



A comparison of hill, micro-, and miniplots with conventional row plots in winter wheat  
by Leslie John Frederickson

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE  
in Agronomy

Montana State University

© Copyright by Leslie John Frederickson (1979)

**Abstract:**

The type of information attainable in early generations of a cereal breeding program is limited, in part, by the amount of seed and land available. An evaluation of several small-size plots was undertaken to determine their suitability as alternatives to conventional row plots in winter wheat research.

Twenty-three winter wheat (*Triti-cum aestivum* L.) cultivars were evaluated in hill, micro-, mini-, and row plots grown under dryland conditions in 1978. In addition, the hill and microplots were irrigated three times during the growing season in nurseries separate from their dryland counterparts.

Comparisons of these small plots versus the row plots were made using overall means, phenotypic correlations between row and small plots, ranges, coefficients of variation, and the percentage of entries that were common in the extreme 10, 25, and 50% of the population. All small plots provided satisfactory results for discriminating among cultivars for heading date, plant height, seed weight, and harvest index. The hill and microplots were as efficient as the row plots in identifying winter wheat cultivars for percent flour protein and mixogram characteristics (peak distance, peak height, and curve pattern). Based on phenotypic correlations between row plot grain yield and small plot harvest index and biological yield, small plot harvest index provided a better indication of row plot grain yield than did small plot grain yield. No advantage using irrigated hill and irrigated microplots versus their dryland counterparts was detected.

Correlation coefficients were calculated between the agronomic and quality characteristics within plot types to determine if the kinds of inter-relationships that occurred in the row plots also existed in the small plots. Cultivars grown in each of the small plot types showed within plot correlations not exhibited by cultivars grown in the row plots, indicating differential ability of cultivars to compete within and between experimental units.

The relative importance of harvest index and biological yield in determining grain yield of winter wheat cultivars was studied using multiple regression analysis. Harvest index and biological yield accounted for 95 to 99% of the variation in grain yield across plot types and the ratios of their standard partial regression coefficients indicated that harvest index was more important than biological yield in determining grain yield, except in the dryland hill and microplots, where both harvest index and biological yield were of equal importance.

18

STATEMENT OF PERMISSION TO COPY

In presenting this thesis in partial fulfillment of the requirements for an advanced degree at Montana State University, I agree that the Library shall make it freely available for inspection. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by my major professor, or, in his absence, by the Director of Libraries. It is understood that any copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Signature L. John Fredrickson  
Date August 12, 1979

A COMPARISON OF HILL, MICRO-, AND  
MINILOTS WITH CONVENTIONAL  
ROW PLOTS IN WINTER WHEAT

by

LESLIE JOHN FREDERICKSON

A thesis submitted in partial fulfillment  
of the requirements for the degree

of

MASTER OF SCIENCE

in

Agronomy

Approved:

G. Allan Taylor  
Chairman, Examining Committee

Hayden Ferguson  
Head, Major Department

Henry J. Parsons  
Graduate Dean

MONTANA STATE UNIVERSITY  
Bozeman, Montana

August, 1979

## ACKNOWLEDGMENTS

The author wishes to express his gratitude and appreciation to Dr. G. Allan Taylor for his guidance and support throughout the pursuit of this degree.

A sincere thanks is also extended to Drs. Jarvis H. Brown, John M. Martin, Raymond L. Ditterline, and Richard E. Lund for serving on the graduate committee and providing invaluable suggestions and guidance throughout the development of this investigation.

A special acknowledgment is given to Dr. Charles F. McGuire. His time and experience were always readily available, even when he was not a member of the graduate committee.

The author would also like to acknowledge the assistance of Dr. E.P. Smith with the analysis of the data used in this thesis.

I would also like to thank my wife, Regina, and my daughter, Angela, for their support and encouragement throughout my college career.

Appreciation to the Montana Wheat Commission for the assistantship that made this research possible is also extended.

TABLE OF CONTENTS

	<u>Page</u>
VITA . . . . .	ii
ACKNOWLEDGMENTS . . . . .	iii
TABLE OF CONTENTS . . . . .	iv
LIST OF TABLES . . . . .	vi
LIST OF FIGURES . . . . .	xi
ABSTRACT . . . . .	xii
INTRODUCTION . . . . .	1
LITERATURE REVIEW . . . . .	3
The Application of Small Plots to Winter Wheat Research . .	3
Comparison of Row and Small Plots for Evaluation of	
Harvest Index, Biological Yield, and Grain Yield . . . .	6
Evaluation of Quality in Winter Wheat . . . . .	10
SECTION I: THE APPLICATION OF SMALL PLOTS TO WINTER	
WHEAT RESEARCH . . . . .	14
INTRODUCTION . . . . .	15
MATERIALS AND METHODS . . . . .	16
Establishment of Field Plots . . . . .	16
Methods of Sampling . . . . .	18
Statistical Methods . . . . .	21
RESULTS AND DISCUSSION . . . . .	24
Evaluation of Wind and Hail Damage . . . . .	24
Comparison of Row and Small Plots for Selection	
Purposes . . . . .	28
SUMMARY . . . . .	46
SECTION II: COMPARISON OF ROW AND SMALL PLOTS FOR	
EVALUATION OF HARVEST INDEX, BIOLOGICAL YIELD,	
AND GRAIN YIELD . . . . .	48
INTRODUCTION . . . . .	49
MATERIALS AND METHODS . . . . .	50
Establishment of Field Plots . . . . .	50
Methods of Sampling . . . . .	50

	<u>Page</u>
Statistical Methods . . . . .	51
RESULTS AND DISCUSSION . . . . .	53
Comparison of Row and Small Plots for Selection Purposes . . . . .	53
Contributions of Harvest Index and Biological Yield to Grain Yield . . . . .	69
SUMMARY . . . . .	72
SECTION III: THE EVALUATION OF WINTER WHEAT QUALITY IN ROW AND SMALL PLOTS . . . . .	
INTRODUCTION . . . . .	74
MATERIALS AND METHODS . . . . .	75
Establishment of Field Plots . . . . .	75
Laboratory Procedures . . . . .	75
Statistical Methods . . . . .	76
RESULTS AND DISCUSSION . . . . .	79
Comparison of Row and Small Plots for Selection Purposes . . . . .	79
Association of Mixogram Data with Other Quality Traits . . . . .	85
Replicated Versus Bulk Mixogram Data . . . . .	91
SUMMARY . . . . .	95
OVERALL SUMMARY . . . . .	96
LITERATURE CITED . . . . .	98
APPENDIX . . . . .	102

## LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Description of the field nurseries used in the comparison of row and small plots . . . . .	17
2	Date, plant available moisture, and amount of water applied to the irrigated hill and microplots . . . . .	19
3	Trait measured and replicates used in the analyses of row and small plots . . . . .	23
4	Summary statistics for percent culms lodged measured on ten cultivars grown in the row and small plots . . . . .	26
5	Summary statistics for percent heads damaged measured on ten cultivars grown in the row and small plots . . . . .	27
6	Cultivar (C) and error (E) mean squares (MS) from the analysis of variance for 11 traits measured in row and small plots . . . . .	30
7	Mean of all entries for each plot type and tests of significance between the means of row and small plots for 11 traits . . . . .	33
8	Phenotypic correlations between row and small plots for 11 traits . . . . .	36
9	Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for 11 traits . . . . .	38
10	Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for 11 traits measured in row and small plots . . . . .	40
11	Correlations between traits within plot types . . . . .	44
12	Cultivar and error mean squares (MS) from the analysis of variance for harvest index, biological yield, and grain yield measured in row and small plots . . . . .	54

<u>Table</u>	<u>Page</u>
13 Mean of all entries for each plot type and tests of significance between the means of row and small plots for harvest index, biological yield, and grain yield . . . . .	55
14 Heritabilities ( $h^2$ ), genotypic ( $V_g$ ), and error ( $V_e$ ) variances for harvest index, biological yield, and grain yield measured in row and small plots . . . . .	58
15 Phenotypic correlations between row and small plots for harvest index, biological yield, and grain yield . . . . .	60
16 Phenotypic correlations between row plot grain yield and small plot harvest index and biological yield . . . . .	60
17 Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for harvest index, biological yield, and grain yield . . . . .	63
18 Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for harvest index, biological yield, and grain yield measured in row and small plots . . . . .	65
19 Correlations between the indirect selection criteria and other agronomic characters within plot types . . . . .	68
20 Coefficients of determination ( $R^2$ ), standard partial regression coefficients for the multiple regressions of grain yield on harvest index and biological yield, and the ratio of harvest index standard partial regression coefficients to biological yield standard partial regression coefficients . . . . .	71
21 Cultivar (C) and error (E) means squares (MS) from the analysis of variance for percent protein, mixogram peak distance, and peak height measured in row and small plots . . . . .	80
22 Mean of all entries for each plot type and tests of significance between the means of row and small plots for percent protein, mixogram peak distance, and peak height . . . . .	80

<u>Table</u>	<u>Page</u>
23 Phenotypic correlations between row and small plots for percent protein, mixogram peak distance, and peak height . . . . .	82
24 Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for percent protein, mixogram peak distance, and peak height . . . . .	82
25 Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for percent protein, mixogram peak distance, and peak height measured in row and small plots . . . . .	84
26 Correlations among seven quality characteristics of winter wheat grown in row plots . . . . .	88
27 Correlations among seven quality characteristics of winter wheat grown in hill plots . . . . .	89
28 Correlations among seven quality characteristics of winter wheat grown in microplots . . . . .	90
29 Correlations between bulk and replicated data for mixogram peak distance and peak height taken from row and small plots . . . . .	93
30 Correlations between bulked mixogram information and other quality characteristics of winter wheat cultivars grown in row and small plots . . . . .	94

## LIST OF APPENDIX TABLES

<u>Table</u>	<u>Page</u>
1 Winter wheat cultivars, entry, and accession numbers used to compare row and small plots . . . . .	103
2 Comparison of error mean squares between row and small plots for 16 traits . . . . .	104
3 Ranked cultivar means for percent culms lodged measured in row and small plots . . . . .	105
4 Ranked cultivar means for percent heads damaged measured in row and small plots . . . . .	106
5 Ranked cultivar means for days to emergence measured in row and small plots . . . . .	107
6 Ranked cultivar means for fall color measured in row and small plots . . . . .	108
7 Ranked cultivar means for spring color measured in row and small plots . . . . .	109
8 Ranked cultivar means for fall growth habit measured in row and small plots . . . . .	110
9 Ranked cultivar means for spring growth habit measured in row and small plots . . . . .	111
10 Ranked cultivar means for heading date measured in row and small plots . . . . .	112
11 Ranked cultivar means for plant height measured in row and small plots . . . . .	113
12 Ranked cultivar means for number of heads/900 cm <sup>2</sup> measured in row and small plots . . . . .	114
13 Ranked cultivar means for number of seeds per head measured in row and small plots . . . . .	115
14 Ranked cultivar means for 100-seed weight measured in row and small plots . . . . .	116

<u>Table</u>		<u>Page</u>
15	Ranked cultivar means for grain yield measured in row and small plots . . . . .	117
16	Ranked cultivar means for harvest index measured in row and small plots . . . . .	118
17	Ranked cultivar means for biological yield mea- sured in row and small plots . . . . .	119
18	Ranked cultivar means for percent protein mea- sured in row and small plots . . . . .	120
19	Ranked cultivar means for mixogram peak distance measured in row and small plots . . . . .	121
20	Ranked cultivar means for mixogram peak height measured in row and small plots . . . . .	122

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Schematic diagram showing mixogram measurements. Line A describes the distance in cm from the start of the mixogram to the point of minimum mobility, or peak (e.g., peak distance). Line B describes peak height in cm . . . . .	77
2	Effects of tempered (13.5% mb) sieved wheat meal on dough development using four winter wheat cultivars grown in row, hill, and microplots. Values under curves are the mean percent protein for each plot type .	86

## ABSTRACT

The type of information attainable in early generations of a cereal breeding program is limited, in part, by the amount of seed and land available. An evaluation of several small-size plots was undertaken to determine their suitability as alternatives to conventional row plots in winter wheat research. Twenty-three winter wheat (Triticum aestivum L.) cultivars were evaluated in hill, micro-, mini-, and row plots grown under dryland conditions in 1978. In addition, the hill and microplots were irrigated three times during the growing season in nurseries separate from their dryland counterparts.

Comparisons of these small plots versus the row plots were made using overall means, phenotypic correlations between row and small plots, ranges, coefficients of variation, and the percentage of entries that were common in the extreme 10, 25, and 50% of the population. All small plots provided satisfactory results for discriminating among cultivars for heading date, plant height, seed weight, and harvest index. The hill and microplots were as efficient as the row plots in identifying winter wheat cultivars for percent flour protein and mixogram characteristics (peak distance, peak height, and curve pattern). Based on phenotypic correlations between row plot grain yield and small plot harvest index and biological yield, small plot harvest index provided a better indication of row plot grain yield than did small plot grain yield. No advantage using irrigated hill and irrigated microplots versus their dryland counterparts was detected.

Correlation coefficients were calculated between the agronomic and quality characteristics within plot types to determine if the kinds of inter-relationships that occurred in the row plots also existed in the small plots. Cultivars grown in each of the small plot types showed within plot correlations not exhibited by cultivars grown in the row plots, indicating differential ability of cultivars to compete within and between experimental units.

The relative importance of harvest index and biological yield in determining grain yield of winter wheat cultivars was studied using multiple regression analysis. Harvest index and biological yield accounted for 95 to 99% of the variation in grain yield across plot types and the ratios of their standard partial regression coefficients indicated that harvest index was more important than biological yield in determining grain yield, except in the dryland hill and microplots, where both harvest index and biological yield were of equal importance.

## INTRODUCTION

Cereal breeders must screen large numbers of experimental lines in their search for optimum gene combinations. This process requires relatively large amounts of land, time, and expense. Recent interest in recurrent selection methods as a means of obtaining new combinations of genes in self-pollinated species has placed a premium on rapid and accurate techniques to evaluate many genotypes.

Several investigators have shown the suitability of small-size plots in early generation testing of several crop species where costs, land, and seed are limiting, and where large numbers of plants must be screened efficiently. The hill plot and its variation, the linear hill plot or microplot, have been suggested as alternatives to the conventional row plot in testing small grains. Many workers have shown that hill plots provide as much precision as row plots in testing for heading date, plant height, percent protein, harvest index, and the components of yield. They have also been used in genetic studies and for screening large populations for reaction to certain diseases. The use of hill plots as precise indicators of comparative yields, however, has met with little success.

The objectives of this investigation were: 1) compare the performance of 23 winter wheat cultivars grown in conventional row plots with their performance in hill, micro-, and miniplots; 2) analyze the relative importance of harvest index and biological yield in determining

grain yield; and 3) evaluate the ten-gram mixograph as a rapid screening technique for certain quality characteristics of winter wheat.

## LITERATURE REVIEW

### The Application of Small Plots to Winter Wheat Research

The need for smaller plot size in agronomic research, especially as it relates to plant breeding, was recognized as early as 1907, when J.B. Norton (27) suggested the use of 17-foot rows to replace the half-acre and acre plots then used for cultivar testing. Norton found this system of yield estimation gave much better comparative values on a uniform field than did the much larger plot sizes. He also noted the possibility of replication, which was impractical with half-acre plots. Row plots are now widely accepted as a precise method of conducting crop research (17).

Bonnett and Bever (6) reported the use of a head-hill procedure for evaluating wheat and oats. Direct comparisons of plant development in head-hills and head-rows grown in the same year were not made. Ross and Miller (31) compared rod rows and hill plots for yield in oats and barley and concluded that hill yield tests with small grains "have value only as a supplement to present testing methods when large numbers of lines are to be screened, seed supply is scarce, and land is limited." Several crops, especially the small grains, have been tested in hill plots, including durum wheat (3), oats (6, 17, 19, 20, 29, 30, 31, 39, 48), spring barley (28, 31), spring wheat (3, 6, 11, 23), and soybeans (32). Perhaps the most extensive evaluation of hill plots has been by Frey with oats (17).

Many variations of the hill plot design (6) have been introduced as

a result of the peculiar competitive relationships inherent in the hill plots due to several plants growing in a small space. Jensen and Robson (20) introduced the linear hill plot (microplot) because they believed that the spatial arrangement in hill plots modified the inter-plot competitive relationships existing in row plots. Smith et al. (39) determined that inter-genotypic competition among hill plots in oats had a major effect upon yield. Schutz and Brim (32) designed a nine-hill plot which successfully removed "70% of the competition bias exhibited by an unbordered hill of soybeans." Jellum et al. (19) inter-planted hill plots with rows of spring wheat to "promote uniform competition between hills."

In addition to altering the plot design itself, several investigators have varied the amount of seed per hill and the distance separating each plot (11, 17, 28, 31). In most cases, 15-30 seeds per hill and 30 cm spacings were found to be satisfactory; although spacing X genotype and seed number X genotype interactions were significant, comparisons with the conventional plots were not greatly affected.

Different planting methods were also evaluated. Bonnett and Bever (6) used a corn planter to plant hill plots of oats and spring wheat. They were able to plant 7,494 head-hills of oats in 34 man-hours. Frey (17) compared the use of a hand hoe, a corn planter, and a stovepipe for planting hill plots of oats. He found all three methods acceptable for measuring the yielding capacity of oat cultivars, but obtained a high coefficient of variation with the corn planter. The hand hoe method was

preferred and two men could plant plots and borders in a 2500-hill experiment in eight hours.

Hill plots are valuable alternatives to row plots because of their suitability as a technique of obtaining many kinds of agronomic information. Bonnett and Bever (6) found head-hills convenient for general note-taking. Other workers have emphasized their use where land and seed were limiting, such as in early-generation screening, or where large numbers of entries must be evaluated (3, 6, 11, 17, 19, 20, 23, 31). Hill plots are comparable to row plots for obtaining data on heading date, plant height, percent protein, heads per unit area, seeds per head, and seed weight in wheat (11, 23); heading date, plant height, heads per unit area, seeds per head, seed weight, date-of-planting, fertilizer response, plant maturity, and harvest index in oats (17, 19, 29); and seeds per head and seed weight in barley (28). In addition, hill plots have been used for genetic studies in wheat (3); purification of varieties of oats and wheat; and screening for disease resistance in wheat (6).

Hill plots were not found satisfactory by some investigators for the evaluation of lodging (19, 31), heading date (31), test weight, and number of heads per plant (28, 31) in oats and spring barley. Baker and Leisle (3) reported that few breeders use hill plots and suggested that this was due to the poor correlations or the different rankings between yields of hill and row plots. However, Frey (17) found that hill plots were as accurate as row plots for yield determination in oats and sugges-

ted that precision may be increased by using more replications. Ergun (11) proposed the use of more genotypes to increase precision. Baker and Leisle (3) and Frey (17) used genotypic rather than phenotypic correlations to compare performance of cultivars for several traits in hill and row plots and found genotypic correlations were higher than phenotypic correlations. Frey (17) argued that genotypic correlations were more appropriate than phenotypic correlations "because genotypic expression is what the plant breeder wishes to measure," and phenotypic correlations may be misleading.

#### Comparison of Row and Small Plots for Evaluation of Harvest Index, Biological Yield, and Grain Yield

Improving one trait, such as grain yield, by selection for other, alternative traits is referred to as indirect selection (33). The requirements of any indirect selection criterion are: 1) the ability to measure many plants in a short time; 2) the genetic variability that exists for the character (i.e., its heritability); 3) the relationship it shows with grain yield; and 4) its repeatability (16, 33).

