Grain Yield Production Efficiency Per Unit of Evapotranspiration

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Water, more than any other factor, limits crop yields in the northern Great Plains when fertility is adequate. Most management practices in dryland agriculture, directly and indirectly, affect the water supply for a crop. Success in crop production, to a large extent, is determined by skills of the operator in conserving and using water with maximum efficiency.

Cole and Mathews (1923) pointed out that water stored prior to planting and growing season rainfall are equally effective in maintaining the wheat crop during its growth, and that neither water stored in the soil prior to planting nor the amount of growing season rainfall, normally, are sufficient of themselves to meet needs of the crop.

Based on data from 1907-1916 from the former Edgeley Experiment Station, they showed that total water used in evapotranspiration (sum of water lost by evaporation from the soil and transpiration from the plant) was linearly related to spring wheat yields. They reported that about 8.2 inches of water were used in evapotranspiration before any grain was produced, and each inch used in evapotranspiration thereafter produced about 5 bushels per acre. This quantity of water used in evapotranspiration before grain is produced was termed the initial yield point (IYP) by Brun *et al.* (1984) This terminology will be used in this report.

Lehane and Staple (1965) determined that the IYP for spring wheat grown on soils of sandy loam, loam, and clay textures was 2.4, 4.9, and 2.3 inches, respectively; each inch of water used in evapotranspiration thereafter produced 2.0, 3.5, and 2.8 bushels per acre, respectively. In their studies, weeds were a problem in some years. Henry *et al.* (1986) summarized studies from the Canadian Prairie Provinces, some conducted as early as 1925 and including those of Lehane and Staples referenced above, and determined that the IYP for hard red spring wheat ranged from 1.4 to 6.0 inches, and thereafter each inch of water used in evapotranspiration produced 3.5 to 5.0 bushels per acre. For soft white spring wheats and the high yielding Canadian spring wheat HY320, the IYP was 3.0 inches and each inch of water used in evapotranspiration thereafter produced 5.6 bushels per acre.

Brun *et al.* (1984) in field studies determined the IYP for spring wheat as 4.9, 6.6, and 6.8 inches at Fargo, Williston, and Minot, respectively, and that each inch of water used in evapotranspiration threafter produced 5.0, 5.0, and 5.2 bushels per acre, respectively. In studies conducted in weighing lysimeters for six years at Fargo, Brun *et al.* (1989) determined an IYP of 6.0 inches for spring wheat and each inch of water used in evapotranspiration thereafter produced 5.8 bushels per acre. These trials were conducted under conditions of best recent technologies. At Mandan, in the 1988 drought year, S.D. Merrill (USDA-ARS, private communication) determined that 4.0 inches water used in evapotranspiration produced about one bushel of hard red spring wheat.

It is apparent that the IYP is not a constant (fixed) value but that it varies with soils, locations, management, and years. It needs to be recognized that the larger the proportion of the total seasonal evapotranspiration used to the IYP, the larger will be the grain yield response per unit of water used after the IYP water requirement is met.

Halvorson and Kresge (1982) and Brown *et al.* (1985) advanced the concept of "flexible cropping"--a decision to plant a crop or to summerfallow--based on amount of soil water stored at planting and expected growing season precipitation. It provides management guidelines to more efficient precipitation use than is associated with a crop-summerfallow system. Information of spring wheat and barley responses to water, with adequate fertility, were based on data developed by Black and Ford (1976).

With technological advances in aspects of production, updated information about the IYP and grain yield response to water is needed to improve estimates of grain yields based on water supply from stored soil water and growing season rain. Techniques to measure the water quantity stored in the soil at or shortly after planting are available and accurate. Development of the technology to predict growing season rainfall with precision is in its early stages (Weare, 1990).

An approach to estimating growing season rainfall amount is to assume that the 30-year average, or so-called "normal" will be received. Brown *et al.* (1985) suggested using rainfall probabilities and maps to estimate probable growing season precipitation, which were included in their publication. Snider *et al.* (1968), Jensen (1972), and Ramirez (1973) have published such probabilities for various segments of the growing season in North Dakota.

This study provides information on the yield response of spring wheat and barley to water in excess of the IYP in the presence of adequate fertility and weed-free conditions, over a period of several years. An IYP of 4.0 inches water was used in the calculation.

