Received: 8 November 2021 | Accepted: 7 February 2022

DOI: 10.1002/agj2.21036

Agronomy Journal

ARTICLE

Soil Fertility & Crop Nutrition

Barley yield and malt characteristics as affected by nitrogen and final irrigation timing

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Assigned to Associate Editor Dileepa Jayawardena.

Abstract

Idaho is a major malt barley (*Hordeum vulgare* L.) producer in the United States. Production is concentrated in the semi-arid Snake River Plain region of southern Idaho. Irrigation and fertilizer N applications are two of the most important managed factors. Research was conducted at the University of Idaho Kimberly Research & Extension Center near Kimberly, ID, to determine yield, grain quality, and malt characteristics as affected by N application rate (0, 56, 112, and 168 kg N ha^{-1}) and final irrigation timing at Feekes 10.0 (boot; F10.0), Feekes 11.2 (soft dough; F11.2), and +7 d after Feekes 11.2 (+7F11.2). Irrigation termination at F10.0 resulted in decreased yields and unacceptable malt characteristics across N rates. Irrigation termination at F11.2 and +7F11.2 yielded 6,439 kg ha^{-1} at a fertilizer N application of 56 kg N ha^{-1}, similar to higher N applications. Greater predicted yields up to 6,886 kg ha^{-1} were calculated by regression analysis with applications up to 147 kg N ha^{-1}. Grain yield, protein, plumps, and test weights did not differ at any N rate for F11.2 or +7F11.2. Malt extract, free amino N, and diastatic power were similar for the F11.2 and +7F11.2 irrigations. Malt β-glucan content did not differ up to 56 kg N ha^{-1} for any treatment, but reductions of up to 30 mg kg^{-1} were measured at higher N rates for the +7F11.2 irrigation. Results warrant further investigations into increased N applications and provide evidence of the effects of irrigation cutoff timing and N for malt barley.

1 | INTRODUCTION

Barley (*Hordeum vulgare* L.) production in the United States is largely focused on two-row spring cultivars used for malting and brewing purposes (Garstang et al., 2011). In contrast to certain crops, barley cultivars remain widely grown over many seasons as maltsters and brewers require consistent, specific, and quite narrow quality characteristics in each and every load of barley that is used (AMBA, 2021). Unmalted barley grain is evaluated after harvest for key quality characteristics including yield, protein, test weight, and plump kernels that influence the malting process. Malted barley is then evaluated for characteristics such as percentage malt extract, diastatic power (DP), and free amino N (FAN). While high grain yields are desirable for growers, the quality of the resulting malt is crucial to profitability because malt that fails to meet quality standards necessary for brewing and distilling is sold for feed at about half the price. Thus, cultivars from breeding

Abbreviations: +7F11.2, +7 d after Feekes 11.2; DP, diastatic power; ET_r, alfalfa-based reference evapotranspiration; ET_c, crop evapotranspiration; F10.0, Feekes 10.0; F11.2, Feekes 11.2; F11.4, Feekes 11.4; FAN, free amino N; K_c, alfalfa-based barley mean stage-specific coefficient.

programs are bred specifically to target a relatively small and narrowly defined set of quality characteristics (AMBA, 2021). However, individual malting barley company parameters and year-to-year barley crop availability causes variation from these exact guidelines in terms of real-world acceptance and rejection.

Nitrogen and irrigation management are grower-managed factors that typically have the largest effect on malt barley grain yield and quality in the semi-arid western United States (Stark & Brown, 1987). Improvements in fertilizer and irrigation management strategies are important for improving fertilizer nitrogen use efficiency that ranges from 35 to 41% globally and was reported up to 53% in irrigated barley in Idaho (Omara et al., 2019; Rogers & Loomis, 2021).

Annual precipitation is low in many areas of the western United States, and thus, irrigation plays a critical role in cropping systems in the region (USDA-ERS, 2019). Reliance is largely placed on snowfall-filling reservoirs and surface water systems along with groundwater pumping from aquifers. Concerns in these systems include droughts reducing snowpack and reduction of aquifer quantities that could force changes in the availability of quality freshwater resources. California, Nebraska, Arkansas, Texas, and Idaho are the top states, in that order, for hectares of land under irrigation (USDA-ERS, 2019). While Idaho is ranked 5th for hectares of production under irrigation, it ranks 2nd, and is only exceeded by California, for total water usage from irrigation (USGS, 2015).

