Final Report

Arizona Grain Research and Promotion Council

December, 2018

Water use and rooting of low input barley

Andrea Carter and Mike Ottman
University of Arizona

Water Use and Rooting of Low Input Barley

M. J. Ottman

Summary

Solum and Solar are low input barley varieties developed for reduced water use by R. T. Ramage of the USDA-ARS and released by the University of Arizona several years ago.. A study was conducted at the Campus Ag Center in Tucson to determine water use and rooting characteristics of these varieties compared to the high input varieties, Cochise and Kopious, using wet (7 irrigations) and dry (2 irrigations) treatments. Low input varieties intercepted more sunlight and had higher biomass at various times during the season than high input varieties under dry conditions. Low input varieties flowered 6-7 days earlier under wet and 4-5 days earlier under dry conditions that high input varieties. Under wet conditions the grain yield of the high and low input varieties were 2.62 and 1.79 T/A, whereas under dry conditions the grain yields were reversed at 1.05 and 1.37 T/A. Test weight of the high input varieties under dry conditions was an unacceptable 42 lbs/bu, whereas the low input varieties averaged 50 lbs/bu. Root length density did not differ among varieties and the root distribution with depth was similar. The fraction of roots in the top foot was 44 and 48% for the high and low input varieties, respectively. Daily water use was similar for the varieties except for the end of the season where the low input varieties used less water since they matured earlier. This study does not support the idea that rooting and water use characteristics of low input varieties gives them an advantage under dry conditions.

Introduction

Barley is one of the world's most important cereal crops, ranking fourth in global cereal production after wheat, maize and rice. (FAO, 2018). A relatively hardy crop, barley has demonstrated a capacity to thrive in arid and semi-arid climates where drought is a determinant of crop productivity. The projected increase in the incidence and severity of drought conditions combined with the predicted decline in water availability has sparked interest in crop production that is less water dependent (Ceccarelli et al., 2010; Cassman, 2003). As a result of the increasing demand for cereal grains, attributable to human and animal consumption, there is an emerging consensus that demand could be better met through the development, dissemination, and adoption of drought tolerant genotypes (Araus 2002; Reynolds 2016).

One obstacle to achieving increased yields to meet global demand is the depressed yields of semi-dwarf cereals under low input conditions (Richards, 1992; Uddin and Marshall, 1989). Though dramatic gains in grain yield were achieved through their development, these high-yielding varieties require significantly more inputs, i.e. water and nitrogen fertilizer (Fita et al., 2015). Comparisons of modern barley and wheat genotypes to standard height varieties indicate physiological changes that may reduce plant performance under drought stress. Semi-dwarf varieties for example have a higher proportion of their roots in the surface soil compared to standard height or pre-Green Revolution varieties. This rooting distribution makes semi-dwarf varieties less able to extract subsoil water compared to standard height varieties and thus they are more susceptible to drought stress (Den Herder et al. 2010; Waines and Ehdaie, 2007). Moreover, in cases of severe water deficit, semi dwarf varieties may be too short for mechanical harvest, or less economically profitable in areas where straw used as animal feed is an important commodity, e.g. West Asia and North Africa (Annicchiarico and Pecetti, 2003). A unique multisite study by Matthews et al. (2006) shows taller genotypes out yield semi-dwarfs in the most droughted environments.

Characterization of the physiological aspects of crops grown under drought conditions is a well-recognized methodology for the identification of important secondary traits when breeding for water-limited environments (Reynolds, 2016; Araus et al., 2008; Blum 1988). Given that most plant water is lost during the process of transpiration, stomatal conductance has been an important focus of drought physiology studies (Blum, 2009). Under drought stress, greater stomatal conductance and transpiration have been found in higher yielding genotypes of wheat, maize and rice measured by leaf gas exchange or canopy temperature (Varone and Gratani, 2015; Chen, 2012; Reynolds, 1994).

