Critical overwintering plant population for the successful production of winter wheat in Montana
by Douglas Lee Holen, Jr

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

Abstract:

Winterkill and injury has long been detrimental to the production of winter wheat (Triticum aestivum) in Montana. Three cultivars differing in winterhardiness were grown in five Montana environments with a control and six reduced plant populations to simulate winterkill. The objectives of this study were to measure the compensation ability of several cultivars over a range of reduced plant populations, determine the threshold plant population at which a significant yield reduction occurs, and to measure secondary plant variable responses to reduced plant populations. Compensation by surviving plants for those lost to winterkill was accomplished by means of increased tillering, larger spikes, and/or increased kernel weight. Yield component compensation often resulted in final yield equivalent to that of the target plant density. With a seeding rate of 67.2 kg/ha, critical plant population to achieve control level yields ranged from 25 percent survival (54 plants/m^2) to 63 percent survival (136 plants/m^2) . Over all five environments, the critical plant population averaged 43 percent (93 plants/m^2) . This is in close agreement with the current recommendation of a 40 to 50 percent stand needed for producers to maintain the existing winter wheat crop.

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by

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date 1-25-96

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ABSTRACT

Winterkill and injury has long been detrimental to the production of winter wheat (Triticum aestivum) in Montana. Three cultivars differing in winterhardiness were grown in five Montana environments with a control and six reduced plant populations to simulate winterkill. The objectives of this study were to measure the compensation ability of several cultivars over a range of reduced plant populations, determine the threshold plant population at which a significant yield reduction occurs, and to measure secondary plant variable responses to reduced plant populations. Compensation by surviving plants for those lost to winterkill was accomplished by means of increased tillering, larger spikes, and/or increased kernel weight. Yield component compensation often resulted in final yield equivalent to that of the target plant density. With a seeding rate of 67.2 kg/ha, critical plant population to achieve control level yields ranged from 25 percent survival (54 plants/m^2) to 63 percent survival (136 plants/m^2). Over all five environments, the critical plant population averaged 43 percent (93 plants/m^2). This is in close agreement with the current recommendation of a 40 to 50 percent stand needed for producers to maintain the existing winter wheat crop.

CHAPTER 1

INTRODUCTION

As stated by Fowler and Carles (1979), "A species' ability to tolerate low temperatures is one of the primary factors determining its area of adaptation and distribution". Montana winter and early spring climatic conditions are often conducive for winterkill or injury to winter wheat (Triticum aestivum L.). The severity and frequency of this occurrence is dependant upon many factors such as: temperature, wind, snow cover, topography, drift patterns, overwintering plant stage, plant diseases, and genetic winterhardiness. Winters with adequate snow, moderate temperatures, and minimal wind, often result in little or no damage to most cultivars (Taylor and Olsen, 1985).

Because of its location and associated climate, Montana agriculture periodically sustains substantial wheat acreage losses due to winter kill and injury (Table 1) (Montana Agricultural Statistics, 1995). Chinooks, low temperatures, lack of snow cover, and frequent winds contribute to plant losses through desiccation, intra and extracellular ice crystal formation, and suffocation due to ice encasement.

Winterkill ranges in severity from 100% plant mortality to no damage, and the spectrum in between. However, typically winterkill occurs in "patches" within a field at locations such as hilltops and depressions. Following spring regrowth, producers must evaluate damage to stands and decide whether the existing crop will yield adequately. This evaluation should consist of determining the average number of healthy plants present in a specific unit area. Ten random counts taken within a field should produce a rough estimate of stand density. The general recommendation published by the Montana State University Extension Service states that sampled fields containing 72 to 90 plants per square yard, will usually produce as much or more than replanted spring wheat. With a normal seeding rate (180 seeds/yard^2), this is 40 to 50 percent of the original stand (Bowman et al., 1995; Juhnke, 1983; Montana State University Extension Service, 1985). Producers with fields containing fewer plants than this have two possible options. Interseeding with an early hard red spring wheat is one possibility with the other being to terminate the winter wheat and replant. Fields with fewer than 30 plants per square yard are recommended to be destroyed and reseeded with a spring cereal crop.

Yield in cereal grains is dependent upon three components: 1.) Number of spikes per unit area; 2.) Number of grains per spike; and 3.) Grain weight (Darwinkel, 1978). For maximized grain production to occur, an undisturbed functioning of the crop is necessary throughout all developmental stages (Darwinkel, 1978). The loss of plants allows for more water, sunlight, and nutrients to be available to the surviving population. Evans and Wardlaw (1976) explain yield component compensation as the allowance of subsequently occurring components of final grain yield to compensate for restrictions and/or losses during earlier stages of development, or to maximize reproductive growth under favorable conditions late in the plant life cycle. It is recognized however, that compensation is mainly achieved by extensive tillering (Darwinkel, 1978) of the surviving plants in the absence of plants lost to winterkill. Under adequate environmental conditions, remaining plant populations can often produce yields equivalent to target population by way of component compensation.

Yield component compensation can be further broken down into intra- and inter-plant competition (Darwinkel, 1978). With a full population, inter-plant competition is experienced between plants which results in more spikes per unit area but fewer and smaller kernels per spike. Reduced populations experience less inter-plant competition but significant intra-plant competition. This competition of water, sunlight, and nutrients occurs within the plant and between vegetative and reproductive growth and specifically between components of reproductive growth or yield. While components of yield accrue in subsequent stages, there is overlapping of these stages in which competition occurs between them for additional growth essentials available due to lost plants. In the absence of plant stresses, the reduced plant population will result in fewer spikes per unit area but more and heavier kernels per spike (Darwinkel, 1978).

Many experiments have been conducted to examine plant responses in terms of yield and yield components for management adjustments to date, rate, depth of seeding, and row spacing. However, little research with cereal grains has been performed on populations diminished by environmental conditions such as frost, hail, wind, poor emergence, seedling mortality, or winterkill. The objectives of this study were to: 1.) Measure the compensation ability of several cultivars over a range of reduced plant populations; 2.) Determine the critical reduced plant population at which a significant yield reduction occurs; and 3.) Measure secondary plant variable responses over a range of reduced plant populations. This study was conducted to verify the current recommendations on viable stand density or to establish a new criteria if needed. The current recommendation dates back some 30 years and doesn't take into account changes in farming practices as well as varietal improvements.

Table 1. Winter wheat planted and harvested acres as affected by winter kill for the past ten years.

