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Deficit irrigation effects on adjunct and all-malt barley yield and quality

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Abstract

Semiarid regions are reliant on irrigation to produce large-yielding and high-quality malt barley (*Hordeum vulgare* L.). Drought in the western United States is of concern as surface and ground water reductions are occurring that affect irrigation water availability. Implementing a seasonal water deficit compared to evapotranspiration (ET) is a potential strategy to reduce water usage if yield and quality can be maintained. Research was conducted in Aberdeen, ID, on the effects of deficit irrigation on yield, grain quality, and malt characteristics. Five genotypes were selected to represent those used for large-scale adjunct brewing and those targeted at the all-malt craft industry. Irrigation was managed at three rates (100%, 75%, and 50%) of estimated crop evapotranspiration (ET_c) using sprinkler irrigation. Total aboveground dry matter was not affected by irrigation until soft dough (Feekes 11.2). Yield was similar within a genotype with irrigation reduction from 100% ET_c to 75% ET_c. Averaged across genotypes, yields were 6936 kg ha^{-1} at 100% ET_c and 6297 kg ha^{-1} at 75% ET_c. At 75% ET_c, protein remained just below the adjunct target (130 g kg^{-1}) for four of five genotypes while all five exceeded the all-malt target (120 g kg^{-1}). Reduced irrigation decreased malt extract and increased diastatic power, where β-glucan either did not differ or increased. Deficit irrigation is promising, particularly for adjunct brewing; however, expected changes to malting quality must be understood and genotype selection, altered fertilizer management, and/or changes to malting criteria may be needed for implementation.

1 | INTRODUCTION

Barley in the western United States is predominately two-row type produced for the end-use of malting and brewing. In Idaho, upward of 85% of production is for malt with 70% of production under irrigation (IBC, 2018; Robertson & Stark, 2003) Irrigation is largely concentrated in the semi-arid areas supplied by surface water from the Snake River alongside groundwater pumping in the southern part of the state. Malt barley production must meet both yield goals and strict quality specifications. Only a limited number of genotypes that consistently yield well enough and meet these strict grain quality and malt guidelines, determined primarily by the brewing industry, are considered acceptable and widely grown (AMBA, 2021). Brewing end-uses are defined in two

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Abbreviations: DP, diastatic power; ET, evapotranspiration; ET_c, estimated crop evapotranspiration; ET_r, alfalfa-based reference evapotranspiration; F10.0, Feekes 10.0; F11.2, Feekes 11.2; F11.4, Feekes 11.4; F4/5, Feekes 4/5; FAN, free amino nitrogen; S/T, soluble protein to total protein ratio; TDM, total aboveground dry matter.

primary categories, with specific quality parameters varying slightly: adjunct brewing, where added starches (e.g., other grains) are used as a source of fermentable sugars during the brewing process and all-malt where no additional starches are used during the brewing process. Historically adjunct brewing predominated in the United States with all-malt specific breeding occurring after the rapid increase in the craft brewing industry in the 2010s (Brewers Association, 2021). One of the major differences between the two types of malting is grain protein targets along with other parameters driven by nitrogen (N) compounds (AMBA, 2021). Adjunct brewing (60% of production) allows slightly higher protein targets (130 g kg^{-1} or less) as compared to all-malt brewing (120 g kg^{-1} or less). Malt requirements are similarly driven by N where soluble protein to total protein ratio (S/T) and free amino nitrogen (FAN) may be slightly higher for adjunct brewing targets.

Semiarid areas of the western United States consist of large, highly productive swathes of agricultural land that are dependent on irrigation for sustainable crop production due to the climate of the region. Historically, crops have been irrigated to meet evapotranspiration (ET) demands to ensure salt accumulation and evaporation are maintained at levels that are optimal for plant growth (Fereres & Soriano, 2006). Globally, expanding human populations have led to declines in both surface and groundwater supplies (Rodell et al., 2018). Many areas in the western United States are experiencing increased population growth and thus, increased urban water demands that can decrease available water for agricultural irrigation (Mackun et al., 2021). Drought conditions are of utmost concern due to the reliance on irrigation and the increased variation in climate extremes that are driving changes in water storage and availability (Adusumilli et al., 2019). These concerns are increased as noted by predictions by the Intergovernmental Panel on Climate Change that droughts will become more severe and frequent as a result of climate change in the upcoming decades (Pachauri et al., 2014). In the region, recent and widespread drought has led to historically low water levels in large reservoirs such as Lake Mead on the Colorado River that are indicative of concerns across the western United States (NASA, 2022). Early irrigation water supply shutoff and water delivery reductions have occurred in surface water supplied irrigation systems that supply large areas of production in Idaho (KMVT, 2022). Thus, improvement in irrigation management must be implemented to ensure food security now and into the future.

Deficit irrigation is one such tool that can reduce water use by applying rates that are below those needed to meet the demand from ET (English, 1990). However, a water deficit throughout the growing season will reduce overall biomass and plant production (Ma et al., 2014). Of equal concern to yield is quality response in many crops grown under irrigation. Thus, the magnitude of these changes must be considered for individual crop yield and quality goals to determine if the benefit of water reductions outweighs economic loss from reduction in crop production. Chai et al. (2015) outline the quality response for a range of crops in their review. Crop-specific quality parameters are a major factor in determining the suitability of deficit irrigation, as these parameters are highly divergent among crops and even within end-uses of a single crop. In non-cereal crops, deficit irrigation effects on crop quality have varied based on the amount of water deficit where positive and negative effects have been described that are dependent on the desired end use of the crop (Chai et al., 2015). In brief, canola (*Brassica napus* L.) had reduced oil production, tomato (*Solanum lycopersicum* L.) had reduced fruit size, oranges (*Citrus sinensis* L.) had reduced fruit size and juice percentage, sugar beet (*Beta vulgaris* L.) had reduced sugar content, potatoes (*Solanum tuberosum*, L.) had reduced US No. 1 tuber size; positive responses were reported for peaches (*Prunus persica* L.) as they had improved coloration and in potatoes (*Solanum tuberosum* L.) where the end-users desired smaller sized tubers, the C_2 yield fraction was increased (Gelly et al., 2004; Ghobadi et al., 2006; Hutton & Loveys, 2011; Kirda et al., 2007; Shahnazari et al., 2007; Stark et al., 2013; Tarkalson & King, 2017; Xie et al., 2012)