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METHODS

Data were obtained from trials with spring wheat conducted in conjunction with the AgRISTARS program (Agriculture and Resource Inventory Surveys Through Aerospace Remote Sensing), and from spring wheat and barley variety trials conducted in cooperation with the Dickinson Research Center. Information on soil type, planting and harvest dates, and variety or number of varieties planted at each site are listed in Table 1.

At the AgRISTARS sites, the first eight listed in Table 1, the farmer cooperator performed all operations involved with seedbed preparation, planting, fertilization, and weed control. All fields were a minimum of 40 acres. Grain yield was measured by harvesting 24 square meter samples (equivalent to 28.7 square yards) from the field from portions of the landscape representing well- and moderately-well drained soils. Number of heads was counted in each square meter area harvested. After threshing and cleaning, 1,000 kernels were randomly selected from a subsample by an electronic seed counter, dried at 156 degrees Fahrenheit and weighed. Kernels per head were calculated from number of heads, grain yield, and kernel weight.

Trials at Mandan were conducted on summerfallow on the Area IV SCDs and USDA-ARS Cooperative Research Farm. Seed was supplied by the Dickinson Research Center. Planting was done with a press drill, preceded in tandem by an offset disk, to a depth of about 1.5 inches, in 6-inch row spacing. Planting rate was about one million viable seeds per acre based on kernel weight, germination percentage, and kernel water concentration. Each wheat and barley variety plot consisted of one drill width (6 feet) 50 feet long; each variety plot was replicated four times. Varieties planted were those grown commonly in the state. Grain yields were measured by cutting and threshing at least 20 square yards of each plot with a small plot combine. Number of heads were counted in one square meter area (1.2 square yards) of each plot. Kernel weight measurement and the calculation of kernels per head were done as previously described.

Soil water content was measured about once a week from planting to harvest with a neutron moisture meter (Stone *et al.*, 1955) by installing steel tubes to a depth of 6 feet. At the AgRISTARS sites, six tubes were placed into moderately-well to well-drained soils. At Mandan, one tube was placed in each replicate of three wheat varieties in 1979; one wheat variety in 1981, 1982, 1985, and 1986; two wheat and two barley varieties in 1983; one barley variety in 1984 and 1987; and one barley and one wheat variety in 1988, 1989, and 1990. Soil bulk density values, to measure water holding capacity, were obtained from 1-foot increment soil cores removed from the holes made to insert the steel tubes. Bulk density was calculated from the oven-dry soil weight of the core and the core volume. The soil core was air-dried, crushed to pass a 2-millimeter sieve, and subsamples used to measure water concentration at 15 bars soil water tension with a pressure plate apparatus (Richards, 1947). Water held at soil water tensions of 15 bars and less was considered to be available to the wheat and barley.

A rain gauge and other sensors to characterize the weather were installed and monitored at the site or within about a mile of the site. Data of the amounts of growing season rainfall are shown in Table 3.

At Mandan, irrigation water was applied by a sprinkler system to wheat in 1981, wheat and barley in 1983, and barley in 1988. The irrigation amounts applied are shown in Table 3.

Table 1. Site, soil type, planting and harvest dates, and variety where data were collected.

Site	Soil type	Planting	Harvest	Variety
		---------- mo/day	----------	
1979 Winter	Barnes-Svea L.	6/01	8/29	Ellar
1979 Marquart	Barnes-Svea L.	5/29	9/05	Cando (durum)
1980 Winter	Barnes-Svea L.	5/02	8/11	Ellar
1980 Ystaas	Barnes-Svea L.	6/02	9/08	Len
1980 Marquart	Barnes-Svea L.	4/30	8/04	Cando (durum)
1981 Winter	Barnes-Svea L.	5/07	8/17	Cando (durum)
1981 Ystaas	Barnes-Svea L.	5/19	8/26	Len
1981 Marquart	Barnes-Svea L.	4/23	8/07	Ward (durum)
1979 Mandan	Williams L.	5/01	8/10	12[1]
1981 Mandan	Williams L.	4/22	8/10	6[1]
1982 Mandan	Williams L.	5/04	8/11	8[1]
1983 Mandan	Williams L.	4/27	8/04-7/28[3]	7-8[2]
1984 Mandan	Williams L.	5/10	8/07-8/02[3]	6-7[2]
1985 Mandan	Williams L.	4/24	8/02-7/23[3]	8-5[2]
1986 Mandan	Williams L.	5/02	8/08-8/01[3]	9-7[2]
1987 Mandan	Williams L.	4/23	7/30-7/15[3]	7-5[2]
1988 Mandan	Williams L.	4/25	7/21-7/15[3]	8-6[2]
1989 Mandan	Williams L.	4/24	7/26-7/21[3]	10-6[2]
1990 Mandan	Williams L.	4/24	8/02-7/27[3]	9-6[2]

[1] Number of varieties of hard red spring wheat

[2] Number of varieties of hard red spring wheat, first number, and spring barley, second number.