With the changing marketplace and increased importance placed on resilient agriculture under varying climate and production scenarios, research to improve irrigation management as well as fertilizer N additions are critical to ensure malt barley sustainability in the irrigated western United States. Qureshi and Neibling (2009) investigated management of final irrigation timings in southern Idaho under a single N rate as a means to optimize water consumption while maintaining grain yield and quality of malt barley. Their research indicated that irrigation cutoff at Feekes 11.2 (F11.2) resulted in optimal yield and quality compared with earlier and later cutoff timings where these factors were reduced. Albrizio et al. (2010) conducted research in the Mediterranean environment of Italy under varying irrigation rates for the duration of the growing season for both six-row barley and durum wheat (*Triticum durum* L.) with results of similar grain N concentrations across water regimes but greater N uptake in the grain and straw at higher irrigations levels. Research on barley, durum, and common wheat (*Triticum aestivum* L.) at varying irrigation treatments and N rates either separately or combined has been conducted with an emphasis on crop yield and plant characteristics, but work in the western United States and on malt quality is limited (Albrizio et al., 2010; Karam et al., 2009; Kibe et al., 2006; Sharma & Verma, 2010; Stevens et al., 2015; Walsh et al., 2020). Verma et al. (2003) reported the effect of N rate and irrigation on malt and wort quality in Indian barley production and noted that applications of 90 kg N ha^{-1} increased malt extract and DP. Other research has measured decreased malt extract at increased N levels when increased grain protein levels occurred (Eagles et al., 1995; Martin & Daly, 1993; Weston et al., 1993). Irrigation increases in Indian research (Verma et al., 2003) resulted in increased DP. Little other work on the effects of irrigation and N management on malted grain quality parameters has been conducted.

Core Ideas

- Irrigation termination at the F10.0 stage caused severe yield and quality issues.
- F11.2 and +7F11.2 yields did not differ and increased with N from 4,769 to 6,845 kg ha^{-1}.
- Grain protein was less than 130 g kg^{-1} at all N rates for F11.2 and +7F11.2.
- Irrigation past F11.2 did not generally improve or detract from quality.
- Malt β-glucan decreased up to 30 mg kg^{-1} at higher N rates for +7F11.2.

Agriculture represents the largest consumption of water in the western United States, and fertilizer N is a substantial input with potentially negative environmental effects if lost to the environment. Management practices for N in irrigated malt barley production in Idaho were developed with the assumption that the barley crop was not limited by water (Stark & Brown, 1987), and irrigation management strategies for barley were developed with the assumption that N was not limiting (Qureshi & Neibling, 2009). To our knowledge, research focused on irrigation cut-off timing under varying N levels has not been studied to determine the effects on barley grain yield and quality or malted grain parameters in the western United States. Increased understanding of the balance of both N and irrigation water under limiting and nonlimiting conditions is critical for improved best management practices for malt barley producers. Thus, the objectives of this research study were to (a) determine grain yield and quality of spring two-row malt barley at multiple fertilizer N application rates and irrigation cutoff timings, (b) determine dry matter production and crop N removal as determined by uptake and partitioning of barley plants at harvest, and (c) evaluate the effect of fertilizer N and irrigation cutoff timing on malt quality parameters.

TABLE 1 Preplant soil chemical properties for the 2015–2017 growing seasons at the Kimberly Research and Extension Center, Kimberly, ID

	2015		2016		2017	
	0–30 cm	30–60 cm	0–30 cm	30–60 cm	0–30 cm	30–60
pH	8.1	8.3	8.3	8.3	8.3	8.5
OC, g kg^{-1}	9.0	4.0	7.0	5.0	8.0	3.0
IC,[a] g kg^{-1}	4.2	–	1.2.	–	7.7	–
TN, g kg^{-1}	1.0	0.6	0.8	0.5	1.1	0.7
NH_4–N,[b] mg kg^{-1}	3.6	1.9	1.9	1.1	2.7	1.3
NO_3–N, mg kg^{-1}	9.5	9.0	8.0	7.4	9.3	6.3
Olsen P, mg kg^{-1}	26.0	–	22.2	–	23.7	–

Note. OC, organic C; IC, inorganic C; TN, total N.

[a]Inorganic C and Olsen P were analyzed for 0-to-30-cm corresponding to Extension fertility guidelines (Robertson & Stark, 2003).