	---------million acres----------		
Year	Planted	Harvested	Not harvested
1985	2.46	1.40	1.06
1986	2.15	2.00	0.15
1987	2.30	2.20	0.10
1988	2.45	2.10	0.35
1989	2.50	1.50	1.00
1990	2.70	2.50	0.20
1991	2.35	1.90	0.45
1992	2.60	2.25	0.35
1993	2.65	2.45	0.20
1994	1.95	1.85	0.10

SOURCE Montana Agricultural Statistics 1995.

CHAPTER 2

LITERATURE REVIEW

Winterhardiness

The ability to tolerate specific stresses such as freezing, icing, flooding, desiccation, and diseases directly determine the level of winterhardiness genetically present in cereal grains (McKersie and Hunt, 1987). Breeding for winterhardy cultivars has long been a troublesome task because of the difficult and time consuming selection process. Currently, measurements used for evaluating the winterhardiness potential of wheat are broken into two primary approaches which include survival under field conditions, and the use of plant characteristics for which differences can be measured and then correlated with field survival (Fowler et al., 1981).

The survival of wheat under field conditions has long been recognized as the ultimate test in determining a cultivar's level of winterhardiness (Fowler et al., 1981). The standard procedure is to plant in an area where winterkill is frequent in order to measure spring survival and resulting yield. This process is slow and often hindered by fluctuations in weather within and between years in that winterhardiness is an interaction between the plant and the environment (DeNoma et al. 1989). Environmental conditions often produce either complete or no winterkill which results in inconclusive field survival trials (Fowler and Gusta, 1979). Variation in stress levels within field experiments make it difficult to identify small but important differences among cultivars even when differential winterkill does occur (Fowler 1979). Because of the limitations inherent in field trials, there has been a continuing search for rapid and efficient methods useful in predicting the cold resistance of cultivars. In the pursuit of a perfect screening method, practically every biochemical, physiological, and morphological character change in the plant during cold acclimation has been carefully examined. From this, a large number of prediction tests have been developed (Fowler et al., 1981).

Prediction Tests for Winterhardiness

While many ideas and disagreements surround winterhardiness, most researchers do agree upon one thing. The crown and surrounding tissues are the plants' vital area. Chen et al. (1983) stated that the crown is the critical plant part in terms of winter survival since it is the site of both root and leaf growth in the spring. Therefore, many experiments have been conducted using the crown as a possible screening tool. Fowler et al. (1981) conducted LT_{50} tests on harvested crowns to determine at what lethal temperature 50 percent of the crowns within a cultivar were killed. Denoma et al. (1989) hypothesized that osmotic potential of hardened wheat crowns might be used as a screening technique for winterhardiness. This was based upon the fact that reduced crown water content is one of the first events that can be measured during cold acclimation (Fowler and Carles, 1979). Nass (1983) and Metcalf et al. (1970) found an inverse relationship between winterhardiness and wheat water content. While these prediction screens have yielded general patterns and tendencies, limitations have prompted other authors to explore additional possibilities.

Fowler et al. (1981), Levitt (1956), and Taylor (1983) reported these seedling characteristics to be associated with winterhardiness: 1.) dark green leaves; 2.) smaller leaf area; 3.) narrow leaves; 4.) prostrate growth habit; 5.) lower crown water content; and 6.) more cuticularized leaves. Barta and Hodges (1970) continued studies done previously to characterize net CO_2 assimilation during hardening as it relates to carbohydrate concentrations and cold hardiness. Dozens of additional tests have been attempted with results being somewhat speculative. Most professionals in this field of expertise will agree that satisfactory tests have yet to be developed. Fowler et al. (1981) suggests that a useful screening test for winterhardiness should include these characteristics: 1.) high repeatability; 2.) simplistic; 3.) strongly correlated with field survival; 4.) quick; 5.) non-destructive; and 6.) require a single plant for analysis. While this paramount test is far from being developed, the incorporation of as many of these characteristics as possible will lead to a more valuable and successful prediction test.

Winterkill

The geographical distribution and yielding capability of most agricultural crops is primarily determined by that specific crop's ability to withstand low temperatures and freezing (Webb et al., 1994). Plant death or injury caused by freezing, icing, flooding, desiccation, and disease during winter season is referred to as winterkill or winter injury. Levitt (1980) reports that when herbaceous plant tissue is subjected to progressively lower freezing temperatures, the water in the plant often supercools, and freezes at specific temperatures related to the ice nucleation point of the tissue. Plant cell death occurs upon the initiation of ice crystal formation at the intracellular level and is inevitably lethal because cell membranes and subcellular structures are mechanically ruptured (Weiser, 1970; Levitt, 1980). McKersie and Hunt (1987) state that in areas with adequate snow cover to insulate winter cereal crop from cold air temperatures, winterkill often occurs in low areas where runoff from melted snow accumulates resulting in ice sheeting and suffocation. Taylor and Olsen (1985) acknowledge plant losses due to ice crystal formation at the cellular level, flooding before freezing, and ice sheeting, but point out conditions conducive for these are typical of wetter regions. Therefore, winterkill in the Great Plains, in the absence of excess soil moisture, is more likely to be caused by desiccation. They support this by stating that desiccation is the principle cause of winterkill in wheat (Taylor and Olsen, 1985; 1986). While a limited number of agronomic practices can be utilized to prevent winterkill caused by midwinter or spring flooding (McKersie and Hunt, 1987), studies have been done with standing stubble to trap snow which provides an insulation layer in areas where snowfall is limited and wind common, as a means of controlling winterkill via management decisions (Black and Bauer, 1990).

Yield Components

Grain yield is the final result of numerous interacting environmental and plant factors (Quisenberry, 1928). Quisenberry (1928), Darwinkel (1978), and Guitard et al. (1961), state that the important characters in determining yield are; the number of spikes per unit area, the number of kernels per spike, and the weight of the kernels. Additionally, environment will greatly influence the relationships of these characters, with the effects not necessarily being identical each year. Darwinkel (1978) agrees with this statement and adds the belief that a strong mutual compensation typically exists between these components.

Yield Component Compensation

One reason for the success of cereals as crops is their capacity for yield component compensation, i.e., for the later-determined components of grain yield to compensate for earlier losses or restrictions of development in addition to taking advantage of favorable conditions late in the crop life cycle (Evans and Wardlaw, 1976). While this concept is well documented and accepted, many authors differ in opinions of which component is most important or if each is of equal importance. Rhode (1963) in his studies of yield components, summarized that individual yield components were not significantly correlated with grain yield. However, most studies show correlations between final yield and its components.