Present high-yielding cultivars of cereal crops are largely the result of two types of breeding programs: defect elimination and direct selection for yield (9). Defect elimination has reduced or eliminated the susceptibility of a crop to disease, insects, frost, drought, high temperature, and lodging. The result has primarily been yield maintenance. Indirect selection for yield potential has generally been limited to the

selection of yield components (i.e., number of heads per unit area, number of seeds per head, and seed weight). However, the manipulation of these components has not been successful because, in small grains, an increase in one component is often followed by a decrease in one or more of the others, a relationship known as component compensation (10).

Many plant breeders rarely practice unrestricted direct selection for yield (1). Restrictions are generally placed on certain agronomic traits, such as maturity and plant height, before selections for yield are made. This process is called restricted direct selection (29, 30). In oats (30) restricted direct selection for yield was found to be only 57% as efficient for improving grain yield as unrestricted direct selection for yield.

Donald and Hamblin (10) and Evans and Wardlaw (12) proposed that selection emphasis should be placed on vegetative characteristics, particularly as they relate to the photosynthetic capacity of the crop canopy and the competitive ability of the plants. Niciporovic (5) recognized that agriculture is a system of exploiting photosynthesis. He defined the "coefficient of effectiveness of formation of the economic part of the total yield" as the fraction of photosynthate that is correctly distributed at the right time to useful parts of the plant. It is determined as the ratio of economic yield to biological yield and can be expressed as a factor less than unity, or as a percentage (10). The economic yield of a crop is that portion which is harvested by the farmer for

later sale (e.g., grain, fiber, oil, or tuber) and biological yield is defined as the total above-ground dry matter accumulation of a plant system (5). Donald (8) proposed the term "harvest index" for the ratio of grain yield to biological yield in cereal crops. This term is identical in meaning to the coefficient of effectiveness, but without its physiological or teleological overtones (10). Harvest index is a direct indicator of the efficiency with which a plant population partitions photosynthate into economic yield and any environmental or genetic factor which affects this partitioning, also affects the magnitude of the harvest index (10).

Significant, positive correlations have been found to exist between harvest index and yield for several crops. Values reported in the literature are: a phenotypic correlation of 0.54 and a genotypic correlation of 0.60 in lentils (37); a phenotypic correlation of 0.50 (38) and genotypic correlations of 0.42 (29) and 0.54 (48) in oats; a phenotypic correlation of 0.66 in spring barley (38); phenotypic correlations of 0.56 (16), 0.62, and 0.75 (26) in spring wheat; and a phenotypic correlation of 0.62 in winter wheat (38).

Singh and Stoskopf (38) found a high degree of variability in the harvest indexes of winter wheat, spring barley, winter barley, winter rye, and oats. Winter wheat showed the greatest variation (range = 18%) and spring barley showed the highest mean (51%). Rosielle and Frey (29) found that the mean harvest index of oats in Iowa had a range of 28% among

1200 F<sub>9</sub> lines and across six environments. Harvest index had a higher standard unit heritability than yield in oats (60 versus 53%), but variation in heritability estimates was noted depending upon the method used to calculate it.

Takeda and Frey (49) suggested that harvest index in oats is near optimum in the Midwest, but that yield increases could also be achieved by increasing biological yield. Harvest index and biological yield have a potential for manipulation that is unavailable when using the heads per unit area, seeds per head, and weight per seed of a small grain. For instance, increases in the yields of oats, spring barley, and spring wheat in Australia have been accomplished by an increase in harvest index without a significant change in biological yield (10, 36, 46). In effect, cereal breeders have applied indirect selection pressure for harvest index without purposively doing so, by selecting directly for yield, shorter straw, and earliness (10).

Several workers (16, 26, 47) have investigated the predictive value of harvest index as an indirect selection criterion. Fischer and Kertesz (16) showed that spaced-plant harvest index was superior to spaced-plant yield as a predictor of yielding ability in large plots of spring wheat. Syme (47) found that the harvest index of potted plants in a glasshouse accounted for 71.7% of the variability in the Fifth International Spring Wheat Yield Nursery yields, and recommended harvest index as an indirect method of predicting relative mean yields of wheat genotypes.

## Evaluation of Quality in Winter Wheat

Wheat quality is defined in terms of the wheat's suitability for a given product (15). Quality in a soft white wheat is defined in terms of milling characteristics and suitability in the manufacture of cakes, cookies, and crackers. On the other hand, quality in hard red wheats is defined in terms of properties that determine utility for hard wheat milling and bread production. For bread-baking purposes, a flour of good quality should have a high water absorption, a medium to medium-long mixing requirement, a small to medium oxidation requirement, satisfactory mixing tolerance and dough-handling properties, good loaf-volume potentialities, and good internal crumb grain and color (15). The amount and quality of protein, especially gluten, is used as a measure of strength in bread wheats (4).

Successful techniques for the milling and baking of wheats and flours were developed before the establishment of wheat and flour testing laboratories. As plant breeders developed new cultivars, they were tested by the milling and baking industry against commercially-acceptable standards (41). Johnson and Swanson (21) and Swanson (41, 42) reviewed the many mechanical devices developed in flour-testing laboratories for evaluating the physical properties of dough in commercially acceptable hard red wheat cultivars. Two of these machines, the Brabender Farinograph and the Swanson and Working Recording Dough Mixer (mixograph), grew in importance at about the same time (34, 45).

The farinograph is a highly standardized instrument and one of the most widely used physical dough testing instruments in the world (15). It was designed to measure the development time of the dough (41) and to provide information on flour absorption and mixing tolerance (15). Shuey (34) surveyed the literature on the farinograph and found that farinogram absorption agreed within one percent of that determined by a baker; peak time was correlated ( $r = 0.88^{**}$ ) with crude protein but not with baking mixing time ( $r = 0.27$ ); farinogram stability was found to give some indication of the mixing tolerance of a flour; and farinogram valorimeter values were correlated with loaf volume ( $r = 0.57^*$ ), flour protein ( $r = 0.67^*$ ), and sedimentation value ( $r = 0.84^{**}$ ).

The mixograph is a high-speed recording dough mixer (15). Swanson (42) stated it was "designed to measure and record automatically the rate of dough development, the duration of resistance against mechanical action, and the rate and extent of increase in mobility of dough as a result of mechanical action." The main difference in the action of the farinograph and the mixograph is that the mixograph dough treatment is much more severe (41). Until recently (14) the mixograph has not been a highly standardized apparatus (15). Swanson and Johnson (44) recognized the need for a basis of description and interpretation of the mixogram, and developed a system using the angular traits of the curve. Several variations on this technique have been reported (21, 25, 50), but distance to peak and curve height remain the most important mixogram characteris-

tics (21). Morris et al. (25) developed a single-figure score for a mixogram based on the area under the curve, but Zalik and Ostafichuk (50) found that this method obscured some of the relevant data on the quality of the doughs being studied.

Johnson et al. (22) reviewed the literature on the interpretation of curve characteristics in a mixogram. They reported that dough development time indicated the amount of mixing required to develop a dough to optimum consistency. The curve height increased directly with increasing protein content and increasing absorption. The width of the curve at the peak was thought to indicate elasticity, but Swanson (43) later modified this interpretation because he found that a starch-water mixture also gave a wide band.

Johnson and Swanson (21) attempted to standardize certain techniques in the mixograph's operation by studying the effects of grinding, tempering, and absorption upon the types of curves produced. Shuey and Gilles (35) evaluated the effect of spring settings and different absorptions on the mixogram characteristics of several different flours. They found that flours reacted differently to different conditions and recommended the use of the two spring settings and absorptions for each flour tested. Finney and Shogren (14) described a highly standardized ten-gram mixograph "for determining mixing requirement, mixing tolerance, water absorption, and for predicting oxidation requirement, dough-handling characteristics, and loaf volume," where flour protein content is

known. Bruinsma et al. (7) introduced a rapid method of determining wheat quality by using tempered (13.5% mb) sieved wheat meal in a ten-gram mixograph. They obtained a correlation coefficient of 0.92 between flour mix peak and meal mix peak and found the association between absorption of flours and meals to be very close ( $r = 0.99$ ).

Several authors (22, 24, 34) have evaluated comparisons between baking results and the values associated with the farinogram and mixogram. Johnson et al. (22) found a better correlation between protein content and loaf volume than with any characteristics of the mixogram and loaf volume. Miller et al. (24) compared the relative contributions of farinogram, mixogram, and sedimentation characteristics to baking data. The only correlations large enough to have predictive value were between baking and mixogram mixing time, flour protein and sedimentation value, and calorimeter value and sedimentation value. Mixogram mixing time was shown to be superior to farinogram mixing time in predicting baking mixing time, and the mixogram weakening angle was a better indicator of the sensitivity of a flour to mixing time than the farinogram mixing tolerance index.

SECTION I: THE APPLICATION OF SMALL  
PLOTS TO WINTER WHEAT RESEARCH

## INTRODUCTION

The size of the field plots used by a plant breeder determines, to a great extent, the amount of materials he is able to evaluate. This is especially true of early generation materials which include tens of thousands of untested genotypes. The hill plot and its variation, the linear hill plot or microplot require less land and seed and have been suggested as alternatives to conventional row plots for obtaining comparable agronomic information. The objective of this investigation was to determine the suitability of small-size plots as alternatives to conventional row plots in winter wheat research.

## MATERIALS AND METHODS

### Establishment of Field Plots

This study was conducted at the Field Research Laboratory near Bozeman, Montana during the 1977-78 growing season. Twenty-two hard red winter wheat cultivars and one soft white winter wheat cultivar (Appendix Table 1) were grown in conventional row plots and three types of small plot on an Amsterdam silt loam, Typic Cryoborall soil.

Six field nurseries were established, one each for row plots and miniplots, and two each (irrigated and dryland) for hill and microplots (Table 1). All nurseries, except the miniplots, were seeded 1.3 cm deep with a cone seeder equipped with six furrow openers spaced 30 cm apart. Prior to seeding, the hill plot experimental areas were marked in 30 cm squares with a hand-drawn marker. The miniplots were seeded 0.6 cm deep with a cone seeder equipped with 12 double disk openers spaced 15 cm apart. The planting dates were 29 Sept. and 5 Oct. 1977 for the row plots and the other five plot nurseries, respectively.

The row plot nursery consisted of four 3 m rows per plot with 30 cm spacings between rows seeded at a rate of 8 g per row. Two rows of border were planted on each side of the nursery. Both hill plot nurseries consisted of one hill per experimental unit and were planted with 1 g seed per plot (approximately 28 seeds). Hill plots were spaced 30 cm apart in perpendicular directions. Two replications at a time were surrounded by two "rows" of border hills, and each side of these nurseries

Table 1. Description of the field nurseries used in the comparison of row and small plots.

Nursery†	Total replicates used	Seed/30 cm of row	Seed required per entry	Rows/plot	Distance between rows	Row length	Harvest size‡	Nursery size §
		g	g		cm	m	m <sup>2</sup>	m <sup>2</sup>
Row-D	6	0.8	192	4	30	3.0	199	497
Hill-I	12	1.0	12	1	30	0.3	25	25
Hill-D	12	1.0	12	1	30	0.3	25	25
Micro-I	12	1.0	12	1	30	0.3	25	52
Micro-D	12	1.0	12	1	30	0.3	25	52
Mini-D	6	0.5	72	6	15	1.2	75	149

† The letters D and I following nurseries are abbreviations for dryland and irrigated, respectively.

‡ Harvest sizes include 23 entries and all replicates used in plot type considered.

§ Nursery sizes given do not include alleys and borders. Nursery size for the microplots include the 10 cm spaces between plots within the row and the 36 cm borders capping each end of the row.

ies were bordered by two solid-planted rows. Each microplot nursery consisted of four microplots planted in a row 2.4 m long. Microplots within the row were 30 cm long with a 10 cm space between plots. A 36 cm border microplot capped each end of the row. Microplots were planted at a rate of 1 g seed per 30 cm. Two rows of microplots were planted on each side of the nurseries as border. The miniplots consisted of six 1.2 m rows with 15 cm between rows. Each row was planted at a rate of 2 g seed. Four-row borders were planted on each side of three parallel runs of the planter.

Irrigation water was applied to the irrigated hill and irrigated microplot nurseries three times during the growing season (Table 2) via a gravity flow, flood-type system. Soil moisture was brought to field capacity as determined by a series of electrical resistance blocks placed within the experimental area. Weeds in all nurseries were hand hoed.

#### Methods of Sampling

Days to emergence, color and growth habit in the fall and spring, heading date, plant height, number of heads/900 cm<sup>2</sup>, number of seeds per head, 100-seed weight, and yield data were taken on the row plots, dryland hill, dryland micro-, and miniplots. Only plant height, number of heads/900 cm<sup>2</sup>, number of seeds per head, 100-seed weight, and yield data were taken on the irrigated hill and irrigated microplots, since they were not considered to be different from their dryland counter-

Table 2. Date, plant available moisture, and amount of water applied to the irrigated hill and microplots.

Date (1978)	Plant available moisture	Water added
	%	cm
19 June	24	14.8
21 June	59	8.2
30 June	25	14.7

parts until after the first irrigation. Percent culms lodged and percent heads damaged by hail were taken on ten entries of all nurseries.

Days to emergence was determined as the number of days from planting until 50% of the possible coleoptiles in a 30 cm length of row or in a hill plot were emerged. Seedling color was recorded on a scale of one to five, with a one equal to the palest green and a five equal to the darkest green. Seedling growth habit was estimated on a scale of one to five, with a one assigned to the most erect seedlings and a five to the most prostrate. Heading date was recorded as the number of days from January 1 until 50% of the heads in a plot were fully out of the boot. Plant height was measured as the height in cm from the soil surface to the tip of the main spike, excluding awns. The number of heads per 900 cm<sup>2</sup> was obtained by counting the number of head-producing tillers in a 900 cm<sup>2</sup> area in all plot types. 100-seed weight was determined by counting 100 seeds from a plot and obtaining their weight in grams. The number of seeds per head was determined by dividing plot yield by the product of the number of heads/900 cm<sup>2</sup> and 100-seed weight. Prior to measuring yield, the center two rows of the row plots were trimmed to 2.4 m and the center four rows of the miniplots were trimmed to 0.9 m. Yield was determined from each hill plot, each microplot, the center two rows of each row plot, and from the center four rows of each miniplot. On 16 July 1978 a hail and wind storm damaged the experimental areas. On 24 July 1978, percent culms lodged and percent heads

damaged were measured to provide an indication of the nature and extent of the damage. Percent culms lodged was estimated as the ratio of the number of lodged culms in a  $900 \text{ cm}^2$  area to the total number of culms in that area, times 100. Percent heads damaged was estimated as the ratio of the number of heads showing at least 5% damage (i.e., missing spikelets or spikelets that were otherwise visibly damaged by hail) to the total number of heads in a  $900 \text{ cm}^2$  area, times 100.

#### Statistical Methods

Six replications of row plots and miniplots and 12 replications of hill plots and microplots were planted in a randomized complete block design. Cultivars were assigned to experimental units by use of a random number table. An analysis of variance for a two-way classification and an F-test were used to determine if cultivars gave equivalent expressions for each of the 11 traits studied. Cultivars were treated as random effects in the two-way model. A test for homogeneous error variances between agronomic data obtained from the row plots and that obtained from the small plots was calculated (Appendix Table 2). A t-test was used to compare the mean of all cultivars in each small plot type with the mean of all cultivars in the row plots for each of the traits studied. The t-statistic was weighted for non-homogeneous error variances (40); when error variances were homogeneous their values and respective degrees of freedom were pooled and Student's t-distribution was followed. Phenotypic correlations based on cultivar means

were computed for each character between row plots and small plots and within plot types. The percent of small plot entries common to the top 10, 25, and 50% of entries for the row plots was calculated for each trait. The number of replications used for each trait in each plot type is presented in Table 3.

Table 3. Trait measured and replicates used in the analyses of row and small plots.

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence	3 ‡	0	12	0	12	6
Fall color	3	0	3	0	3	3
Spring color	3	0	3	0	3	3
Fall growth habit	3	0	3	0	3	3
Spring growth habit	3	0	3	0	3	3
Heading date	6	0	12	0	12	6
Plant height	6	12	12	12	12	6
Number of heads/900 cm <sup>2</sup>	3	5	5	5	5	3
Number of seeds/head	3	5	5	5	5	3
100-seed weight	3	5	5	5	5	3
Yield	6	12	12	12	12	6
Percent culms lodged	4	4	4	4	4	2
Percent heads damaged	4	4	4	4	4	2

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

‡ Numbers in body of table are the number of replicates used to measure each trait.

## RESULTS AND DISCUSSION

### Evaluation of Hail and Wind Damage

The field nurseries used in this investigation were damaged by wind and hail on 16 July 1978, six days after the last cultivar had headed. Ten of the 23 entries in these nurseries were selected to represent the range of plant types and used to evaluate the nature and extent of the damage. A comparison between row and small plots for hail- and wind-induced lodging and hail-induced head damage was made.

Significant differences for percent culms lodged existed among the cultivars of the row, irrigated hill, irrigated micro-, and dryland microplots. Significant differences among the cultivars of the dryland hill plots and miniplots were not detected (Table 4). Significant differences among cultivars for percent heads damaged were detected for all plot nurseries except the miniplots (Table 5).

A t-test was used to determine if the mean of the small plot experiments differed from the mean of the row plots for percent culms lodged and percent heads damaged (Tables 4 and 5). For percent culms lodged, only the means for the dryland hill and dryland microplots were significantly different from the mean of the row plots. Both small plot nurseries exhibited lower overall means and their correlation coefficients for percent culms lodged with the row plots were nonsignificant, indicating these two nurseries suffered relatively little from hail- and wind-induced lodging. Because of the peculiar spatial arrangement of cultivars grown in hill and microplots, the mass of lodg-

ing-susceptible cultivars, which occurred in the row and miniplots, may not have been great enough to force other lodging-susceptible as well as non-susceptible cultivars to lodge. Although cultivars grown in the two irrigated nurseries shared the spatial arrangements of their dryland counterparts, the fact that these cultivars were irrigated presumably increased their relative susceptibility to lodging. This may have been especially true in the irrigated microplots since the cultivars grown in that plot type had a greater mean plant height than the cultivars grown in the row plots (Table 7).

All small plot means for percent heads damaged were not statistically different from the row plot mean (Table 5). The correlation coefficients between the row plot nursery and each small plot nursery for percent heads damaged were positive and highly significant, indicating that the cultivars grown in the small plots reacted to hail-induced head damage in a manner similar to row plot cultivars.

The amount of variability for percent lodged culms and percent heads damaged within each plot type was high. The range of expression across plot types for percent culms lodged was 20.0 to 81.3% (Table 4) and for percent heads damaged, 7.5 to 17.0% (Table 5). The number of cultivars in all plot types exhibiting a large effect from hail were small for both percent culms lodged and percent heads damaged (Appendix Tables 3 and 4). The range in coefficients of variation (C.V.) across plot types for percent lodged culms was 41 to 293% (Table 4). Because the overall

Table 4. Summary statistics for percent culms lodged measured on ten cultivars grown in the row and small plots.

Statistic	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
MS (C)‡	3496.0**	1824.0*	222.8	651.1*	355.8*	1425.0
MS (E)§	35.1	724.4	321.7	217.8	120.3	478.3
df (C)	9	9	9	9	9	9
df (E)	27	27	27	27	27	9
$\bar{X}..$ (%)¶	14.4	21.3	6.1*	8.5	4.3*	22.5
C.V. (%)	41.1	126.4	293.9	173.6	255.1	97.2
Range (%)	81.3	52.5	20.0	42.5	27.5	80.0
r #		0.72*	0.45	0.73*	0.30	0.83*

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

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡,§ MS (C) and MS (E) are cultivar and error mean squares, respectively.

¶ Numbers are overall plot means and asterisks indicate a significant difference exists between the mean of the row plot and the mean of the small plot under consideration.

