Evapotranspiration patterns and water use efficiencies of ten winter wheat genotypes

by Sayed Muzafaruddin Hashimi

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Agronomy
Montana State University

Abstract:
Ten diverse genotypes, fourteen sampling dates and eight soil depths were utilized in examining evapotranspiration patterns and water use efficiency of winter wheat.

Although no significant differences were found among genotypes for total evapotranspiration, significant variations were noted among sampling dates and soil depths. The genotype X sampling date, genotype X soil depth and date X depth interactions for water remaining in the soil profile were also significant. Significant differences among the ten winter wheats were found for leaf area, grain yield, number of heads, number of seeds per head, 100 seed weight, plant height and heading date.

Evapotranspiration increased from the late tillering stage in early May, to stem extension in June and peaked during heading and grain filling in July. Evapotranspiration greatly decreased during the June-July maturation stage.

The examination of eight soil profile depths showed that winter wheat water use decreased with depth. Although significant amounts were-used from the lower four feet, the upper four feet accounted for 88 percent of the total water used, with 54 percent coming from the top foot.

The ten winter wheats removed plant available water differentially at different dates, or growth stages, and from different soil depths.

Water use differences at the five, six, seven and eight foot depths were indicative of differential rooting patterns.

Positive correlations were found between water use efficiency and yield and yield components. Negative relationships were noted between water use efficiency and plant height, heading date and leaf area.

Under conditions of this study, the shorter, earlier maturing winter wheats were the best adapted genotypes where yield and water use efficiency were considered.

Statement of Permission to Copy

In presenting this thesis in partial fulfillment of Masters of Science in Agronomy at Montana State University, I agree that the library shall make it freely available for inspection. I also agree that permission to copy this thesis for scholarly purposes may be granted by my major professor or by the Director of Libraries in his absence. It shall not be permitted to copy this thesis for financial gain without my written permission.

Signature G. Allan Taylor for S. M. Hashimi
Sayed Muzafaruddin Hashimi

Date 11/30/72

EVAPOTRANSPIRATION PATTERNS AND WATER USE EFFICIENCIES OF TEN WINTER WHEAT GENOTYPES

by

SAYED MUZAFARUDDIN HASHIMI

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree

of

MASTER OF SCIENCE

in

Agronomy

Approved:

Head, Major Department

Chairman, Examining Committee

Graduate Dean

MONTANA STATE UNIVERSITY
Bozeman, Montana

December, 1972

ACKNOWLEDGEMENT

The author would like to express his sincere gratitude to Dr. G. Allan Taylor for his patience, consideration and valuable assistance during the course of this study and preparation of the thesis.

Sincere appreciation is extended to Dr. Paul L. Brown for his valuable criticisms and encouragement in the course of this investigation.

A special thanks to Dr. Gerald E. Nielsen, Professor Robert F. Eslick and Dr. Hayden Ferguson for their constructive advices and criticisms.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

ABSTRACT

Ten diverse genotypes, fourteen sampling dates and eight soil depths were utilized in examining evapotranspiration patterns and water use efficiency of winter wheat.

Although no significant differences were found among genotypes for total evapotranspiration, significant variations were noted among sampling dates and soil depths. The genotype X sampling date, genotype X soil depth and date X depth interactions for water remaining in the soil profile were also significant. Significant differences among the ten winter wheats were found for leaf area, grain yield, number of heads, number of seeds per head, 100 seed weight, plant height and heading date.

Evapotranspiration increased from the late tillering stage in early May, to stem extension in June and peaked during heading and grain filling in July. Evapotranspiration greatly decreased during the June-July maturation stage.

The examination of eight soil profile depths showed that winter wheat water use decreased with depth. Although significant amounts were used from the lower four feet, the upper four feet accounted for 88 percent of the total water used, with 54 percent coming from the top foot.

The ten winter wheats removed plant available water differentially at different dates, or growth stages, and from different soil depths. Water use differences at the five, six, seven and eight foot depths were indicative of differential rooting patterns.

Positive correlations were found between water use efficiency and yield and yield components. Negative relationships were noted between water use efficiency and plant height, heading date and leaf area.

Under conditions of this study, the shorter, earlier maturing winter wheats were the best adapted genotypes where yield and water use efficiency were considered.

INTRODUCTION

Both genetic and environmental factors influence crop growth. In arid and semiarid regions water is the most limiting of the environmental factors affecting wheat production. Wheat is primarily grown under dryland conditions on a worldwide basis.

With an adequate supply of nutrients and a favorable growing season yields of dryland wheat are primarily influenced by plant available soil water and genotype. Growth is affected not only by limited water but also by reduced nutrient uptake, since movement of nutrients from the soil solution into the plant is dependent on available soil water.

To a certain extent wheat growers can conserve water through improved cultural practices which reduce runoff and erosion and enhance soil water storage. In those years lacking sufficient stored soil water, wheat cultivars possessing high water use efficiency would help maximize production.

Information concerning water use of wheat during various growth stages is limited. The determination of pattern and efficiency of water utilization among wheat cultivars would provide information applicable to both wheat production and breeding.

Winter wheat (*Triticum aestivum* L. em Thell) was chosen for this study. A wide array of genotypes were utilized in examining: (1) evapotranspiration patterns and (2) water use efficiency of winter wheat genotypes.