Phenology is another major consideration when breeding for water-limited environments particularly when expected seasonal moisture or timing of stress is known (Araus et al., 2008). Genotypes can be generally classified as either short duration or long duration types. Short growth types are characterized by early maturity and a higher likelihood of escaping terminal drought stress i.e. stress at the critical reproductive stage (anthesis) (Blum, 2009). Under drought stress at pre-anthesis stages (tillering and stem elongation) earlier flowering genotypes of barley have been found to outperform late flowering genotypes (Al-Ajlouni et al., 2016). Long-duration genotypes generally exhibit longer intervals to anthesis, greater water use, and deeper root systems allowing for increased soil moisture extraction, if available (Mitchell et al., 1996).

Barley is characterized by fast-pre-anthesis growth and high tiller output, traits that are used to explain why barley is well adapted to dry areas (Ceccarelli et al., 2010). Described as fast development of leaf area and/or shoot biomass, early seedling vigor is attributed to barley's advantageous growth over wheat in Mediterranean-type environments (Lopez-Castaneda et al., 1995; Gregory et al., 1992). Vigorous early growth and canopy shading serve to reduce evaporation from the soil surface thereby increasing available water for crop transpiration (Blum 2009).

Vigorous root systems are another effective means by which cereals can maximize soil moisture use, particularly if able to access subsoil moisture during reproductive growth when additional water is used for grain development and filling (Blum, 2009; O'Toole, 1982). Root vigor describes early and fast root extension and proliferation, greater root biomass, and greater root length density (Palta and Watt, 2009). A study of wheat roots by Kirkegaard et al. (2007) demonstrated an additional 10 mm of water accessed by roots from the subsoil late in the season (post anthesis) increased grain yield by over 0.50 t ha $^{-1}$. Given that barley is most sensitive to drought stress during anthesis, deeper roots would suggest a genotypes ability to avoid yield losses.

Much of the research on differences between semi-dwarfs and standard height cereals has focused on yield or has been conducted under controlled environment conditions. In addition, there is a scarcity of work that has compared rooting patterns with above ground plant development in the field. The purpose of this study was therefor to compare growth, phenology, yield and rooting characteristics of semi-dwarf and standard height varieties under high and low irrigation conditions. The results of this research will help to elucidate physiological responses and adaptations of barley to drought stress.

Material and Methods

Site Characteristics

Field studies were conducted to study barley performance under high and low irrigation conditions. A trial was conducted in 2018 at the University of Arizona, Campus Agricultural Station in Tucson, AZ located at 32°9΄36″N, and 110°33΄36″W. Soil type was a Gila very fine sandy loam (coarse-loamy, mixed, superactive, calcareous, thermic Typic Torrifluvent). The field was fallow prior to the 2018 planting.

Cultural Methods

Four varieties of spring feed barleys were selected for comparison in this experiment. Two varieties of semi-dwarf spring barley Cochise and Kopious were planted along with two standard-height, low-input varieties, Solar and Solum. Cochise and Kopious are considered high-input, high-yielding genotypes. Solar and its predecessor Solum were developed as one-irrigation barleys suitable for use in crop-rotation in the arid southwest or to be sown after winter rains in rainfed cropping systems.

In 2017 planting occurred on 7 Dec. and established with sprinkler irrigation from 12 Dec. to 1 Jan. The seed was planted into dry, flat soil.   The seed was planted with a seed spacing of 6 inches. The low input varieties were planted at a seeding rate of 70 lbs/acre and the high input varieties were planted at a seeding rate of 140 lbs/acre.

Nitrogen was applied in the form of urea (46–0–0) at a rate of 50 lbs N/A at emergence. During the growing season, an additional 100 lb/A of N was applied to the wet irrigation treatment. The source of the irrigation water was tertiary-treated municipal sewage effluent.

Weeds and insects were controlled mechanically as needed. Each plot was 7 rows wide with row spacing of 6 inches and plot length of 30 ft.   The experimental design was Latin square.