Spikes per unit area were reported to be closely associated with differences in yield by Stickler (1961), Quisenberry (1928), and Evans and Wardlaw (1976). Cook and Veseth (1991) point out that the tillering capacity of winter wheat provides a genetic buffer and insurance against the variable environments of north America. They continue by stating that under extreme conditions, yield is a direct function of main stems and spikes independent of management or variety. However, given a thinned stand as a result of winterkill and unusually favorable growing conditions thereafter, survivors can make up the difference with the production of additional tillers. Darwinkel (1978) and Quisenberry, (1928) reported that kernels per spike was highly correlated with yield. While acknowledging that kernels per spike was associated with yield, Stickler (1961) believed the contribution of that component was considerably less than spikes per unit area. It is recognized that variation in kernel weight allows for yield compensation late in the life cycle, but that larger compensation must occur earlier in the crop life cycle (Evans and Wardlaw, 1976; Darwinkel, 1978). Many authors concluded kernel weight was not as important a factor in final yield determination as spikes per unit area and kernels per spike (Quisenberry, 1928; Briggle et al., 1967; Stickler, 1961). Others simply report a significant correlation between kernels per unit area which combines the first two components with yield (Darwinkel, 1978; Miller et al., 1991). Dry and hot conditions typical to Montana during grain fill would probably prove kernel weight to be an important component of yield.

Plant Responses to Differing Populations

Field plant populations can fluctuate for many reasons. Abiotic and biotic factors lead to a wide range of populations. Measuring plant responses allow producers to make educated decisions based on establishing or maintaining field densities. As plant populations increase, spikes per unit area increase (Stickler et al., 1964; Puckridge and Donald, 1967; Darwinkel, 1978; Blue et al., 1990; Black and Bauer, 1990). The same was found to be true of final yield. As plant density increased, yield increased, peaked, and then declined (Stickler et al., 1964; Darwinkel, 1978; and Blue et al., 1990). The second developing component, kernels per spike, decreased with an increase in plant population under experimental conditions (Kumbhar and Larik, 1982; Puckridge and Donald, 1967; Briggle et al., 1967; Evans and Wardlaw, 1976; Darwinkel, 1978; and Miller et al., 1991). Kernel weight displayed a general trend of decreasing in relation to rising plant populations (Kumbhar and Larik, 1982; Puckridge and Donald, 1967; Briggle et al., 1967; Evans and Wardlaw, 1976; Darwinkel, 1978). As a direct response to competition, an increased plant population resulted in taller plants (Puckridge and Donald, 1967; Briggle et al., 1967), and more tillers or spikes per plant (Puckridge and Donald, 1967; Briggle et al., 1967; Darwinkel, 1978; Black and Bauer, 1990). While other plant traits such as test weight, heading date, and protein content have been examined, not enough data has been generated to draw meaningful conclusions. Again, all plant responses are variable and year and location dependent, but can be predicted under a typical environment.

Effects of Management Practices on Yield

Producers have long strived to combine the optimal rate of seeding and row spacing with date and depth of seeding to maximize small grain yields. The recommended seeding rate in Montana is 33.6 to 67.2 kg/ha for dryland production and 67.2 to 84 kg/ha for irrigated production with heavier seeding rates applicable to plump seed of high test weight or varieties with larger kernel size (Montana State University Extension Service, 1985). Recommended seeding dates fall between September 1 and 15 for the northern and eastern parts of the state and September 10 to 25 for the rest of the state. The general rule of thumb is to seed when the soil temperature stays below 13 degrees Celsius, except for brief periods during the day. The Crop Management Handbook for Wheat and Barley Production in Montana provides the same recommendations but include some expanded generalizations: Winter wheat planted before September 1 runs a high risk of disease, September 1 thru 10 is best in winter stress areas, September 7 thru 20 is most common in major growing areas, September 20 thru October 1 is reasonably safe in south-central Montana, October 1 thru 15 remains low risk, October 15 thru 30 is very high risk for winterkill, and anything after November 1 is likely superior to spring wheat but environmentally sensitive. Spacing affects root development, plant growth, and ultimately yield. Spacing plants too closely results in excess competition between plants and lowers yield while excessively wide spacing will allow water, sunlight, and nutrients to go unused (Kumbhar and Larik, 1982). Delaying the date of seeding in small grains results in decreased yields because individual components of yield have less time to be fully exploited (Stevens, 1965; Darwinkel et al., 1977). Seeding rate was found to have no effect on yield by Stevens (1965) and Darwinkel et al. (1977) because of the mutual compensation of yield components. Frederick and Marshall (1985) found increases in yield with increased seeding rates in only three of eight trials. This relationship was reported until a population was reached in which additional plants were detrimental to yield due to intense inter-plant competition. Unanimously, yield increased as row spacings were decreased (Siemens, 1963; Frederick and Marshall, 1985; Marshall and Ohm, 1987; Beuerlein and LaFever, 1989a; 1989b). The results in seeding rate studies prompted two authors to suggest current seeding rates were too high (Boyd, 1952; Woodward, 1956).

CHAPTER 3

MATERIALS AND METHODS

Three winter wheat cultivars differing in levels of genetic winterhardiness, 'Kestrel', 'Judith', and 'Neeley', were seeded at three Montana locations in 1993 and six Montana locations in 1994 (Fig. 1). Kestrel, Judith, and Neeley have relatively high, medium, and low winterhardiness, respectively (Table 2). Planting dates and plot dimensions varied among environments (Table 3). Environments also differed in annual precipitation, winter temperatures, soil types, and soil series (Tables 4 and 5). All trials were located in non-irrigated fields, however, Bozeman 1995 was irrigated prior to planting due to an extremely dry seedbed. The two Bozeman trials had a rotation of wheat, peas, and fallow. All trials were seeded into tilled soil which had been summer fallowed the previous season.

Seven treatments were implemented to simulate differing levels of winter plant survival. Treatments were defined as percentages of control stand (67.2 kg/ha, 215 plants/m^2) and reported as plants/meter^2 (Table 6). Actual stands were less than target stands at some locations due to poor emergence and natural winterkill. Straw was applied to control treatments (100% survival) and then held down with stakes and twine in 1993 to eliminate any natural winterkill. This resulted in smothering of the seedlings in the spring of 1994 at Bozeman. Plants were lost and survivors showed the effects of stunting throughout the growing season. Based on these observations, it was determined that the control treatment no longer represented the target density and the control was lost from the 1994 Bozeman trial. In 1994, plantings had two sets of control checks. One control plot was covered with straw held in place by mesh netting and the other left uncovered. The control treatment with the highest level of survival was used for analysis.