LITERATURE REVIEW

Kramer (1963) indicated that growth of plants is controlled directly by plant water stress and indirectly by soil moisture stress. He also mentioned that water is: (1) a constituent of cells, (2) a solvent in which salts and other nutrients move from cell to cell and organ to organ, (3) a reagent in photosynthetic and hydrolytic reactions, and (4) maintains cell turgidity. Plants under water stress close their stomata, preventing CO_2 entrance, which reduces the process of photosynthesis. Photosynthetic rate decreased under water stress due to dehydration of protoplasm.

Kaul (1966), working with spring wheat in Canada, stated that the output of CO_2 increased about two percent with slight moisture stress, with greater water stress CO_2 output was decreased about 50 percent. He showed that the decrease in respiration due to water stress cannot be accounted for by increased rate of CO_2 fixation in the dark.

In winter wheat the development of a dense root system was observed by Kmoch et al. (1957) at soil water tensions above 15 atmospheres. Under favorable field soil water conditions roots penetrated up to 13 feet. El Nadi (1969) reported that water stress during the vegetative stage caused significant reduction in wheat plant height and number of tillers per plant but not dry weight. Grain filling and maturation were more sensitive to drought than the vegetative period of growth. Water stress from 25 days after planting to the milk stage reduced yield and kernel weight significantly. Lehane and Staple (1962) stated that as the soil water tension increased the rate of wheat growth decreased. Shortage of water during heading and grain filling resulted in inefficient moisture use.

Stone and Tucker (1969) showed a significant negative linear relationship between nitrogen content of grain and the amount of water applied to the soil during the early growing season of wheat. Water applied after the vegetative stage did not effect the nitrogen content. The explanation of the negative correlation between nitrogen content of grain and water applied to the soil surface was attributed to nitrate movement below the zone of high nutrient absorption and reduced nitrate concentration in the soil solution.

Experiments of Lehane and Staple (1965), at Swift Current, Saskatchewan, Canada, indicated that most of the available soil moisture had been used by spring wheat by harvest time. They also observed that wheat used 91, 85 and 91 percent of the available water in loam, sandy loam and clay soils, respectively. Greater moisture stress in clay soils resulted in less early wheat growth and transpiration in dry season so that more water was available during growing, filling and maturity stages. In dry seasons, wheat yields were higher in clay soils than loam and sandy loam soils when similar amounts of water were used. Leggett (1959) reported that rainfall in Washington during the growing season is slightly more effective than stored soil moisture. He also pointed out that available soil moisture is equally important under both dryland and irrigated farming systems.

Brown (1971), working under dryland conditions in Montana, reported that normal rainfall provided more water than the amount used by winter wheat plants until early heading. After heading winter wheat was highly dependent on stored soil water. The water requirements of plants increased as growth advanced and with increasing nitrogen rates of 0, 67, and 268 kg/ha. At the pseudo-stem stage, daily water use rates of 1.00, 1.25 and 1.50 mm/day (0.04, 0.05 and 0.06 in/day) were observed for the respective nitrogen treatments. Maximum water use rates at the headed stage were 4.0, 4.5 and 5.2 mm/day for the three treatments. Total water used was 22.1, 27.2 and 31.5 cm for the 0, 67 and 268 kg/ha nitrogen treatments. Grain yields were more than doubled with N fertilization. Jong and Rennie (1969) found no significant difference in water utilization on fertilized and unfertilized spring wheat on fallow land at the Swift Current Station in Saskatchewan, Canada.

Widstrom et al. (1965), utilizing eight oat cultivars, showed that variation in tillering and heading dates were responsible for a large part of the observed varietal differences. They reported a positive relationship between heading date and water use, a high correlation between water requirements and water used by oats and a positive correlation between water requirements and dry matter production. Aspanail (1965) noted that soil water stress between flowering and ripening of barley significantly reduced grain size. Grain size reduction was greatest when water stress occurred in early stages of grain development. Severe stress caused grain to be thin and shrivelled.

Campbell and Ferguson (1969), using growth chambers, showed that the amount of water used by spring wheat was directly related to light intensity and temperature. An increase in day temperature from 21 to 27^{o}C reduced total water use as a result of high drymatter production at the lower temperature. Plants grown under high soil water stress used less water than those grown under low water stress. During warm days, total water used varied with variation in light intensity. With high light intensity and cool days, plants used water rapidly. An increase in water stress at any stage of growth, except tillering, reduced water use efficiency.

Lehane and Staple (1962) reported that wheat subjected to early water stress used less water, with the efficiency in grain production equal to that grown under optimum conditions. Water shortage during heading and grain filling resulted in inefficient water use. Both grain and drymatter production were higher under optimum water conditions.

Stephens et al. (1943), using 1912-1928 data, concluded that the water requirements of spring wheat was considerably greater than that of winter wheat. This was due to early maturity of winter wheat and cooler temperature during the growing season. Ferguson (1965) was among the first in a study of the relationship between evapotranspiration and growth stages of wheat. He showed the largest evapotranspiration occurred in the top 18 inches of soil. There were significant differences among growth stages for evapotranspiration. Five year records showed that weekly evapotranspiration increased until flowering and then declined. Pohjakas et al. (1967) obtained mean water use of 589-688, 526, 486, 610, and 560 mm for perennial forages, wheat, barley, sugar beets and potatoes respectively. Consumptive use of water was highest for alfalfa and the alfalfa-timothy mixture with other perennial forages being slightly lower. The lowest water users were barley, canning peas and wheat.