Soil Water Measurements

Neutron probe access tubes were installed to a depth of 6 ft to measure volumetric water content at depth increments of 1 ft.   Soil water was measured about three times between irrigations with a neutron probe (CPN Model 503DR, Campbell Pacific Nuclear International Inc., Concord, CA).   The neutron probe was calibrated by regressing volumetric water content against standardized neutron count ratios using multiple paired measurements when soil was wet and dry. Volumetric soil moisture content for the neutron probe calibration was determined from gravimetric water content and bulk density.

Soil Water Retention Characterization

Soil water characteristics previously reported by Miller and Ottman (2010) were used. Soil bulk density was 1.48 g cm^{-3}. Volumetric soil water content was 0.24 $m^3 m^{-3}$ at field capacity (θvFC), 0.085 $m^3 m^{-3}$ at permanent wilting point ($\theta vPWP$), and plant-available water ($\theta vPAW$) was 0.155 $m^3 m^{-3}$. The differences in soil water characteristics among depths were small and less than the standard error of these measurements, so values were averaged across depths.

Irrigation Treatments

The experiment included two irrigation treatments: high and low. The frequency of irrigations in the high irrigation treatment were based on levels of soil water depletion (SWD), with irrigations occurring at 50% depletion or approximately every two weeks. The low irrigation treatment received one irrigation treatment post-emergence at the three leaf stage in addition to the irrigation at establishment. The source of irrigation water was tertiary-treated municipal effluent and was applied through flood irrigation except for the sprinkler irrigation at establishement..

The amount of irrigation water to be applied was calculated from soil water depletion in the top four feet divided by irrigation water application efficiency. The application efficiency, ratio of water stored in the root zone to water applied, value used was 0.8, which is within the potential attainable values of 0.75–0.90 reported by Tanji and Hanson (1990). Water usage was calculated from soil water depletion using neutron probe readings taken 3 days after the completion of the previous irrigation and within 1 day before the subsequent irrigation.   The soil water measurement profile of 0 to 4 ft was considered sufficient for scheduling irrigations since it represents the volume of soil where most of the water uptake occurs. The active rooting zone for water uptake was estimated from the Arizona Irrigation Scheduling System (AZSCHED). See Table 1 for irrigation amounts and dates.

Neutron probe counts from 0 to 6 ft were used to calculate period water use for each variety by the water balance method, with precipitation and irrigation included and runoff assumed to be negligible. The period water use values were summed at the end of the season for total water use amounts of each variety.

Plant Measurements

Measurements of plant biomass and interception of photosynthetically active radiation (PAR) were taken throughout season around five leaf, first node, boot, and flowering. Stomatal conductance was measured at anthesis. Date of heading, flowering, and physiological maturity were also recorded.   Biomass was obtained from 18 inches of two rows. Dry weight was assessed after samples had dried at 60˚ C for 2 to 10 days depending on growth stage.

Intercepted PAR was measured with a Sunfleck Ceptometer (Decagon Devices, Pullman, WA). The sensor was placed on the soil surface and oriented at about a 45 degree angle from the row to the center of the furrow for 3 averaged readings. The measurements were taken within 1 h of solar noon on clear days. The PAR was measured at the soil surface within the canopy, along with companion measurements of incident PAR outside the influence of the canopy to obtain a measure of PAR interception as a percentage of incident. Stomatal conductance was assessed using a leaf porometer (Decagon Devices, Pullman, WA) by taking one reading from the abaxial surface of the second leaves from the top of 8 plants per irrigation treatment for a total of 16 readings each year. Heading date was recorded when 50% of the heads were past the leaf collar. Flowering date was recorded when 50% of heads had anthers extruded. Maturity date was noted when 50 % of heads and peduncle had changed to tan color.

At harvest, biomass yield, height, and lodging were assessed as well as grain yield, test weight, and seed weight. Plant height was averaged from 10 heads as the length of stem to the top of the head. For final biomass yield 1 m^2 of whole barley plants were hand harvest and dried at 60˚ C for 10 days. Grain weight was subsequently assessed from the 1 m^2 sample. For final grain yield, 5 rows by 1.5 m were hand harvest and threshed. Clean seed was assessed for test weight and seed weight.