While barley has drought tolerance potential, yield and quality response must be considered under consistent deficit amounts to determine their suitability to meet the needs of end-users with strict requirements (Mosaddek Ahmed et al., 2016). In small-grain cereal crops specifically, crop water stress early in crop development and around anthesis can reduce yield through a reduction in number of kernels per area and mean weight of kernels (Calderini et al., 2001; Carter

Core Ideas

- Grain yields were similar within a genotype with a reduction in irrigation from 100% to 75% crop evapotranspiration (ET_c).
- Total aboveground dry matter yields at the F10 (boot) stage, when forage is commonly harvested, were unaffected by irrigation rate.
- Adjunct (130 g kg^{-1}) but not all-malt (120 g kg^{-1}) protein was met with irrigation reduction to 75% ET_c.
- With decreased irrigation, malt extract and soluble protein to total protein ratio decreased, diastatic power increased, and β-glucan did not differ or increase.
- Irrigation reductions to 75% ET_c are promising for adjunct targets; caution is needed for all-malt targets.

& Stoker, 1985; Fischer, 1985; Pardo et al., 2022; Savin & Slafer, 1991). Grain quality parameters can be negatively impacted under water-stressed conditions particularly when stress occurs during grain fill (Qureshi & Neibling, 2009; Rogers et al., 2022; Stevens et al., 2015). Protein content is particularly susceptible to negative effects as water stress results in less N dilution in the grain due to yield accumulation, and thus, increased protein that is detrimental to malting (Jahromi et al., 2022; Rogers et al., 2022; Stevens et al., 2015; Walsh et al., 2020). Additionally, genotype variation in grain protein under full and water-stressed conditions has been measured (Liang et al., 2022). A recent study reported results from 3-years on barley grown in Spain using drip irrigation that determined application rates based on a modeling approach developed for the crop and region (Pardo et al., 2020, 2022). Their results indicated generally similar yield and quality parameters when water was applied at 80% of their no deficit rate. Similarly, recent work in Idaho and Montana with soft white wheat (*Triticum aestivum* L.) reported that irrigation at 75% of ET was sufficient to meet yield and quality goals as compared to the 100% rate (Walsh et al., 2020).

Deficit irrigation is a promising tool to reduce water usage for small-grain cereal crops. However, in high-input, irrigated production in the western United States, high yields and high quality must be shown to be consistently attainable compared to current production levels to allow the strategy to be successful. Researchers investigating deficit irrigation for malt barley must consider these crop requirements and include grain yield, grain quality, and malt quality evaluations for a complete understanding of the factors that drive acceptability within the industry. Thus, the objectives of this research were to evaluate five genotypes of malt barley (ARS-02820, Gemcraft, Harrington, Moravian 69, Voyager) under three levels of irrigation (50% crop evapotranspiration [ET_c], 75% ET_c, 100% ET_c) for their response in terms of (a) total aboveground dry matter (TDM) production and total-N uptake; (b) grain yield; (c) grain quality (protein, plump kernels, test weight); and (d) malting quality (malt extract, S/T, diastatic power [DP], β-glucan fiber, and FAN).

2 | MATERIALS AND METHODS

2.1 | Site description

Research was conducted in independent locations during the 2017 and 2018 growing seasons at the University of Idaho, Aberdeen Research and Extension Center near Aberdeen, ID, USA (42.95 N, 112.83 W) at 1342 m elevation. The study site was located in a cold semiarid climate (BSk) as defined by the Köppen-Geiger climate classification system (Kottek et al., 2006). The sites were situated on a Declo loam soil (Coarse-loamy, mixed, superactive, mesic Xeric Haplocalcids) where the previous crop was oats (*Avena sativa* L.) removed as hay (USDA-NRCS, 2019). Similar to King et al. (2022), contributions from upward soil water flux were assumed as zero due to the ground water table being more than 5 m below the surface (IDWR, 2022). Preplant soil chemical properties are reported in Table 1. Analyses were conducted based on Miller et al. (2013). Soil pH was determined potentiometrically with a 2:1 soil/deionized water ratio. In short, loss on ignition was determined by combustion in a muffle furnace at 360°C (Storer, 1984). Ammonium (NH_4-N) and nitrate (NO_3-N) were determined by 2M KCl extract and spectrophotometric analysis (Mulvaney, 1996). Phosphorus was determined by bicarbonate extraction and spectrophotometric analysis based on the study of Olsen (1954). $CaCO_3$ was measured using a pressure calcimeter based on the study of Sherrod et al. (2002).

TABLE 1 Preplant soil chemical properties for the years 2017 and 2018 growing seasons at the Aberdeen Research and Extension Center.

Property	2017		2018	
	0–30 (cm)	30–60 (cm)	0–30 (cm)	30–60 (cm)
pH	8.1	8.3	8.2	8.3
SOM[a] (g kg^{-1})	13.3	10.0	15.0	14.1
NH_4-N (mg kg^{-1})	3.6	2.6	3.8	2.3
NO_3-N (mg kg^{-1})	10.1	13.0	20.8	21.7
Olsen P[b] (mg kg^{-1})	13	–	18	–
$CaCO_3$ (g kg^{-1})	90	–	85	–

Abbreviation: SOM, soil organic matter.

[a]Determined by loss on ignition (Miller et al., 2013).

[b]Olsen P and $CaCO_3$ analyzed for 0–30 cm corresponding to extension fertility guidelines (Robertson & Stark, 2003).