A randomized complete block design with three replications was used at all locations. Each experimental site was seeded at a rate of 66 seeds/meter of row or 67.2 kg/ha with row spacings of 0.3 meter. Individual plots consisted of six rows at 6.1 meter in length.

Winterkill simulation was accomplished with seed replacement of 'Fortuna' spring wheat at levels equal to desired winterkill percentages (Table 7). Provided with typical winter conditions, spring wheat planted in the fall will winterkill. To fully simulate winterkill, a full stand of seedlings was needed during fall stand establishment with stand reduction occurring during the winter. Fortuna was chosen because it is awnless and recognizable based on seedling characteristics, which allowed spring wheat survival to be visually determined. Three trials were lost due to the overwintering success of Fortuna. Favorable climatic conditions including constant snow cover and mild temperatures enhanced spring wheat survival and resulted in non-usable mixed stands of spring and winter wheat. A fourth trial (Moccasin 1994) was lost to fall and early spring wind damage (Table 3).

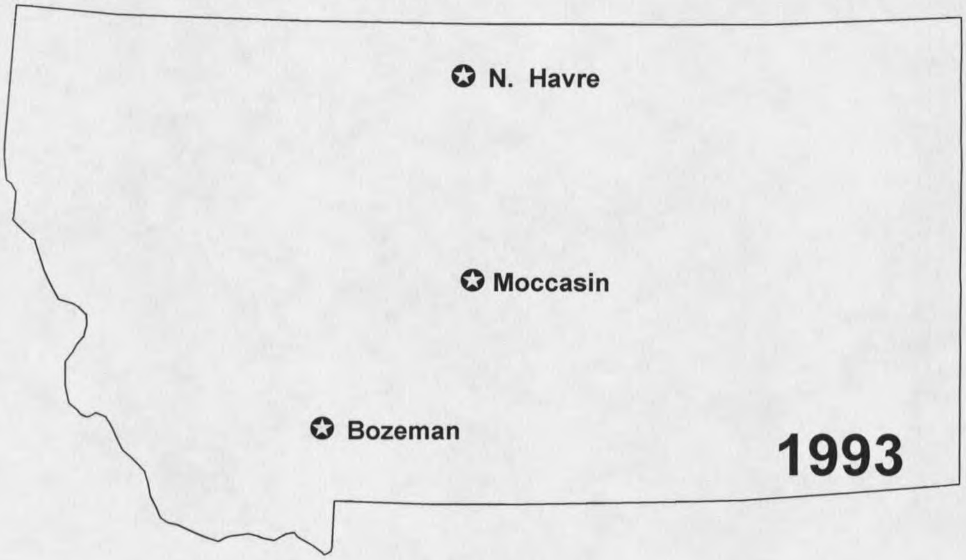
Weed control was carried out on a field need basis. These studies were conducted within larger fields and herbicide application was done in a manner consistent with the entire field. While weeds were more problematic in this study than the overall field, no additional steps to control them were taken in an attempt to simulate actual winterkill problem sites. Herbicide application is outlined in Table 8.

The collection of data was identical for each of the five harvested trials. Plants per meter^2 were counted shortly after spring regrowth began. Two 0.91 meter plant counts were made in each plot. Counts were taken at the same location of rows two and five of all plots. Plant counts were then converted to an area basis. Heading data was recorded when 50% of the spikes were 50% emerged from the boot. No heading notes were collected at North Havre due to the remoteness of the site. Spikes per meter^2 were counted in the same area and manner as plants per meter^2. All viable spikes were included in the total. The division of spikes per meter of row by plants per meter of row estimated tillers per plant. Height was measured between physiological and harvest maturity at the front of each plot. Just prior to harvest, 20 random spikes were selected from each plot and threshed with a belt thresher. The seed number and weight of the composite 20 spike sample was used to calculate kernels per spike and 1000 kernel weight. The center four rows of each plot were harvested with a plot combine and reported as kilograms per hectare.

Plot area was established by measuring and/or trimming to desired length (Table 3). Seed was cleaned and processed to obtain grain volume weight (kilograms per meter^3) using official grain standard procedures. At this time, 100 gram subsamples were submitted to the Montana State University cereal quality lab for grain protein evaluation using an Infratec whole kernel analyzer.

Data for all variables were analyzed via analysis of variance using MSUstat 5.1. Locations were analyzed separately, and across locations in 1995. Bozeman 1994 was omitted from the combined analysis because of missing data. Regression analysis tables included in figures 2 thru 5 were also computed using MSUstat 5.1.

Figure 1. Nursery sites of trials planted in 1993 and 1994.



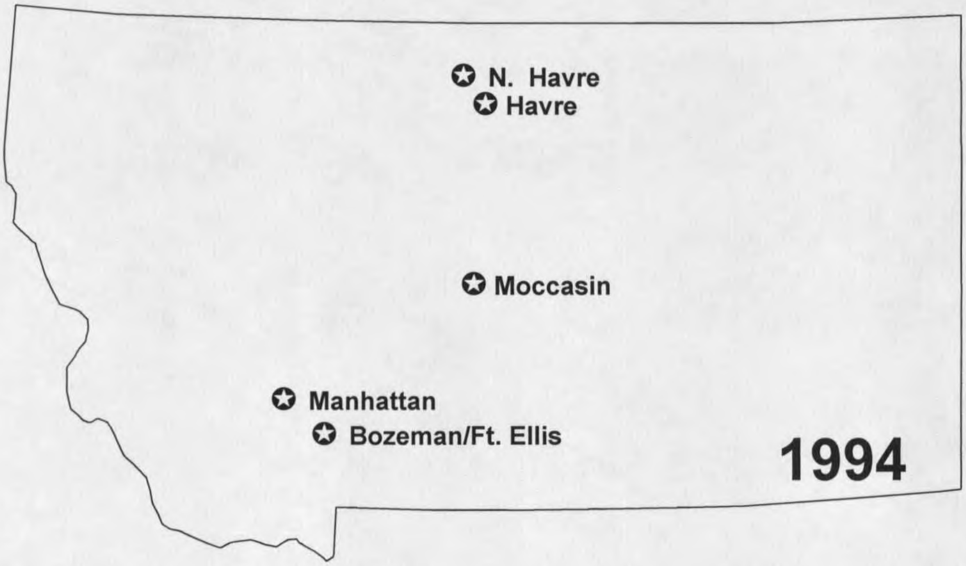


Table 2. Pedigrees and winterhardiness ratings of the three cultivars used in study.