[3] First number refers to wheat harvest, the second to barley.

RESULTS

Available soil water content data to 5 feet measured at weekly intervals are shown for the 1989 spring wheat variety trial at Mandan together with the measured rainfall amount received between dates of soil water content measurements (Table 2). This illustrates the kind of information collected at each location on water supply and use. These data show the change in water content by depth with time and reflect the approximate rate of downward vertical penetration of roots, assuming that water depletion is evidence of the presence of roots. A summary of this kind of information was published by Bauer *et al.* (1989a), which included most of the trials reported here. Also, the data in Table 2 show that water loss was recorded to the 4-foot depth on this well-drained soil, supporting reports that spring wheat roots penetrate to at least this depth (Bauer and Young, 1969; Bauer *et al.*, 1989a).

Comparisons of water use by wheat and barley were made at Mandan in 1983, 1988, 1989, and 1990. These show that water loss to 4 feet soil depth averaged about 0.77 inches more on wheat than barley (Table 3). Depth of root penetration, however, was essentially the same (data not shown). Water loss to 4 feet from wheat was 1.13 and 1.81 inches more than from barley in 1983 and 1990, respectively. Part of the reason for the 1990 difference appears to be that the wheat plots had 1.33 inches more water present at planting than the barley plots, even though the entire site was summerfallow in 1989. While the data are inconclusive, it would seem reasonable that water use differences between wheat and barley planted on the same day could differ because of the shorter growing season required by barley (Bauer *et al.*, 1989b).

Table 2. Change in soil water content to five-foot soil depth and rainfall between soil water measurement dates, Mandan, 1989. (A minus sign indicates a water loss.) Amidon spring wheat was planted April 24.

		Soil depth (feet)					
Date	D.S.[1]	0-1	1-2	2-3	3-4	4-5	Rain
		inches water					inches
4/25	—	1.63[2]	1.94[2]	2.56[2]	2.04[2]	1.80[2]	1.71
5/02	—	0.53	0.36	0.11	0.25	0.05	0.04
5/09	0.6	-0.13	-0.10	-0.04	0.13	0.10	0.12
5/16	2.8	-0.19	-0.10	-0.06	-0.06	0.11	0.12
5/23	3.1	-0.25	-0.12	-0.06	-0.03	0.01	1.54
6/01	5.4	0.45	-0.04	-0.06	-0.06	-0.05	0.00
6/06	6.4	-0.68	-0.06	0.06	0.09	0.07	0.16
6/15	6.9	-0.76	-0.80	-0.19	-0.13	-0.05	0.24
6/22	8.1	-0.37	-0.72	-0.56	-0.16	-0.07	0.08
6/28	9.0	-0.12	-0.14	-0.53	-0.20	-0.04	0.00
7/06	10.8	-0.36	-0.24	-0.64	-0.34	0.03	0.28
7/12	12.1	0.03	-0.09	-0.17	-0.24	-0.06	0.24
7/19	13.4	-0.00	-0.03	-0.05	-0.10	-0.01	0.00
7/26	15.0	-0.09	0.00	-0.04	-0.08	-0.02	
"Used"[3]		1.94	2.08	2.23	0.93	-0.07[4]	4.53

[1] Development stage, expanded Haun scale.
[2] Available soil water content. (Water held at 15 bars tension and less).
[3] Difference in soil water content between April 25 and July 26.
[4] More water was present on 7/26 than on 4/25.

Data of wheat and barley agronomic characteristics and water use at each of the sites are shown in Table 3. Wheat grain yield, at 12 percent water by weight, ranged from 17.4 to 59.6 bushels per acre, and barley grain yield ranged from 27.0 to 87.0 bushels per acre. The lowest yield was recorded in 1988 for both species. Over the years, growing season rainfall ranged from 3.61 to 15.06 inches (including as much as 7.80 inches irrigation some years) and soil water removal to 4 feet between planting and harvest ranged between 1.32 and 7.78 inches. As previously reported (Bauer and Young, 1969), the largest amount of water removed from the soil usually was in years with less than average growing season rainfall.