El Rahman et al. (1967) found significant yield and height differences in barley with 120, 210 and 320 mm rainfall treatments. The differences were less pronounced at early growth stages. Both fresh and dry weight increased with rainfall levels. Yield differences were due to variation in number of seeds per head and kernel weight. The low rainfall treatment resulted in reductions of 39 and 48 percent in number of seeds per head and mean grain weight, respectively. Warder et al. (1963) reported that wheat fertilized with 40.5 and 16.0, and 150 pounds of nitrogen per acre on both stubble and fallow, used more water than the check between seeding and heading time. The fertilized treatments showed increased growth during the early part of growing season and matured four to eight days earlier than the check.

Jong and Ranni (1969) indicated that 45 to 80 percent of the yield variations of unfertilized spring wheat Saskatchewan were due to variation in water use. They also reported that water use was responsible for 20 percent of variation in spring wheat yields in North Dakota. The data from stubble land revealed that water use efficiency decreased with the increase in water use, but the correlation was only significant on unfertilized stubble plots on the lower slope positions of the field. They mentioned that 12 to 15 cm of soil available water is needed for spring wheat before any yield is obtained and above this the yield increased 80-110 kg/ha for each additional cm of water. They further reported that water use efficiency of wheat (mg of grain/g of water) increased significantly with fertilization. Total water use was slightly higher on stubble than on fallow but the difference was not statistically significant.

Fischer and Kohn (1966), in Australia, reported the competitive differences among wheat cultivars for water was the most important influencing variations in vegetative growth which resulted in grain yield differences. There were indications that high levels of nitrogen in the soil changes the nature of competition. Initially, low soil nitrogen increased the leaf area to total dry weight ratio 30 percent during early spring. A very high soil nitrogen failed to produce any extra dry weight or increase leaf area. The higher nitrogen level significantly increased shoot production and decreased the percentage of shoot survival, number of heads and grain yield.

Leggett (1959), working in eastern Washington, reported that four inches of water are needed to establish a wheat crop and about six bushels per acre are produced for every additional inch of available water. Lehane and Staple (1965) found that five inches of available water were needed in Saskatchewan before any grain was produced. Wheat yields increased by 3.5 to 4 bushels per acre for each additional inch of water.

Hobbs et al. (1963) studied the effects of levels of minimum available soil water on crop yields. Plots were irrigated to restore the root zone to field capacity when 25, 50 and 75 percent of available water was depleted. Wheat yield reached a maximum when the soil water was maintained at or slightly below that of 50 percent of available water. They suggested that generally irrigation should not be delayed after the soil moisture had been depleted to 50 percent level.

MATERIALS AND METHODS

Genotypes

Ten winter wheat genotypes were used in this study: (a) Winalta (CI 13670), possesses good winter hardiness and mid to late season maturity; (b) ID 5006 (NRN_{10}/STR//*2CNN) and Nugaines (CI 13968), are both high yielding, late maturity semidwarfs with poor winter hardiness; (c) Wanser (CI 13844), has an erect growth habit, medium height, late maturity, high yield potential, and low degree of winter hardiness; (d) Cheyenne (CI 13885), is a late maturing, broadly adapted cultivar with fair winter hardiness; (e) Froid (CI 13872), is a late maturing, tall and possesses excellent winter hardiness; (f) Crest (CI 13880), is a medium height, early maturing cultivar, with poor winter hardiness; (g) MT 6928 (TX55-391-56-D8/WMT2-II-4-3), is an early maturing, high yielding semidwarf line with poor winter hardiness; (h) Yogo SS4662, is a Montana Yogo isogenic semidwarf line; (i) Itana (CI 12933), has mid to late season maturity, erect plant habit and a low degree of winter hardiness.

Experimental Design

A completely randomized block design with ten genotypes, eight soil depths and fourteen soil water sampling dates was used in this study at the Plant and Soil Science Field Research Laboratory, Bozeman, Montana. The nine characteristics measured included moisture depleted from the entire eight foot soil profile and from each foot increment, leaf area ($cm^2/.305\ m^2$), grain yield, number of heads/48 ft^2, number of seeds per head, 100 seed weight (g), plant height (in) and heading date.

An analysis of variance for each character (Tables 1, 5 and 11) and correlation among characters (Table 13) were made. Duncan's Multiple Test was utilized to examine means. Field plots, seeded September, 1970, at 90 pounds per acre consisted of twelve, ten-foot rows one foot apart (120 ft^2) replicated four times. Grain yields (harvested August 4, 1971) were determined for 48 ft^2.

The field location was an Amsterdam silt loam soil of the subgroup Cryoborall with available nitrogen ranging from 14.4 ppm in the upper foot to 2.0 ppm in the sixth foot of soil. The fallowed soil contained 12.0, 6.0, and 0.45 m.eq. of calcium, magnesium, and sodium, respectively, per one hundred grams of soil in the top six inches. This soil holds approximately 1.50 inches of plant available water per foot of depth.

Soil Moisture Measurement

Soil moisture was measured weekly, May 5 to August 4, 1971, in one foot increments to a depth of eight feet. Two methods used to measure soil moisture were: (1) gravemetric method for the top six inches of soil; (2) Nutron moisture meter for the remaining seven and one-half feet.