Cultivar	Pedigree	Winterhardiness Rating†
Kestrel	Norstar*2/Vona	5
Judith	Lancota/Froid// NE69559/Winoka	3
Neeley	Heglar/3/Norin10/ Staring//2*Cheyenne	3

† 1= Wintertender, 5= Winterhardy

Table 3. Experimental protocols for trials planted in nine Montana environments.

Location	Harvest Year	Planting Date	No. of Reps†	Rows/ Plot	Harvested Rows/ Plot	Harvested Plot area m^2
1 Bozeman	1994	9/29/93	3	6	4	5.95
2 Moccasin	1994	9/30/93	3	6	-‡	-
3 N. Havre	1994	10/7/93	3	6	-	-
4 Bozeman	1995	9/23/94	3	6	4	6.32-7.71
5 Ft. Ellis	1995	10/7/94	3	6	-	-
6 Havre	1995	9/28/94	3	6	4	5.95
7 Manhattan	1995	10/6/94	3	6	-	-
8 Moccasin	1995	9/27/94	3	6	4	4.10-5.11
9 N. Havre	1995	9/30/94	3	6	4	5.95

† Number of replications
‡ Missing values indicates locations not harvested

Table 4. Fertilizer formulation, placement, and amount for trials in five Montana environments.

	Fertilizer		
Location	Form	Place	Amount kg/ha
1 Bozeman†	46-0-0	preplant	196
2 Bozeman‡	46-0-0	preplant	146
3 Havre	70-40-25	preplant	78N 45P 28K
4 Moccasin	46-0-0	preplant	67N
	18-46-0	with seed	10N 26P
	46-0-0	topdress	22N
5 N. Havre	30-15-7	preplant	34N 17P 8K

† 1994
‡ 1995

Table 5. Total precipitation, soil series, and soil type for trials in five Montana environments.

Location	Total Precipitation† (cm)	Soil Series	Soil Type
1 Bozeman‡	27.12	Bozeman	Silt loam
2 Bozeman§	46.23	Bozeman	Silt loam
3 Havre	34.80	Telstad	Clay loam
4 Moccasin	51.54	Judith	Clay loam
5 N. Havre	31.75	Telstad	Loam

† Precipitation received from planting date to harvest date
‡ 1994
§ 1995

Table 6. Target and realized plant population treatments established to simulate winter wheat stand loss.

Percent Stand Survival	10	20	30	40	50	75	100
Target population†	22	43	65	86	108	161	215
Realized population‡	22	40	65	83	97	140	187§

† Plants per meter^2

‡ Combined over five locations

§ Treatment does not include Bozeman 1994

Table 7. Winterkill simulation by means of winter and spring wheat seed mixtures to obtain variable survival rates.

Target Stand Survival	Winter Wheat Seeds	Spring Wheat Seeds	Total seeds/ 6.1m row
10%	40	360	400
20%	80	320	400
30%	120	280	400
40%	160	240	400
50%	200	200	400
75%	300	100	400
100%	400	0	400

Table 8. Weed control treatments in five Montana environments.

Environment	Treatment Date	Herbicide	Rate
Bozeman	4/23/94	Bromoxynil & MCPA	1.46L/ha
Bozeman	5/11/95	Bromoxynil	1.46L/ha
Havre	5/17/95	Bromoxynil & MCPA	1.73L/ha
Moccasin	5/17/95	Clopyralid & 2,4-D	2.35L/ha
North Havre	5/11/95	Tribenuron + 2,4-6 ester	0.02L/ha + 0.86L/ha

CHAPTER 4

RESULTS

Bozeman 1994

At Bozeman in 1994, treatments defined by various plant densities varied significantly for spikes/m^2, kernels per spike, kernel weight, and grain yield (Table 9). General trends indicated that winter wheat compensated for stand reductions through increased tillering, more kernels per spike, and heavier kernels. With a decrease in plants per meter^2 from 161 to 22 plants/m^2, spike density remained relatively constant from 161 to 65 plants/m^2, then decreased rapidly at the lower plant populations. Kernels per spike and kernel weight increased as plant population decreased. Grain yield exhibited a pattern similar to spikes per meter^2, remaining relatively constant until plant population was reduced to 43 plants/m^2, at which point further compensation was not great enough to overcome stand loss. Environmental conditions at this location were nearly ideal for plant growth and yield component compensation. Adequate moisture, moderate temperatures, and high fertility resulted in high grain yields maximized with the equivalent of a 30% stand (65 plants/m^2). Cultivars did not vary for spikes/m^2, but varied for kernels per spike, kernel weight, and grain yield (Table 9). Kestrel was the lowest yielding cultivar at this location with the lowest kernel weight but the greatest number of kernels per spike. Judith was intermediate for yield and kernel weight and had the fewest kernels per spike. Neeley was the highest yielding cultivar with an intermediate number of kernels per spike but the heaviest kernels. The cultivar X plant population interaction was significant for kernel weight only.

Plant population also had significant effects on height, heading date, protein content, test weight, and tillers per plant (Table 10). Reduced plant population was associated with reduced height, later maturity, and higher protein content although differences were small and of limited practical significance. Test weight declined continuously and tillers/plant increased continuously from the highest to lowest plant population. Results demonstrate the high degree of potential yield compensation that can occur due to increased tillering as plant populations decrease. Cultivars varied for height, heading date, protein content, and test weight, but not for tillers/plant (Table 10). Judith and Neeley were highest for protein content and Kestrel and Judith had the lowest test weight. Kestrel was the tallest cultivar, was intermediate for heading date, and had the lowest protein content. Judith was the shortest cultivar and had the earliest heading date. Neeley had the highest test weight but was the last to head. Cultivar X plant population interactions were significant for heading date and highly significant for test weight demonstrating differences among cultivars in their response to reduced plant populations.

Table 9. Mean values of yield components and grain yield as affected by plant population and cultivar at Bozeman in 1994.