Method of Root Analysis

Following final harvest, soil core samples were taken at 1 ft increments to a depth of 6 ft using a 2 inch wide auger. Samples were collected from 2 of the 4 reps per irrigation treatment (16 plots total) from the center of the final harvest area. Core samples were air dried and processed through a soil grinder. 150 g of soil from each incremental depth was washed using a Gibson Root Washer. Water containing roots was passed through filter paper and length estimates made using the modified line intersect method of Tennant (1975).

Root profile walls were dug at pre-anthesis and after physiological maturity to access root growth in situ. A 6 ft m trench traversing the plots was dug and the profile washed with water to expose the roots. Density of roots within a 10 by 10 cm grid was ranked on a scale of 1 to 10 along the total profile. Photos of each grid segment were used to quantify root density using image processing software).

Statistical Analysis

The data were analyzed by the PROC MIXED procedure using SAS version 9.4.

Weather

The weather data was recorded by the Arizona Meteorological Network (AZMET) Campus Agricultural Center weather station, located about 0.5 km from the experimental plots.

Results and Discussion

The fraction of photosynthetically active radiation (fPAR) intercepted by the crop differed among varieties depending on irrigation treatment (Table 2). For the wet irrigation treatment, fPAR did not differ for the low compared to high input varieties. There were some differences among varieties with groups, however. Kopious tended to have highest fPAR and Cochise the lowest. For the dry treatment, the low input varieties had higher fPAR at all measurement times compared to high input varieties.

Biomass yield differed among varieties depending on irrigation treatment (Table 3). For the wet irrigation treatment, biomass yield did not differ for low or high input varieties compared as groups except for the last sampling time where the low input varieties outperformed the high input varieties. For the dry treatment, the low input varieties had higher biomass at the first and last measurement times compared to high input varieties.

Differences in phenology among varieties were similar whether grown under wet or dry conditions, although the crop progressed faster under the dry treatment for all varieties (Table 4). The low input varieties flowered 6-7 days earlier under wet and 4-5 days earlier under dry conditions compared to varieties bred for high water conditions. Similarly, the varieties bred for low water matured 9 days earlier under wet and 6 days earlier under dry conditions compared to varieties bred for wet conditions. Cochise reached phenological stages earlier than Kopious and Solum reached phenological stages earlier than Solar.

Yield and yield components differed among varieties depending on irrigation treatment (Table 5). For the wet irrigation treatment, total yield, grain yield, and harvest index were higher for the high input compared to low input varieties, and vice versa for kernel weight and plant height. For the dry treatment, the low input varieties had similar total yield and higher grain yield compared to high input varieties in contrast to the results under wet conditions. Kernel weight and plant height were higher for the low input varieties compared to the high input varieties under dry conditions similar to the results wet conditions.

Root length density from soil cores was generally similar among varieties regardless of irrigation treatment (Table 6). Root length density decreased rapidly with depth and the root distribution in the soil profile was similar regardless of whether or not the varieties were high or low input. The exception was the 2-3 ft depth in the dry treatment where the low input varieties had higher root density than the high input varieties. The fraction of roots in the top foot was 44 and 48% for the high and low input varieties, respectively. If there is a difference in root distribution we not able to detect statistically, the difference would be small and not relevant. We observed some interesting differences in root distribution by digging a trench an observing roots using the profile wall method. The low input varieties had proliferation of roots and associated mycorrhizae in patches along the root profile wall that we did not observe with the high input varieties, and the significance of this finding is undetermined at this time.