# Correlation coefficient between row and small plots for percent culms lodged.

Table 5. Summary statistics for percent heads damaged measured on ten cultivars grown in the row and small plots.

Statistic	Plot Type †					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
MS (C)‡	72.4**	56.2*	90.8**	23.9**	16.5*	40.0
MS (E)§	8.4	21.9	19.1	5.3	5.7	8.6
df (C)	9	9	9	9	9	9
df (E)	27	27	27	27	27	27
$\bar{X}..$ (%)¶	7.6	7.7	7.6	6.3	6.0	6.6
C.V. (%)	38.1	61.7	57.5	36.5	39.8	44.4
Range(%)	15.8	13.3	17.0	8.2	7.5	14.5
r #		0.89**	0.96**	0.93**	0.98**	0.88**

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

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡,§ MS (C) and MS (E) are cultivar and error mean squares, respectively.

¶ Numbers are overall plot means.

# Correlation coefficients between row and small plots for percent heads damaged.

means for each small plot were either not significantly different or smaller than the mean of the row plot nursery, the larger C.V.'s of the small plots can be attributed to larger standard errors. The C.V.'s for percent heads damaged in the two microplot nurseries and the mini-plot nursery were similar to that of the row plot nursery. The C.V.'s in the two hill plot nurseries were considerably larger than that of the row plot nursery (Table 5). The overall means of the hill plot nurseries for this trait were not significantly different from the row plot mean, but the standard errors of the former plot types were about twice as large as that of the latter.

The results of this evaluation indicated all but the dryland hill and dryland microplot nurseries were affected by hail- and wind-induced lodging and by hail-induced head damage in a manner similar to the row plots. The dryland hill and microplots, however, were not as severely affected by hail- and wind-induced lodging as the row plots, although hail-induced head damage was similar to the row plot nursery.

#### Comparison of Row and Small Plots for Selection Purposes

##### Analysis of Variance

Eleven characteristics of 23 winter wheat cultivars were compared in row and small plots. Significant differences among cultivar means across plot types were detected for heading date, plant height, 100-seed weight, and yield (Table 6). Significant differences among the cultivars for days to emergence were detected in the row and miniplots;

for fall color in the row, dryland micro-, and miniplots; for fall growth habit in the dryland hill, dryland micro-, and miniplots; for spring growth habit in the dryland micro- and miniplots; for number of heads/900 cm<sup>2</sup> in the row, dryland hill, irrigated micro-, dryland micro-, and miniplots; and for the number of seeds per head in the row, irrigated micro-, and miniplots. Of the six plot types studied, significant cultivar F-tests for all traits were detected only in the analysis of the miniplot nursery.

Because the hypothesis of equal cultivar means in the analyses of several traits (i.e., spring color, fall growth habit, and spring growth habit measured in the row plots; days to emergence, fall color, spring growth habit, and number of seeds per head measured in the dryland hill plots; number of heads/900 cm<sup>2</sup> and number of seeds per head measured in the irrigated hill plots; and days to emergence and number of seeds per head measured in the dryland microplots) was not rejected by an F-test (Table 6), comparisons of individual cultivar means between row and small plots were made with caution (18).

#### Comparison of Overall Means

The overall means of the cultivars grown in the small plots for fall color, fall growth habit, spring color, spring growth habit, heading date, 100-seed weight, and number of seeds per head were not significantly different from the overall means for these traits in the row plot nursery (Table 7).

Table 6. Cultivar (C) and error (E) means squares (MS) from the analysis of variance for 11 traits measured in row and small plots.

Trait		Plot Type†					
		Row-D		Hill-I		Hill-D	
		MS	df	MS	df	MS	df
Days to emergence	(C)	0.90**	22	---	---	3.11	22
	(E)	0.30	110	---	---	2.05	242
Fall color	(C)	0.52**	22	---	---	0.22	22
	(E)	0.12	44	---	---	0.19	44
Spring color	(C)	0.19	22	---	---	0.32**	22
	(E)	0.23	22	---	---	0.15	44
Fall growth habit	(C)	0.44	22	---	---	0.72**	22
	(E)	0.26	22	---	---	0.32	44
Spring growth habit	(C)	0.86	22	---	---	0.31	22
	(E)	0.22	22	---	---	0.45	44
Heading date	(C)	44.80**	22	---	---	83.51**	22
	(E)	0.30	110	---	---	1.20	242
Plant height	(C)	869.90**	22	1365.51**	22	965.46**	22
	(E)	11.20	44	15.22	242	16.31	242
Heads/900 cm <sup>2</sup>	(C)	266.70**	22	166.35	22	163.74**	22
	(E)	99.60	44	126.02	88	75.24	88
Seeds/head	(C)	17.67*	22	27.19	22	47.57	22
	(E)	9.70	44	30.77	88	45.41	88
100-seed weight	(C)	0.25**	22	0.48**	22	0.39**	22
	(E)	0.03	44	0.06	88	0.02	88
Yield	(C)	170.70**	22	513.71**	22	338.97**	22
	(E)	18.00	110	92.37	242	71.51	242

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

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

(Continued) 30

Table 6. (Continued).

		Plot Type†					
		Micro-I		Micro-D		Mini-D	
		MS	df	MS	df	MS	df
Days to emergence	(C)	---	---	0.59	22	1.60*	22
	(E)	---	---	0.50	242	0.62	110
Fall color	(C)	---	---	0.46**	22	0.47**	22
	(E)	---	---	0.08	44	0.11	44
Spring color	(C)	---	---	0.43**	22	0.27**	22
	(E)	---	---	0.13	44	0.07	44
Fall growth habit	(C)	---	---	0.80**	22	0.74**	22
	(E)	---	---	0.17	44	0.26	44
Spring growth habit	(C)	---	---	0.84*	22	1.10**	22
	(E)	---	---	0.41	44	0.27	44
Heading date	(C)	---	---	66.10**	22	38.32**	22
	(E)	---	---	1.51	242	0.36	110
Plant height	(C)	1591.16**	22	1140.02**	22	668.60**	22
	(E)	27.04	242	26.66	242	15.54	110
Heads/900 cm <sup>2</sup>	(C)	308.74*	22	194.44*	22	470.27*	22
	(E)	162.13	88	119.03	88	225.92	44
Seeds/head	(C)	51.69*	22	31.59	22	21.04**	22
	(E)	29.02	88	20.35	88	9.11	44
100-seed weight	(C)	0.45**	22	0.53**	22	0.22**	22
	(E)	0.03	88	0.04	88	0.03	44
Yield	(C)	692.13**	22	410.71**	22	195.79**	22
	(E)	172.89	242	103.69	242	38.94	110

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

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

Although planting date in the small plots was seven days later than in the row plot nursery, days to emergence in the dryland hill and dryland microplots were not significantly different than in the row plots. Growing conditions, as expressed by temperature and precipitation, did not change to a great extent during the period from planting the row plots to seedling emergence in the small plots. The mean days to emergence in the miniplots, however, was earlier than in the row plots and this was attributed to shallower planting depth in the miniplots.

Mean plant height in the dryland micro- and miniplots were similar in magnitude to plant height in the row plots. Generally, plants were taller in the irrigated nurseries, although only the dryland hill and irrigated microplots expressed significance. Throughout the growing season the cultivars grown in the dryland hill plots appeared less vigorous, in terms of amount of tillering and plant height, than those grown in the other nurseries. This observation was evident in a tendency for dryland hill plot cultivars to be shorter, on the average, than those in the row plots.

The significantly greater number of head-producing tillers expressed in the miniplots was the result of sampling both rows in the 30 cm spacing, thus doubling the number of heads/900 cm<sup>2</sup>. The 10 cm spaces between the entries in the microplots (p. 18) had no significant effect on the number of heads/900 cm<sup>2</sup> (Table 7). This may be attributable to an apparent lack of border effect. During the planting operation some

Table 7. Mean of all entries for each plot type and tests of significance between the means of row and small plots for 11 traits.

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence ‡	17.3	--	16.4	--	16.0	15.1**
Fall color §	3.4	--	3.3	--	3.4	3.5
Spring color §	3.2	--	3.5	--	3.3	3.5
Fall growth habit ¶	2.7	--	2.9	--	2.8	2.9
Spring growth habit ¶	2.8	--	3.2	--	3.4	3.1
Heading date #	171.0	--	171.5	--	171.2	171.0
Plant height (cm)	110.7	112.8	105.5**	114.8*	107.6	108.1
Heads/900 cm <sup>2</sup>	67.4	53.8	42.1**	81.1	62.2	96.2**
Seeds/head	13.7	17.5	17.8	20.1*	18.9	14.8
100-seed weight (g)	3.0	3.2	3.0	3.1	3.0	3.1
Yield (q/ha)	27.0	35.4**	30.8	51.6**	43.5**	46.9**

\*,\*\* Significantly different from the row plot mean at the 0.05 and 0.01 levels, respectively.

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

‡,§,¶,# Days from planting until 50% of possible coleoptiles emerged, scale 1-5 (5 = darkest green), scale 1-5 (5 = most prostrate), and days from January 1, respectively.

seed landed in these 10 cm spaces and the plants were allowed to grow until heads/900 cm<sup>2</sup> was measured, at which time they were cut at harvest level and not included in the count.

Another indication of the reduced vigor of the cultivars grown in the dryland hill plots was exhibited by the significantly lower mean number of heads/900 cm<sup>2</sup> than occurred in the row plots. The reduced vigor of the cultivars grown in the dryland hill plots was ascribed to the intra-plot competition for nutrients and less growing space available per plant as noted by other workers (20, 32, 39). Conversely, intra-plot competition may not have been as severe in the irrigated hill plots due to an assumed lack of water stress.

Generally, cultivars grown in the small plots yielded more grain per unit area of land than cultivars grown in the row plots as shown by their significantly greater means (Table 7). This tendency was not expressed by the cultivars grown in the dryland hill plots, which had a mean yield similar to the row plots.

#### Correlation Between Row and Small Plots

Phenotypic correlations between the traits measured in the row plots and those same traits measured in the small plots were calculated (Table 8). Correlation coefficients between the small and row plots for days to emergence, number of heads/900 cm<sup>2</sup>, and number of seeds per head were not significantly different from zero, indicating that none of the small plot types studied would be satisfactory for evaluating these

characteristics. Correlation coefficients between small and row plots for heading date, plant height, and 100-seed weight were positive and highly significant, suggesting any of the plot types considered would be expected to give satisfactory results in evaluating winter wheat cultivars for these characteristics. Only the dryland microplots exhibited a significant association with the row plots for fall growth habit and only the miniplots exhibited a significant correlation with the row plots for spring growth habit; although significant, these correlations may be meaningless since significant differences among cultivars in the row plots for these traits were not detected (Table 6).

Correlations for yield in the irrigated hill plots and dryland microplots were significant but low. Yield of miniplot cultivars showed a highly significant correlation with yield in row plots, suggesting that miniplots could be used as an alternative to row plots for measuring yield. However, miniplots were not considered to be a suitable alternative to row plots because of the difficulty in planting and the greater land and seed requirements relative to the other small plot types (Table 1).

#### Common Entries

Several investigators (12, 21, 23) have used the number of entries in hill plots common to the top 10, 20, and 50% of the entries in row plots as a criterion of comparison. For comparison of row and small plots in this investigation, I arranged the means of the 11 traits

Table 8. Phenotypic correlations between row and small plots for 11 traits.

Trait	Plot Type †				
	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence	--	0.20	--	0.09	0.10
Fall color	--	0.61**	--	0.72**	0.75**
Spring color	--	-0.04	--	-0.35	-0.23
Fall growth habit	--	0.38	--	0.52*	0.28
Spring growth habit	--	0.40	--	0.30	0.46*
Heading date	--	0.97**	--	0.96**	0.96**
Plant height	0.95**	0.97**	0.94**	0.96**	0.96**
Heads/900 cm <sup>2</sup>	0.10	0.23	0.06	0.34	0.28
Seeds/head	0.23	-0.16	-0.14	0.11	0.29
100-seed weight	0.83**	0.84**	0.81**	0.73**	0.81**
Yield	0.44*	0.30	0.36	0.41*	0.62**

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

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

from high to low so that entries common in both row and small plots could be compared at three selection intensities (Appendix Tables 5 to 15). The percent of entries in small plots in common with row plots at each selection intensity are presented in Table 9.

Selection on the basis of entries in the top 10% of small plots common to the row plots correctly identified those cultivars expressing the highest values for fall color in the dryland hill plots, spring growth habit in the dryland microplots, heading date in the miniplots, and plant height in all small plots. Although only two entries in the 10% category were possible for selection purposes, none of the small plots had cultivar means ranked in the same order as the row plots for all 11 traits and significant reversals were detected in even the most highly correlated traits (i.e., fall color, heading date, and 100-seed weight) indicating that this selection intensity was not too severe. Selection of the top 25% of entries common to the row plots reduced the number of correct classifications to heading date in all small plots and 100-seed weight in the irrigated hill plots. Selection of the top 50% of cultivars common to the row plots reduced perfect classification to heading date and plant height in the dryland hill plots.

This criterion of comparison provided an indication of the suitability of small plots for selection purposes similar to that obtained by the use of phenotypic correlations. Because the amount of land and seed used in these small plots was from one-tenth to one-third of that

Table 9. Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for 11 traits.

Trait	Plot Type†														
	Hill-I			Hill-D			Micro-I			Micro-D			Mini-D		
	10	25	50‡	10	25	50	10	25	50	10	25	50	10	25	50
Days to emergence	--	--	--	0	0	50	--	--	--	50	33	58	0	17	50
Fall color	--	--	--	100	83	67	--	--	--	50	67	75	50	67	75
Spring color	--	--	--	0	33	50	--	--	--	0	0	42	0	17	42
Fall growth habit	--	--	--	0	17	58	--	--	--	0	50	58	50	50	33
Spring growth habit	--	--	--	50	50	67	--	--	--	100	33	67	50	67	50
Heading date	--	--	--	50	83	100	--	--	--	50	83	92	100	83	92
Plant height	100	100	92	100	100	100	100	100	92	100	100	92	100	100	83
Heads/900 cm <sup>2</sup>	0	17	58	0	17	67	0	33	42	50	50	50	0	33	58
Seeds/head	0	50	67	0	17	58	0	33	50	0	50	58	0	50	58
100-seed weight	50	100	83	50	67	83	50	67	75	50	83	83	50	50	83
Yield	50	50	67	50	50	67	50	67	67	50	67	75	50	83	75

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

‡ Selection intensities used in the comparison of row and small plots.

used in the row plots, a plant breeder would be able to save a larger proportion of the entries in the field and evaluate more genotypes than when using row plots, thereby increasing the accuracy with which selections were made. Depending on the selection intensity applied, the use of common entries indicated that the small plot types studied could be adopted for selection of cultivars with the highest values for heading date, plant height, and 100-seed weight. Only the dryland micro- and miniplots gave similar results when selecting for yield, especially at the lower selection intensities.

#### Relative Variation Within Plot-Size Experiments

Other workers (17) have complained of the greater range in expression of a given trait measured on cultivars grown in hill plots. However, since the number of replications used in the analysis of an agronomic character in hill plots is usually greater than when row plots are used, an increase in the range is expected (40). In this investigation the range in performance for the 11 traits of the cultivars grown in row and small plots were similar (Table 10). The magnitude of the coefficients of variation (C.V.) in small plots relative to row plots were similar for days to emergence, fall color, fall growth habit, spring color, spring growth habit, heading date, plant height, the number of heads per 900 cm<sup>2</sup>, and 100-seed weight (Table 10). Both hill and both microplot nurseries exhibited somewhat higher C.V.'s for the number of seeds per head than did the row plots. Because the plot means for this trait were

Table 10. Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for 11 traits measured in row and small plots.

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence‡						
C.V. (%)	3.2	--	8.7	--	4.4	5.2
$\frac{s}{\bar{X}}$	0.6	--	1.4	--	0.7	0.8
$\bar{X}$	17.3	--	16.4	--	16.0	15.1
R	1.7	--	2.2	--	0.8	1.7
Fall color §						
C.V. (%)	10.2	--	13.1	--	8.2	9.6
$\frac{s}{\bar{X}}$	0.4	--	0.4	--	0.3	0.3
$\bar{X}$	3.4	--	3.3	--	3.4	3.5
R	1.3	--	0.8	--	1.1	1.0
Spring color §						
C.V. (%)	15.1	--	11.0	--	10.3	7.7
$\frac{s}{\bar{X}}$	0.5	--	0.4	--	0.4	0.3
$\bar{X}$	3.2	--	3.5	--	3.5	3.3
R	1.0	--	1.0	--	1.0	1.0
Fall growth habit¶						
C.V. (%)	18.7	--	19.2	--	14.6	17.8
$\frac{s}{\bar{X}}$	0.5	--	0.6	--	0.4	0.5
$\bar{X}$	2.7	--	2.9	--	2.8	2.9
R	1.3	--	1.8	--	1.7	1.7
Spring growth habit¶						
C.V. (%)	16.7	--	20.8	--	19.0	16.7
$\frac{s}{\bar{X}}$	0.5	--	0.7	--	0.6	0.5
$\bar{X}$	2.8	--	3.2	--	3.4	3.1
R	2.0	--	1.0	--	2.2	2.0
Heading date #						
C.V. (%)	0.3	--	0.6	--	0.7	0.4
$\frac{s}{\bar{X}}$	0.5	--	1.1	--	1.2	0.6
$\bar{X}$	171.0	--	171.5	--	171.2	171.0
R	9.5	--	9.6	--	9.1	8.8
Plant height (cm)						
C.V. (%)	3.0	3.5	3.8	4.5	4.8	3.7
$\frac{s}{\bar{X}}$	3.3	3.9	4.0	5.2	5.2	3.9
$\bar{X}$	110.7	112.8	105.5	114.8	107.6	108.1
R	51.2	43.8	40.0	46.8	43.1	45.5

(Continued)

Table 10. (Continued).

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Heads/900 cm <sup>2</sup>						
C.V. (%)	14.9	20.9	20.6	15.7	17.5	15.6
$\frac{s}{\bar{X}}$	10.0	11.2	8.7	12.7	10.9	15.0
$\bar{X}$	67.4	53.8	42.1	81.1	62.2	96.2
R	32.6	23.2	21.8	28.8	24.6	58.0
Seeds/head						
C.V. (%)	22.6	31.6	37.8	26.8	23.9	20.4
$\frac{s}{\bar{X}}$	3.1	5.5	6.7	5.4	4.5	3.0
$\bar{X}$	13.7	17.5	17.8	20.1	18.9	14.8
R	9.8	8.4	14.8	13.0	8.4	10.5
100-seed weight (g)						
C.V. (%)	6.1	7.5	4.9	5.5	6.4	5.4
$\frac{s}{\bar{X}}$	0.2	0.2	0.1	0.2	0.2	0.2
$\bar{X}$	3.0	3.2	3.0	3.1	3.0	3.1
R	1.3	1.4	1.4	1.4	1.7	1.3
Yield (q/ha)						
C.V. (%)	15.7	27.2	27.4	25.5	23.4	13.3
$\frac{s}{\bar{X}}$	4.2	9.6	8.5	13.1	10.2	6.2
$\bar{X}$	27.0	35.4	30.8	51.6	43.5	46.9
R	19.8	25.7	19.3	29.1	23.0	23.7

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡, §, ¶, # Days from planting till 50% of possible coleoptiles emerged, scale 1-5 (5 = darkest green), scale 1-5 (5 = most prostrate), and days from January 1, respectively.

not significantly different from that in the row plots (Table 7), the larger C.V.'s were attributed to greater standard errors in the hill and microplots. The C.V.'s for yield in all small plot types were larger than that of the row plots, especially in the hill and microplots.