The grain yield per inch of water used in evapotranspiration after the IYP, Table 3, ranged from 3.2 to 8.1 bushels per acre of wheat and from 2.5 to 8.8 bushels per acre of barley. The values shown are the grain yield per inch of water after 4 inches of water and one bushel of grain are subtracted from total water use and grain yield, respectively. The averages, as shown, are 5.1 and 6.8 bushels per acre per inch of water for wheat and barley, respectively. In terms of grain weight, the average response was 306 pounds of wheat and 326 of barley.

Grain yield produced per inch of water used in evapotranspiration will vary from year to year because the rate of water loss by evaporation from the soil and transpiration from the plants can differ annually. The atmospheric factors of temperature, wind speed, and humidity determine the rate of water evaporation. Water stress in plants usually will develop when soil water supply is low, but stress can occur whenever the water evaporation from the plant (transpiration) exceeds the rate at which water is removed from the soil by the plant.

Potential grain yield is reduced whenever the crop is stressed. Water stress during the tillering stage--in hard red spring wheat and barley, tillers which produce heads form between about the 3-leaf and 6-leaf development stages of the main stem--can prevent tiller production, thereby reducing the number of heads per plant. Bauer (1980), Black (1982), and Bauer *et al.* (1990) have shown that the number of heads per unit area largely determine level of grain yield in wheat and barley. Water stress also can cause tiller abortion, reducing the potential head number.

A water stress at flowering stage of wheat and other cereal crops generally is considered to reduce grain yield potential more than if the stress occurs at other stages (Bauer, 1972) because the potential number of seeds per head is determined at flowering stage. Water stress occurring during grain filling reduces the potential kernel weight (Jensen, 1971).

Stress also is induced by unfavorable temperature. Frank *et al.* (1987, 1988) showed that when average maximum air temperature was 60 F or less during the 4 to 5.5 leaf stage (the stage when the head is initiated and formed) wheat heads had 19 or more spikelets. But when the average max-

Table 3. **Spring wheat and barley agronomic characteristics, water use, and grain yield per inch of water used in evapotranspiration after the initial yield point (IYP) at North Dakota sites, 1979-1990.**

Year	Site	Heads	Kernel weight	Kernel/ head[3]	Yield[2]	Rain[9]	Soil water[10]	Grain[11] yield per inch water
		WHEAT						
		Agronomic characters						
		no/yd²	mg	no	bu/ac	inches	inches	
1979	Winter	312	29.66	21.3	35.2	5.65	5.43	4.8
1979	Marquart[1]	298	35.88	31.6	59.6	6.86	4.47	8.0
1980	Winter	293	35.73	22.5	41.9	8.81	2.97	5.3
1980	Ystaas	489	32.14	16.9	42.7	10.15	2.84	4.6
1980	Marquart[1]	295	33.15	28.0	48.9	3.61	6.27	8.1
1981	Winter[1]	345	26.40	28.4	45.9	10.06	3.66	4.6
1981	Ystaas	395	30.02	18.5	38.6	7.83	3.23	5.3
1981	Marquart[1]	369	29.63	29.7	57.0	12.61	2.17	5.2
1979	Mandan	319	29.99	19.6	33.0	5.92	4.45	5.0
1981	Mandan	445	26.84	20.8	44.4	15.06[4]	1.32	3.5
1982	Mandan	461	29.51	20.9	51.4	8.52	5.49	5.0
1983	Mandan	455	29.68	28.4	39.5	9.68[5]	6.46	3.2
1984	Mandan	375	24.62	29.7	51.1	4.27	7.14[7]	6.8
1985	Mandan	360	30.34	29.2	53.1	9.17	7.78	4.0
1986	Mandan	367	31.36	25.8	47.5	12.00	4.64	3.7
1987	Mandan	353	34.81	23.1	48.9	10.58	3.28[7]	4.9
1988	Mandan	228	26.44	19.4	17.4	3.29	5.38	3.5
1989	Mandan	339	22.33	24.2	31.9	4.53	7.18	4.0
1990	Mandan	374	30.07	29.3	52.3	6.86	4.73	6.8
							Avg.	5.1
		BARLEY						
1983	Mandan	476	34.19	26.5	87.0	9.37[5]	5.33	8.0
1984	Mandan	389	35.39	21.8	66.0	4.27	7.14	8.8
1985	Mandan	401	35.84	23.9	84.2	9.17	7.78[8]	6.2
1986	Mandan	372	41.88	24.4	75.2	11.69	4.34[8]	6.2
1987	Mandan	380	33.15	25.3	79.2	9.48	3.28	8.9
1988	Mandan	495	33.62	8.9	27.0	9.06[6]	5.23	2.5
1989	Mandan	356	24.11	24.7	41.7	4.53	7.18	5.3
1990	Mandan	375	34.35	23.2	49.1	6.86	2.92	8.3
							Avg.	6.8