[b]Estimated available inorganic N (kg N ha^{-1}) is calculated by multiplication of each increment NH_4–N and NO_3–N soil test (mg kg^{-1}) by a factor of 4.5 and summation for kg N ha^{-1} (Robertson & Stark, 2003).

2 | MATERIALS AND METHODS

2.1 | Site description

Research trials investigating the effects of final irrigation timing at multiple fertilizer N application rates were conducted at the University of Idaho Kimberly Research & Extension Center near Kimberly, ID, during the 2015 to 2017 growing seasons. The Kimberly Research & Extension Center is located at about 1,200 m of elevation at a latitude of 42.55˚ and is classified as having a cold semi-arid climate (BsK) in the Köppen-Geiger climate classification system (Kottek et al., 2006). Each site-year was conducted in an independent location on a Portneuf silt-loam soil (coarse-silty, mixed, superactive, mesic Durinodic Xeric Haplocalcids) where the previous crop was sugar beet (*Beta vulgaris* L.) (USDA-NRCS, 2019). Initial soil fertility values were determined by compositing four samples from individual blocks from 0-to-30- and 30-to-60-cm depths using an 8-cm diameter bucket auger. Samples were subsequently dried at 40 ˚C and ground to pass a 2-mm sieve. Initial soil chemical properties were determined and are presented in Table 1 (Miller et al., 2013). Sample pH was determined potentiometrically using a 1:1 soil/deionized water. Total C and total N were measured via high temperature combustion, and organic C was determined based on total C minus inorganic C using pressure calcimetry (Nelson & Sommers, 1996; Sherrod et al., 2002). Ammonium– and nitrate–N (NH_4–N, NO_3–N) were determined via 2-M KCL extraction and spectrophotometric analysis (Mulvaney, 1996). Olsen soil P was measured for the 0-to-30-cm depth, corresponding to fertilizer recommendation guidelines (Robertson & Stark, 2003). Soil P was analyzed using the bicarbonate extraction based on Olsen (1954) followed by colorimetric analysis of the extracts.

2.2 | Experimental design & plot management

Experiments were arranged as a factorial design with three final irrigation timings [Feekes 10.0 (F10.0), F11.2, and +7 d Feekes 11.2 (+7F11.2)] with four preplant fertilizer N application rates (i.e., 0, 56, 112, 168 kg N ha^{-1}) arranged in a randomized complete block design with five blocks. The study was a split-plot design where the main plot was final irrigation timing based on growth stage (i.e., F10.0, F11.2, and +7F11.2) and the sub-plot was N application rate (0, 56, 112, and 168 kg N ha^{-1}). Cumulative growing degree (˚C) days (Bauer et al., 1992; Bauer et al., 1984) were previously reported for southern Idaho by Rogers et al. (2018). In their study, F10.0, F11.2, and Feekes 11.4 (maturity; F11.4) occurred at 888, 1,112, and 1,539 cumulative growing degree days, respectively, which were relatively similar to Miller et al. (2001) in Montana. The current experiment was repeated at different locations within the University of Idaho, Kimberly Research and Education Center over three growing seasons (2015, 2016, and 2017).

The widely grown cultivar Moravian 69 was selected for use in the trial. Moravian 69 was released by Coors Brewing in 2005 and represents nearly 12% of total Idaho production (AMBA, 2020). The cultivar is produced for adjunct brewing, which has specific quality targets that differ from all-malt brewing and distilling (AMBA, 2021). Main-plot areas were 9 × 9 m where individual N rate sub-plots were 1.5 × 9 m with 1-m buffers between N rate sub-plots and a 5-m buffer between main plots. The seedbed was prepared by disking and roller-harrowing in the spring. Fertilizer N was applied prior to planting to individual plot areas by hand as urea (460 g N kg^{-1} urea) and incorporated to a depth of approximately 8 cm using a spring-tooth harrow. No additional P