2.2 | Experimental design, plot management, and genotype selection

The study was a factorial design arranged as a split-plot where the main plot was irrigation treatment (50%, 75%, and 100% of calculated ET_c) and the sub-plot was genotype with four replications of each treatment combination. Five genotypes were included that were developed primarily for either all-malt or adjunct brewing. Block and year were treated as random effects (Carmer et al., 1989; Moore & Dixon, 2015). Plots were seeded at a depth of 3 cm with a 7-row grain drill on an 18-cm row spacing at a rate of 2 million seeds ha^{-1} on April 23 and April 18, in 2017 and 2018, respectively (Robertson & Stark, 2003). Individual sub-plots were 1.5 m by 18 m with 1-m fallow buffers between sub-plots and 5 m buffers between main plots. Prior to planting, phosphorus was applied as monoammonium phosphate at a rate of 57 kg ha^{-1} where supplemental N as urea was applied to achieve a total N rate (inorganic-N + applied N) of 212 kg N ha^{-1} in 2017. Fertilizer was incorporated to a depth of 8 cm by tillage to minimize

N losses from volatilization (Dari & Rogers, 2021; Jones et al., 2013). No supplemental fertilizer was applied in 2018 as soil levels were sufficient based on University of Idaho Extension recommendations (Robertson & Stark, 2003). As is common in the region for malt barley, a plant growth regulator (trinexapac-ethyl, 12%) was applied at a rate of 1034 mL ha^{-1} to reduce lodging potential.

Genotypes were chosen to represent predominant adjunct-lines grown on large amounts of irrigated hectares in the region, Voyager (44% of production) and Moravian 69 (14% of production) (AMBA, 2020). Voyager is a high yielding genotype that was released in 2011 by Busch Agricultural Resources for usage in adjunct brewing, and Moravian 69 is a Coors Brewing release from 2005 for adjunct brewing with high yield and favorable malting characteristics (Marshall et al., 2019). Gemcraft was selected as it is the first barley genotype released in North America specifically targeted to all-malt brewer specifications and is a 2018 release of the USDA-ARS and the Idaho Agricultural Experiment Station that has been favored by the craft brewing industry for its favorable malting and flavor characteristics. The USDA-ARS experimental line ARS028-20 was selected as it had shown potential under water-stressed conditions in preliminary trials (not reported). Harrington was released in 1981 by the Crop Development Center at the University of Saskatchewan where it has been a dominate genotype and represents a benchmark for malting quality where traditional adjunct brewing predominated during its time of major usage.

2.3 | Irrigation and evapotranspiration

Irrigation water was pumped from a groundwater source through an irrigation pipe system that supplies water throughout the Aberdeen Research and Extension Center. A custom irrigation system was constructed and fit to existing risers to supply water to the study-level system. Three sprinklers (Hunter MP 3000 Rotator) were located on each side of the main plot/irrigation level with the center sprinkler irrigating a 180° spray pattern and the end sprinklers irrigating a 90° spray pattern at a height of 1.2 m. Each irrigation treatment level could be independently controlled using shut-off valves allowing for irrigation rates to be controlled by the time of applications. Weekly irrigations were applied at 50%, 75%, and 100% of estimated crop $\mathrm{ET_c}$ as follows:

$$\mathrm{ET_c} = \mathrm{ET_r} \times K_c, \tag{1}$$

where alfalfa-based reference ($\mathrm{ET_r}$) was calculated using the American Society of Civil Engineers standardized Penman-Monteith equation using data collected from the Agrimet Cooperative Agricultural weather network located within 1 km of the sites (USBR, 2016a). Alfalfa-based mean crop coefficients (K_c) for barley differ with growth stage and were 0.20 at emergence, up to 1.03 at full cover, down to 0.30 at maturity/harvest (Allen et al., 1998; Allen & Wright, 2002; USBR, 2016a). Water was applied weekly to account for $\mathrm{ET_c}$ over the time period. Irrigations were terminated following the crops reaching the Feekes 11.2 growth stage (Neibling et al., 2017).

2.4 | Plant tissue and grain harvest

Plant tissue was collected from the opposite plot ends as yield measurements excluding outside rows in individual split-plot levels (Rogers et al., 2018). Whole plants were collected for TDM by cutting a 1-m row section at the soil surface at the Feekes 4/5 (F4/5), Feekes 10.0 (F10.0; boot), Feekes 11.2 (F11.2; soft dough), and Feekes 11.4 (F11.4; maturity) growth stage (Large, 1954). All samples were oven-dried at 65°C to a constant moisture when no weight change occurred. Sample dry weights were used to determine TDM at each growth stage. Samples were subsequently ground to 1 mm in a Wiley Mill (Thomas Scientific). Total N concentrations were determined by high-temperature combustion on an Elementar VarioMaxCN Analyzer (Elementar Americas) based on the principles of the Dumas method. Nitrogen uptake was calculated using the measured weights and concentrations.

Prior to harvest, rows one and seven were removed from individual sub-plots and lengths were trimmed to a uniform 9-m length to exclude areas used for tissue sampling and to reduce border effects. Harvest occurred on August 1, 2017 and August 15, 2018 using a small-plot combine equipped with a HarvestMaster grain system (Juniper Systems) where final grain yields were corrected to 145 g kg^{-1} moisture content. For each plot, an approximate 1000 g barley grain subsample was collected, de-awned and cleaned (Pfeuffer, Sample Cleaner, Model SLN) for use in subsequent grain quality analyses. Grain test weights were determined as lb bu^{-1} and converted to g L^{-1} based on USDA federal grain inspection standards (USDA, 2013). Plump kernels were determined as those remaining on a 6/64 screen after mechanical sieving based on USDA (1997) guidelines. Grain protein was determined by N determination and conversion via high temperature combustion on an Elementar Variomax CN analyzer (ISO, 2016).

2.5 | Malt analysis

Malting was conducted by the USDA-ARS Cereal Crops Research Unit in Madison, WI. Stand-alone steep tanks, germinators, and kilns were custom built based on Schmitt et al. (2013) where schedules are detailed at USDA-ARS (2020). Measured parameters were analyzed based on procedures described by ASBC (1992) using both malt and wort (liquid extract from congress mash) procedures. The Malt-4 procedure was used to determine percentage malt extract and a density meter (Anton Parr, DMA5000) was used to determine specific gravity. The Wort-12 procedures were used to determine FAN and analyzed spectrophotometrically. The Malt-6c ferricyanide procedure was used to determine DP via spectrophotometry and the Wort-18 fluorescence method was used to determine β-glucan fluorometrically.