Variables	Spikes/ m^2	Kernels/ spike	Kernel weight	Grain yield
			mg	kg/ha
Plant Population(T)				
plants/m^2				
22	277.5	64.0	41.4	5067
43	432.6	55.0	39.2	6082
65	532.6	47.5	38.2	6360
86	563.1	44.2	37.8	6556
108	562.3	42.4	36.8	6494
161	623.5	40.4	37.1	6574
215†				
LSD (0.05)	39.5	3.1	1.2	225
CV (%)	8.3	6.7	3.3	3.8
Cultivar(C)				
Kestrel	511.6	53.9	34.1	5913
Judith	480.6	44.4	39.6	6189
Neeley	503.6	48.5	41.7	6464
LSD (0.05)	ns‡	2.2	0.9	159
Interaction				
C*T	ns	ns	*	ns

* significant at the 0.05 probability level

† treatment lost to smothering

‡ nonsignificant at the 0.05 probability level.

Table 10. Mean values of height, heading date, protein content, test weight, and tillers/plant as affected by plant population and cultivar at Bozeman in 1994.

Variables	Height	Heading date	Protein content	Test weight	Tillers/ plant
	cm	Julian days	%	kg/m^3	
<u>Plant Population(T)</u>					
plants/m^2					
22	96.7	163.9	12.3	758.6	14.6
43	98.2	163.6	12.1	781.9	10.3
65	100.1	163.6	12.0	794.9	6.8
86	100.2	163.3	12.0	796.9	5.9
108	100.0	163.1	12.0	799.2	5.5
161	100.3	162.9	12.1	803.9	4.4
215†					
LSD (0.05)	1.6	0.3	0.2	4.4	1.8
CV (%)	1.7	0.2	1.6	0.6	24.7
<u>Cultivars(C)</u>					
Kestrel	102.5	164.8	11.8	781.1	8.2
Judith	96.8	160.0	12.2	781.1	7.9
Neeley	98.4	165.4	12.3	804.7	7.8
LSD (0.05)	1.1	0.2	0.1	3.1	ns‡
<u>Interaction</u>					
C*T	ns	*	ns	**	ns

*,** significant at the 0.05 and 0.01 probability levels, respectively.

† treatment lost to smothering

‡ nonsignificant at the 0.05 probability level.

1995 Combined Analysis

In a combined analysis over the 1995 locations, plant population, cultivar, and location had significant effects on all measured variables (Table 11 and 12). All cultivar X plant population interactions were non-significant indicating responses to decreased plant populations were similar in all cultivars. All cultivar X location interactions were significant. With the exception of kernels per spike, all plant population X location interactions were also significant. All cultivar X plant population X location interactions were non-significant except protein content, test weight, and tillers per plant. As plant population decreased from 215 to 22 plants per meter^2, generalized responses were as follows: a linear decrease in spikes per meter^2, a 50% increase in kernels per spike, a slight increase in kernel weight, and a 34% decrease in grain yield. Neeley and Kestrel were highest in yield, Neeley with relatively fewer spikes per meter^2 but with large spikes and heavy kernels, and Kestrel with many spikes per meter^2 and large spikes but small kernels.

Kernels per spike varied significantly among treatments, cultivars, and locations. With a decrease in plants per meter^2, kernels per spike increased linearly from 36.3 to 53.5. Neeley and Kestrel produced the highest number of kernels per spike. Kernels per spike was greatest at Bozeman (48.7 kernels per spike), followed by Havre, North Havre, and Moccasin. The cultivar X location interaction was highly significant although all other interactions were nonsignificant.

Kernel weight varied significantly among plant populations, cutlivars, and locations. As plant population decreased, kernel weight increased slightly (36.6 mg to 38.2 mg). Neeley produced the heaviest kernels (39.6), followed by Judith and Kestrel. Kernel weights were the heaviest at Bozeman, intermediate at Havre and Moccasin, and lowest at North Havre. Cultivar X location and plant population X location interactions were significant. The plant population X location interaction arose because plant population influenced kernel weight at only one of the four locations.

Significant differences were detected among plant populations, cultivars, and locations for grain yield. Yield remained relatively constant with diminishing plant population to about 50% stand (108 plants per meter^2), then declined steadily to the lowest plant population. On average, Neeley and Kestrel were the top yielders. Bozeman by far was the best yielding location (7078 kg/ha), followed by Havre, Moccasin, and North Havre (2508 kg/ha). The cultivar X location interaction for grain yield was highly significant.

Other responses to decreased plant population include a decrease in height, slightly later maturity, slightly higher protein, lower test weight and more tillers per plant. Neeley was the tallest cultivar, while Judith was the shortest. Neeley was the last cultivar to head and Judith the earliest. Judith and Neeley had the highest protein content. Kestrel and Neeley had the highest test weight. Kestrel and Judith produced the most tillers per plant. Moccasin due to a visually recognizable nitrogen deficiency, had the fewest tillers per plant. Because cultivar X location and plant population X location interactions were predominantly significant, responses were examined in individual 1995 environments.

Table 11. Mean values of yield components and grain yield as affected by plant population and cultivar over four locations in 1995.

Variables	Spikes/ m^2	Kernels/ spike	Kernel weight	Grain yield
			mg	kg/ha
<u>Plant Population(T)</u>				
plants/m^2				
22	257.4	53.5	38.2	3265
43	320.1	49.5	37.7	4004
65	359.9	47.0	37.5	4259
86	386.9	43.2	37.8	4485
108	417.3	42.1	37.7	4738
161	471.8	38.7	37.0	4872
215	522.9	36.3	36.6	4975
LSD (0.05)	24.3	1.5	0.6	180
CV (%)	13.3	7.4	3.4	8.8
<u>Cultivar(C)</u>				
Kestrel	411.8	45.8	34.6	4393
Judith	396.2	40.4	38.3	4213
Neeley	364.7	46.9	39.6	4507
LSD (0.05)	15.9	1.0	0.4	118
<u>Location (L)</u>				
Bozeman	516.2	48.7	41.8	7078
Havre	450.6	44.9	37.0	4630
Moccasin	291.4	40.7	38.9	3269
North Havre	305.3	43.0	32.4	2508
<u>Interactions</u>				
CxT	ns†	ns	ns	ns
CxL	*	**	**	**
TxL	**	ns	**	*
CxTxL	ns	ns	ns	ns

*,** significant at the 0.05 and 0.01 probability levels, respectively.

† nonsignificant at the 0.05 probability level.

Table 12. Mean values of height, heading date, protein content, test weight, and tillers/plant as affected by plant population and cultivar over four locations in 1995.