Evapotranspiration Determined

Available soil moisture was computed for the eight one foot depths and fourteen dates. The weekly evapotranspiration totals were calculated as follows: The amount of soil water used from each of the eight, one-foot increments was determined by subtracting the current values from those of the previous sampling date. The summation across the eight, one-foot segments, plus rainfall during that week gave total evapotranspiration from the eight foot soil profile. Weekly figures summed resulted in total growing season (May 5 to August 4) evapotranspiration.

Water Remaining in Soil Profile

Water remaining in the soil profile at each sampling date was the result of evapotranspiration of the genotypes. Evapotranspiration could have been used in examining interactions in this study, but the author chose to use water remaining in the soil profile.

The genotype X date, genotype X depth and depth X date interactions accumulated in the error term in the statistical analysis of evapotranspiration. The method used for computing these interactions involved plant available water remaining in the soil profile. This is justified on the basis of the reciprocal nature of soil water used and water remaining in the soil profile.

Climatic Conditions

The 1958-1970 mean monthly rain for May, June and July was 2.35, 2.80 and 1.42 inches, respectively. In 1971, the year this study was conducted, 2.07, 2.85 and 0.25 inches of rain were recorded for the respective months.

The 1958-1970 mean monthly temperatures for May, June and July were 39.1, 46.7 and 50.1°F, respectively. In 1971, for the same months, average temperatures of 50.5, 46.7 and 63°F were recorded.

The below average rainfall and above average temperatures during the 1971 growing season provided good experimental conditions for studying water use in winter wheat.

RESULTS AND DISCUSSION

Genotypes and Evapotranspiration

There were no significant differences among the ten winter wheat genotypes for total evapotranspiration during the May through July growth period (Table 1). Evapotranspiration means ranged from 11.36 for MT 6928 to 13.66 inches for Itana (Table 2). The lack of statistically significant differences among the ten genotypes emphasizes the importance of the relationship of evapotranspiration and other plant characteristics which are discussed later.

Dates and Evapotranspiration

The variation among dates for water use were significantly different (Table 1). The average weekly evapotranspiration by winter wheat ranged from 0.14 to 1.56 inches for the weeks of May 5 and June 23, respectively (Table 3). Evapotranspiration in general, increased from early May to mid-June and decreased as the season progressed to late July (Figure 1). The sharp decrease from May 12 to May 19 shown in Figure 1 is the result of 0.66 inches of rain and cooler temperatures which reduced evapotranspiration.

When the May to July growing period is segmented into growth stages, as in Figure 2, it becomes evident that evapotranspiration of winter wheat varies a great deal. For late tillering, stem extension, heading-grain filling and maturation there were 1.84, 3.94, 5.36 and 1.06 inches of water used, respectively. The foregoing differences are related to growth and environmental patterns which change as the season progresses.

The relatively low evapotranspiration of 1.84 inches during the later tillering stage can be partially accounted for by cool temperatures and limited vegetative growth. Figure 1 is evapotranspiration from stored soil water and rainfall. Additionally, high humidity contribute to the lower evapotranspiration.

The higher evapotranspiration of 3.94 and 5.36 inches during stem extension and heading-grain filling, respectively, were anticipated. As the season progresses, wheat plants grow vigorously, rapidly increasing vegetative growth. This, combined with increased daily temperatures, a drier and more turbulent atmosphere, results in greatly increased evapotranspiration.

The reduction in evapotranspiration during maturation can be attributed to two factors. First, most of the available moisture has been removed from the soil profile by this time. Secondly, winter wheat leaves and stems gradually die, losing their transpiration ability.

Depths and Evapotranspiration

The variations among the eight, one-foot increments in the soil profile differed significantly for evapotranspiration (Table 1). The means ranged from 6.65 inches of water used from the top one foot to 0.10 from the eighth foot (Table 4). Each mean differed significantly from every other mean.

The large amount of evapotranspiration from the surface foot of soil is due to repeated depletion and replenishment by seasonal rains. The winter wheats in this study used 53.7 percent of their total water from the upper one foot and 26.5 percent from the second and third foot soil depths (Table 4). The four through seven foot depths contributed 17.4 percent with only 0.8 percent of the total water depleted coming from the eighth foot.

The evapotranspiration pattern shown in Figure 3 is the result of greater root density and activity in the upper three feet, accumulation of rainfall in this region and evaporation, especially in the top foot. Early in the growing season water use activities of winter wheat is restricted to the upper one or two feet since root systems are confined to this segment. As the growing season progresses roots extend downward and extract moisture from greater depths.

It is difficult to make a clear concise statement with respect to root densities with these data. It seems apparent, however, that root densities are greatest in the upper three or four feet of the soil profile (Figure 3). This coincides of the common knowledge that root densities decrease with depth.

Genotypes X Dates and Evapotranspiration

Remaining available water

In order to study the genotype X date interaction for evapotranspiration it was necessary to examine inverse data, that is available water remaining in the soil profile (see MATERIALS AND METHODS). The analysis of variance showed the genotype X date interaction to be significant (Table 5). This, of course, indicates that genotypes removed water from the soil profile differentially at different dates during the growing season.

Table 6 includes information which varifies the significant genotype X date interaction. The water remaining means in Table 6 indicate that genotypes differed in their rankings at different dates.