1 Durum wheat. All other wheats are hard red spring.

2 Expressed at 12% water concentration. Yields and kernel weight of each variety trial are an average of all varieties.

3 Calculated from heads/yd², grain yield, and kernel weight.

4 Includes 7.80 inches of irrigation.

5 Includes 4.05 inches of irrigation.

6 Includes 5.77 inches of irrigation.

7 Access tubes were in barley.

8 Access tubes were in wheat.

9 Rainfall recorded at the site from planting to harvest.

10 Difference in soil water content to 4 feet from planting to harvest.

11 Bushels/acre/inch in excess of 4 inches water loss by evapotranspiration. The value is the quotient of the grain yield minus one bushel, divided by the sum of growing season rainfall plus soil water removed from planting to harvest, minus 4 inches. Calculation of the value is based on the assumption that 4 inches of water are lost by evapotranspiration to produce one bushel of grain.

imum temperature was 80 F during the same stage, the spikelet number was reduced to 14 spikelets per head on the main stem.

Kernel number per head usually is a reflection of the number of spikelets per head. Fewest kernels per head (Table 3) occurred at the 1980 and 1981 Ystaas sites and the 1979 and 1988 Mandan sites. Average maximum air temperatures during the plant development stage when head size was determined was 74 and 67 at Ystaas and 70 and 78 F at Mandan, respectively. Tashiro and Wardlaw (1990) reported that the kernel number per head of the Australian wheat variety Banks was reduced 11 percent with a rise in day/night temperature from 70/61 F to 86/77 F over a 10-day period immediately following onset of flowering. The upper spikelets were more affected than the spikelets at the base of the head.

Although both stored soil water and growing season rainfall contribute to grain yield, an inch of water stored in the soil generally is considered to be more efficient in producing grain, contributing more to grain yield, than an equal amount of water from growing season rainfall. Much of the water from rain, and especially if the rainfall amount is less than about an inch over a 24-hour period or falls on dry soil, is held in the uppermost part of the soil. Hence, much of this water is subject to loss by direct evaporation from the soil, especially when roots in this part of the soil are no longer active. Water stored in the soil below about 4 to 5 inches is relatively safe from evaporation (Staple, 1964). The water removed from the soil by roots passes through the plant before evaporating.

Black and Bauer (1986) suggested that information about the amount of grain yield produced per inch of water is useful as a guideline in determining potential wheat yields. Figure 1 is a revision of the original estimates of Black and Ford (1976) and of Black and Bauer (1986) to reflect the estimation that 4 inches of water are needed to produce the first bushel of grain, that is, the IYP. The available water (Figure 1) refers to the amount of water stored to 4 feet at planting plus the projected growing season rainfall.

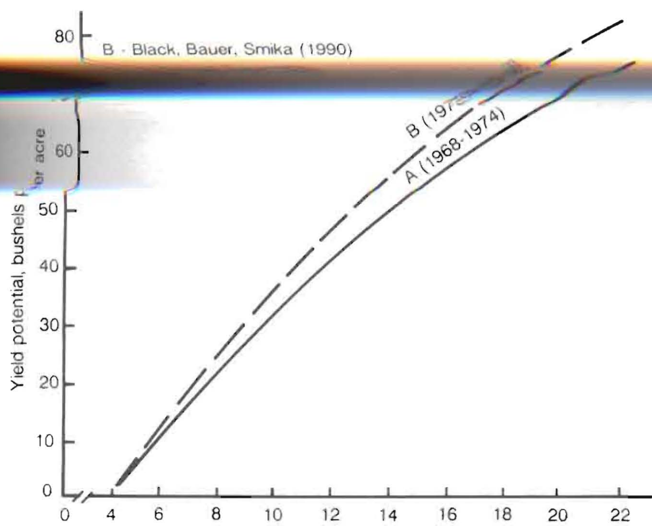

Figure 1. Potential wheat grain yields in relation to supply of available water (stored to four feet at planting plus growing season rainfall).

