period (r = 0.677), plant height (r = -0.686) and leaf width (r = 0.673). A significant correlation at the 95% confidence level was found in the dense seeded treatment with year of release and days to heading (r = -0.522). The traits that are correlated to year of release have shown significant change over time, those traits that aren't correlated have not shown significant change over time. Highly significant positive change has been shown with increased plot weight, increased weight/sqft or plant, increased harvest index, longer grain fill period, and wider leaf width. Also, the shorter stature is shown in modern wheat due to the addition of the semi-dwarfing genes. The tables that follow show a visual scale of the change with these traits and year of release.

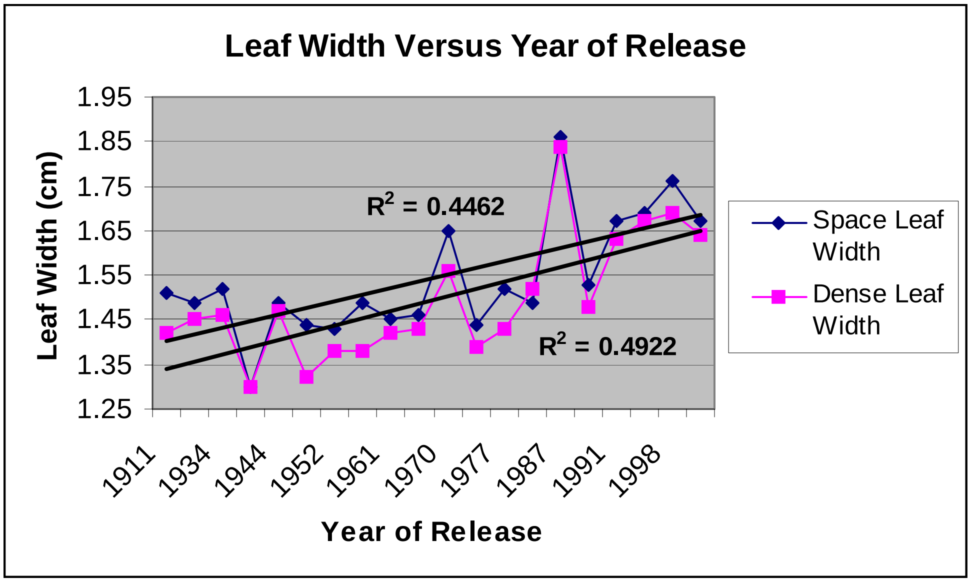

Plot Weight Versus Year of Release
Plot Weight (g)
1800.00
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
R² = 0.7368
R² = 0.5651
Space Plot Weight
Dense Plot Weight


Weight/sqft or Plant Versus Year of Release
Weight (g)
50.00
40.00
30.00
20.00
10.00
0.00
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
R² = 0.6222
R² = 0.6015
Space Weight/Sqft or Plant
Dense Weight/sqft or Plant


Harvest Index Versus Year of Release
Harvest Index
0.50
0.45
0.40
0.35
0.30
0.25
0.20
R$^2$ = 0.4598
R$^2$ = 0.4363
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
Space Harvest Index
Dense Harvest Index


Grain Fill Period Versus Year of Release
Number of Days
49.00
47.00
45.00
43.00
41.00
39.00
37.00
35.00
R$^2$ = 0.4072
R$^2$ = 0.4757
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
Space Grain Fill Period
Dense Grain Fill Period


Plant Height Versus Year of Release
Plant Height (cm)
120.00
110.00
100.00
90.00
80.00
70.00
60.00
R$^2$ = 0.4763
R$^2$ = 0.4695
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
Space Plant Height
Dense Plant Height


Leaf Width Versus Year of Release
Leaf Width (cm)
1.95
1.85
1.75
1.65
1.55
1.45
1.35
1.25
R$^2$ = 0.4462
R$^2$ = 0.4922
1911
1934
1944
1952
1961
1970
1977
1987
1991
1998
Year of Release
Space Leaf Width
Dense Leaf Width