Evapotranspiration

Although water remaining in the soil profile reflects an accurate picture of the genotype X date interaction a more reasonable discussion and understanding is possible in a consideration of evapotranspiration. Since evapotranspiration, or water removed from the soil profile, and water remaining are inversely related such a discussion is warranted.

Evapotranspiration during the first week was similar for the ten genotypes (Figure 4 and Table 7). During the remainder of the growing season genotypes used water differentially.

For the week of May 12-19 MT 6928, Yogo SS4662, Froid, Wanser, Nugaines, ID 5006 and Itana were the low water users. During the next week, however, all genotypes were very similar for water amount of water used (Figure 4). Another example of a genotype X date interaction is noted for Itana and MT 6928 later in the growing season. During the week of June 30-July 7 most genotypes used 1.0 to 1.5 inches of water (Figure 4 and Table 7). Itana, however, was high at 2.30 inches and

MT 6928 low at 0.79. The heavy evapotranspiration by Itana during this time was probably the result of a heavy infection of stripe rust.

Winalta, ID 5006 and Wanser used more water during June than the other genotypes (Figure 4). During this month most genotypes exhibited peak evapotranspiration, except for Itana and Yogo SS4662, whose peaks coincided with high levels of stripe rust during early July. Additionally ID 5006 used high amounts of water during early July.

A further indication of a genotype X date interaction is noted when evapotranspiration during various stages is examined. Seven of the ten genotypes used more than 1.75 inches of water during late tillering (Figure 5). Winalta, Nugaines, Wanser and Crest accounted for 2.24, 2.05, 1.99 and 1.94 inches of water, whereas MT 6928, ID 5006 and Froid used only 1.72, 1.50 and 1.46 inches, respectively.

During stem extension, May 26 to June 16, evapotranspiration for eight of the ten genotypes accounted for over three inches of water (Figure 5). Crest and MY 6928 both used less than that amount. Winalta was the top water user with 4.59 inches.

The picture changes somewhat for the heading and grain-filling growth stage (Figure 5). Six of the ten genotypes used more than 5.25 inches of water. Crest, a low water user in earlier stages, used 6.21 inches during this growth and Itana 6.14. The genotypes Cheyenne, Wanser, MT 6928 and Froid accounted for only 5.01, 4.96, 4.79 and 4.41 inches of moisture, respectively.

During the maturation growth stage, July 14 to 28, both Froid and MT 6928 were high water users, utilizing 1.98 and 1.93 inches of water, respectively. Both were among the low water users in the previous growth stage. Crest, the highest water user during heading and grain-filling, was the second lowest during maturation, using 0.66 inches of plant available water.

Overall, Winalta, Cheyenne, Nugaines and Wanser exhibited less variation among growth stages with respect to evapotranspiration (Figure 5). Other genotypes, however, exhibited a great deal of variation in this regard. Crest was generally a moderate to low water user except during heading and grain-filling where it was the maximum water user. Both Froid and MT 6928 were moderate water users, but utilized maximum amounts of 1.98 and 1.93 inches, respectively, during maturation.

Genotypes X Depths and Evapotranspiration

As previously mentioned in MATERIALS AND METHODS, a statistical analysis of water remaining in the soil profile was utilized in examining interactions and discussion of evapotranspiration.

Table 5 shows the genotype X depth interaction for water remaining in the soil profile to be significant. Duncan's Multiple Range revealed that significant differences among genotypes occurred for each of the eight depths (Table 8). Discussion is confined primarily to a consideration of water used rather than water remaining.

Evapotranspiration from the first foot of the soil profile did not vary greatly among the ten winter wheat genotypes (Figure 6 and Table 9). The values ranged from 6.49 to 6.74 inches of water for Nugaines and Winalta, respectively, with an overall mean of 6.65.

The same can generally be said for the second foot except that the genotypes did change rankings. Winalta again was the highest water user, utilizing 1.83 inches, while Crest and MT 6928 were lowest with 1.60 (Figure 6 and Table 9). Other genotypes with high evapotranspiration values include Cheyenne, Wanser, Nugaines and ID 5006. Froid, Itana and Yogo SS4662 tended to use lower amounts of water from the second foot. The mean evapotranspiration was 1.71 inches.

An average of 1.57 inches of water was depleted from the third foot depth with Wanser the highest at 1.73 inches (Figure 6 and Table 9). The remaining genotypes depleted considerably less water. MT 6928, as in the case of the two foot depth, was the low water user with 1.43 inches.

At the four foot depth the ranking of the ten genotypes with respect to evapotranspiration was similar to the previous depths. Wanser, depleting 1.09 inches of water, had the highest value (Figure 6 and Table 9). All other genotypes removed more than .85 inches from this depth. MT 6928 again was in the low group, using 0.89 inches of water.

At the five foot depth the genotype rankings change considerably. In general two genotype groupings are evident. One group, including Nugaines, ID 5006, Cheyenne, Winalta and Itana, depleted more than .80

inches of water (Figure 6 and Table 9). The other group, Crest, MT 6928, Wanser, Froid and Yogo SS4662 utilized less than .70 inches.

Itana, Cheyenne and ID 5006 used more than .50 inches of water from the sixth foot in the soil profile (Figure 6 and Table 9). The remaining genotypes utilized less than .40 inches, with Crest low at .22.

Although evapotranspiration values were low in the seventh and eighth foot depths the differences among genotypes were significant (Figure 6, Tables 5, 8 and 9). Itana depleted more water from both depths than the other genotypes.