Water use generally did not differ among varieties with only a few exceptions (Table 7). For the wet irrigation treatment, Cochise had high and Kopious had low daily water use compared to the other varieties from March 12-18. During this time period and from March 31 – April 4, Cochise extracted a greater percentage of its water from deeper depths than the other varieties (data not presented). The high input varieties used more water from April 10 to 25 in the wet treatment than the low input varieties which were nearing maturity. Overall, under high water conditions, the high input varieties had about a 5% higher daily water use than the low input varieties due to the earlier maturity of the low input varieties. Under dry conditions, the daily water use was similar among variety types except for the time period between March 2-9 where the low input varieties had about a 10% higher daily water use and at the end of the season. The low input varieties had lower daily water use at the last two measurement times since these varieties were approaching maturity. Water use averaged over the season under dry conditions was similar across varieties unlike under wet conditions. Any differences among varieties in water use were small and not of practical significance.

References

Al-Ajlouni, Z. I., Al-Abdallat, A. M., Al-Ghzawi, A. L. A., Ayad, J. Y., Elenein, J. M. A., Al-Quraan, N. A., & Baenziger, P. S. (2016). Impact of pre-anthesis water deficit on yield and yield components in barley (hordeum vulgare L.) plants grown under controlled conditions. *Agronomy, 6*(2), 33. doi:10.3390/agronomy6020033

Araus, J. L., Slafer, G. A., Royo, C., & Serret, M. D. (2008). Breeding for yield potential and stress adaptation in cereals. *Critical Reviews in Plant Sciences, 27*(6), 377-412. doi:10.1080/07352680802467736

Araus, J., Slafer, G., Reynolds, M., & Royo, C. (2002). Plant breeding and drought in C-3 cereals: What should we breed for? *Annals of Botany, 89*, 925-940. doi:10.1093/aob/mcf049

Blum, A. (2009). Effective use of water (EUW) and not water-use efficiency (WUE) is the target of crop yield improvement under drought stress. *Field Crops Research, 112*(2), 119-123. doi:10.1016/j.fcr.2009.03.009

Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). MEETING CEREAL DEMAND WHILE PROTECTING NATURAL RESOURCES AND IMPROVING ENVIRONMENTAL QUALITY. *Annual Review of Environment and Resources, 28*, 315-358

CECCARELLI, S., GRANDO, S., MAATOUGUI, M., MICHAEL, M., SLASH, M., HAGHPARAST, R., . . . NACHIT, M. (2010). Plant breeding and climate changes. *The Journal of Agricultural Science, 148*(6), 627-637. doi:10.1017/S0021859610000651

Ceccarelli, S., & Grando, S. (1996). Drought as a challenge for the plant breeder. *Plant Growth Regulation, 20*(2), 149-155. doi:10.1007/BF00024011

Fita, A., Rodríguez-Burruezo, A., Boscaiu, M., Prohens, J., & Vicente, O. (2015). Breeding and domesticating crops adapted to drought and salinity: A new paradigm for increasing food production. *Frontiers in Plant Science, 6*(NOVEMBER), 978. doi:10.3389/fpls.2015.00978

Gregory, P. J., Tennant, D., & Belford, R. K. (1992). Root and shoot growth, and water and light use efficiency of barley and wheat crops grown on a shallow duplex soil in a mediterranean-type environment. *Australian Journal of Agricultural Research, 43*(3), 555-573. doi:10.1071/AR9920555

Kirkegaard, J. A., Lilley, J. M., Howe, G. N., & Graham, J. M. (2007). Impact of subsoil water use on wheat yield. *Australian Journal of Agricultural Research, 58*(4), 303-315. doi:10.1071/AR06285

Lynch, J. (2007). Roots of the second green revolution. *Australian Journal of Botany, 55*(5), 493-512. doi:10.1071/BT06118

Mitchell, J. H., Fukai, S., & Cooper, M. (1996). Influence of phenology on grain yield variation among barley cultivars grown under terminal drought. *Australian Journal of Agricultural Research, 47*(5), 757-774.