Soil fertility must be adequate to produce maximum grain yield from a given quantity of water. Of the soil-derived nutrients, nitrogen is needed in largest quantity. The amount needed in the soil to produce a bushel of spring wheat is variously estimated at about 2.0 to 2.4 pounds. Available nitrogen content of the soil can be measured by soil test. The difference in available nitrogen amount then needed to attain the grain yield potential estimated from the projected water supply (Figure 1) can be supplied with fertilizers. In this approach the assumption is made that the amount in the soil and the amount supplied from fertilizer are equally effective in producing grain yield.

Hard red spring wheat yields in the 75 to 80 bushel per acre range are not a common occurrence in North Dakota at research sites where water use is monitored, nor for that matter, is it common to have an available water supply of 20 inches under rainfed conditions. Hence, few data exist to test the "validity" of Figure 1 at these yield levels. At Carrington in 1973 (Bauer 1980), the average grain yield of five hard red spring wheat cultivars was 79.1 bushels per acre when supplied with 19.57 inches of water (the sum of 7.30 inches rain, 8.50 inches irrigation applied with a gravity system, and 3.77 inches stored soil water). Assuming the IYP was 4 inches water (as in Table 3), grain yield per inch of water used in evapotranspiration was 4.8 bushels per acre. Lukach at Langdon (private communication with John Lukach, Langdon Experiment Station) measured hard red spring wheat yields of about 80 bushels per acre in 1985. Stored available soil water content at planting was at least 7.2 inches to 4 feet soil depth, and growing season rainfall was 15.96 inches. No soil water content measurements were made at harvest, so the soil water depletion was not calculated. The crop, however, had access to a sufficient quantity of water to attain the yields suggested by Figure 1.

Estimation of the potential wheat grain yield from the water supply as shown in Figure 1 assumes that growing season evapotranspiration is equal to the sum of the water supply stored to 4 feet at planting plus the growing season rainfall. Brun *et al.* (1989) showed that these two values are similar up to about 15 inches of water (50 to 60 bushels per acre), but diverge at higher water contents. With a supply of 20 to 25 inches water, they expected 3 or more inches water to remain in the soil at harvest. Bauer and Young (1969) showed that soil water content at harvest seldom was depleted to the permanent wilting point to depths greater than 3 feet. This suggests that only part of the water below the 3-foot depth should be considered to be contributing to grain yield. Bauer *et al.* (1989a) subsequently have shown [illegible] to 6-foot depth, thereby utilizing water essentially equivalent to the available water content to the 4-foot depth.

Chances of achieving any yield goal are greatest when best management practices are used by the producer. Best management includes timeliness of operations involving planting and pest control, best adapted variety, planting rate, fertilization, and other practices which affect grain yield, and therefore water use efficiency. Unforeseen events, such as an atmospheric stress (prolonged high temperature), less than average growing season rainfall, and other inclement weather will reduce water-use efficiency and therefore potential grain yield.

REFRENCES

1. Bauer, Armand. 1972. Effect of water supply and seasonal distribution on spring wheat yields. North Dakota Ag. Exp. Sta. Bull. 490.

2. Bauer, Armand. 1980. Responses of tall and semidwarf hard red spring wheats to fertilizer nitrogen rates and water supply in North Dakota 1969-1974. North Dakota Ag. Exp. Sta. Bull. 510.

3. Bauer, Armand and R.A. Young. 1969. Influence of management and environmental factors on extent of water depletion by spring wheat. North Dakota Ag. Exp. Sta. Res. Rpt. No. 23.

4. Bauer, Armand, A.L. Black, and A.B. Frank. 1989a. Soil water use by plant development stage of spring and winter wheat. North Dakota Ag. Exp. Sta. Bull. 519.

5. Bauer, Armand, A.L. Black, and A.B. Frank. 1989b. Why spring barley matures earlier than spring wheat. Better Crops with Plant Food 73 (3):14-15.