#### Associations Between Traits Within Plot Types

Correlation coefficients between all possible combinations of the 11 traits measured within each plot type were computed to determine if the types of relationships existing between the agronomic characters in the row plots also occurred in the small plots (Table 11). Only those associations expressing significance in at least one plot type are given. The transformation from  $r$  to a quantity  $z$ , as given by Snedecor and Cochran (40), was used to "test the hypothesis that two sample values of  $r$  were drawn at random from the same population."

Correlation coefficients calculated within the row plots showed that spring color and fall color were negatively associated, and fall color and spring growth habit, fall color and heading date, fall color and plant height, fall growth habit and plant height, spring growth habit and heading date, number of seeds per head and 100-seed weight, and number of seeds per head and yield were all positively correlated. There were also low, but significant negative associations between the number of heads/900 cm<sup>2</sup> and both heading date and number of seeds per head.

In the small plots the correlation coefficients between heading date and spring habit in the dryland hill and miniplots, fall color and

plant height in the miniplots, number of heads/900 cm<sup>2</sup> and number of seeds per head in the miniplots, and number of seeds per head and yield in the dryland micro- and miniplots were all positively related. A test of the hypothesis of equal correlations was not rejected. Negative relationships in the row plots for spring color and fall color, and for heads/900 cm<sup>2</sup> and seeds per head were positive in the dryland hill, dryland micro-, and miniplots for the former, and positive in the dryland hill and dryland microplots for the latter association. The relationship of number of seeds per head and 100-seed weight was positive in the row plots but negative in the irrigated microplots.

Each of the small plots exhibited significant correlations among the 11 agronomic traits that were not detected in the row plots. These associations were attributed to the inter- and intra-cultivar competitive relationships in small plots noted by other workers (20, 32,49). Although hill, micro-, and row plots were all spaced 30 cm apart, the proximity of one cultivar to another in the small plots was much greater than existed in the row plots. In the hill and miniplots, several plants were grown in a very concentrated area, increasing competition for sunlight and nutrients.

Table 11. Correlations between traits within plot types.

Association	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence						
vs. fall color	-0.07	--	-0.06	--	0.39	0.53**
vs. fall growth habit	0.02	--	-0.27	--	-0.51*	-0.64**
vs. heads/900 cm <sup>2</sup>	-0.03	--	-0.29	--	-0.45*	-0.10
vs. yield	0.00	--	-0.40	--	-0.54**	-0.34
Fall color						
vs. spring color	-0.52**	--	0.63**	--	0.76**	0.63**
vs. fall growth habit	0.30	--	-0.14	--	-0.17	-0.50*
vs. spring growth habit	0.66**	--	0.28	--	0.25	0.34
vs. heading date	0.50*	--	0.34	--	0.24	0.40
vs. plant height	0.62**	--	0.03	--	0.28	0.49*
vs. yield	-0.20	--	-0.37	--	-0.47*	-0.57**
Spring color						
vs. spring growth habit	-0.17	--	0.28	--	0.24	0.47*
vs. heading date	-0.21	--	0.48*	--	0.20	0.59**
Fall growth habit						
vs. plant height	0.44*	--	0.03	--	0.19	-0.07
Spring growth habit						
vs. heading date	0.60**	--	0.50*	--	0.24	0.49
Heading date						
vs. plant height	0.40	--	0.46*	--	0.42*	0.28
vs. heads/900 cm <sup>2</sup>	-0.43*	--	-0.35	--	-0.15	-0.09
vs. yield	-0.21	--	-0.47*	--	-0.43*	-0.34
Plant height						
vs. heads/900 cm <sup>2</sup>	0.02	0.02	0.07	0.41	0.44*	0.19
vs. seeds/head	-0.04	0.02	-0.13	-0.11	-0.21	-0.45*

(Continued)

Table 11. (Continued).

Association	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Heads/900 cm <sup>2</sup>						
vs. seeds/head	-0.45*	0.43*	0.42*	-0.02	0.50*	-0.67**
vs. 100-seed weight	-0.12	-0.17	-0.02	0.33	0.21	-0.43*
vs. yield	0.27	0.69**	0.69**	0.50*	0.71**	-0.21
Seeds/head						
vs. 100-seed weight	0.75**	0.02	-0.24	-0.45*	-0.15	0.04
vs. yield	0.62**	0.36	0.13	0.27	0.60**	0.69**

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

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

## SUMMARY

A comparison was made between conventional row plots and three types of small plots utilizing 23 winter wheat cultivars and 11 agronomic characteristics. In addition, the hill and microplots were grown in two environments, irrigated and dryland.

All plot nurseries were damaged by wind and hail six days after the last cultivar had headed. An evaluation of this damage showed that cultivars grown in the small plot nurseries reacted to hail-induced head damage and wind- and hail-induced lodging in a manner similar to the cultivars grown in the row plots.

Four criteria of comparison between row and small plots were used in this investigation. These included a comparison of row and small plots for each trait using overall means, phenotypic correlations between row and small plots for each trait, an evaluation of the number of entries of small plots common to the entries of row plots at three selection intensities, and an evaluation of simple correlations between traits within each plot type.

The results of this investigation indicate that any of the small plots tested were useful in selection for heading date, plant height, and 100-seed weight with reasonable assurance that the best cultivars were identified. The relationships between row plots and dryland micro- and miniplots for these traits were generally closer than between the row and other small plots, as shown by their higher correlation coefficients and a greater percent of common entries, especially at the lower

selection intensities. The cultivars grown in the dryland hill plots appeared to be less vigorous, in terms of plant height, number of heads per 900 cm<sup>2</sup>, and yield, than those grown in the other small plots. Relationships between agronomic characters within small plot types differed substantially from these relationships in the row plot nursery. This was attributed to the differential ability of cultivars to compete within and between experimental units.

Although the information obtained for this investigation was derived from one location-year, data for heading date, plant height, 100-seed weight, and yield agreed closely with the results of other investigators. Information on the number of heads/900 cm<sup>2</sup> and the number of seeds per head did not substantiate the results of previous workers, especially in wheat. These results may have been related to the hail and wind damage that occurred.

SECTION II: COMPARISON OF ROW AND SMALL PLOTS FOR EVALUATION  
OF HARVEST INDEX, BIOLOGICAL YIELD, AND GRAIN YIELD

## INTRODUCTION

Harvest index is the ratio of economic to biological yield and provides an indication of the efficiency with which a plant population partitions photosynthate into economic yield.

Harvest index and biological yield lend themselves to artificial manipulation in a manner unavailable using the number of heads per unit area, number of seeds per head, and seed weight, because they do not appear to suffer from component compensation. Thus, an increase in either the biological yield or harvest index of a crop should result in a direct increase in its economic yield without affecting the magnitude of the other component.

The purpose of this investigation was to determine the relative importance of harvest index and biological yield to grain yield and to provide information on the use of small plots as a technique of evaluating winter wheat cultivars for harvest index, biological yield, and grain yield.

## MATERIALS AND METHODS

### Establishment of Field Plots

This study was conducted at the Field Research Laboratory near Bozeman, Montana, during the 1977-78 growing season. Twenty-two hard red winter wheat cultivars and one soft white winter wheat cultivar (Appendix Table 1) were grown in both conventional row plots and three types of small plot on an Amsterdam silt loam, Typic Cryoborall soil. Six field nurseries were established by the methods described in Section I.

### Methods of Sampling

Ten traits were measured in most plot types. Days to emergence, fall and spring seedling color, heading date, plant height, number of heads/900 cm<sup>2</sup>, number of seeds per head, and grain yield were determined by the methods described in Section I. Days to emergence, fall and spring seedling color, and heading date were not measured in the irrigated small plots, since they were not considered to be different from their dryland counterparts until after the first irrigation (Table 2). At maturity, plants in a plot were harvested at ground level and field dried. Biological yield was determined as the weight of the total above-ground dry matter of the harvested portion of the plot (p. 20) and expressed as q/ha. Harvest index was calculated as the ratio of grain yield to biological yield and expressed as a factor less than unity.

## Statistical Methods

Six replications of row plots and miniplots and 12 replications of hill plots and microplots were planted in a randomized complete block design. Cultivars were assigned to experimental units by use of a random number table. An analysis of variance for a two-way classification and an F-test were used to determine if cultivars gave equivalent expressions for harvest index, biological yield, and grain yield. Cultivars were treated as random effects in the two-way model. A test for homogeneous error variances between agronomic data obtained from the row plots and that obtained from the small plots was calculated (Appendix Table 2). A t-test was used to compare the mean of all cultivars in each small plot type with the mean of all cultivars in the row plots for harvest index, biological yield, and grain yield. The t-statistic was weighted for non-homogeneous error variances (40); when error variances were homogeneous, their values and respective degrees of freedom were pooled and Student's t-distribution was followed. Phenotypic correlations based on cultivar means were computed for each character between row and small plots and within plot types. The percent of small plot entries common to the top 10, 25, and 50% of entries for the row plots was calculated for each trait. Expectations of mean squares were equated to their numerical values and genotypic ( $V_g$ ) and error ( $V_e$ ) variance components were computed. Narrow sense heritabil-

ities on an entry mean basis were determined by the formula: heritability ( $h^2$ ) =  $V_g/[V_g + V_e/r]$ , where  $r$  = the number of replications in the experiment. The relative contributions of harvest index and biological yield to grain yield were determined using multiple regression analysis within each plot type.

## RESULTS AND DISCUSSION

### Comparison of Row and Small Plots for Selection Purposes

#### Analysis of Variance

Significant differences among cultivar means within each plot type were detected for harvest index, biological yield, and grain yield. (Table 12).

#### Comparison of Overall Means

For harvest index, irrigated hill and irrigated microplot means did not differ significantly from the row plot mean, but in the dryland hill, dryland micro-, and miniplots, means were significantly greater than the row plot mean (Table 13). Only the dryland hill plot nursery exhibited a non-significant difference in biological yield from the overall expression in the row plots. As discussed earlier (p. 34), cultivars grown in the dryland hill plots were not as vigorous in their growth, in terms of plant height, number of heads/900 cm<sup>2</sup>, and grain yield, as were cultivars grown in the other plot types. There was a tendency in the small plots for greater yield per unit land area than occurred in the row plots as shown by their significantly greater means. This tendency was not expressed by the cultivars grown in the dryland hill plots, which had a mean yield similar to the row plot yield. An examination of the mean cultivar expressions for harvest index and biological yield in the dryland hill plots suggests, since mean yield between the row and dryland hill plots was not different, that the en-

Table 12. Cultivar and error means squares (MS) from the analysis of variance for harvest index, biological yield, and grain yield measured in row and small plots.

Trait	Plot Type†					
	Row-D		Hill-I		Hill-D	
	MS	df	MS	df	MS	df
Harvest index						
Cultivar	0.01**	22	0.01**	22	0.01**	22
Error	0.001	110	0.002	242	0.002	242
Biological yield						
Cultivar	297.00**	22	2283.10**	22	1147.64**	22
Error	91.40	110	570.80	242	573.82	242
Grain yield						
Cultivar	170.70**	22	513.70**	22	338.97**	22
Error	18.00	110	92.40	242	71.51	242

Trait	Plot Type†					
	Micro-I		Micro-D		Mini-D	
	MS	df	MS	df	MS	df
Harvest index						
Cultivar	0.01**	22	0.01**	22	0.01**	22
Error	0.002	242	0.001	242	0.002	110
Biological yield						
Cultivar	3999.29**	22	2413.66**	22	710.25**	22
Error	1142.65	242	603.42	242	287.48	110
Grain yield						
Cultivar	692.13**	22	410.71**	22	195.79**	22
Error	172.90	242	103.69	242	38.94	110

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

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

Table 13. Mean of all entries for each plot type and tests of significance between the means of row and small plots for harvest index, biological yield, and grain yield.

Plot type†	Harvest index	Biological yield (q/ha)	Grain yield (q/ha)
Row-D	0.26	105.2	27.00
Hill-I	0.27	131.4**	35.40**
Hill-D	0.29**	105.4	30.81
Micro-I	0.26	196.0**	51.62**
Micro-D	0.29**	152.3**	43.50**
Mini-D	0.30**	157.5**	46.91**

\*\* Significantly different from the row plot mean at 0.01 level.

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

tries grown in the latter plot types were more efficient in partitioning photosynthate to the developing kernels than those grown in the row plots. An explanation for this effect is tendered by the concept that in a dense community of plants, upper leaves are over-illuminated and lower leaves are shaded (8). Since fewer head-producing tillers per plot were found in the dryland hill plots (Table 7), more sunlight was able to penetrate the crop canopy, possibly increasing photosynthetic efficiency.

#### Relative Heritabilities in Row and Small Plots

Heritability on an entry mean basis for harvest index, biological yield, and grain yield were computed using the components of variance for all plot types (Table 14). Heritability for harvest index ranged from 0.64 to 0.87, for biological yield from 0.50 to 0.75, and for grain yield from 0.75 to 0.89 across plot types. Because the value of the heritability for a character depends on the magnitude of all the components of variance, a change in any one of these will affect it. Small plot genotypic variances were tested for homogeneity with row plot genotypic variances using an F-ratio (40). Degrees of freedom for this test were probably inflated which may have caused too many genotypic variances to be accepted as homogeneous. In all small plot types, except the irrigated hill plots, genotypic variances for harvest index were significantly different than that of the row plots (Table 14). For biological yield, only the dryland hill plot genotypic variance

was homogeneous with the row plot genotypic variance. In all small plot types, genotypic variances for grain yield were homogeneous with row plot genotypic variance. In all small plot types, except the irrigated microplots, error variances for harvest index, biological yield, and grain yield were significantly larger than those of the row plots (Table 14). These results indicate that differences in the estimates of heritabilities between the row and small plots were due to environmental (e.g., plot type) and sampling error (note: since one environment was used in the calculation of the variance components, no estimate of a genotypic X environment interaction was available).

The relative magnitude of the estimates of heritability for the three traits within each plot type were similar, except in the irrigated micro-, dryland micro-, and miniplots. In the irrigated microplots, all heritability values for the three traits were nearly the same. In the dryland microplots, heritability of harvest index was greater than either biological yield or grain yield, while in the miniplots, heritability of grain yield was greater than either harvest index or biological yield (Table 14).

Because heritabilities were computed using variance components from the analysis of homozygous genotypes, these values are estimates of narrow sense heritability. Heritability estimates for yield and harvest index were of similar magnitude and relatively high across all plot types and ample genetic variability existed for these traits

Table 14. Heritabilities ( $h^2$ ), genotypic ( $V_g$ ), and error ( $V_e$ ) variances for harvest index, biological yield, and grain yield measured in row and small plots.

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Harvest index						
$(h^2)$	0.87	0.86	0.83	0.75	0.84	0.64
$(V_g)$	0.0015	0.0010	0.0083**	0.0006*	0.0053**	0.0006*
$(V_e)$	0.0014	0.0019**	0.0021**	0.0024**	0.0012	0.002**
Biological yield						
$(h^2)$	0.69	0.75	0.50	0.71	0.75	0.60
$(V_g)$	34.27	142.69**	47.82	238.05**	150.85**	70.46*
$(V_e)$	91.40	570.80**	573.82**	1142.65**	630.42**	287.48**
Grain yield						
$(h^2)$	0.89	0.82	0.79	0.75	0.75	0.80
$(V_g)$	25.45	35.11	22.29	43.27	25.59	26.14
$(V_e)$	18.00	92.37**	71.51**	172.89**	103.69**	38.94**

\*,\*\* Significantly different from the row plot variance component at the 0.05 and 0.01 levels, respectively.

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

even in this set of elite cultivars.

#### Correlation between Row and Small Plots

Phenotypic correlations between the traits measured in the row plots and those measured in the small plots were calculated (Table 15). Correlation coefficients between the small and row plots for harvest index were significant and positive in all small plots except the irrigated microplots. The correlation between harvest index in the row plots and irrigated microplots, however, was not different from zero, suggesting that the irrigated microplots would not be satisfactory for selection of harvest index. Correlation coefficients between the small and row plots for biological yield were not different from zero, except in the miniplots, where it was highly significant. The irrigated hill, dryland micro-, and miniplots gave significant, positive correlations with the row plots for grain yield; only the correlation coefficient computed for the miniplots was considered high enough for selection purposes.

Phenotypic correlations between row plot grain yield and small plot harvest index and biological yield were also computed (Table 16). Correlation values between hill and microplot harvest index and row plot grain yield were larger than the correlations between hill and microplot grain yields and row plot grain yield. Although a test for equal correlation coefficients (40) between the grain yield-grain yield and grain yield-harvest index correlations from the row plots and the irrigated

Table 15. Phenotypic correlations between row and small plots for harvest index, biological yield, and grain yield.

Trait	Plot Type†				
	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Harvest index	0.59**	0.47*	0.34	0.47*	0.49*
Biological yield	0.14	0.12	0.17	0.23	0.58**
Grain yield	0.44*	0.30	0.36	0.41*	0.62**

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

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

Table 16. Phenotypic correlations between row plot grain yield and small plot harvest index and biological yield.

Plot type†	Small plot trait	
	Harvest index	Biological yield
Hill-I	0.56**	0.01
Hill-D	0.50*	0.02
Micro-I	0.44*	0.05
Micro-D	0.57**	0.11
Mini-D	0.59**	0.16

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

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

hill and dryland microplots was not rejected, the grain yield-harvest index correlations were accepted at a higher level of probability. Therefore, indirect selection of hill and microplot harvest index for row plot grain yield should provide more satisfactory results than direct selection of grain yield in these plot types. A test for equal correlation coefficients between the grain yield-grain yield and grain yield-harvest index associations from row plots and miniplots was not rejected, thus, no advantage would be achieved by indirect selection of harvest index in the miniplots for row plot grain yield. The correlation coefficients between row plot grain yield and small plot biological yield were not different from zero, therefore none of the small plots used in this investigation would be satisfactory for indirect selection of row plot grain yield using small plot biological yield.

#### Common Entries

Several investigators (12, 21, 23) have used the number of entries in hill plots common to the top 10, 20, and 50% of the entries in row plots as a criterion of comparison. For comparison of row and small plots in this investigation, I arranged the means of the three traits from high to low so that entries common in both row and small plots could be compared at three selection intensities (Appendix Tables 15 to 17). The percent of entries in small plots in common with row plots at each selection intensity are presented in Table 17.

At the 10% selection intensity only 50% of the entries in the irrigated and dryland hill plots were common to the top 10% in the row plots for harvest index. The dryland microplots were useful in classifying 83% of the top 25% entries in the row plots. The other plot types had from 58 to 75% of the entries in common with the row plots at the 25 and 50% selection intensities.

For biological yield, the miniplots correctly identified 50% of the cultivars at the 10% selection intensity. The best selection across small plot types for biological yield did not occur until the 50% selection intensity was used, where from 50 to 75% of the entries common to the row plots were selected.

For grain yield, all small plots were useful in identifying half of the entries common to the row plots at the 10% level. With 25% selection intensity, the range across small plot types was 50 to 83%, with the miniplots exhibiting the highest value and the two hill plot nurseries showing the lowest. At the 50% selection intensity, the irrigated microplots and the dryland hill plots were useful in correctly identifying 67% and the dryland microplots and miniplots were useful in correctly identifying 75% of the entries in common with the best 50% in the row plots.

This criterion of comparison between row and small plots gave a better indication of the suitability of small plots for selection purposes than did the use of phenotypic correlations, especially for se-

Table 17. Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for harvest index, biological yield, and grain yield.

Trait	Plot Type†								
	Hill-I			Hill-D			Micro-I		
	10	25	50‡	10	25	50	10	25	50
Harvest index	50	50	67	50	67	75	0	67	58
Biological yield	0	0	67	0	0	50	0	17	50
Grain yield	50	50	67	50	50	67	50	67	67

Trait	Plot Type†					
	Micro-D			Mini-D		
	10	25	50	10	25	50
Harvest index	0	83	58	0	50	67
Biological yield	0	33	58	50	33	75
Grain yield	50	67	75	50	83	75

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡ Selection intensities used in the comparison of row and small plots.

lection of high biological yield, where correlations in all but the miniplots were non-significant (Table 15).