Palta, J., & Watt, M. (2009). Chapter 13 - vigorous crop root systems: Form and function for improving the capture of water and nutrients. (pp. 309-325) Elsevier Inc. doi:10.1016/B978-0-12-374431-9.00013-X

Reynolds, M., & Langridge, P. (2016). Physiological breeding. *Current Opinion in Plant Biology, 31*, 162-171. doi:10.1016/j.pbi.2016.04.005

Tambussi, E. A., Nogués, S., Ferrio, P., Voltas, J., & Araus, J. L. (2005). Does higher yield potential improve barley performance in mediterranean conditions? A case study. *Field Crops Research, 91*(2-3), 149-160. doi:10.1016/j.fcr.2004.06.002

Waines, J. G., & Ehdaie, B. (2007). Domestication and crop physiology: Roots of green-revolution wheat. *Annals of Botany*, *100*(5), 991-998. doi:10.1093/aob/mcm180
Watt, M., Silk, W., & Passioura, J. (2006). Rates of root and organism growth, soil conditions, and temporal and spatial development of the rhizosphere. *Annals of Botany*, *97*(5), 839-855. doi:10.1093/aob/mc1028

Table 1. Soil water depletion and irrigation amounts for a barley irrigation trial conducted in Tucson, 2018. The growing season precipitation was 2.17 inches received in December, January, and February.

	High irrigation		Low irrigation	
Date	Soil water depletion	Irrigation	Soil water depletion	Irrigation
		inches		inches
Dec	n/a	4.0	n/a	4.0
10-Jan	n/a	2.1	n/a	2.1
19-Feb	0.49	4.3	0.48	4.1
9-Mar	0.47	3.1		10.2
23-Mar	0.48	3.2		
6-Apr	0.50	3.4		
26-Apr	0.84	3.5		
total		23.5		10.2

Table 2. Effect of variety under two irrigation treatments on fraction of photosynthetically active radiation (PAR) intercepted for a trial conducted in Tucson in 2018

Irrigation treatment	Variety adaptation	Variety	2-Feb	23-Feb	20-Mar	27-March
Wet	High water	Cochise	0.459	0.668	0.911	0.596
		Kopious	0.623	0.864	0.973	0.719
		AVG	0.541	0.766	0.942	0.657
	Low water	Solar	0.534	0.811	0.946	0.652
		Solum	0.481	0.752	0.943	0.613
		AVG	0.508	0.781	0.944	0.632
		Variety	**	**	**	**
		Variety adaptation	ns	ns	ns	ns
		CV (%)	8.2	5.2	1.0	5.0
		$LSD_{.05}$	0.069	0.065	0.015	0.052
Dry	High water	Cochise	0.369	0.626	0.872	0.529
		Kopious	0.588	0.856	0.955	0.692
		AVG	0.479	0.741	0.914	0.611
	Low water	Solar	0.577	0.821	0.955	0.684
		Solum	0.607	0.817	0.958	0.706
		AVG	0.592	0.819	0.957	0.695
			**	**	**	**
		Variety	**	**	**	**
		Variety adaptation	**	**	*	**
		CV (%)	11.3	5.4	3.1	6.9
		$LSD_{.05}$	0.097	0.067	0.047	0.072

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.

Table 3. Effect of variety under two irrigation treatments on biomass yield for a trial conducted in Tucson in 2018.

Irrigation treatment	Variety adaptation	Variety	7-Feb	23-Feb	16-Mar	27-Mar
			T/A	T/A	T/A	T/A
Wet	High water	Cochise	0.40	1.24	4.30	7.39
		Kopious	0.63	1.35	6.08	8.18
		AVG	0.52	1.29	5.19	7.78
	Low water	Solar	0.60	1.61	6.57	9.28
		Solum	0.54	1.41	5.38	9.72
		AVG	0.57	1.51	5.97	9.51
		Variety	ns	ns	ns	ns
		Variety adaptation	ns	ns	ns	*
		CV (%)	21.3	19.3	21.7	15.2
		$LSD_{.05}$	0.18	0.43	1.94	2.11
Dry	High water	Cochise	0.30	1.26	4.06	5.34
		Kopious	0.72	1.40	5.36	7.45
		AVG	0.51	1.33	4.71	6.39
	Low water	Solar	0.70	2.22	5.91	8.98
		Solum	0.64	1.82	5.93	10.55
		AVG	0.67	2.02	5.92	9.76
		Variety	**	ns	ns	*
		Variety adaptation	*	ns	ns	**
		CV (%)	22.9	40.9	25.6	21.3
		$LSD_{.05}$	0.22	1.10	2.18	2.76

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.