2.6 | Statistical analysis

Plant and grain tissue, grain yield, grain quality, and malt quality parameters along with measured ET were analyzed using generalized linear mixed modeling in PROC GLIMMIX in SAS version 9.4 (SAS Institute). Analyses were conducted according to a split-plot design where irrigation level (main plot) and genotype (sub plot) were fixed factors. Block and year were treated as random effects (Carmer et al., 1989; Moore & Dixon, 2015). Mean separations were performed when appropriate using Fisher's protected least significant difference (LSD) at the $p = 0.05$ level.

3 | RESULTS AND DISCUSSION

3.1 | Growing season conditions

Barley planting in the region usually begins in early to mid-April with harvest occurring in August. Twenty-year average temperatures during these months range from a low of 6.8˚C in April to a high of 20.6˚C in July with precipitation totaling 98 mm over these years (NOAA, 2021). During 2017, average monthly temperatures during the growing season were similar to warmer than average, ranging from a low of 6.8˚C in April to 23.0˚C in August (USBR, 2016b). Precipitation of 103 mm in 2017 was slightly greater than the 20-year average. The 2018 season experienced warmer than average temperature ranging from 8.1 to 21.8˚C from April to July, respectively, but only received 60% of the average precipitation (59 mm). Conditions in the study are consistent with concerns over climate change related to increased average temperatures and increased likelihood of extremes and variability in weather events (Cook et al., 2020; O'Neill et al., 2017).

Drought is of particular concern in the western United States as increased demands from rapidly growing populations in urban areas and the competition for other services are balanced with the need for agricultural food production in a water-limited region (Narducci et al., 2019). These competing demands indicate the importance of optimizing water management in barley production to determine optimal practices for grain yield and quality. Cumulative ET_r, ET_c, and precipitation + irrigation (PI) for 100% ET_c, 75% ET_c, and 50% ET_c from emergence to maturity are presented in Figure 1. The 2018 crop had a slightly longer growing season and thus, greater cumulative seasonal ET_r and ET_c were calculated despite similar precipitation and irrigation during the season to meet ET_c demands. The 100% ET_c treatment weekly irrigation amount increased PI to near estimated ET_c until maturity.

TABLE 2 ANOVA *p*-values for total aboveground dry matter (TDM) and total nitrogen (TN) uptake as affected by irrigation rate, barley genotype, and growth stage (GS) at time of sampling at the Aberdeen Research and Extension Center.

Source of variation	TDM	TN
	p-value	
Irrigation	0.033	0.120
Genotype	< 0.001	0.290
Irrigation × Genotype	0.989	0.800
GS	< 0.001	< 0.0001
Irrigation × GS	< 0.001	0.370
Genotype × GS	0.343	0.999
Genotype × Irrigation × GS	0.999	0.999

3.2 | Seasonal total aboveground dry matter and total nitrogen uptake

Total aboveground dry matter varied based on the interaction of growth stage and irrigation as well as based on the main effect of genotype where TN uptake only differed based on growth stage (Table 2). Growth and uptake followed a generally similar pattern and magnitude to those previously reported by Rogers et al. (2019) in the region (Figure 2). No differences were measured in TDM based on irrigation rates at either F4/5 or F10.0. At F11.2, the 50% ET_c rate had reduced TDM as compared to the 75% and 100% ET_c rates which did not differ. Stevens et al. (2015) saw less consistent biomass increases at harvest in relation to irrigation in North Dakota where only two of the six years in their study had differences in biomass when irrigated was compared to non-irrigated production possibly due to a much higher average precipitation from April to August (272 mm). Malt barley grain yield and quality is the primary focus of this research, but forage barley production is of increasing interest in the region. These interests are present due to the need for high quality forages in a region containing one of the largest concentrations of dairy cattle (*Bos taurus*) production in the United States (USDA-NASS, 2022). Forage quality decreases with maturity and thus, barley for forage is often cut at the F10.0 stage

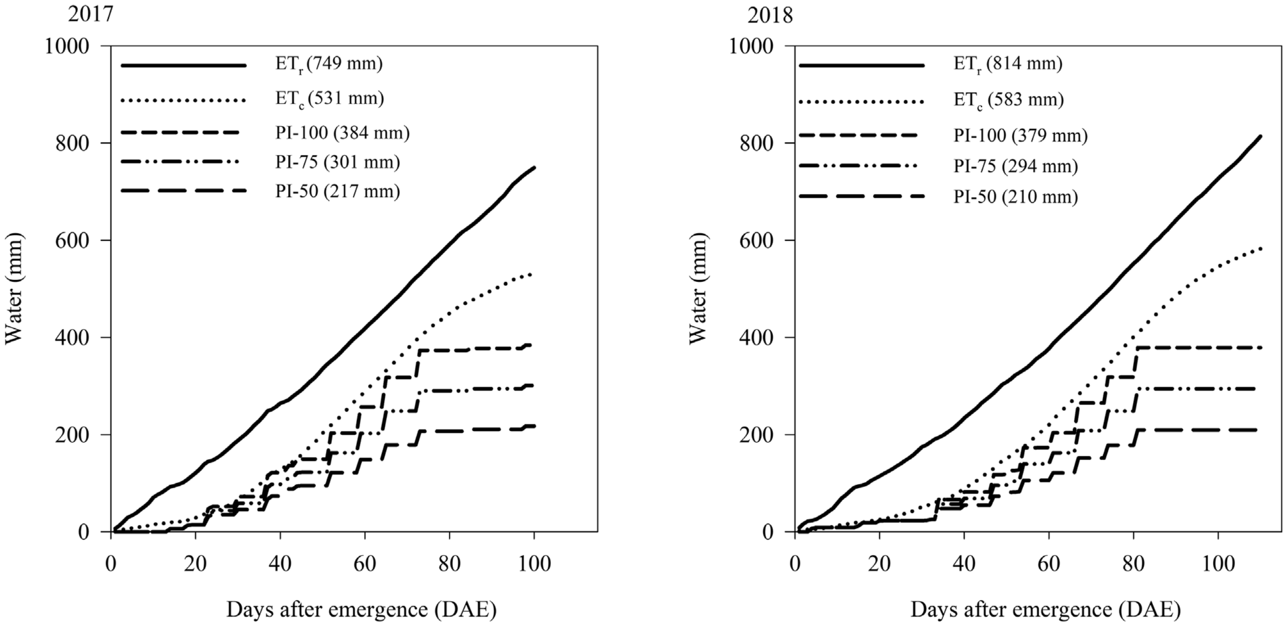

FIGURE 1 Cumulative water (mm) for the years 2017 and 2018 growing season for alfalfa-based crop reference evapotranspiration (ET$_r$), crop evapotranspiration (ET$_c$), and precipitation plus irrigation (PI) for the 100% ET$_c$ (PI-100), 75% ET$_c$ (PI-75), and 50% ET$_c$ (PI-50) application rates for malt barley at the Aberdeen Research and Extension Center.