#### Relative Variation Within Plot-Size Experiments

The range in performance for harvest index of the cultivars grown in the row and small plots was similar (Table 18). For biological yield, the range among cultivars grown in the irrigated hill and irrigated microplots, and the dryland microplots was two to three times greater than in the row plots. The range in performance among the cultivars grown in the irrigated hill and irrigated microplots was somewhat greater than that exhibited in the row plots for grain yield, a result attributed to differential cultivar response to irrigation. The other three small plot nurseries, however, were not greatly different than the row plot nursery for grain yield.

The coefficients of variation (C.V.) in small plots and row plots for harvest index were similar, as were their standard errors (Table 18). The C.V.'s and standard errors for grain yield in both types of hill and microplots were about twice as large as in the row plots. Since the C.V.'s and standard errors for harvest index were essentially the same across plot types, this suggests another advantage for using small plot harvest index to predict row plot grain yield. Both hill and microplot nurseries had C.V.'s about twice as large as those in the row and miniplots for biological yield. These differences were attributed to the greater standard errors of the former plot types than

Table 18. Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for harvest index, biological yield, and grain yield measured in row and small plots.

Trait†	Plot Type‡					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Harvest index						
C.V. (%)	15.38	14.81	17.24	19.23	10.34	16.67
s	0.04	0.04	0.05	0.05	0.03	0.05
$\bar{X}$	0.26	0.27	0.29	0.26	0.29	0.30
R	0.15	0.14	0.13	0.11	0.10	0.11
Biological yield						
C.V. (%)	9.10	18.18	22.73	17.25	16.13	10.77
s	9.56	23.89	23.95	33.80	24.56	16.96
$\bar{X}$	105.20	131.40	105.40	196.00	152.30	157.50
R	43.40	48.60	37.60	77.70	56.80	48.80
Grain yield						
C.V. (%)	15.70	27.20	27.43	25.51	23.40	13.31
s	4.20	9.60	8.50	13.10	10.20	6.20
$\bar{X}$	27.00	35.40	30.80	51.60	43.50	46.90
R	19.80	25.70	19.30	29.10	23.00	23.70

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡ Units for biological yield and grain yield are q/ha.

occurred in the row and miniplots.

The greater variation shown in all small plot types for biological yield, and in the hill and microplots for grain yield, is an indication of the broader range of expression among cultivars which has been explained by the differential competitive relationships of cultivars grown in hill plots by other workers (20, 32, 39). However, a greater range is also expected as the number of replications used to measure a trait is increased (40).

#### Associations Between Traits Within Plot Types

Correlation coefficients between all possible combinations of the ten traits measured within each plot type were computed to determine if the types of relationships between harvest index, biological yield, and the other agronomic characters in the row plots also occurred in the small plots (Table 19). Only those associations expressing significance in at least one plot type are given. The transformation from  $r$  to a quantity  $z$ , as given by Snedecor and Cochran (40), was used to "test the hypothesis that two sample values of  $r$  were drawn at random from the same population."

Correlation coefficients calculated within the row plots showed that the number of seeds per head and harvest index, grain yield and harvest index, and biological yield and grain yield were positively correlated. Only the dryland microplots exhibited all three of these relationships, and a test of the hypothesis of equal correlations was

not rejected. All plot types expressed the significant, positive association between grain yield and the two selection criteria (e.g., harvest index and biological yield) and a test of the equality between the row plot correlations and those of the small plots was not rejected.

Each of the small plots exhibited significant correlations between the two selection criteria and the other agronomic traits that were not detected in the row plots. Harvest index in the dryland hill and dryland microplots was negatively associated with fall seedling color and heading date. Biological yield and the number of heads per 900 cm<sup>2</sup> in both types of hill and microplot nurseries; biological yield and harvest index in the dryland hill and dryland microplots; the number of seeds per head and harvest index in the two microplot nurseries; biological yield and the number of seeds per head in the dryland microplots and miniplots; and biological yield and plant height in the irrigated microplots were all positively correlated. The dryland microplots exhibited significant correlations between the two selection criteria and each of the other agronomic characters, except for biological yield and plant height. These differences between row and small plots were attributed to the inter- and intra-cultivar competitive relationships in small plots noted by other workers (20, 32, 39). Although the cultivars grown in the hill, micro-, and row plots were equally spaced 30 cm apart, the proximity of one

Table 19. Correlations between the indirect selection criteria and other agronomic characters within plot types.

Association	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Harvest index						
vs. fall color	-0.12	--	-0.47*	--	-0.55**	-0.35
vs. spring color	0.18	--	-0.33	--	-0.44*	-0.27
vs. heading date	-0.11	--	-0.45*	--	-0.56**	-0.33
vs. plant height	-0.22	-0.02	-0.23	-0.37	-0.48*	-0.37
vs. seeds/head	0.62**	0.29	0.02	0.42*	0.50*	0.39
vs. grain yield	0.89**	0.87**	0.85**	0.79**	0.75**	0.75**
Biological yield						
vs. days to emergence	0.16	--	-0.32	--	-0.45*	0.13
vs. plant height	0.00	0.31	0.11	0.42*	0.00	-0.11
vs. heads/900 cm <sup>2</sup>	0.34	0.79**	0.84**	0.75**	0.91**	-0.30
vs. seeds/head	0.39	0.27	0.27	0.05	0.48*	0.56**
vs. grain yield	0.65**	0.76**	0.85**	0.68**	0.81**	0.59**

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

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

cultivar to another in the small plots was much closer than existed in the row plots. In the hill and miniplots, several plants were grown in a very concentrated area, thus increasing competition for soil nutrients.

#### Contributions of Harvest Index and Biological Yield to Grain Yield

The contributions of harvest index and biological yield to grain yield within each plot type were determined using multiple regression analysis (Table 20). The variation in grain yield within each plot type was almost completely accounted for by harvest index and biological yield. Their respective coefficients of determination ranged from 0.95 in the row plots to 0.99 in the dryland microplots. The standard partial regression coefficients of harvest index to grain yield and biological yield to grain yield were significantly different from zero at the 0.01 level. The ratios of the standard partial regression coefficients of harvest index to those of biological yield indicated that the relative contribution of harvest index to grain yield was greater than that of biological yield across all plot types. However, the ratios measured for the dryland hill and dryland microplots were not much greater than 1.0, indicating that both harvest index and biological yield were of equal importance in determining grain yield in these two plot types.

These results indicate that selection for harvest index would

tend to increase grain yield in most of the plot types more than would selection for biological yield. Rosielle and Frey (29) showed that indirect selection for grain yield in oats through harvest index had little value when compared with unrestricted direct selection for grain yield. Fischer and Kertesz (16) have shown that spaced-plant harvest index is superior to spaced-plant grain yield as a predictor of yielding ability in large plots of spring wheat. This investigation has shown that harvest index in hill and microplots was a better predictor of row plot grain yield than grain yield measured in these two plot types.

Table 20. Coefficients of determination ( $R^2$ ), standard partial regression coefficients for the multiple regressions of grain yield on harvest index and biological yield, and the ratio of harvest index standard partial regression coefficients to biological yield standard partial regression coefficients.

Plot Type†	$R^2$	bl2.3‡	bl3.2 §	Ratio
Row-D	0.95	0.77**	0.41**	1.86
Hill-I	0.98	0.69**	0.51**	1.36
Hill-D	0.97	0.58**	0.57**	1.03
Micro-I	0.98	0.72**	0.60**	1.20
Micro-D	0.99	0.61**	0.60**	1.02
Mini-D	0.96	0.79**	0.63**	1.26

\*\* Significant at the 0.01 level for  $H_0: \beta_k = 0$ .

† The letters D and I following plot types are abbreviations for dry-land and irrigated, respectively.

‡, § bl2.3 and bl3.2 = standard partial regression coefficients of grain yield on harvest index and biological yield, respectively.

## SUMMARY

Harvest index, biological yield, and grain yield were obtained from 23 winter wheat cultivars grown in conventional row and three types of small plots. The contributions of harvest index and biological yield to grain yield within each plot type were determined using multiple regression analysis. The variation in grain yield within each plot type was almost completely accounted for by harvest index and biological yield. The relative contributions of harvest index and biological yield to grain yield within plot types, as given by the ratios of their standard partial regression coefficients (i.e.,  $b_{12.3}/b_{13.2}$ ), showed that harvest index was more important than biological yield in determining grain yield in the cultivars studied. Narrow sense heritabilities on an entry mean basis were calculated from the components of variance; these values showed that harvest index was at least as heritable as grain yield in all plot types except the miniplots and biological yield was not as heritable as grain yield or harvest index, except in the irrigated microplots and miniplots.

A comparison of row and small plots for harvest index, biological yield, and grain yield indicated that irrigated hill and dryland microplots provided satisfactory results when used to select cultivars for harvest index. Only the dryland micro- and miniplots were found useful in selection of high-yielding cultivars and only the miniplots provided satisfactory results when selecting for high biological yield.

SECTION III: THE EVALUATION OF WINTER WHEAT  
QUALITY IN ROW AND SMALL PLOTS

## INTRODUCTION

The mixograph and farinograph are widely accepted tools for screening wheat cultivars or early generation lines when information on baking quality is needed. The ten-gram mixograph, using tempered (13.5% mb) sieved wheat meal, has been proposed as a rapid method of obtaining information on wheat quality when the amount of grain is small, such as when small-size plots are used in a breeding program. The objectives of this investigation were: 1) compare the quantity of flour protein obtained from cultivars grown in row and small plots; 2) compare the curve characteristics and cultivar patterns obtained from the ten-gram mixograph run on samples of wheat grown in row and small plots; and 3) compare the relative associations of percent flour protein, mixogram data, and farinogram data obtained from row and small plots.

## MATERIALS AND METHODS

### Establishment of Field Plots

This study was conducted with materials grown at the Field Research Laboratory near Bozeman, Montana, during the 1977-78 growing season. Winter wheat grain samples were obtained from 22 hard red winter wheat cultivars and one soft white winter wheat cultivar (Appendix Table 1) grown in conventional row plots, hill plots, and microplots on an Amsterdam silt loam, Typic Cryoborall soil. The three field nurseries were established by the methods described in Section I for the row, dryland hill, and dryland microplots.

### Laboratory Procedures

Quality measurements were made at the Cereal Quality Laboratory, Montana State University. Quality analyses included the measurement of flour protein quantity and mixograph data on samples from all three plot experiments. In addition, farinograph absorption, peak time, stability, and valorimeter measurements were taken on flour samples from cultivars grown in the row plot experiment.

The percent flour protein (percent protein) was determined with an Infra Red Reflectance Analyzer, manufactured by Technicon Industrial Systems, on 4 g samples from each plot type. The grain samples used to obtain mixograph information were tempered to 13.5% and ground in a Udy Cyclone Mill with a 1 mm screen. A Strand sifter with a 250  $\mu$ m screen was used to obtain 10 g of sieved wheat meal (7). The mix-

ograph was operated according to the procedures given by Finney and Shogren (14). Method 54-21 of the A.A.C.C. (2) was used to obtain the farinograph data on the row plot samples.

Fig. 1 illustrates the manner in which mixogram information was obtained. Time of dough development (hereafter referred to as peak distance) was determined by the distance in cm from the start of the mixogram to the point of minimum mobility, or peak (A). This value could also have been expressed in minutes, where the time to pass between two curved lines was about one minute. Peak height was obtained as the distance in cm from the base of the mixogram to the top of the curve at the peak (B).

#### Statistical Methods

A standard analysis of variance for a two-way classification and an F-test were used to determine if cultivars gave equivalent expressions for percent protein, mixogram peak distance, and peak height. Cultivars were treated as random effects in the two-way model. A test for homogeneous error variances between quality data obtained from the row plots and that obtained from the small plots was calculated (Appendix Table 2). A t-test was used to compare the mean of all cultivars in each small plot type with the mean of all cultivars in the row plots for percent protein, mixogram peak distance, and peak height. The t-statistic was weighted when error variances were non-homogeneous (40); when error variances were homogeneous, their values and respec-

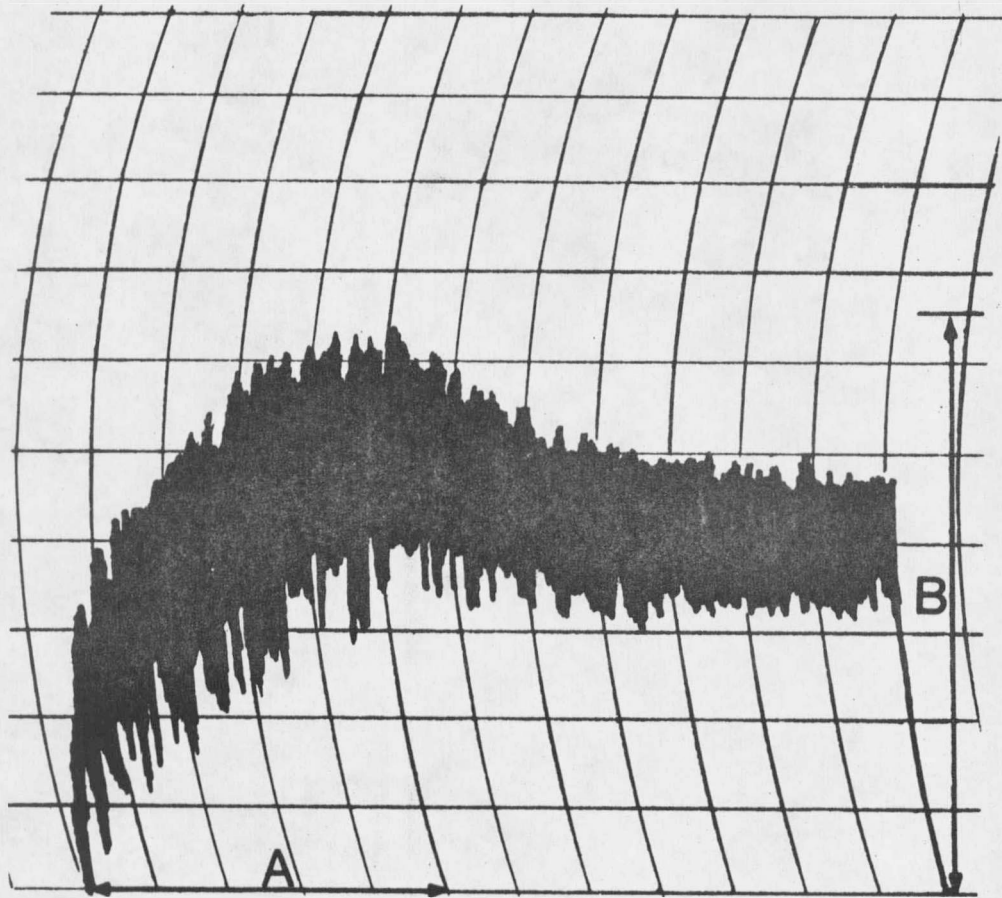


Fig. 1. Schematic diagram showing mixogram measurements. Line A describes the distance in cm from the start of the mixogram to the point of minimum mobility, or peak (e.g., peak distance). Line B describes peak height in cm.

tive degrees of freedom were pooled and Student's t-distribution was followed. Phenotypic correlations based on cultivar means were computed between row and small plots for each characteristic. The percent of small plot entries common to the top 10, 25, and 50% of entries for the row plots was calculated for each trait. All possible correlations among the three traits measured in all plot experiments and the four farinograph traits measured in the row plots were also computed based on cultivar means.

## RESULTS AND DISCUSSION

### Comparison of Row and Small Plots for Selection Purposes

#### Analysis of Variance

Significant differences among cultivars for percent protein and mixogram peak distance were detected in all plot types. Significant differences among the cultivars for mixogram peak height were detected in the row and hill plots only (Table 21).

#### Comparison of Overall Means

A t-test was used to compare the means for percent protein, mixogram peak distance, and peak height of all cultivars grown in the small plots to all cultivars grown in the row plots (Table 22). All means for all traits were equivalent except percent protein in the hill plots, where it was significantly greater than that in the row plots.

Phenotypic correlations, based on cultivar means, between the traits measured in the row plots and those measured in the small plots were calculated (Table 23). Correlation coefficients between the small and row plots for each of the three characteristics were significant and positive. The relationship between small and row plot cultivar expressions for percent protein and mixogram peak distance were very high, indicating that either of the small plots might successfully be employed to classify winter wheat cultivars for these characteristics. The association between cultivars grown in row and small plots for mixogram peak height was significant but accounted for only 23% of the variation shown in the row plots for this trait. Since significant

Table 21. Cultivar (C) and error (E) mean squares (MS) from the analysis of variance for percent protein, mixogram peak distance, and peak height measured in row and small plots.

Trait		Plot Type					
		Row		Hill		Micro	
		MS	df	MS	df	MS	df
Protein	(C)	2.68**	22	3.20**	22	2.08**	22
	(E)	0.09	110	0.09	110	0.08	110
Peak distance	(C)	0.81**	22	0.89**	22	0.64**	22
	(E)	0.08	44	0.13	44	0.11	44
Peak height	(C)	0.81*	22	0.95**	22	0.49	22
	(E)	0.39	44	0.42	44	0.34	44

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

Table 22. Mean of all entries for each plot type and tests of significance between the means of row and small plots for percent protein, mixogram peak distance, and peak height.

Trait	Row	Plot Type	
		Hill	Micro
Protein (%)	13.5	13.8*	13.6
Peak distance (cm)	3.6	3.7	3.9
Peak height (cm)	5.9	5.8	6.2

\* Significantly different from the row plot mean at the 0.05 level.

differences among microplot cultivars for mixogram peak height were not detected, the interpretation of comparisons between row and microplot cultivar means must be made with caution (18).

#### Common Entries

The mean expression for percent protein, mixogram peak distance, and peak height of cultivars grown in the three plot-size experiments and their relative ranking are presented in Appendix Tables 18 to 20. Several investigators (12, 21, 23) have used the number of entries in hill plots common to the top 10, 20, and 50% of the entries in row plots as a criterion of comparison. The percent of entries in small plots in common with row plots at selection intensities of 10, 25, and 50% are presented in Table 24 for the three quality characteristics.

Selection on the basis of the top 10% entries common to the row plots correctly identified 100% of the cultivars expressing the highest values in the row plots for percent protein. Selection of the top 25% entries for percent protein correctly identified 83% of the high protein cultivars in both small plots. Fifty percent selection intensity correctly classified 83 and 92% of the entries in hill plots and microplots, respectively, for percent protein. On the basis of common entries, both hill and microplots should provide satisfactory results if used instead of row plots to obtain information on percent protein.

The microplots showed the greatest selection potential for mixogram peak distance and peak height, especially at the 50% selection

Table 23. Phenotypic correlations between row and small plots for percent protein, mixogram peak distance, and peak height.

Trait	Plot Type	
	Hill	Micro
Protein	0.96**	0.93**
Peak distance	0.79**	0.78**
Peak height	0.48*	0.49*

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

Table 24. Percent of small plot entries common to the top 10, 25, and 50% entries grown in the row plots for percent protein, mixogram peak distance, and peak height.

Trait	Plot Type					
	Hill			Micro		
	10	25	50†	10	25	50
Protein	100	83	83	100	83	92
Peak distance	0	33	83	0	67	83
Peak height	0	33	58	0	17	67

† Selection intensities used in the comparison of row and small plots.

intensity. Correlations for peak height between the row and small plots were positive and significant but lower than those for percent protein and peak distance (Table 23). However, selection efficiency in small plots for this trait could be improved by simultaneously considering percent protein, since both peak height and percent protein provide an indication of baking absorption (13, 22).