Variables	Height	Heading date	Protein content	Test weight	Tillers/ plant
	cm	Julian days	%	kg/m^3	
Plant Population(T)					
plants/m^2					
22	83.7	173.5	12.1	741.1	12.5
43	85.4	172.9	11.9	753.9	8.1
65	85.3	172.6	11.6	757.3	6.0
86	87.0	172.5	11.4	760.4	4.9
108	86.7	172.2	11.3	765.1	4.5
161	87.5	172.2	11.3	766.3	3.5
215	90.0	172.0	11.1	767.4	2.9
LSD (0.05)	1.6	0.4	0.2	3.9	0.6
CV (%)	3.9	0.5	3.7	1.1	21.0
Cultivars(C)					
Kestrel	90.2	172.7	10.6	763.0	6.4
Judith	84.1	177.4	12.0	747.7	6.3
Neeley	95.2	173.6	12.1	765.7	5.5
LSD (0.05)	1.0	0.3	0.1	2.6	0.4
Location (L)					
Bozeman	103.8	173.8	12.0	795.6	6.8
Havre	85.2	165.6	11.3	761.7	7.6
Moccasin	83.5	178.2	10.8	785.3	4.0
North Havre	73.6	172.5	12.2	692.6	5.9
Interaction					
CxT	ns†	ns	ns	ns	ns
CxL	**	**	**	**	*
TxL	**	**	**	**	**
CxTxL	ns	ns	*	*	**

*,** significant at the 0.05 and 0.01 probability levels, respectively.

† nonsignificant at the 0.05 probability level.

Bozeman 1995

At Bozeman in 1995, treatments varied significantly for spikes/m^2, kernels per spike, kernel weight, and grain yield (Table 13). Patterns of change in yield components and yield in response to reduced plant population were similar at Bozeman in 1995 to those previously reported for Bozeman in 1994. As plant population decreased by 90%, the number of spikes per meter^2 decreased linearly by over 50%, kernels per spike increased by nearly 50%, and kernel weight increased by 14% over the range of plant populations. Grain yield remained statistically constant until plant population was reduced between 108 and 86 plants/m^2, at which point surviving plants could no longer compensate for those lost earlier. Environmental conditions at this location were again nearly ideal for plant growth and yield component compensation. Adequate moisture, moderate temperatures, and generous amounts of fertilizer resulted in very high grain yields maximized with the equivalent of a 50% stand (108 plants/m^2), however, in this environment a 20% plant population resulted in 90% of maximum yield. Cultivars did not vary for spikes/m^2, but did differ for kernels per spikes, kernel weight, and grain yield (Table 13). Kestrel was the lowest yielding cultivar at this location with the lowest kernel weight and intermediate kernels per spike. Judith was the highest yielding cultivar with the lowest number of kernels per spike and intermediate kernel weight. Neeley was intermediate for yield with the heaviest kernel weight and most kernels per spike. Cultivar X plant population interaction was not significant for all traits.

Plant population also had significant effects on height, protein content, and tillers per plant (Table 14). Reduced plant population was associated with reduced height and to a smaller degree, higher protein content. Tillers per plant increased continuously from the highest to lowest plant population. Results again demonstrate the high degree of potential yield compensation that can occur due to increased tillering as plant populations decrease. Cultivars varied significantly for heading date, protein content, and tillers per plant. Kestrel and Judith produced the most tillers/plant. Kestrel had an intermediate heading date and the lowest protein content. Judith was the earliest to head and was intermediate in protein content. Neeley had the highest protein content but was the latest to head. Cultivar X plant population interactions were not significant for any of the traits.

Table 13. Mean values of yield components and grain yield as affected by plant population and cultivar at Bozeman in 1995.

Variables	Spikes/ m^2	Kernels/ spike	Kernel weight	Grain yield
			mg	kg/ha
Plant Population(T)				
plants/m^2				
22	326.9	59.7	44.6	5877
43	403.6	53.4	43.0	6862
65	476.3	50.9	41.7	7166
86	520.8	47.4	41.9	7092
108	546.2	46.0	41.6	7443
161	635.9	42.3	40.4	7613
215	703.7	41.3	39.1	7535
LSD (0.05)	56.9	2.4	1.3	340
CV (%)	11.6	5.1	3.1	5.1
Cultivar(C)				
Kestrel	521.8	49.7	38.3	6646
Judith	536.2	45.2	43.0	7405
Neeley	490.6	51.2	44.0	7201
LSD (0.05)	ns†	1.5	0.8	223
Interaction				
CxT	ns	ns	ns	ns

† nonsignificant at the 0.05 probability level.

Table 14. Mean values of height, heading date, protein content, test weight, and tillers/plant as affected by plant population and cultivar at Bozeman in 1995.

Variables	Height	Heading Date	Protein content	Test weight	Tillers/ plant
	cm	Julian days	%	kg/m^3	
Plant Population(T)					
plants/m^2					
22	95.7	173.8	12.2	797.2	12.6
43	101.1	173.4	11.9	798.1	8.9
65	100.7	173.9	11.9	796.9	7.3
86	103.9	173.9	11.8	796.8	6.2
108	105.1	173.6	11.9	802.5	5.0
161	107.7	174.0	11.9	789.9	4.1
215	112.1	174.3	12.0	787.9	3.5
LSD (0.05)	3.4	ns†	0.2	ns	1.0
CV (%)	3.5	0.4	1.6	1.3	15.1
Cultivars(C)					
Kestrel	103.6	174.1	11.1	797.9	7.3
Judith	104.9	171.1	12.0	791.1	6.9
Neeley	102.8	176.3	12.7	797.9	6.2
LSD(0.05)	ns	0.5	0.1	ns	0.6
Interaction					
CxT	ns	ns	ns	ns	ns

† nonsignificant at the 0.05 probability level.