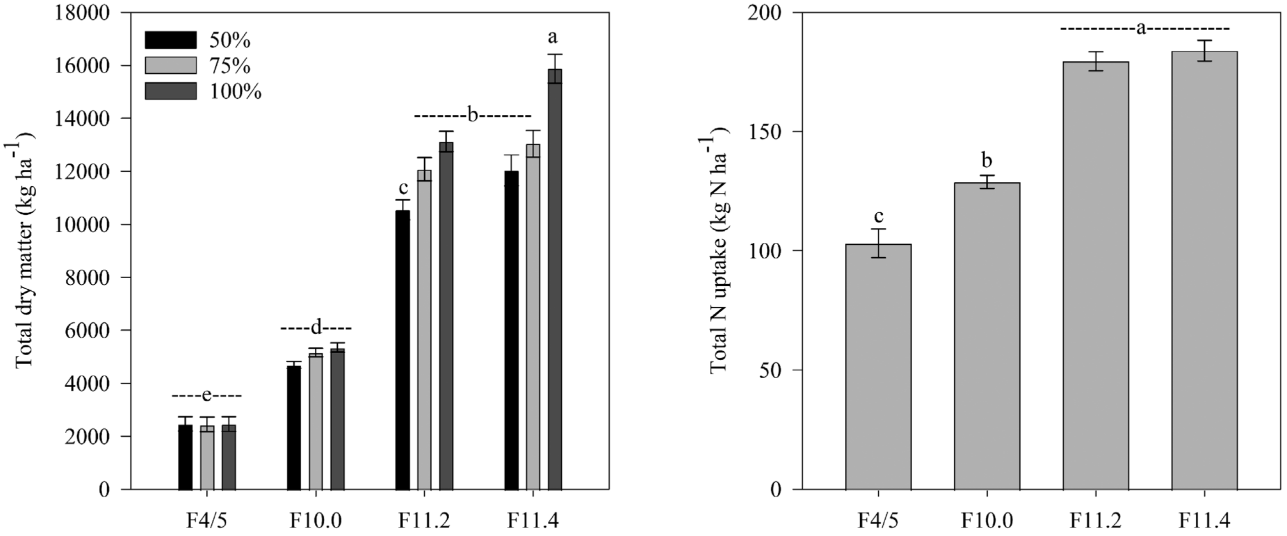

FIGURE 2 Total aboveground dry matter production at Feekes 4/5, 10.0, 11.2, and 11.4 for the 100%, 75%, and 50% crop evapotranspiration (ET$_c$) application rates and total nitrogen (N) uptake at Feekes 4/5, 10.0, 11.2, and 11.4 for malt barley. Different letters indicate differences as compared using Fisher's protected least significant difference (LSD) at $p < 0.05$.

in the region due to the high quality of the plant material for silage (Ronga et al., 2020; Shewmaker, 2005). Current results provide evidence of the potential to retain TDM yields up to the F10.0 stage with a 50% reduction in water inputs; however, to achieve maximum TDM at F11.4, the 100% irrigation rate was needed. Further research focused on quality and double-crop warm-season grass rotations could prove important for managing barley for forages in water-limited regions with large-scale dairy operations. Total aboveground dry matter ranged from 7778 to 8903 kg ha^{-1} for genotypes averaged across irrigations and growth stages (Table 3). Total N uptake was not affected by either irrigation or genotype and ranged from a low 103 kg ha^{-1} at F4/5 to highs of 179 kg ha^{-1} and 184 kg ha^{-1} at F11.2 and F11.4, respectively (Figure 2).