#### Relative Variation Within Plot-Size Experiments

The range in performance for percent protein, mixogram peak distance, and peak height were similar for the hill and row plots, but the range of these traits was noticeably lower in the microplots (Table 25). Other investigators have shown the range in performance for agronomic traits measured in hill plots was wider than when those traits were measured in row plots (32, 39).

The size of the coefficients of variation in the two small plot types for the three quality traits were similar with those obtained from the row plots (Table 25). Error variances for all of the traits were homogeneous between the small and row plots (Appendix Table 2), and, except for percent protein measured in the hill plots, all means were equal between the row and small plots (Table 22).

#### Comparison of Cultivar Mixogram Patterns Between Plot Types

In addition to providing information on baking mixing requirements and mixing tolerance, the mixogram pattern has qualitative characteristics that are functions of cultivar differences (22). Patterns from flours of known baking qualities can be compared with patterns produced

Table 25. Coefficients of variation (C.V.), standard errors (s), overall means ( $\bar{X}$ ), and range of performance (R) for percent protein, mixogram peak distance, and peak height measured in row and small plots.

Trait	Plot Type		
	Row	Hill	Micro
Protein (%)			
C.V. (%)	2.20	2.10	2.10
$\frac{s}{\bar{X}}$	0.30	0.29	0.29
$\bar{X}$	13.50	13.80	13.60
R	3.48	3.61	3.05
Peak distance (cm)			
C.V. (%)	7.80	9.70	8.50
$\frac{s}{\bar{X}}$	0.28	0.36	0.20
$\bar{X}$	3.60	3.70	3.90
R	2.10	2.00	1.60
Peak height (cm)			
C.V. (%)	10.60	11.10	9.40
$\frac{s}{\bar{X}}$	0.63	0.64	0.58
$\bar{X}$	5.90	5.80	6.20
R	1.90	2.30	1.20

by experimental lines, and the differences between patterns can be used as a criterion for selection (14).

Fig. 2 shows mixograms produced from four cultivars grown in the three plot types. 'Winalta,' 'Centurk,' and 'MT 6928' are hard red winter wheats of similar protein content. They differ in distance to peak, with 'Centurk' showing the smallest and 'MT 6928' the largest values across plot types (Appendix Table 19), and peak height, with 'MT 6928' showing the smallest value across plot types (Appendix Table 20). 'Winalta' is a quality standard in Montana, and patterns from cultivars or experimental lines are compared to the 'Winalta' pattern for selection purposes.

'Nugaines' is a soft white winter wheat with low protein content and low absorption, characteristics suitable in the manufacture of pastries and related products (15). Its mixogram pattern is included in Fig. 2 to show the similarities across plot types.

#### Association of Mixogram Data With Other Quality Traits

Correlation coefficients between all possible combinations of the three quality characteristics measured in all plot types plus the four farinograph traits measured in the row plots were computed to determine if the types of percent protein, mixograph, and farinograph inter-relationships in the row plots also occurred in the small plots (Tables 26 to 28). The transformation from  $\underline{r}$  to a quantity  $\underline{z}$ , as given by Snedecor and Cochran (40), was used to "test the hypothesis that two

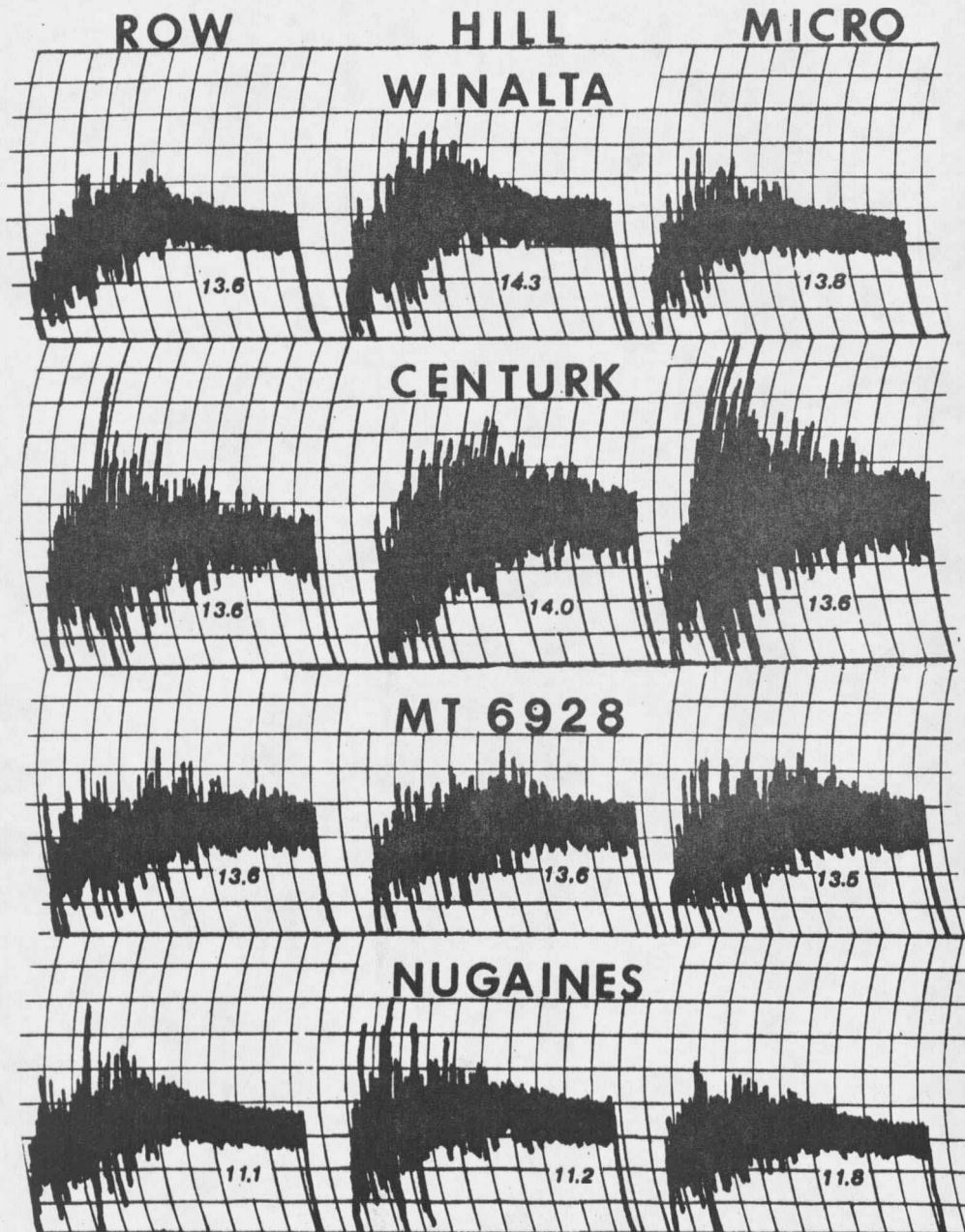


Fig. 2. Effects of tempered (13.5% mb) sieved wheat meal on dough development using four winter wheat cultivars grown in row, hill, and microplots. Values under curves are the mean percent protein for each plot type.

sample values of  $r$  were drawn at random from the same population."

Within the row plot experiment, percent protein was significantly correlated with farinogram absorption and valorimeter value (Table 26). Mixogram peak height was positively and significantly associated with farinogram absorption, stability, and valorimeter value. Shuey (34) reported that farinogram peak time was highly correlated with crude protein ( $r = 0.88$ ), but this relationship was not observed, possibly due to the narrow range in protein content of cultivars used in this study. The significant positive association between percent protein and farinogram valorimeter value has been reported in the literature (34). Highly significant positive correlations between several farinogram traits were also found, but because these measurements are generally evaluated separately by the cereal chemist, no further investigation of these relationships was made. The correlations among quality traits in small plots common to those in the row plots were homogeneous (Tables 27 and 28).

Quality information obtained from the small plots exhibited relationships not expressed by row plot quality information, such as the high, positive correlation between hill plot mixogram peak height and farinogram stability. This relationship indicated that mixogram peak height would provide some indication of the flour's tolerance to mixing (Table 27). The positive relationships between protein content and farinogram peak time and stability were similar to values repor-

Table 26. Correlations among seven quality characteristics of winter wheat grown in row plots.

Characteristic	PRO	PKD	PKH	FAB	FPT	FST	FVA
Percent protein (PRO)	1.00						
Mixogram peak distance (PKD)	-0.16	1.00					
Mixogram peak height (PKH)	0.38	-0.19	1.00				
Farinogram absorption (FAB)	0.51*	-0.29	0.58**	1.00			
Farinogram peak time (FPT)	0.40	0.39	0.39	0.28	1.00		
Farinogram stability (FST)	0.38	0.27	0.45*	0.17	0.70**	1.00	
Farinogram valorimeter (FVA)	0.52*	-0.11	0.54**	0.40	0.65**	0.57**	1.00

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

Table 27. Correlations among seven quality characteristics of winter wheat grown in hill plots.

Characteristic	PRO	PKD	PKH	FAB	FPT	FST	FVA
Percent protein (PRO)	1.00						
Mixogram peak distance (PKD)	-0.09	1.00					
Mixogram peak height (PKH)	0.48*	0.20	1.00				
Farinogram absorption (FAB)	0.52*	-0.12	0.43*	1.00			
Farinogram peak time (FPT)	0.44*	0.31	0.55**	0.28	1.00		
Farinogram stability (FST)	0.42*	0.32	0.52*	0.17	0.70**	1.00	
Farinogram valorimeter (FVA)	0.56**	-0.13	0.65**	0.40	0.65**	0.57**	1.00

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

Table 28. Correlations among seven quality characteristics of winter wheat grown in microplots.

Characteristic	PRO	PKD	PKH	FAB	FPT	FST	FVA
Percent protein (PRO)	1.00						
Mixogram peak distance (PKD)	0.11	1.00					
Mixogram peak height (PKH)	0.07	0.08	1.00				
Farinogram absorption (FAB)	0.38	-0.30	0.25	1.00			
Farinogram peak time (FPT)	0.33	0.38	0.40	0.28	1.00		
Farinogram stability (FST)	0.31	0.47*	0.39	0.17	0.70**	1.00	
Farinogram valorimeter (FVA)	0.44*	0.08	0.56**	0.40	0.65**	0.57**	1.00

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

ted in the literature (34). Correlation coefficients obtained from microplot quality data did not agree as closely with those obtained in the row plots as did the hill plot data (Table 28).

#### Replicated Versus Bulk Mixogram Data

The mixograph information (peak distance and peak height) utilized in this investigation was obtained from replicated grain samples from each plot type. A bulk of the replicates was also used to obtain mixogram peak distance and peak height and correlation coefficients were computed within plot types between the replicated and bulked values for these traits (Table 29).

Correlation coefficients were positive and highly significant for both peak distance and peak height for all but the microplots. These results indicate the suitability of using bulked grain samples from row and hill plots when information on mixogram peak distance and peak height are needed. Information on peak distance obtained from the microplot grain samples indicated that replication of mixograms for this plot type would be necessary to obtain similar results when determining peak height.

The correlations of mixogram information obtained from bulked samples of wheat with percent protein and row plot farinogram data within each plot type are presented in Table 30. A comparison of these quality relationships with the relationships exhibited using replicated grain samples (Tables 26 to 28) showed that most quality inter-

relationships were maintained. The differences that did occur were: row plot mixogram peak height and farinogram peak time were unrelated in the replicated samples, but a significant, positive relationship was detected for these traits using bulked grain samples; in the hill plots, positive associations between mixogram peak height and farinogram peak time and stability were detected using replicated samples, but not in the bulk samples; and relationships between mixogram peak distance and farinogram peak time and mixogram peak height and farinogram absorption were not detected in replicated microplot samples, but significant, positive correlations were obtained from the bulk samples.

Table 29. Correlations between bulk and replicated data for mixogram peak distance and peak height taken from row and small plots.

Plot Type	Mixogram Characteristic	
	Peak Distance	Peak Height
Row	0.78**	0.73**
Hill	0.78**	0.76**
Micro	0.82**	0.49*

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

Table 30. Correlations between bulked mixogram information and other quality characteristics of winter wheat cultivars grown in row and small plots.

Trait	Plot Type					
	Row		Hill		Micro	
	Peak Distance	Peak Height	Peak Distance	Peak Height	Peak Distance	Peak Height
Percent protein	-0.35	0.27	-0.12	0.50*	0.08	0.30
Farinogram absorption	-0.39	0.54**	-0.15	0.43*	-0.23	0.57**
Farinogram peak time	0.21	0.45*	0.27	0.40	0.51*	0.51*
Farinogram stability	0.11	0.44*	0.32	0.36	0.62**	0.33
Farinogram valorimeter	-0.30	0.68**	0.01	0.52**	0.10	0.40

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

## SUMMARY

Flour protein content and mixograph information (peak distance and peak height) were obtained from winter wheat cultivars grown in conventional row plots and two types of small plot and a comparison was made between them. A ten-gram mixograph, using sieved wheat meal, was adopted to determine distance to peak and peak height and to compare cultivar curve patterns.

This investigation has shown that either hill or microplots would provide satisfactory information on protein content and mixogram characteristics, especially when the number of entries is large or when the amount of seed and land available is limited, such as in early generations of a breeding program.

## OVERALL SUMMARY

Twenty-three winter wheat cultivars were evaluated in hill, micro-, mini-, and row plots grown under dryland conditions in 1978. In addition, the hill and microplots were irrigated three times during the growing season in nurseries separate from their dryland counterparts. Comparisons of these small plots with the row plots were made utilizing thirteen agronomic and four quality characteristics as criteria for determining their suitability as alternatives to the row plots in winter wheat research.

All plot nurseries were damaged by wind and hail six days after the last cultivar had headed. An evaluation of this damage, using ten of the 23 cultivars, determined that cultivars grown in the small plot nurseries reacted to hail-induced head damage and wind- and hail-induced lodging in a manner similar to the cultivars grown in the row plots.

Comparisons of the small plots versus the row plots using overall means, phenotypic correlations between row and small plots, ranges, coefficients of variation, and the percentage of entries that were common in the extreme 10, 25, and 50% of the population indicated that the hill, micro-, and miniplots were suitable alternatives to row plots to discriminate among cultivars for heading date, plant height, seed weight, and harvest index. The hill and microplots were as efficient as the row plots in identifying winter wheat cultivars for percent flour protein and mixogram characteristics (peak distance, peak height,

and curve pattern). No advantage using irrigated hill and irrigated microplots was detected.

The cultivars grown in the dryland hill plots were less vigorous, in terms of plant height, number of heads/900 cm<sup>2</sup>, and grain yield, than those grown in the row plots. Relationships between agronomic and quality characteristics within small plot types differed substantially from these relationships in the row plot nursery and this was attributed to the differential ability of cultivars to compete within and between experimental units.

The relative importance of harvest index and biological yield to grain yield within plot types was determined using multiple regression analysis. Harvest index and biological yield accounted for 95 to 99% of the variation in grain yield across plot types and the ratios of their standard partial regression coefficients indicated that harvest index was more important than biological yield in determining grain yield except in the dryland hill and microplots, where both harvest index and biological yield were of equal importance.

#### LITERATURE CITED

1. Allard, R.W. 1960. Principles of plant breeding. John Wiley and Sons, Inc. New York, London, Sydney. p. 180.
2. American Association of Cereal Chemists. 1962. Approved methods of the AACC. The Association: St. Paul, Minn.
3. Baker, R.J. and D. Leisle. 1970. Comparison of hill and rod row plots in common and durum wheats. Crop Sci. 10: 581-583.
4. Baldrige, D.E. 1959. An examination of the wheat meal fermentation time test as a tool for evaluating the quality of red hard winter wheat F<sub>2</sub> derived lines. M.S. Thesis. Montana State University. 47 p.
5. Black, J.N. and D.J. Watson. 1960. Photosynthesis and the theory of obtaining high crop yields, by A.A. Niciporovic. Field Crop Abstr. 13: 169-175.
6. Bonnett, O.T. and W.M. Bever. 1947. Head-hill method of planting head selections of small grains. Agron. J. 39: 442-445.
7. Bruinsma, B.L., P.D. Anderson, and G.L. Rubenthaler. 1978. Rapid method to determine quality of wheat with the mixograph. Cereal Chem. 55: 732-735.
8. Donald, C.M. 1962. In search of yield. Aust. Inst. Agr. Sci. 28: 171-178.
9. Donald, C.M. 1968. The breeding of crop ideotypes. Euphytica 17: 385-403.
10. Donald, C.M. and J. Hamblin. 1976. The biological yield and harvest index of cereals as agronomic and plant breeding criteria. Adv. Agron. 28: 361-405.
11. Ergun, Y. 1971. Comparison of hill and row plots for evaluating genotypes and the effect of missing areas on plot yield of spring wheat (Triticum aestivum L.). M.S. Thesis. N. Dak. State Univ. 45 p.
12. Evans, L.T. and I.F. Wardlaw. 1976. Aspects of the comparative physiology of grain yield in cereals. Adv. Agron. 28: 301-359.

13. Finney, K.F. 1945. Methods of estimating and the effect of variety and protein level on the baking absorption of flour. *Cereal Chem.* 22: 149-158.
14. Finney, K.F. and M.D. Shogren. 1972. A ten-gram mixograph for determining and predicting functional properties of wheat flours. *Baker's Digest* 46(2): 32-35, 38-42, 77.
15. Finney, K.F. and W.T. Yamazaki. 1967. Quality of hard, soft, and durum wheats. In *Wheat and Wheat Improvement*. Agronomy Monograph No. 13, chap. 14. American Society of Agronomy, Madison, WI.
16. Fischer, R.A. and Z. Kertesz. 1976. Harvest index in spaced populations and grain weight in microplots as indicators of yielding ability in spring wheat. *Crop Sci.* 16: 55-59.
17. Frey, K.J. 1965. The utility of hill plots in oat research. *Euphytica* 14: 196-208.
18. Guenther, W.C. 1973. *Concepts of statistical inference*. (2nd Ed.). McGraw-Hill Book Company.
19. Jellum, M.D., C.M. Brown, and R.D. Seif. 1963. Hill and row plot comparisons for yield in oats. *Crop Sci.* 3: 194-196.
20. Jensen, N.F. and D.S. Robson. 1969. Miniature plots for cereal testing. *Crop Sci.* 9: 288-289.
21. Johnson, J.A., Jr., and C.O. Swanson. 1942. The testing of wheat quality by recording dough mixer curves obtained from sifted wheat meals. *Cereal Chem.* 216-229.
22. Johnson, J.A. Jr., C.O. Swanson, and E.G. Bayfield. 1943. The correlation of mixograms with baking results. *Cereal Chem.* 20: 625-644.
23. Khadr, F.H., A.A. Kassem, and A.A. ElKhishen. 1970. Hill versus row plot for testing wheat lines. *Crop Sci.* 10: 449-450.
24. Miller, B.S., B. Hays, and J.A. Johnson. 1956. Correlation of farinograph, mixograph, sedimentation, and baking data for hard red winter wheat flour samples varying widely in quality. *Cereal Chem.* 33: 277-290.