Havre 1995

At Havre in 1995, treatments varied significantly for spikes/m^2, kernels per spike, and grain yield (Table 15). Yield component responses to reduced plant populations displayed general trends similar to previously discussed locations with the exception of kernel weight which was not affected by plant population. With decreasing plant population, spikes/meter^2 decreased and kernels per spike increased. Yield remained nearly constant with diminishing plant populations from 215 to 86 plants/m^2 (40%), then decreased incrementally as stands were further reduced. At less than 40% stand, plants could no longer fully compensate for stand loss. While dry seedbed conditions existed at seeding, conditions at this location were favorable for plant growth and yield component compensation. Fertility and temperatures were good with higher than normal rainfall present throughout the growing season. No severe stresses occurred. Cultivars varied for spikes/m^2, kernels per spike, kernel weight, and grain yield (Table 15). Kestrel and Neeley were the highest yielding cultivars at this location with Kestrel producing the highest spike density and most kernels per spike but lowest kernel weight. Judith was the lowest yielding cultivar with the fewest kernels per spike and intermediate spike density and kernel weight. Neeley had the heaviest kernels, intermediate kernels per spike, and the lowest spike density. The cultivar X plant population interaction was significant for kernel weight and grain yield, and highly significant for kernels per spike. The presence of this interaction suggests that cultivars were responding differently to the plant population treatments at this location. Results were cultivar specific and treatment means were not descriptive of individual cultivar responses.

Plant population had significant effects on heading date, protein content, test weight, and tillers per plant, but did not affect height (Table 16). Responses to decreased plant stands were similar to those observed at Bozeman in 1994, although greater in magnitude. Relative to control plant density (215 plants/m^2), the lowest plant population treatment was on average 2.1 days later heading, 1.3% higher in protein content, 34.2 kg/m^3 lower in test weight, and had 15.9 more tillers/plant. The large increase in tillers per plant (630%) demonstrates the tremendous plasticity and huge compensatory potential of tillering to overcome losses in plant stands. Enhanced tillering as stands were reduced from 100% to 10% stabilized spikes per meter^2 which decreased only by about 40% and yield which was reduced by about 33% due to the 90% stand loss. Cultivars varied for all traits except heading date. Kestrel was tallest and had the lowest protein content. Judith and Neeley were similar in height, protein content, and tillers per plant. Judith had the lowest test weight. Cultivar X plant population interactions were highly significant for height and tillers/plant. Again cultivars reacted differently and specifically to decreasing plant populations.

Table 15. Mean values of yield components and grain yield as affected by plant population and cultivar at Havre in 1995.

Variables	Spikes/ m^2	Kernels/ spike	Kernel weight	Grain yield
			mg	kg/ha
Plant Population(T)				
plants/m^2				
22	332.9	55.6	36.4	3415
43	410.4	51.2	36.4	4260
65	432.6	46.7	37.0	4577
86	442.6	44.0	37.7	4874
108	483.0	41.7	37.3	5119
161	501.2	38.2	36.9	5155
215	551.8	36.9	37.0	5037
LSD (0.05)	47.0	1.9	ns†	296
CV (%)	11.0	4.4	3.3	6.7
Cultivar(C)				
Kestrel	472.1	49.1	34.2	4862
Judith	447.1	40.8	37.9	4201
Neeley	432.7	44.9	38.8	4839
LSD (0.05)	30.8	1.2	0.8	194
Interaction				
C*T	ns	**	*	*

*,** significant at the 0.05 and 0.01 probability levels, respectively.

† nonsignificant at the 0.05 probability level.

Table 16. Mean values of height, heading date, protein content, test weight, and tillers/plant as affected by plant population and cultivar at Havre in 1995.

Variables	Height	Heading date	Protein content	Test weight	Tillers/ plant
	cm	Julian days	%	kg/m^3	
Plant Population(T)					
plants/m^2					
22	83.7	167.0	12.1	738.6	18.9
43	86.1	166.1	11.7	753.5	10.3
65	85.2	165.4	11.3	757.3	7.1
86	85.6	165.8	11.1	763.6	5.6
108	85.8	165.0	10.8	771.3	4.9
161	85.2	164.9	10.9	775.1	3.6
215	84.6	164.9	10.8	772.8	3.0
LSD (0.05)	ns†	0.6	0.3	5.7	1.4
CV (%)	3.3	0.4	2.8	0.8	19.1
Cultivars(C)					
Kestrel	91.9	165.5	10.0	767.1	8.2
Judith	81.6	165.5	11.9	751.9	7.6
Neeley	82.0	165.7	11.9	766.3	7.0
LSD (0.05)	1.8	ns	0.2	3.7	0.9
Interaction					
C*T	**	ns	ns	ns	**

** significant at the 0.01 probability level.

† nonsignificant at the 0.05 probability level.

Moccasin 1995

At Moccasin in 1995, treatments varied significantly for spikes/m^2, kernels per spike, and grain yield (Table 17). General trends indicated that compensation for stand reductions occurred with increased spikes/plant and more kernels per spike. With deceasing plant population, spikes per meter^2 decreased and kernels/spike increased as in the three previously discussed locations. However, kernel weight was unchanged as at Havre in 1995. Yield remained relatively constant with diminishing plant populations from 215 to 108 plant/m^2 (50%), then decreased incrementally as stands were further reduced. At less than 50% stand, compensation for losses in stand was no longer possible. Environmental conditions at this location were not quite as conducive to high yields and component compensation as those dicussed earlier. Stand establishment was less than that of the previous three locations possibly due to poor emergence and/or natural winterkill. Spike density and yields were likely reduced because of a nitrogen deficiency induced by high rainfall early in the growing season and identified visually by general yellowing of the plants. No other stresses were observed. Cultivars did not vary for grain yield, but varied for all yield components (Table 17). Kestrel had the lowest kernel weight and an intermediate number of kernels per spike at this location. Judith was intermediate for kernel weight with the fewest kernels per spike. Kestrel and Judith had the highest spike density. Neeley had the heaviest kernels and most kernels per spike with the lowest spike density. The cultivar X plant population interaction was not significant for any of these traits.

Plant population had significant effects on height, heading date, protein content, test weight, and tillers/plant (Table 18). Relative to control plant density (215 plant/m^2), the lowest plant population treatment was 4.8 cm shorter, 4.4 days later heading, 0.9% higher in protein content, 36.2 kg/m^3 lower in test weight, and had 6.5 more tillers/plant. Again tillering is the component most responsible for yield compensation although not as pronounced as at Havre in 1995. The increase in tillers per plant at this location in response to decreasing plant population was 425%. Cultivars varied significantly for all traits. Kestrel and Neeley were the tallest and had the fewest tillers per plant. Kestrel was intermediate for heading date and test weight, and had the lowest protein content. Judith had the earliest heading date, the highest protein content, and the lowest test weight. Neeley had the highest test weight, intermediate protein content, and the latest heading date. The cultivar X plant population interactions were highly significant for test weight and tillers per plant. The conditions present resulted in cultivars differing in ability to produce tillers and accumulate test weight.