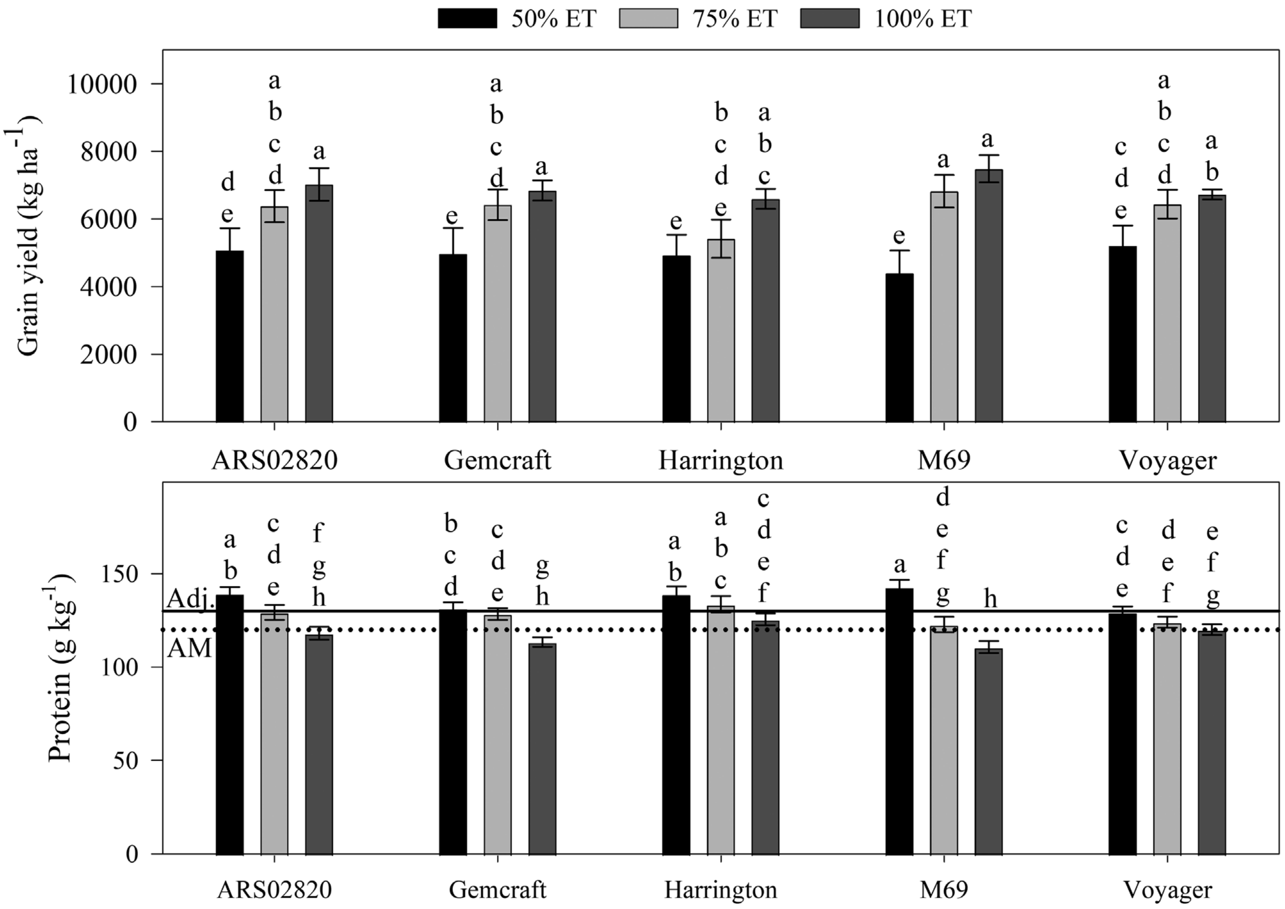

FIGURE 3 Grain yield and protein for five malt barley genotypes irrigated with 100%, 75%, and 50% crop evapotranspiration (ET_c) application rates. The all-malt (AM) protein target is ≤ 120 g kg^{-1} and the adjunct protein target is ≤130 g kg^{-1} (AMBA, 2021). Different letters indicate differences as compared using Fisher's protected least significant difference (LSD) at $p < 0.05$. Error bars represent standard errors about individual treatment means.

TABLE 3 Total aboveground dry matter (TDM) for barley genotypes averaged across irrigation and growth stage at the Aberdeen Research and Extension Center.

Genotype	TDM (kg ha^{-1})
ARS02820	8253bc
Gemcraft	7898c
Harrington	8532ab
Moravian 69	7778c
Voyager	8904a

Note: Different letters indicate differences as compared using Fisher's protected LSD at $p < 0.05$.

3.3 | Grain yield and quality

Grain yield and protein differed based on the irrigation by genotype interaction where plumps and test weights only differed based on the irrigation and genotype main effects (Table 4). Grain yields ranged from a low of 4405 kg ha^{-1} for Moravian 69 at 50% ET_c to a high of 7485 kg ha^{-1} for Moravian 69 at 100% ET_c (Figure 3). Within a genotype, the 100% ET_c irrigation yields were always greater than the 50% ET_c irrigation yields and did not differ from the 75% ET_c irrigation yields. Yields at 75% ET_c irrigation for Moravian-69 and Gemcraft were greater than their 50% ET_c irrigation yields but did not differ for the other genotypes. Across genotypes 100% ET_c irrigation yield was greater than 50% ET_c excluding Harrington 100% ET_c where yield was 6597 kg ha^{-1}, which did not differ from Voyager 50% ET_c where yield was 5219 kg ha^{-1}. Harrington was released in 1981 and is no longer widely grown for commercial production in the region but is considered a standard barley genotype to use as a check for malting quality and thus, the yield amounts for Harrington were as expected (Marshall et al., 2019).

In research from Spain, reductions in barley yields occurred with increasing stress but the differences in yield with a conservative deficit approach were deemed acceptable (Pardo et al., 2022). Grain yield in barley is typically considered to have a low sensitivity to drought (González et al., 2008; Pardo et al., 2020; Samarah et al., 2009; Thabet et al., 2018). However, barley production in the semiarid west is concentrated in high-value malting barley, where yields are typically

TABLE 4 ANOVA *p*-values for barley grain yield, grain protein, plump kernels, and test weight as affected by irrigation rate and genotype at the Aberdeen Research and Extension Center.

Source of variation	Yield	Protein	Plump	Test weight
	p-value			
Irrigation	0.017	< 0.001	0.008	< 0.001
Genotype	0.073	0.002	< 0.001	0.032
Irrigation × Genotype	0.031	0.007	0.328	0.317

large and strict quality specifications must be met. Research has shown that barley grain quality can be decreased, particularly when the water deficit occurs during grain formation (Carter & Stoker, 1985; Qureshi & Neibling, 2009; Rogers et al., 2022). Of major interest to the end-product of malt and beer production is the end protein levels that are critical for the malting process. Adjunct brewing targets ≤130 g kg^{-1} protein, whereas all-malt brewing targets ≤120 g kg^{-1} (AMBA, 2021). In the current study, grain protein varied based on the interaction of irrigation and genotype (Table 4). Protein generally increased with reduced irrigation where the 50% ET_c protein levels were the highest of those measured. Researchers in Spain reported that proteins stayed below malt requirements for all stress levels and no differences (≤6 g kg^{-1} difference) in grain protein were reported when deficit irrigation was applied down to 70% of optimal based on MOPECO, economic optimization for irrigation model (López-Urrea et al., 2020; Pardo et al., 2022). In contrast, it was observed in the current study that grain protein content increased an average of 10 g kg^{-1} in all genotypes except Voyager when irrigation was reduced from 100% ET_c to 75% ET_c. Differences in amount of drought stress, genotype, climate, and solar radiation due to elevation and latitude are likely factors that influenced the greater response seen in Idaho to deficit irrigation as compared to research in Spain. The magnitude of protein increase due to drought stress also varied among genotypes, and thus, some genotypes may be especially susceptible to elevated proteins under drought stressed conditions. Gordon et al. (2020) evaluated a large number of barley genotypes and found clear genotype variation with specific selections maintaining lower protein under terminal drought. Additionally, N applications were controlled at a single rate in the study and lower N rates could be further researched as they have been shown to positively reduce grain protein; however, these N reductions can also negatively affect yield. Adjunct malt targets of 130 g kg^{-1} were met at 100% ET_c for all genotypes and at 75% ET_c with the exception of Harrington. The all-malt target protein level was not met for any genotype when irrigation was reduced to 75% ET_c or lower and was not met for Harrington even at 100% ET_c. The lower limits for all-malt brewing may prove difficult to achieve in the region with reduced irrigation inputs, and thus, genotype selection and breeding focused on retention of lower protein levels under drought stress will prove critical for improving the sustainability for these end-users.