25. Morris, V.H., C.E. Bode, and H.K. Heizer. 1944. The use of the mixogram in evaluating quality in soft wheat varieties. *Cereal Chem.* 21: 49-57.
26. Nass, H.G. 1973. Determination of characters for yield selection in spring wheat. *Can. J. Plant Sci.* 53: 755-762.
27. Norton, J.B. 1907. Notes on breeding oats. *Amer. Breeders Assoc. Rep.* 3: 280-285.
28. Park, S.J., E. Reinbergs, and L.S.P. Song. 1977. Grain yield and its components in spring barley under row and hill plot conditions. *Euphytica* 26: 521-526.
29. Rosielle, A.A. and K.J. Frey. 1975. Estimates of selection parameters associated with harvest index in oat lines derived from a bulk population. *Euphytica* 24: 121-131.
30. Rosielle, A.A. and K.J. Frey. 1975. Application of restricted selection indices for grain yield improvement in oats. *Crop Sci.* 15: 544-547.
31. Ross, W.M. and J.D. Miller. 1955. A comparison of hill and conventional yield tests using oats and spring barley. *Agron. J.* 47: 253-255.
32. Schutz, W.M. and C.A. Brim. 1967. Inter-genotypic competition in soybeans. I. Evaluation of effects and proposed field plot design. *Crop Sci.* 7: 371-376.
33. Searle, S.R. 1965. The value of indirect selection: I. Mass selection. *Biometrics* 21(3): 682-707.
34. Shuey, W.C. (Ed.). 1972. The farinograph handbook. American Association of Cereal Chemists, Inc. St. Paul, Minn. 71 p.
35. Shuey, W.C. and K.A. Gilles. 1966. Effect of spring settings and absorption on mixograms for measuring dough characteristics. *Cereal Chem.* 43: 94-103.
36. Sims, H.J. 1963. Changes in the hay production and the harvest index of Australian oat varieties. *Aust. J. Exp. Agr. Anim. Husb.* 3: 198-202.
37. Singh, T.P. 1977. Harvest index in lentil (*Lens culinaris* Medik.). *Euphytica* 26: 833-839.

38. Singh, I.D. and N.C. Stoskopf. 1971. Harvest index in cereals. *Agron. J.* 63: 224-226.
39. Smith, O.D., R.A. Kleese, and D.D. Stuthman. 1970. Competition among oat varieties grown in hill plots. *Crop Sci.* 10: 381-384.
40. Snedecor, G.W. and W.G. Cochran. 1974. *Statistical methods* (6th ed.). The Iowa State Univ. Press. Ames, Iowa. 593 p.
41. Swanson, C.O. 1936. Physical tests to determine quality in wheat varieties. *Cereal Chem.* 13: 179-201.
42. Swanson, C.O. 1939. Variations in dough-development curves. *Cereal Chem.* 16: 625-643.
43. Swanson, C.O. 1940. Factors which influence the physical properties of dough. I. Effects of autolysis on the characteristics of dough mixer curves. *Cereal Chem.* 17: 679-689.
44. Swanson, C.O. and J.A. Johnson. 1943. Description of mixograms. *Cereal Chem.* 20: 39-42.
45. Swanson, C.O. and E.B. Working. 1933. Testing the quality of flour by the recording dough mixer. *Cereal Chem.* 10(1): 1-29.
46. Syme, J.R. 1970. A high-yielding Mexican semi-dwarf wheat and the relationship of yield to harvest index and other varietal characteristics. *Aust. J. Exp. Agric. Anim. Husb.* 10: 350-353.
47. Syme, J.R. 1972. Single-plant characters as a measure of field plot performance of wheat cultivars. *Aust. J. Agric. Res.* 23: 753-760.
48. Takeda, K. and K.J. Frey. 1976. Contributions of vegetative growth rate and harvest index to grain yield of progenies from *Avena sativa* X *A. sterilis* crosses. *Crop Sci.* 16: 817-821.
49. Takeda, K. and K.J. Frey. 1977. Growth rate inheritance and associations with other traits in backcross populations of *Avena sativa* X *A. sterilis*. *Euphytica.* 26: 309-317.
50. Zalik, S. and M. Ostafichuk. 1960. Note on a method of appraising mixogram data. *Cereal Chem.* 37: 105-106.

APPENDIX

Appendix Table 1. Winter wheat cultivars, entry, and accession numbers used to compare row and small plots.

Entry number	Cultivar	Accession number
1	Winalta	CI 13670
2	Centurk	CI 15075
3	Cheyenne	CI 8885
4	Warrior	CI 13190
5	Winoka	CI 14000
6	Hiplains	CI 17262
7	Sundance	CI 15327
8	Trapper	CI 13990
9	Lancer	CI 13547
10	Nugaines	CI 13968
11	Wanser	CI 13844
12	Froid	CI 13872
13	Crest	CI 13880
14	Roughrider	CI 17439
15	Advanced line (TX 55-391-56-D8/WMT 11-4-3)	MT 6928
16	Advanced line (YG/CNN 11-5-5//YGSS 4662 20-4-1-1)	MT 7216
17	Advanced line (LCR/WLT 102-4-14)	MT 7244
18	Advanced line (MT 6319 *2/LCR)	MT 7420
19	Advanced line (RG/CNN 39-18-7//WLT)	MT 7431
20	Marias II	MT 7801
21	Bohls Selection	MT 7802
22	NAPB 1289	NA 1289
23	Rocky	NA 1316

Appendix Table 2. Comparison of error mean squares between row and small plots for 16 traits.

Trait	Plot Type†					
	Row-D	Hill-I	Hill-D	Micro-I	Micro-D	Mini-D
Days to emergence	0.30	--	2.05 **	--	0.50 *	0.62 **
Fall color	0.12	--	0.19	--	0.08	0.11
Spring color	0.23	--	0.15	--	0.13	0.07 **
Fall growth habit	0.26	--	0.32	--	0.17	0.26
Spring growth habit	0.22	--	0.45 *	--	0.41	0.27
Heading date	0.30	--	1.20 **	--	1.51 **	0.36
Plant height	11.20	15.22 **	16.31 **	27.04 **	26.66 **	15.54 *
Heads/900 cm <sup>2</sup>	99.60	126.02	75.24	162.13 *	119.03	225.92 **
Seeds/head	9.7	30.77 **	45.41 **	29.02 **	20.35 *	9.11
100-seed weight	0.03	0.06 *	0.02 *	0.03	0.04	0.03
Yield	18.00	92.37 **	71.51 **	172.89 **	103.69 **	38.93 **
Harvest index	0.001	0.002**	0.002**	0.002**	0.001	0.002**
Biological yield	91.4	570.80 **	573.82 **	1142.65 **	603.42 **	287.48 **
Percent protein	0.09	--	0.09	--	0.08	--
Mixogram peak distance	0.08	--	0.13	--	0.11	--
Mixogram peak height	0.39	--	0.42	--	0.34	--

\*,\*\* Significantly different from the row plot error mean square at the 0.05 and 0.01 levels, respectively.

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

Appendix Table 3. Ranked cultivar means for percent culms lodged measured in row and small plots.

Plot Type†											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult.‡	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
%		%		%		%		%		%	
81.3	12	52.5	12	20.0	20	42.5	1	27.5	14	80.0	12
57.5	1	47.5	1	15.0	12	15.0	12	15.0	12	45.0	1
5.0	14	35.0	3	11.3	12	7.5	15	0.0	2	35.0	3
0.0	2	35.0	14	10.0	3	5.0	21	0.0	21	30.0	2
0.0	21	32.5	21	5.0	2	4.9	3	0.0	10	30.0	20
0.0	10	10.0	2	0.0	21	4.9	14	0.0	15	5.0	14
0.0	15	0.0	10	0.0	10	4.9	20	0.0	3	0.0	21
0.0	3	0.0	15	0.0	15	0.0	2	0.0	1	0.0	10
0.0	20	0.0	20	0.0	14	0.0	10	0.0	20	0.0	15
0.0	16	0.0	16	0.0	16	0.0	16	0.0	16	0.0	16
8.6 §		39.1		26.0		21.4		15.9		49.5	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

‡ Refer to Appendix Table 1 for cultivar names.

§ L.S.D. at 0.05 level.

Appendix Table 4. Ranked cultivar means for percent heads damaged measured in row and small plots.

Plot Type†											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult.‡	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
%		%		%		%		%		%	
19.3	21	17.0	21	20.5	21	12.8	21	11.5	21	17.5	21
8.0	14	10.8	10	8.3	20	7.5	16	6.3	10	10.0	12
7.0	2	7.5	12	7.8	16	6.3	2	6.3	14	7.5	10
6.8	12	7.5	16	7.3	14	6.0	14	5.8	3	7.5	14
6.8	16	6.8	3	6.5	2	5.3	10	5.5	12	5.5	1
6.5	10	6.8	20	6.5	10	5.3	15	5.5	16	4.5	3
6.4	1	6.0	14	6.0	12	5.3	20	5.3	1	4.0	20
6.0	20	5.9	1	5.5	3	5.0	12	5.3	20	3.5	2
5.8	3	5.0	2	4.3	15	4.8	3	5.0	2	3.0	15
3.5	15	3.8	15	3.5	1	4.5	1	4.0	15	3.0	16
4.2 §		6.8		6.3		3.3		5.8		6.6	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively.

‡ Refer to Appendix Table 1 for cultivar names.

§ L.S.D. at 0.05 level.

Appendix Table 5. Ranked cultivar means for days to emergence measured in row and small plots.

Plot Type†							
Row-D		Hill-D		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.
18.3	16	17.4	21	16.4	9	16.0	3
17.8	23	17.3	9	16.3	16	15.8	5
17.7	6	17.0	5	16.2	3	15.7	12
17.7	10	17.0	8	16.3	11	15.7	21
17.7	15	16.8	18	16.3	14	15.5	16
17.7	17	16.6	4	16.1	15	15.3	1
17.7	21	16.6	16	16.0	4	15.3	4
17.5	1	16.5	1	16.0	5	15.3	9
17.5	5	16.5	3	16.0	8	15.3	17
17.3	11	16.5	14	16.0	10	15.2	8
17.3	18	16.5	20	16.0	18	15.2	11
17.3	20	16.5	22	16.0	21	15.2	13
17.2	22	16.4	7	15.9	22	15.2	15
17.0	3	16.4	12	15.8	1	15.2	18
17.0	4	16.3	6	15.8	6	14.8	14
17.0	7	16.3	15	15.8	13	14.8	22
17.0	8	16.3	23	15.8	19	14.7	10
17.0	9	16.2	17	15.7	2	14.7	19
17.0	12	16.1	10	15.7	20	14.7	20
17.0	13	16.1	11	15.7	23	14.5	2
17.0	14	15.8	2	15.6	7	14.5	6
17.0	19	15.4	13	15.6	12	14.2	23
16.7	2	15.3	19	15.6	17	14.0	7
0.6 ¶		1.2		0.6		0.9	

† The letter D following plot types is an abbreviation for dryland.

‡ Days from planting until 50% of the coleoptiles were emerged.

§ Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 6. Ranked cultivar means for fall color measured in row and small plots.

Plot Type†							
Row-D		Hill-D		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.
4.2	5	3.7	1	4.0	5	4.0	1
4.0	1	3.7	5	4.0	12	4.0	4
4.0	14	3.7	12	4.0	14	4.0	5
4.0	16	3.7	14	4.0	15	4.0	12
3.8	12	3.7	16	4.0	16	4.0	14
3.8	19	3.6	17	3.8	9	3.8	9
3.7	7	3.5	6	3.7	1	3.8	16
3.7	17	3.5	10	3.7	3	3.8	17
3.5	3	3.5	11	3.5	19	3.7	18
3.5	9	3.4	13	3.5	20	3.5	3
3.3	4	3.3	15	3.3	13	3.5	21
3.3	6	3.3	19	3.3	17	3.3	6
3.3	18	3.3	21	3.3	18	3.3	7
3.3	20	3.2	18	3.2	4	3.3	8
3.0	2	3.1	3	3.2	3	3.2	6
3.0	8	3.1	4	3.2	7	3.2	10
3.0	11	3.1	7	3.2	11	3.1	19
3.0	13	3.1	9	3.2	21	3.0	2
3.0	15	3.1	23	3.0	8	3.0	11
3.0	21	3.0	8	3.0	10	3.0	13
3.0	23	3.0	20	2.9	2	3.0	15
2.9	10	2.9	2	2.9	22	3.0	22
2.9	22	2.9	22	2.9	23	3.0	23
0.6¶		0.7		0.5		0.6	

† The letter D following plot types is an abbreviation for dryland.

‡ Scale 1-5 (5 = darkest green).

§ Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 7. Ranked cultivar means for spring color measured in row and small plots.

Row-D		Plot Type†				Micro-D		Mini-D	
Mean‡	Cult.§	Hill-D		Mean	Cult.	Mean	Cult.	Mean	Cult.
3.8	11	4.0	14	4.0	1	4.0	1	4.0	1
3.8	13	3.8	1	4.0	5	4.0	5	4.0	5
3.7	4	3.8	10	4.0	14	4.0	14	3.7	10
3.3	2	3.8	16	4.0	15	4.0	15	3.7	14
3.3	6	3.8	17	4.0	16	4.0	16	3.5	7
3.3	10	3.7	6	3.8	20	3.8	20	3.5	8
3.3	18	3.7	7	3.7	12	3.7	12	3.5	16
3.3	20	3.7	12	3.7	13	3.7	13	3.5	18
3.3	21	3.7	18	3.7	17	3.7	17	3.3	3
3.3	22	3.7	19	3.7	18	3.7	18	3.3	4
3.2	1	3.7	20	3.5	7	3.5	7	3.3	6
3.2	7	3.5	5	3.5	9	3.5	9	3.3	9
3.2	8	3.5	11	3.3	4	3.3	4	3.3	17
3.2	16	3.3	4	3.3	8	3.3	8	3.3	21
3.2	19	3.3	8	3.3	11	3.3	11	3.2	13
3.2	23	3.3	21	3.2	3	3.2	3	3.2	20
2.8	3	3.3	22	3.2	21	3.2	21	3.1	12
2.8	5	3.2	13	3.2	22	3.2	22	3.0	2
2.8	9	3.0	2	3.0	2	3.0	2	3.0	11
2.8	12	3.0	3	3.0	6	3.0	6	3.0	15
2.8	14	3.0	9	3.0	10	3.0	10	3.0	19
2.8	15	3.0	15	3.0	19	3.0	19	3.0	22
2.8	17	3.0	23	3.0	23	3.0	23	3.0	23
1.0 ¶		0.6		0.6		0.6		0.4	

† The letter D following plot types is an abbreviation for dryland.

‡ Scale 1-5 (5 = darkest green).

§ Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 8. Ranked cultivar means for fall growth habit measured in row and small plots.

Row-D		Hill-D		Micro-D		Mini-D	
Mean†	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.
3.3	1	3.8	13	3.7	22	3.7	2
3.3	7	3.8	22	3.5	6	3.7	7
3.3	13	3.7	7	3.5	7	3.3	6
3.0	2	3.3	14	3.5	23	3.3	13
3.0	3	3.2	5	3.3	12	3.3	18
3.0	6	3.2	8	3.3	13	3.3	23
3.0	12	3.2	10	3.0	1	3.2	14
3.0	17	3.2	23	3.0	4	3.2	15
3.0	20	3.1	17	3.0	9	3.0	8
3.0	22	3.0	1	3.0	14	3.0	20
2.7	4	3.0	2	3.0	20	3.0	21
2.7	5	3.0	4	2.9	17	2.9	19
2.7	14	3.0	9	2.7	5	2.9	22
2.7	18	2.9	6	2.7	21	2.7	1
2.7	19	2.8	3	2.3	2	2.7	4
2.3	8	2.7	12	2.3	3	2.7	11
2.3	9	2.7	15	2.3	8	2.3	3
2.3	11	2.7	19	2.3	10	2.3	5
2.3	15	2.3	11	2.3	15	2.3	9
2.3	16	2.3	16	2.3	18	2.3	16
2.3	21	2.3	18	2.3	19	2.3	17
2.3	23	2.3	20	2.0	11	2.0	10
2.0	10	2.0	21	2.0	16	2.0	12
0.8 ¶		0.9		0.7		0.8	

† The letter D following plot types is an abbreviation for dryland.

‡ Scale 1-5 (5 = most prostrate).

§ Refer to Appendix Table 1 for Cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 9. Ranked cultivar means for spring growth habit measured in row and small plots.

Plot Type†							
Row-D		Hill-D		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.
3.8	1	3.7	5	4.5	14	4.0	5
3.8	5	3.7	18	4.3	6	4.0	14
3.8	14	3.5	1	4.0	9	4.0	18
3.8	16	3.5	7	3.8	2	3.8	1
3.5	7	3.5	12	3.8	5	3.8	7
3.3	19	3.5	13	3.8	18	3.7	12
3.2	4	3.5	16	3.7	7	3.7	22
3.2	8	3.3	2	3.5	12	3.3	2
3.2	18	3.3	8	3.4	16	3.3	8
3.0	10	3.3	14	3.3	1	3.3	23
2.8	6	3.3	17	3.3	8	3.2	17
2.8	21	3.3	21	3.3	13	3.0	3
2.7	9	3.3	22	3.3	22	3.0	10
2.7	12	3.2	3	3.2	3	2.9	21
2.7	22	3.2	11	3.2	17	2.8	13
2.5	17	3.0	4	3.2	20	2.8	15
2.3	2	3.0	9	3.2	23	2.7	9
2.3	11	3.0	10	3.1	10	2.7	19
2.3	23	3.0	20	2.9	15	2.6	16
2.2	3	2.7	6	2.8	19	2.3	4
1.8	13	2.7	15	2.7	4	2.3	6
1.8	15	2.7	19	2.7	11	2.3	20
1.8	20	2.7	23	2.3	21	2.0	11
1.0 ¶		1.1		1.1		0.9	

† The letter D following plot types is an abbreviation for dryland.

‡ Scale 1-5 (5 = most prostrate).

§ Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 10. Ranked cultivar means for heading date measured in row and small plots.

Plot Type†							
Row-D		Hill-D		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.
177.3	7	178.2	7	177.5	7	176.8	7
175.0	10	175.1	12	174.1	12	174.5	10
174.2	12	174.1	10	173.9	10	174.2	12
173.3	3	173.9	3	173.5	14	174.0	3
173.2	14	173.7	5	173.1	3	173.3	5
173.0	5	173.5	1	172.7	18	173.0	18
172.8	16	173.5	14	172.6	16	172.8	1
172.8	18	173.3	18	172.5	5	172.8	14
172.5	1	173.1	16	172.5	11	172.3	16
172.5	19	172.5	11	172.1	1	171.3	11
172.0	8	172.3	8	171.7	8	171.2	8
171.8	11	170.6	19	170.7	4	170.0	4
169.5	4	170.5	4	170.1	6	169.8	19
168.8	6	169.8	9	170.1	19	169.2	17
168.8	17	169.5	6	169.5	22	168.8	6
168.7	9	169.2	22	169.3	9	168.8	9
168.5	15	169.0	17	169.2	20	168.8	13
168.5	20	169.0	20	169.2	21	168.8	21
168.5	22	169.0	23	169.1	17	168.8	22
168.5	23	168.9	15	168.8	15	168.7	15
168.0	13	168.9	21	168.7	13	168.7	23
167.8	2	168.6	2	168.6	23	168.2	20
167.8	21	168.6	13	168.4	2	168.0	2
0.6 ¶		0.9		1.0		0.7	

† The letter D following plot types is an abbreviation for dryland.

‡ Days from January 1.

§ Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 11. Ranked cultivar means for plant height measured in row and small plots.