Both Itana and ID 5006 were high water users at the fourth through the eighth foot depths. This indicates deep rooting patterns and abilities to utilize deep soil water. Cheyenne, in withdrawing large amounts of water from the fifth, sixth and seventh foot depths, evidently is not as deep rooted as Itana and ID 5006.

Although the shorter genotypes Yogo SS4662, MT 6928, Crest, Nugaines, and ID 5006, tended to remove less water from the deeper depths it is difficult to draw conclusions with respect to relationship of the height of the above ground portion and the extent of rooting patterns.

Depth X Date and Water Remaining in Soil Profile

The variation resulting from the depth X date interaction for water remaining in the soil was significant (Table 5). Duncan's Multiple

Range Test and the mean values in Table 10, indicate that water not depleted varied significantly with sampling date and depth of soil profile.

Early in the growing season rainfall added water to top one foot in excess of that used by the winter wheat (Figure 7). After June 2 moisture was rapidly depleted from this zone. The sharp rise, on June 30, in the amount of water left is the result of a 1.95 inch rainfall during the previous week.

Winter wheat depleted increasing amounts of water from the second foot about May 12, during late tillering (Figure 7). Although water depletion at the third and fourth foot depths increased gradually from May 19, the greatest increase was noted about June 9, during stem extension. There was a tendency for water to be used from the fifth and sixth foot zones as early as June 2 (Figure 7). The most rapid depletion, however, occurred after June 23 during heading.

Changes in plant available water at the seventh and eighth foot depths, although small, are evident. Very little water was depleted from these zones until late in the growing season during grain-filling and maturation (Figure 7).

Figure 7 shows that winter wheat draws most of its water from the upper four feet of the soil profile through the heading and early grain-filling growth stages. The amounts of plant available water remaining in this zone were reduced to virtually zero by the week of July 21-28.

Winter wheats appear to use increasing amounts of water from the fifth and sixth foot depths at heading time, about June 23 (Figure 7). Both the seventh and eighth foot zones contributed moisture to the growth of winter wheat only late in the growing season during maturation.

It appears that the sixth, seventh and eighth foot zones would be important soil moisture reservoirs during dry growing seasons. Some winter wheats, according to these data, have root systems capable of drawing moisture from these depths.

Rainfall during the summer growing season probably does not penetrate much beyond the one foot depth. This is evident from an examination of Figure 8, where major fluctuations in available soil water, which coincide with rainfall, occur only at the one foot depth.

Agronomic Characteristics and Evapotranspiration

Yield and yield components

The yield differences among the ten winter wheat genotypes were significant (Table 11). The means ranged from highs of 73.5 and 69.6 bushels per acre for Nugaines and Crest, to a low of 44.7 for Yogo SS4662 (Figure 8 and Table 12). A negative correlation coefficient of -.116, although not significant, indicates that in general as yields increase evapotranspiration should decrease (Table 13).

The indication that high yielding genotypes are more efficient users of water is justified. As previously mentioned, no significant differences were found among the ten winter wheat genotypes for total evapotranspiration (Table 1). A significant positive correlation, then, of .945 between yield and water use efficiency, was anticipated (Table 13). Since genotypes did not differ significantly for total water use any increase in yield resulted in a higher water use efficiency. An examination of Figure 10 shows that in terms of "water use efficiency" (grain produced per unit of available water used) the high yielding genotypes Crest, Nugaines and MT 6928 yielded 6.0, 5.9 and 5.9 bushels per inch of water, respectively (Figure 9). The low yielding genotypes Froid, Winalta, Yogo SS4662 and Itana produced only 4.6, 4.1, 3.9 and 3.6 bushels per inch of available soil water, respectively.

There was significant variation among the ten genotypes for the three yield components, number of heads per eight square feet, number of seeds per head and 100 seed weight (Table 11).

In general, the greatest variation among the yield components occurred for number of heads (Table 12). A positive correlation coefficient of .338 indicates that yield and number of heads react in a similar manner. An examination of Table 12 shows that the highest yielding genotypes also had high numbers of heads per unit area and seeds per head. A correlation coefficient of .418 indicates a positive relationship between yield and number of seeds (Table 13).

The positive correlation coefficient of .392 between 100 seed weight and yield was not expected, compared to many observations which indicate the reverse is more likely (Table 13). The fact that two genotypes, Itana and Yogo SS4662, were heavily infected with stripe rust may have influenced this relationship to a large degree.

Both number of seeds per head and number of heads per unit area were negatively correlated with water use (Table 13). The latter assumes a greater importance with a value of -.464. A positive correlation coefficient of .458 between number of heads and water use efficiency is reasonable since head number is a component of yield and generally related to yield in a positive manner (Table 13). Additionally, the other two yield components, number of seeds/head and 100 seed weight, both were positively correlated with water use efficiency.

In this study, under field conditions previously discussed, the yield of winter wheat was positively correlated with the three components of yield. These data very likely should be processed omitting Itana and Yogo SS4662, the two diseased genotypes.

Plant Height

The variation for plant height among the ten winter wheat genotypes was significant (Table 11). The range was from 42.5 and 42.0 inches for Itana and Froid to 27.0 and 27.5 inches for Nugaines and ID 5006, respectively (Table 12).