TABLE 5 Barley plump kernels and test weights for genotype main effect at the Aberdeen Research and Extension Center.

Genotype	Plump kernels (%)	Test weight (g L^{-1})
ARS02820	86.3b	680a
Gemcraft	85.1b	668b
Harrington	86.3b	678a
Moravian 69	87.2b	673ab
Voyager	94.8a	668a

Note: Different letters indicate differences as compared using Fisher'sprotected LSD at $p < 0.05$.

TABLE 6 Barley plump kernels and test weights for irrigation main effect at the Aberdeen Research and Extension Center.

Irrigation (%)	Plump kernels (%)	Test weight (g L^{-1})
100	91.4a	687a
75	89.2a	680a
50	83.2b	661b

Note: Different letters indicate differences as compared using Fisher's protected LSD at $p < 0.05$.

Plump kernels varied based on genotype and irrigation main effects (Table 4). Voyager resulted in greater percentage plump kernels, 94.8%, as compared to other genotypes which did not differ and averaged 86.2% (Table 5). No difference was measured between the 100% ET_c and 75% ET_c irrigation rates where plump kernels were 91.4% and 89.2%, respectively (Table 6). The 50% ET_c irrigation had a reduction in plump kernels to 83.2%. Thus, the 100% ET_c and 75% ET_c rate were similar in being near the target of >90% defined by (AMBA, 2021) for malting barley where the 50% ET_c rate would be substantially below specifications. Research from Spain where plump kernels are defined in a similar but slightly different manner (i.e., Fraction II = % grain >2.5 mm) resulted

TABLE 7 ANOVA p-values for barley malt quality parameters: Malt extract, soluble to total protein ratio (S/T), diastatic power (DP), β-glucan (BG), and free amino nitrogen (FAN) as affected by irrigation rate and genotype at the Aberdeen Research and Extension Center.

Source of variation	Malt extract	S/T	DP	BG	FAN
	p-value				
Irrigation	<0.0001	0.0005	0.0068	0.0069	0.9574
Genotype	<0.0001	<0.0001	<0.001	<0.0001	<0.001
Irrigation × Genotype	0.0298	0.1595	0.0784	0.013	0.4175

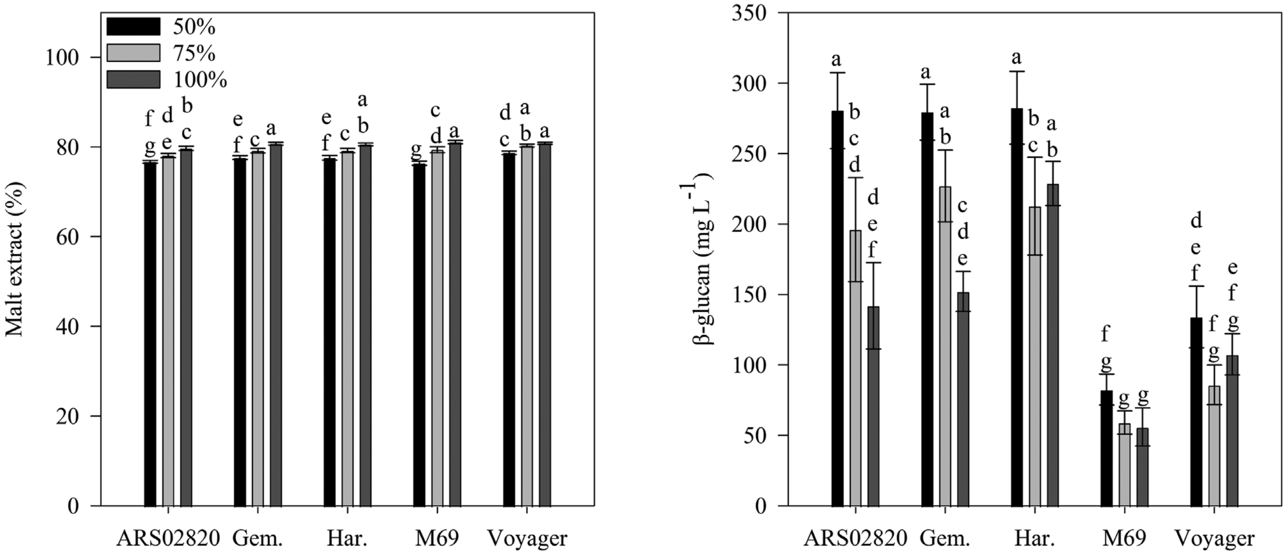

FIGURE 4 Malt extract and β-glucan for five malt barley genotypes irrigated with 100%, 75%, and 50% crop evapotranspiration (ET_c) application rates at the Aberdeen Research and Extension Center. Different letters indicate differences as compared using Fisher's protected least significant difference (LSD) at $p < 0.05$. Error bars represent standard errors about individual treatment means. Gem., Gemcraft; Har., Harrington.

in similar results where nearly no difference in plump kernels were measured (Pardo et al., 2022). Test weights were all well above US grade 1 barley and the minor differences were not relevant to agronomic decisions or end-use goals (USDA-FGIS, 2016).