Plot Type†											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult.‡	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
cm		cm		cm		cm		cm		cm	
128.7	12	130.8	7	119.2	7	133.9	7	123.2	12	123.2	12
126.2	7	130.2	12	117.9	12	133.4	12	120.8	7	120.7	7
124.2	18	123.2	3	113.4	8	126.7	3	116.9	8	119.8	3
121.0	5	122.2	1	112.2	1	126.1	1	115.2	3	118.7	8
119.5	1	121.6	18	111.2	5	124.8	8	114.9	18	117.0	1
117.3	3	121.4	8	110.8	18	122.8	5	114.8	1	116.2	5
117.0	9	119.7	5	110.2	3	121.4	14	114.7	5	114.5	18
116.7	8	118.5	14	109.6	20	120.9	18	113.5	4	113.0	20
116.0	19	116.4	9	109.3	9	118.8	9	111.3	9	112.7	11
115.8	20	114.7	19	108.6	19	117.3	11	111.1	20	111.3	14
115.3	14	114.1	4	108.3	14	117.2	20	109.7	11	111.0	4
114.2	11	113.1	11	108.1	11	116.7	4	108.6	14	110.0	16
111.7	4	112.6	20	107.4	4	114.7	19	107.2	6	109.3	9
110.3	16	112.0	6	105.9	6	113.1	6	106.7	17	107.0	17
110.3	17	110.5	17	105.6	16	113.0	16	106.2	16	105.7	19
106.2	22	110.3	22	103.9	17	110.2	17	105.4	19	105.5	6
105.5	23	108.6	16	102.7	22	108.6	22	104.2	22	105.0	22
103.5	6	106.7	2	100.3	23	106.7	23	102.7	2	102.7	23
103.2	2	105.5	23	99.6	13	106.1	2	101.1	23	100.7	13
100.2	13	101.8	13	98.3	2	103.4	13	99.0	13	98.5	2
96.8	21	99.2	15	92.8	21	102.4	15	95.0	21	96.3	21
88.5	15	94.3	21	91.4	15	94.8	21	92.5	15	90.8	15
77.5	10	87.0	10	79.2	10	87.1	10	80.1	10	77.7	10
3.8 §		3.1		3.2		4.2		4.1		4.5	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. ‡ Refer to Appendix Table 1 for cultivar names. § L.S.D. at 0.05 level.

Appendix Table 12. Ranked cultivar means for number of heads/900 cm<sup>2</sup> measured in row and small plots.

Plot Type †											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult. ‡	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
86.7	20	65.4	13	50.8	1	96.6	8	71.4	20	123.3	22
85.3	18	61.8	2	49.2	19	92.2	13	70.6	2	109.0	2
83.7	23	60.2	12	48.4	6	92.0	18	70.4	1	108.7	9
80.7	22	59.2	22	48.4	13	89.6	19	68.8	7	107.7	18
75.0	17	57.6	7	47.0	18	88.6	3	68.2	18	107.0	6
72.7	8	56.8	15	46.6	15	86.4	5	67.2	13	105.3	5
68.7	11	56.8	19	45.6	17	85.8	12	65.8	3	104.0	13
68.3	9	56.2	6	45.2	22	84.8	1	65.4	8	103.0	12
67.0	15	56.2	8	44.8	20	84.4	7	65.2	23	102.0	11
66.3	2	56.2	11	44.4	2	83.2	2	64.8	4	100.7	14
66.3	4	55.6	4	44.2	5	81.0	17	63.0	5	100.7	19
65.3	5	54.8	5	43.4	11	79.6	6	62.8	19	96.3	4
65.3	13	54.6	17	42.4	8	79.6	22	62.0	22	93.3	17
65.3	19	54.2	23	42.2	7	79.4	4	61.6	17	92.3	8
63.7	6	52.6	18	40.8	16	79.4	11	60.6	6	92.0	3
63.7	10	51.8	1	39.0	9	79.2	21	59.4	11	91.0	16
61.3	14	51.8	9	39.0	21	76.0	9	59.0	15	90.0	20
61.0	3	51.0	14	37.8	14	75.0	23	57.2	21	89.0	10
59.0	1	47.0	20	37.4	23	73.4	15	56.2	14	88.3	7
59.0	12	46.6	21	35.4	4	73.2	20	55.6	16	82.7	23
56.3	21	45.2	16	34.0	3	69.0	10	55.0	12	80.3	15
54.3	7	44.6	3	32.8	10	69.0	16	53.6	9	79.7	1
54.0	16	42.2	10	29.0	12	67.8	14	46.8	10	65.3	21
16.4 §		14.1		10.9		16.0		13.7		24.7	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. ‡ Refer to Appendix Table 1 for cultivar names. § L.S.D. at 0.05 level.

Appendix Table 13. Ranked cultivar means for number of seeds per head measured in row and small plots.

		Plot Type†									
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult. #	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
18.9	2	21.4	7	28.0	18	28.4	7	23.4	23	22.4	23
17.1	13	21.0	23	20.6	16	27.8	15	23.2	15	19.6	15
16.6	1	20.8	13	20.6	20	23.8	23	22.8	2	17.6	21
16.5	10	19.6	2	20.4	15	23.0	8	22.2	1	17.2	7
15.8	7	19.6	8	19.6	2	21.8	2	21.6	5	16.9	2
15.4	12	19.2	5	19.4	22	21.6	22	20.6	7	16.7	10
15.0	21	19.2	21	19.2	11	20.4	10	20.2	13	16.1	1
14.8	5	19.0	6	18.6	5	20.4	18	19.6	18	15.7	16
14.5	16	19.0	12	18.6	21	20.0	13	19.2	8	15.1	3
14.3	22	18.6	16	18.0	1	19.8	6	19.0	16	14.0	13
14.0	14	18.6	22	17.6	7	19.6	4	18.4	17	14.0	17
13.6	3	18.0	11	17.6	13	19.6	21	18.4	21	13.8	20
13.2	18	17.0	14	17.4	10	19.2	12	18.2	10	13.6	6
13.1	4	16.4	4	17.0	6	19.2	20	18.2	20	13.4	19
13.0	9	16.2	1	16.8	4	18.8	16	17.8	3	13.2	5
12.3	15	15.6	3	16.8	23	18.8	19	17.8	4	13.1	12
12.2	17	15.6	10	16.2	8	18.6	9	17.8	22	13.0	11
12.2	19	15.6	17	15.6	19	18.0	1	16.6	6	12.9	14
11.2	6	15.4	20	15.4	17	17.8	14	16.6	11	12.8	4
11.1	11	15.0	15	14.8	3	17.8	17	16.4	19	12.4	9
11.1	23	15.0	19	14.4	12	17.2	3	15.6	9	12.4	18
9.9	8	14.6	9	13.8	9	15.8	11	15.2	14	12.2	8
9.1	20	13.0	18	13.2	14	15.4	5	15.0	12	11.9	22
5.1 §		7.0		8.5		6.8		5.7		5.0	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. # Refer to Appendix Table 1 for cultivar names. § L.S.D. at 0.05 level.

Appendix Table 14. Ranked cultivar means for 100-seed weight measured in row and small plots.

Plot Type †											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
3.75	21	4.16	21	3.77	21	3.87	21	4.03	21	3.99	21
3.42	19	3.60	5	3.33	11	3.58	17	3.35	7	3.42	17
3.41	17	3.51	17	3.32	17	3.45	11	3.32	17	3.40	3
3.33	11	3.37	11	3.27	3	3.42	1	3.27	11	3.29	20
3.20	7	3.34	7	3.18	5	3.41	3	3.24	3	3.24	5
3.14	1	3.32	1	3.16	1	3.41	5	3.23	1	3.23	11
3.10	9	3.32	3	3.10	19	3.27	7	3.14	5	3.22	19
3.09	20	3.27	4	3.09	7	3.20	4	3.14	20	3.16	1
3.07	5	3.24	19	3.05	9	3.20	19	3.11	6	3.12	13
2.99	3	3.16	2	3.01	8	3.12	8	3.08	9	3.07	6
2.97	10	3.14	9	2.94	4	3.12	13	3.06	8	3.07	9
2.95	14	3.06	14	2.94	14	3.10	14	3.05	19	3.07	14
2.95	23	3.06	20	2.91	13	3.10	20	2.99	4	3.04	7
2.88	12	3.04	8	2.91	20	3.08	9	2.97	13	3.04	23
2.88	13	3.02	10	2.86	6	3.06	2	2.97	14	3.01	10
2.84	4	3.01	12	2.86	10	3.01	23	2.97	16	2.95	22
2.84	8	2.97	13	2.82	16	2.97	22	2.96	2	2.93	8
2.84	22	2.96	23	2.79	2	2.92	6	2.89	23	2.93	16
2.80	18	2.93	22	2.77	18	2.90	18	2.85	22	2.91	4
2.75	2	2.91	6	2.76	22	2.84	16	2.79	18	2.85	18
2.73	16	2.86	18	2.76	23	2.81	12	2.76	12	2.84	2
2.57	15	2.75	16	2.72	12	2.78	10	2.51	10	2.83	12
2.47	6	2.74	15	2.37	15	2.49	15	2.32	15	2.66	15
0.30¶		0.30		0.18		0.21		0.19		0.27	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. ‡ grams. § Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 15. Ranked cultivar means for grain yield measured in row and small plots.

Plot Type†											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
36.5	23	50.2	13	41.3	13	65.2	13	55.2	2	62.2	23
34.4	13	47.1	2	41.2	2	63.1	19	50.3	13	57.0	2
33.4	2	42.3	17	35.9	22	62.1	7	50.1	17	51.7	13
33.2	10	40.5	19	35.6	19	60.9	2	48.8	7	51.4	21
32.3	17	39.6	8	35.3	17	59.4	23	48.7	1	49.6	7
32.0	21	39.5	7	34.4	20	58.3	21	48.4	23	49.0	17
31.1	5	38.8	23	34.2	8	58.1	17	46.6	19	48.8	19
29.6	18	37.5	1	34.0	6	53.1	3	46.6	21	48.6	3
29.0	22	37.4	22	34.0	7	51.0	15	46.2	5	48.0	5
28.9	1	37.2	20	32.7	5	50.7	8	45.9	8	48.0	22
27.6	19	35.6	4	32.4	1	50.4	1	45.0	22	47.1	10
26.3	9	35.3	5	31.0	21	50.3	22	44.0	6	47.0	11
26.0	12	34.7	9	29.2	15	49.8	4	43.6	3	47.0	16
25.8	11	33.8	21	29.2	23	49.4	6	42.9	20	46.9	15
25.2	20	33.7	12	27.2	18	49.4	18	41.9	4	46.7	20
24.0	4	32.3	6	27.1	4	49.2	12	41.1	18	46.4	9
23.6	7	32.0	3	27.0	9	48.7	14	40.6	15	44.9	1
22.6	3	31.4	11	26.5	3	48.7	20	39.8	9	43.0	6
21.9	14	30.0	18	26.0	16	47.3	5	36.8	11	39.9	18
21.7	16	29.9	15	25.5	11	44.9	11	36.4	16	39.5	8
20.2	8	29.1	14	25.4	10	41.7	9	34.7	10	39.2	12
19.1	15	24.8	10	23.0	14	38.8	10	34.4	14	38.9	4
16.6	6	21.4	16	22.0	12	36.1	16	32.2	12	38.5	14
4.9 ¶		7.7		6.8		10.5		8.1		7.1	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. ‡ q/ha. § Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 16. Ranked cultivar means for harvest index measured in row and small plots.

Plot Type†											
Row-D		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean	Cult. #	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
0.33	13	0.34	2	0.37	2	0.32	23	0.33	17	0.36	9
0.32	10	0.33	13	0.33	13	0.31	2	0.33	23	0.35	2
0.32	17	0.30	17	0.33	22	0.31	21	0.32	2	0.35	23
0.30	2	0.30	23	0.31	7	0.30	17	0.32	21	0.33	17
0.29	21	0.29	1	0.31	17	0.29	7	0.30	9	0.32	7
0.28	5	0.29	3	0.31	20	0.28	13	0.30	10	0.32	10
0.27	12	0.29	19	0.31	21	0.28	19	0.30	13	0.32	21
0.27	23	0.28	4	0.30	23	0.27	4	0.29	1	0.32	22
0.26	1	0.28	9	0.30	1	0.27	15	0.29	6	0.31	13
0.26	4	0.28	21	0.30	4	0.26	1	0.29	7	0.30	5
0.26	18	0.27	5	0.30	5	0.26	3	0.29	19	0.29	3
0.26	22	0.27	8	0.30	6	0.26	6	0.29	22	0.29	19
0.25	9	0.27	20	0.30	19	0.26	20	0.28	4	0.28	1
0.25	19	0.27	22	0.29	8	0.26	22	0.28	5	0.28	6
0.24	20	0.26	7	0.29	10	0.25	8	0.28	8	0.28	8
0.23	3	0.26	12	0.27	3	0.25	9	0.28	15	0.28	11
0.23	7	0.25	6	0.27	9	0.25	10	0.27	3	0.28	12
0.23	11	0.24	10	0.26	15	0.25	14	0.27	16	0.28	15
0.23	14	0.24	14	0.26	16	0.23	5	0.27	20	0.28	20
0.22	8	0.23	11	0.25	11	0.23	12	0.26	18	0.27	4
0.21	16	0.22	18	0.25	12	0.23	18	0.25	11	0.27	16
0.18	6	0.21	15	0.25	18	0.22	11	0.24	14	0.25	14
0.18	15	0.20	16	0.24	14	0.21	16	0.23	12	0.25	18
0.04	§	0.03		0.04		0.04		0.03		0.05	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. # Refer to Appendix Table 1 for cultivar names. § L.S.D. at 0.05 level.

Appendix Table 17. Ranked cultivar means for biological yield measured in row and small plots.

Row-D		Plot Type†									
		Hill-I		Hill-D		Micro-I		Micro-D		Mini-D	
Mean‡	Cult.§	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.	Mean	Cult.
135.2	23	151.9	7	125.2	13	232.9	13	172.5	2	177.7	23
113.9	18	152.1	13	118.7	19	225.4	19	168.3	7	174.1	16
112.2	11	146.7	8	117.9	8	214.8	18	167.9	1	168.3	19
111.5	22	142.4	15	113.9	17	214.1	7	167.7	13	167.9	11
111.3	2	141.0	17	113.3	6	213.9	12	165.0	5	167.5	15
111.2	1	139.7	19	112.3	15	205.7	5	163.9	8	167.6	3
111.1	5	138.5	2	111.4	2	204.2	3	161.5	3	166.8	13
110.4	19	138.5	22	111.0	20	204.1	11	160.7	19	166.8	20
110.3	21	137.8	20	109.7	7	202.8	8	158.9	20	162.9	2
106.1	15	136.5	11	109.0	5	196.5	2	158.1	18	160.6	21
105.2	9	136.4	18	108.8	18	194.8	14	155.2	22	160.4	1
105.0	20	130.7	5	108.8	22	193.8	1	151.8	17	160.0	5
104.2	13	129.6	12	108.0	1	193.7	17	151.7	6	159.6	18
103.8	10	129.3	1	102.0	11	193.5	22	149.6	4	155.0	7
103.3	16	129.3	23	100.0	9	190.0	6	147.2	11	154.0	14
102.6	7	129.2	6	100.0	16	188.9	15	146.7	23	153.6	6
100.9	17	127.1	4	100.0	21	188.1	21	145.6	21	150.0	22
98.3	3	123.9	9	98.1	3	187.3	20	145.0	15	148.5	17
95.2	14	121.3	14	95.8	14	185.6	23	143.3	14	147.2	10
92.3	4	120.7	21	94.2	23	184.4	4	140.0	12	144.1	4
92.3	12	110.3	3	90.3	4	171.9	16	134.8	16	141.1	8
92.2	6	107.0	16	88.0	12	166.8	9	132.7	9	140.0	12
91.8	8	103.3	10	87.6	10	155.2	10	115.7	10	128.9	9
10.9 ¶		19.1		19.2		27.1		19.7		19.4	

† The letters D and I following plot types are abbreviations for dryland and irrigated, respectively. ‡ q/ha. § Refer to Appendix Table 1 for cultivar names.

¶ L.S.D. at 0.05 level.

Appendix Table 18. Ranked cultivar means for percent protein measured in row and small plots.

Row		Plot Type		Micro	
Mean	Cult.†	Mean	Cult.	Mean	Cult.
%		%		%	
14.60	18	14.90	18	14.87	12
14.30	12	14.73	12	14.57	18
14.22	14	14.48	5	14.23	14
14.10	16	14.48	14	14.03	19
14.00	5	14.27	1	14.00	5
13.90	19	14.27	19	14.00	22
13.82	7	14.22	16	13.93	16
13.73	8	14.10	7	13.88	7
13.72	22	14.03	22	13.80	1
13.67	3	14.02	2	13.63	3
13.63	1	13.92	3	13.57	2
13.62	15	13.80	23	13.50	8
13.60	2	13.78	21	13.50	15
13.60	13	13.65	8	13.47	9
13.43	6	13.62	4	13.47	21
13.35	21	13.57	15	13.45	11
13.35	23	13.47	9	13.38	23
13.30	4	13.45	11	13.37	13
13.27	9	13.42	13	13.35	4
13.05	11	13.33	6	13.25	20
13.03	17	13.15	20	13.22	6
13.02	20	13.13	17	13.07	17
11.10	10	11.28	10	11.82	10
0.40 ‡		0.40		0.40	

† Refer to Appendix Table 1 for cultivar names.

‡ L.S.D. at 0.05 level.

Appendix Table 19. Ranked cultivar means for mixogram peak distance measured in row and small plots.

Row		Plot Type				Micro	
		Hill					
Mean	Cult.†	Mean	Cult.	Mean	Cult.	Mean	Cult.
cm		cm		cm		cm	
4.6	22	4.8	23	4.6	5		
4.3	4	4.6	15	4.6	12		
4.2	11	4.5	22	4.6	15		
4.2	23	4.3	13	4.4	22		
4.0	13	4.3	21	4.3	4		
4.0	15	3.9	3	4.3	13		
4.0	20	3.9	4	4.3	23		
3.9	1	3.8	6	4.2	11		
3.9	5	3.8	11	4.1	1		
3.9	10	3.8	12	4.0	8		
3.8	12	3.8	20	4.0	21		
3.7	3	3.7	1	3.9	3		
3.7	6	3.7	8	3.9	10		
3.7	8	3.6	5	3.9	19		
3.7	19	3.6	10	3.8	20		
3.4	21	3.6	14	3.7	18		
3.3	14	3.6	19	3.6	6		
3.3	18	3.3	9	3.4	9		
3.2	7	3.2	7	3.4	14		
3.1	16	3.1	16	3.3	2		
2.9	9	3.1	18	3.3	7		
2.8	17	2.8	2	3.3	17		
2.5	2	2.8	17	3.0	16		
0.5‡		0.6		0.5			

† Refer to Appendix Table 1 for cultivar names.

‡ L.S.D. at 0.05 level.

Appendix Table 20. Ranked cultivar means for mixogram peak height measured in row and small plots.

Row		Plot Type		Micro	
Mean	Cult.†	Mean	Cult.	Mean	Cult.
cm		cm		cm	
6.9	5	6.7	19	6.7	2
6.5	3	6.6	23	6.7	8
6.5	9	6.5	2	6.7	19
6.5	18	6.3	3	6.7	20
6.4	1	6.2	9	6.6	4
6.4	8	6.2	13	6.6	6
6.3	14	6.1	5	6.5	5
6.2	21	6.1	20	6.5	18
6.1	11	6.0	1	6.4	3
6.1	22	6.0	6	6.4	9
6.0	2	6.0	8	6.3	1
6.0	4	6.0	21	6.3	13
6.0	20	5.9	12	6.3	22
5.9	19	5.8	18	6.3	23
5.8	6	5.7	22	6.0	16
5.8	16	5.6	14	5.9	11
5.7	23	5.6	15	5.9	12
5.6	17	5.6	16	5.9	17
5.3	12	5.4	11	5.8	15
5.3	13	5.2	17	5.7	10
5.2	7	5.1	4	5.6	7
5.2	15	5.0	7	5.6	14
5.0	10	4.4	10	5.5	21
1.0#		1.1		1.0	

† Refer to Appendix Table 1 for cultivar names.

# L.S.D. at 0.05 level.