Table 4. Effect of variety under two irrigation treatments on phenology by date for a trial conducted in Tucson in 2018.

Irrigation Treatment	Variety	Heading	Flowering	Physiological Maturity
Wet	Cochise	20-Mar	22-Mar	6-May
	Kopious	22-Mar	24-Mar	30-Apr
	Solar	15-Mar	17-Mar	26-Apr
	Solum	13-Mar	14-Mar	23-Apr
	Variety	**	**	**
	Low vs high	**	**	**
	CV (%)	0.007	0.007	0.003
	LSD $_{.05}$	2.17	2.17	0.8535
Dry	Cochise	19-Mar	19-Mar	24-Apr
	Kopious	20-Mar	20-Mar	23-Apr
	Solar	14-Mar	16-Mar	19-Apr
	Solum	13-Mar	14-Mar	16-Apr
	Variety	**	**	**
	Low vs high	**	**	**
	CV (%)	0.005	0.003	0.004
	LSD $_{.05}$	1.51	1.14	1.31

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.

Table 5. Effect of variety under two irrigation treatments on barley yield and yield components for a trial conducted in Tucson in 2018.

Irrigation treatment	Variety adaptation	Variety	Total Yield	Grain Yield	Harvest Index	Test Weight	Kernel Weight	Lodging	Plant height
			T/A	T/A		lb/bu	g/1000	%	inches
Wet	High water	Cochise	6.20	2.51	0.40	---	30.0	0	33
		Kopious	7.27	2.74	0.38	---	32.6	0	32
		AVG	6.73	2.62	0.39	---	31.3	0	32
	Low water	Solar	6.01	2.12	0.34	---	40.7	4	41
		Solum	4.54	1.45	0.32	---	44.3	2	39
		AVG	5.28	1.79	0.33	---	42.5	3	40
		Variety	*	*	ns	---	**	ns	**
		Variety adaptation	*	**	*	---	**	ns	**
		CV (%)	19	22	14.2	---	7.2	273	5.1
		$LSD_{.05}$	1.82	0.78	0.083	---	4.2	7	3
Dry	High water	Cochise	3.76	1.21	0.32	42.3	20.6	0	23
		Kopious	4.25	0.89	0.21	41.6	18.4	0	24
		AVG	4.01	1.05	0.27	42.0	19.5	0	23
	Low water	Solar	5.05	1.63	0.32	54.1	27.3	0	38
		Solum	3.54	1.11	0.32	46.6	27.7	0	37
		AVG	4.30	1.37	0.32	50.3	27.5	0	37
		Variety	**	*	ns	**	**	---	**
		Variety adaptation	ns	*	ns	**	**	---	**
		CV (%)	9	21.2	28.7	4.4	13.6	---	3.6
		$LSD_{.05}$	0.60	0.41	0.1	3.3	5.1	---	2

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.

Table 6. Effect of variety under two irrigation treatments on barley root length density for a trial conducted in Tucson in 2018.