3.4 | Malting quality

Malt extract and β-glucan, measured in the wort, differed based on the interaction of irrigation and genotype (Table 7). Malt extract generally decreased with increasing drought stress (Figure 4). Despite significant decreases in malt extract from 100% ET_c to 75% ET_c for all genotypes except Voyager, the largest decrease was only 1.7%. While greater malt extract is positive, these reductions should be considered in light of the overall sustainability of the crop under deficit irrigation. β-Glucan of 55.9 mg L^{-1} to 282.5^{-1} mg L^{-1} was measured in the study (Figure 4). This is within the range of around 100–300 mg L^{-1} that is generally reported in the literature and considered typical for production and laboratory worts (Jin et al., 2004). β-Glucan varied greatly among cultivars with 100% ET_c irrigations roughly in the order from lowest to highest of Moravian 69, Voyager, ARS-02820, Gemcraft, and Harrington (Figure 4). The two adjunct lines, Moravian 69 and Voyager, did not differ and Moravian 69 in particular had very low β-glucan levels across all irrigation levels. No difference was measured between the 50% ET_c, 75% ET_c, and 100% ET_c rates for either Moravian 69 or Voyager. In contrast, ARS-02820 and Gemcraft had greater β-glucan at the 50% ET_c rate as compared to the 100% ET_c rate. In the literature, the response of β-glucan has been inconsistent with no effect, increased, and decreased levels occurring due to irrigation stress. Pardo et al. (2020) observed no significant effect on β-glucan from drought stressed conditions and Coles et al. (1991) measured no effect if drought occurred after the accumulation of β-glucan. De Ruiter (1999) reported an increase in β-glucan under drought stress conditions in New Zealand. Coles et al. (1991) reported a decrease when stress occurred prior to the accumulation of β-glucan. The results of the cur-

TABLE 8 Malted barley soluble protein to total protein ratio (S/T), diastatic power (DP), and free amino nitrogen (FAN) for genotype main effect averaged across irrigation rates at the Aberdeen Research and Extension Center.

Genotype	S/T (%)	DP (°)	FAN (mg kg^{-1})
ARS02820	37.2d	164.0bc	194.8d
Gemcraft	39.3c	157.6c	219.8c
Harrington	39.3c	166.8b	238.2b
M69	40.8b	141.9d	236.9b
Voyager	43.6a	174.4a	252.6a

Note: Different letters indicate differences as compared using Fisher's protected LSD at $p < 0.05$.

TABLE 9 Malted barley soluble protein to total protein ratio (S/T) and diastatic power (DP) for irrigation main effect averaged across genotypes at the Aberdeen Research and Extension Center.

Irrigation (%)	S/T (%)	DP (°)
50	36.5c	173.4a
75	40.2b	162.6a
100	43.4a	146.8b

Note: Different letters indicate differences as compared using Fisher's protected LSD at $p < 0.05$.

rent study provide evidence that sustained deficit irrigation throughout the season increases β-glucan, and the degree of this effect is genotype dependent.

S/T and DP differed based on main effects of irrigation and genotype only where FAN only differed based on genotype (Table 7). Targets for S/T are between 40% and 47% and 38% and 45% for adjunct and all-malt brewing, respectively (AMBA, 2021). DP targets are >140 and between 110 and 150 for adjunct and all-malt brewing, respectively. The S/T ratio was greatest from Voyager (43.6%) and Moravian 69 (40.8%) and lower from the other genotypes indicating a separation between adjunct lines and all-malt lines (Table 8). The S/T ratio decreased with reduced irrigation to 36.5% slightly below both the adjunct and all-malt targets (Table 9). DP differed with the two adjunct lines at the extremes with Voyager at 174.4° and Moravian 69 at 141.9°. DP increased and was within the acceptable target for adjunct brewing at all irrigation levels but was only within the target range at 100% ET_c for all-malt brewing. Free amino N is generally considered to increase with greater overall grain protein content (Luo et al., 2019; Rogers et al., 2022). However, despite an increase in grain protein/N with decreased irrigation, no irrigation effect was measured from FAN and only genotype differences were measured. A greater range of protein concentrations than seen in this study may be needed to allow differences to become statistically significant. When differences are not measured in FAN, future work may find it useful to look at amino acid profile changes that occur as potential markers for drought stress tolerance of the plant (Lanzinger et al., 2015). Further work is needed for investigating reductions in N applications to determine if protein and other N driven parameters can be reduced while maintaining acceptable yields. Similar to recommendations for producing malt in minor production areas for craft brewers, the implementation of deficit irrigation to reduce barley's water footprint may require the adjustment of malting methods to accommodate different malting quality parameters produced by the changes in cultural practices (Brouwer et al., 2016).

4 | CONCLUSION

Continued concerns of water availability in semiarid regions must be considered for the long-term sustainability of barley production. Deficit irrigation will prove beneficial in reducing water usage and improving the sustainability of malt barley production if grain and malt quality can be maintained sufficiently despite the detrimental effects caused by drought stress. Reductions of water to 75% ET_c for the two adjunct targeted lines maintained yield and quality at or near target levels. All-malt lines were generally similar with the main exception of grain protein. The lower protein target of all-malt lines was not achieved at 75% ET for any of the genotypes and may prove difficult for growers to meet consistently with deficit irrigation. Genotype response to deficit irrigation also shows that care must be taken to select lines that best maintain yield and quality under these conditions. Reduced irrigation generally resulted in decreased malt quality (malt extract, S/T, DP, and β-glucan) in comparison to target levels. Thus, adjustments to malting methods may also need to be considered if deficit irrigation is sought as a means to reduce water usage in barley. Larger breeder selection trials would help to identify lines with the least negative response to deficit irrigation levels. In the long term, selection of genotypes with stable malting characteristics under deficit irrigation conditions will be needed. Investigation of genotypes to varying N management under deficit irrigation will be needed to establish best management practices for yield and quality. Positive and negative aspects of deficit irrigation were investigated in this study. Meeting all-malt targets could prove difficult with the studied genotypes but reductions in water use for adjunct lines appear to have large potential. Despite some limitiations, deficit irrigation is a promising tool for reducing water usage while maintaining yield and quality of malt barley in semiarid areas of the western United States.

AUTHOR CONTRIBUTIONS

Christopher W. Rogers: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodol-

ogy; project administration; resources; software; supervision; validation; visualization; writing—original draft; writing—review & editing. **Gongshe Hu**: Conceptualization; investigation; writing—review & editing. **Bradley A. King**: Data curation; formal analysis; methodology; writing—review & editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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