Table 13 shows plant height to be negatively correlated with number of seeds per head, number of heads per unit area, yield, water use and water use efficiency, but positively correlated with 100 seed weight.

The correlation coefficient of -.723 of plant height with the yield component number of heads per unit area indicates that the shorter, or semidwarf, winter wheats tiller more than the tall types (Tables 12 and 13). The shorter genotypes in general also had heavier seeds, higher yields, earlier heading dates and were efficient water users (Figure 10 and Table 12).

The negative association of height and water use efficiency in Table 13 is reasonable. This relationship is a result of no significant difference among the ten genotypes for total water used (Table 1) and the negative correlation of plant height and yield (Table 13). Four of the five top yielding winter wheat genotypes were short (Table 12).

The semidwarf Yogo SS4662 did not exhibit characteristics similar to the other short genotypes. As mentioned previously, this likely is accounted for by the heavy infestation of stripe rust with the resulting atypical reaction.

Heading Date

The variation in heading dates among the ten winter wheats was significant (Table 11). The early heading genotypes Crest, MT 6928, Wanser, and Cheyenne used soil water more efficiently than did the later genotypes Itana, Winalta, Froid and ID 5006 (Figure 10 and Table 12).

The negative correlation between heading date and water use efficiency (Table 13) indicates that in arid or semiarid conditions early maturing genotypes of winter wheat are desirable. Early maturing genotypes escape the periods of high temperature and increased evapotranspiration. Soil moisture then is more available to the earlier genotypes during the critical time of flowering and grain-filling.

Leaf Area

The variation among the ten winter wheats for leaf area was significant (Table 11). Mean leaf area ranged from 7898 cm^2/.308 ft^2 for ID 5006 to 4014 for Crest. Both genotypes were relatively high yielders (Table 12).

Negative correlations were noted for leaf area and 100 seed weight, number of heads, yield, and water use efficiency (Table 13). The negative and positive correlations of -.38 and .53 between leaf area and water use efficiency and water use, respectively, are noteworthy (Table 13). Since leaf area was measured at only one growth stage, it cannot be concluded that genotypes with high leaf areas tend to use soil water with less efficiency than those with lower leaf areas. The foregoing correlations, however, do indicate an examination of leaf area development of winter wheat might be warranted. This should provide useful information concerning the type of wheat plant best suited for production in semiarid dryland regions.

The high positive correlation of heading date and leaf area was anticipated (Table 13). Generally those winter wheat genotypes which have late heading dates tend to develop greater leaf areas as a result of the longer growing period.

SUMMARY

The analyses of variance showed significant differences among thirteen sampling dates and eight soil depths for evapotranspiration, and among genotype X sampling dates, genotype X soil depth and date X depth interactions for water remaining in the soil profile (Tables 1 and 5). Significant differences were noted among the ten winter wheat genotypes for all of the agronomic characteristics measured (Table 11).

The lack of significant differences for total water use among the ten winter wheat genotypes was not anticipated (Table 1). The method of analysis, mentioned in RESULTS AND DISCUSSION, may have contributed to this situation. In unpublished data, Brown (personal communication) noted significant variations among winter wheat genotypes for water use. Additionally, significant genotype differences for water remaining in the soil were found in this study (Table 5).

Water use by winter wheat, in general, increased from early May to a peak the weak of June 23 and decreased as the season progressed to late July (Figure 1). When this time period was segmented, as in Figure 2, it was evident that winter varied greatly for water use during different growth stages.

Increasing dry matter and daily temperatures and a drier and more turbulent atmosphere, resulted in greatly increased water use as the growing season progressed. The highest water use occurred during the heading and grain-filling stage, with decreasing amounts for stem

---

Brown, P. L. Personal communication.

extension, late tillering and maturation, respectively. The reduction in evapotranspiration during maturation is attributed to the removal of most of the plant available soil water from the profile by this time, and to the fact that winter wheat plants gradually die and lose their ability to transpire. These results are correlated by Brown (1971), Ferguson (1965), Lehane and Staple (1965) and Stephens et al. (1943).

The examination of eight soil profile depths revealed that winter wheat water decreased with depth. The upper four feet accounted for 88 percent of the total water used, with 54 percent coming from the top foot (Figure 3 and Table 4). Ferguson (1965), working with spring wheat in Canada, reported the largest differences in evapotranspiration occurred in the top 18 inches of soil.

Significant amounts of water were used from the seven and eight foot depths. Kmoch et al. (1957) reported that winter wheat roots penetrated up to 13 feet under favorable field soil water conditions.

The water use pattern shown in Figure 3 is the result of greater root density and activity in the upper four feet of the soil profile. Although it is difficult, from these data, to make a clear concise statement with respect to rooting patterns, it is apparent, that root densities and activities decreased with increased soil depth.

The ten winter wheat genotypes removed water from the soil profile differentially at different dates (Tables 5 and 6). This significant genotype X date interaction was evident in the consideration of growth stages.

During late tillering seven of the ten genotypes used more than 1.75 inches of water, whereas during stem extension eight of the ten genotypes accounted for over three inches of water used (Figure 5). During heading and grain-filling and maturation, respectively, six and five of the ten winter wheat genotypes were in the high water use group.

In general, Winalta, Cheyenne, Nugaines, and Wanser showed the least variation for water use among sampling dates and growth stages (Figures 4 and 5). The cultivar Crest, generally a moderate to low water user, used maximum amounts during heading and grain filling. Both Froid and MT 6928, generally moderate water users, utilized maximum quantities during maturation.