6. Bauer, Armand, A.L. Black, A.B. Frank, and E.H. Vasey. 1990. Agronomic characteristics of spring barley in the northern Great Plains. North Dakota Ag. Exp. Sta. Bull. 523.

7. Black, A.L. 1982. Long-term N-P fertilizer and climate influences on morphology and yield components of spring wheat. Agron. J. 74:651-657.

8. Black, A.L. and Armand Bauer. 1986. Optimizing winter wheat management in the Northern Great Plains region. **In** Implementing maximum economic yield (MEY) systems, workshop. North Dakota Coop. Ext. Ser., July 8-10.

9. Black, A.L., and R.H. Ford. 1976. Available water and soil fertility relationships for annual cropping systems. Montana Coop. Ext. Ser. Bull. 1132:286-290.

10. Brown, Paul L., A.L. Black, C.M. Smith, J.W. Enz, and J.M. Caprio. 1985. Soil water guidelines and precipitation probabilities in Montana and North Dakota, for barley, winter wheat, and spring wheat in flexible cropping systems. Montana Coop. Ext. Ser. Bull. 356.

11. Brun, L.J., E.J. Deibert, E.W. French, and B.K. Hoag. 1984. Technology impact on evapotranspiration — yield relations for spring wheat in North Dakota. North Dakota Ag. Exp. Sta. Farm Res. 42(2):8-9, 25.

12. Brun L.J., J.W. Enz, and J.K. Larsen. 1989. Spring wheat and water use relationships at Fargo, North Dakota — six year summary. North Dakota Ag. Exp. Sta. Farm Res. 46(6):9-12.

13. Cole, John S. and O.R. Mathews. 1923. Use of water by spring wheat on the Great Plains. USDA Bull. 1004.

14. Frank, A.B., A. Bauer, and A.L. Black. 1987. Effects of air temperature and water stress on apex development in spring wheat. Crop. Sci. 27:113-116.

15. Frank, A.B., A. Bauer, and A.L. Black. 1988. Effects of air temperature on head development in spring wheat. North Dakota Ag. Exp. Sta. Farm Res. 45(4):16-18.

16. Halvorson, A.D. and P.O. Kresge. 1982. Flexcrop: A dryland cropping sytems model. USDA Prod. Res. Rpt. No. 180.

17. Henry, J.L., J.B. Bole, and R.C. McKenzie. 1986. Effect of nitrogen water interactions on yield and quality of wheat in western Canada. **In** A.E. Slinkard and D.B. Fowler (ed.) Wheat production in Canada — A Review. Proc. Canadian Wheat Production Symp., 3-5 Mar. 1986, Saskatoon, Sask.

18. Jensen, R.E. 1971. Seasonal water deficits in barley. Ph.D. Thesis, North Dakota State University, Fargo, ND.

19. Jensen, Ray E. 1972. Climate of North Dakota. Natl. Weather Service and North Dakota State University, Fargo, ND.

20. Lehane, J.J. and W.J. Staple. 1965. Influence of soil texture, depth of soil moisture storage, and rainfall distribution on wheat yields in southwestern Saskatchewan. Can. J. Soil Sci. 45:207-219.

21. Ramirez, J.M. 1973. The agro-climatology of North Dakota. North Dakota Coop. Ext. Ser. Bull. No. 16.

22. Richards, L.A. 1947. Pressure membrane apparatus construction and use. Agr. Eng. 47:131-138.

23. Snider, Arlin E., Armand Bauer, and Enoch Norum. 1968. Growing season precipitation probabilities in North Dakota. North Dakota Coop. Ext. Ser. Bull. No. 4.

24. Staple, W.J. 1964. Dryland agriculture and water conservation. **In** Research on water, ASA Spec. Pub. No. 4, Am. Soc. Agron., Madison, WI.

25. Stone, J.F., D. Kirkham, and A.A. Read. 1955. Soil moisture determination by a portable neutron scattering moisture meter. Soil Sci. Soc. Am. Proc. 19:419-423.

26. Tashiro, Toro and I.F. Wardlaw. 1990. The effect of high temperature at different stages of ripening on grain set, grain weight and grain dimensions in the semi-dwarf wheat 'Banks'. Ann. Bot. 65:51-61.

27. Weare, Bryan. 1990. Use of long-range weather forecasts in crop predictions. California Agr. 44(2):28-29.