			Root length density						
Irrigation treatment	Variety adaptation	Variety	0-1 ft	1-2 ft	2-3 ft	3-4 ft	4-5 ft	5-6 ft	AVG
			cm root/cm^3 soil						
Wet	High water	Cochise	0.91	0.29	0.35	0.11	0.03	0.07	0.29
		Kopious	0.72	0.53	0.38	0.12	0.08	0.09	0.32
		AVG	0.82	0.41	0.37	0.11	0.05	0.08	0.31
	Low water	Solar	0.59	0.32	0.30	0.12	0.11	0.08	0.25
		Solum	0.83	0.26	0.13	0.12	0.12	0.04	0.25
		AVG	0.71	0.29	0.22	0.12	0.12	0.06	0.25
		Variety	ns	ns	ns	ns	ns	ns	ns
		Variety adaptation	ns	ns	ns	ns	ns	ns	ns
		CV (%)	14	30	39	57	53	90	51
		$LSD_{.05}$	ns	ns	ns	ns	ns	ns	ns
Dry	High water	Cochise	0.47	0.28	0.08	0.05	0.02	0.03	0.15
		Kopious	0.50	0.17	0.11	0.06	0.06	0.05	0.16
		AVG	0.49	0.22	0.09	0.06	0.04	0.04	0.16
	Low water	Solar	0.36	0.12	0.20	0.13	0.02	0.02	0.14
		Solum	0.34	0.16	0.23	0.05	0.04	0.02	0.14
		AVG	0.35	0.14	0.21	0.09	0.03	0.02	0.14
		Variety	ns	ns	ns	ns	ns	ns	ns
		Variety adaptation	ns	ns	*	ns	ns	ns	ns
		CV (%)	15	55	27	80	46	55	65
		$LSD_{.05}$	ns	ns	ns	ns	ns	ns	ns

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.

Table 7. Effect of variety under two irrigation treatments on daily water use over various time periods for a trial conducted in Tucson in 2018.

Irri-gation treat-ment	Variety adap-tation	Variety	Jan18-Feb07	Feb19-Mar02	Mar02-Mar09	Mar09-Mar12	Mar12-Mar18	Mar18-Mar22	Mar22-Mar31	Mar31-Apr04	Apr04-Apr10	Apr10-Apr25	Avg
Wet	High water	Cochise	0.07	0.17	0.20	.	0.27	0.29	.	0.34	.	0.32	0.24
		Kopious	0.08	0.14	0.19	.	0.18	0.28	.	0.29	.	0.26	0.20
		AVG	0.07	0.16	0.19	.	0.23	0.28	.	0.32	.	0.29	0.22
	Low water	Solar	0.07	0.15	0.19	.	0.21	0.28	.	0.32	.	0.23	0.21
		Solum	0.07	0.15	0.18	.	0.22	0.26	.	0.32	.	0.24	0.21
		AVG	0.07	0.15	0.18	.	0.22	0.27	.	0.32	.	0.24	0.21
		Variety	ns	ns	ns	.	*	ns	.	ns	ns	**	**
		Variety adap-tation	ns	ns	ns	.	ns	ns	.	ns	ns	**	ns
		Variety x depth	ns	ns	ns	.	**	ns	.	**	ns	ns	ns
		CV (%)	30	27	23	.	39	40	.	27		24	34
		$LSD_{.05}$	ns	ns	ns	.	0.01	ns	.	ns	ns	0.01	0.01
Dry	High water	Cochise	0.07	0.15	0.19	0.17	0.17	0.22	0.11	0.16	0.11	0.04	0.14
		Kopious	0.08	0.20	0.22	0.21	0.21	0.26	0.13	0.13	0.08	0.02	0.15
		AVG	0.07	0.17	0.20	0.19	0.19	0.24	0.12	0.14	0.10	0.03	0.14
	Low water	Solar	0.08	0.18	0.22	0.18	0.18	0.22	0.12	0.17	0.10	0.04	0.15
		Solum	0.08	0.17	0.22	0.22	0.19	0.27	0.13	0.12	0.06	0.01	0.15
		AVG	0.08	0.18	0.22	0.20	0.18	0.25	0.13	0.14	0.08	0.02	0.15
		Variety	ns	ns	ns	ns	ns	ns	ns	ns	**	**	ns
		Variety adap-tation	ns	ns	*	ns	ns	ns	ns	ns	*	ns	ns
		Variety x depth	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
		CV (%)	41	41	21	43	35	44	49	52	47	54	44
		$LSD_{.05}$	ns	ns	ns	ns	ns	ns	ns	ns	0.01	0.01	ns

ns, *, ** = not significant at P = 0.05 and significant at P = 0.05 and P = 0.01, respectively.