Tables 5 and 8 show that the ten winter wheat genotypes differentially used water from the eight soil depths. Large differences for water use, among the ten genotypes were not found in the top four feet of the soil profile, although the differences were significant and changes in rank were noted.

Large water depletion differences at the five, six, seven and eight foot depths are indicative of differential rooting patterns of the ten winter wheat genotypes. Among the ten genotypes, Itana and ID 5006 possessed the best root systems for using water from the lower four depths. Cheyenne was similar, except for a reduction in water depleted from the eight foot soil depth. All other genotypes had less extensive root systems since they did not use large amounts of water from the lower soil depths.

In this study winter wheat depleted water differentially with respect to soil depths and sampling dates (Tables 5 and 10). Figure 7 illustrates this significant depth X date interaction.

Winter wheat, in this study, drew most of its water from the upper five feet of the soil profile through heading and early grain-filling (Figure 7). By the week of July 21 virtually all of the plant available water had been removed. Progressive rooting patterns are shown by removal of significant amounts of water from the upper four feet during late tillering (mid-May), from the fifth and sixth foot depths at heading (about June 23) and from the seven and eight foot levels during maturation (late July). The six, seven and eight foot soil depths would be important soil water reservoirs during dry growing seasons.

As previously indicated, among the ten winter genotypes, significant differences were found for yield and yield components, leaf area, plant height and heading date (Tables 11 and 12). Additionally, correlations were made among these characters (Table 13).

The significant difference among genotypes for yield and a significant correlation of .945 between yield and water use efficiency shows that the high yielding winter wheats used in this study were most efficient in their use of soil water.

Positive correlation coefficients were found for the three components of yield, number of heads, number of seeds per head and 100 seed weight. The positive correlation between 100 seed weight and yield varied from that generally observed. This was due to the heavy stripe rust infection of two genotypes which reduced yields and seed weight.

The positive correlations between number of heads, number of seeds per head and 100 seed weight would indicate that those winter wheat which have higher mean yield components would tend to be efficient water users.

Plant height was negatively correlated with number of seeds per head, number of heads, yield, water use and water use efficiency (Table 13). It was positively correlated with 100 seed weight. Under the conditions of this study the shorter winter wheats were the best adapted genotypes when yield and water use efficiency were considered.

The negative correlation between heading date and water use efficiency indicates that under semiarid dryland conditions early maturing winter wheats are desirable. They escape the periods of high temperature and increased evapotranspiration.

The correlation between leaf area and water use efficiency was negative. Since leaf area was measured at only one growth, it cannot be concluded that winter wheats in semiarid regions should possess low leaf areas.

Table 1. Analysis of variance of evapotranspiration of winter wheat.

Source of Variation	Degrees of Freedom	Mean Squares
Genotypes	9	0.0476
Dates	12	1.8658**
Depth	7	45.9969**

** Significant at .01 level

Table 2. Evapotranspiration (inches) of ten winter wheat genotypes during four growth stages.

	Growth Stages				
Genotypes	Late tillering May 5-19	Stem extension May 19-June 16	Heading and grain filling June 16-July 14	Maturation July 14-Aug 4	Total
Itana	1.81	4.56	6.14	1.15	13.66
Winalta	2.24	4.59	5.50	0.81	13.14
ID 5006	1.50	4.40	5.89	0.96	12.75
Nugaines	2.05	4.25	5.39	0.85	12.54
Wanser	1.99	4.40	4.96	0.66	12.01
Cheyenne	1.88	4.00	5.01	0.99	11.88
Froid	1.46	3.78	4.41	1.98	11.63
Crest	1.94	2.71	6.21	0.66	11.52
Yg SS4662	1.82	3.75	5.28	0.64	11.49
MT 6928	1.72	2.92	4.79	1.93	11.36

Table 3. Weekly evapotranspiration of winter wheat.

Dates	Evapotranspiration (inches)
May 5	0.14 b
12	1.03 a
19	0.61 a
26	0.96 a
June 2	1.02 a
9	1.02 a
16	1.21 a
23	1.56 a
30	1.25 a
July 7	1.33 a
14	1.09 a
21	0.67 a
28	0.18 b

Values followed by the same letter do not differ at 0.05 level according to Duncan's Multiple Range Test.

Table 4. Evapotranspiration by winter wheat from eight one-foot soil profile increments.

Depth (ft)	Evapotranspiration (inches) Average	Evapotranspiration (inches) Percent of total
1	6.65 a	53.7
2	1.71 b	13.8
3	1.57 c	12.7
4	0.96 d	7.8
5	0.74 e	6.0
6	0.44 f	3.6
7	0.21 g	1.7
8	0.10 h	0.8

Values followed by the same letter do not differ at 0.05 level according to Duncan's Multiple Range Test.

Table 5. Analysis of variance for water remaining (inches plant available water per foot of soil) for genotypes, dates, depths and interactions.

Sources of Variation	Degrees of Freedom	Mean Squares
Genotypes	9	0.2338 **
Dates	13	9.2671 **
Genotypes X Dates	117	0.0106 **
Depth	7	24.0559 **
Genotypes X Depth	63	0.0363 **
Dates X Depth	91	0.7366 **

** Significant at .01 level.