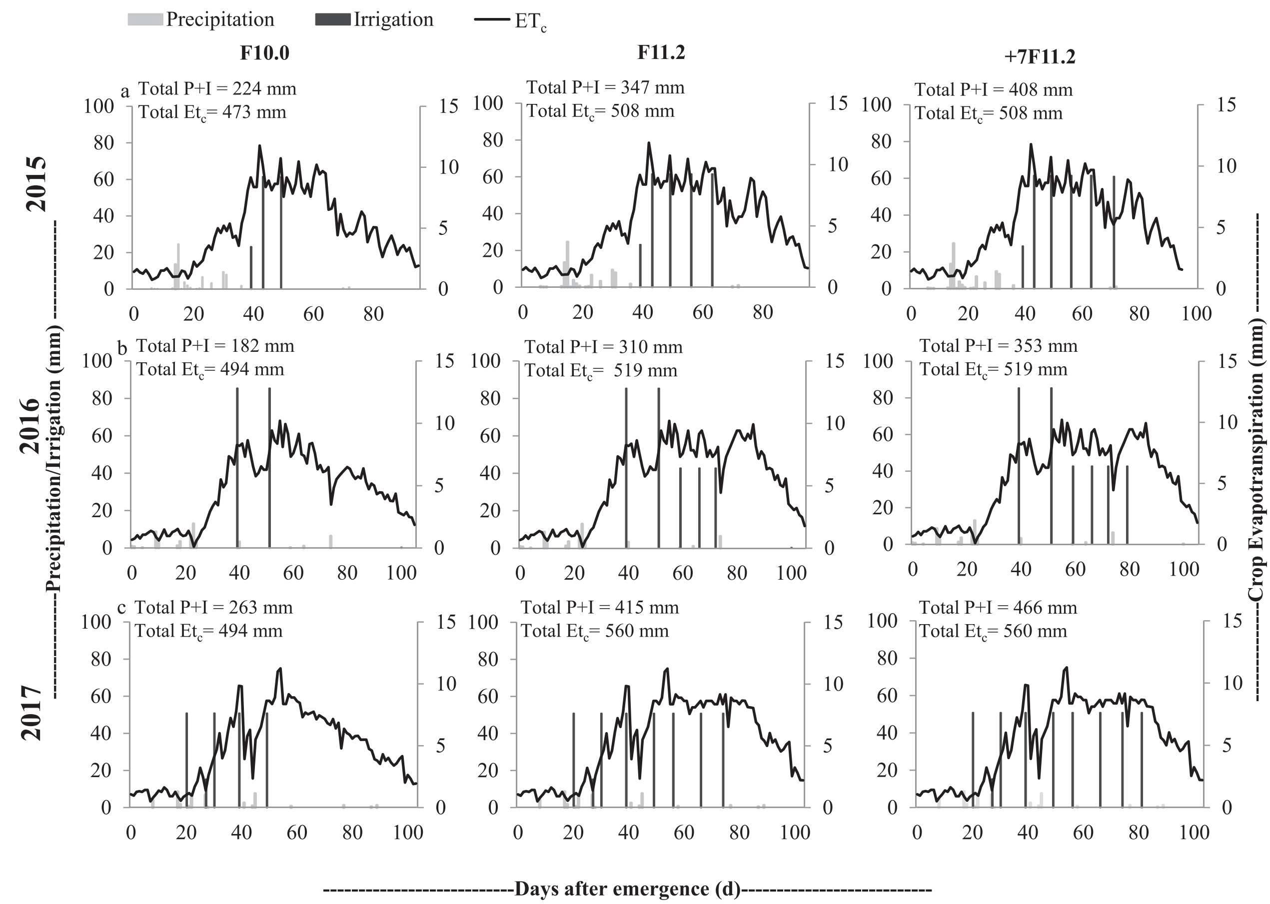

FIGURE 1 Daily crop evapotranspiration (ET_c), precipitation (P), and irrigation (I) applied from planting to harvest for irrigated malt barley in Kimberly, Idaho for (a) 2015, (b) 2016, and (c) 2017. Different growth stages are abbreviated as F10.0, Feekes 10.0; F11.2, Feekes 11.2; +7F11.2, +7 d Feekes 11, and seasonal total P + I and ET_c are reported

fertilizer was applied to plots as soil-test P levels were above fertilizer recommendation levels (Robertson & Stark, 2003). Barley was planted at a depth of 3 cm following University of Idaho Extension guidelines using a 7-row grain drill at a seeding rate of 2 million seeds ha^{-1} and a row spacing of 18 cm on 21 Apr., 18 Apr., and 19 Apr. in 2015, 2016, and 2017, respectively (Robertson & Stark, 2003).

2.3 | Irrigation management

A sprinkler irrigation system was used for this study where each side of the main plot was comprised of three Hunter MP 3000 Rotator sprinklers with the center being set to 180° and the two ends at 90°. Sprinklers were set 0.9 m above ground level and evenly spaced on the edges of the main plots for a total of six sprinklers per main plot. A uniform application of irrigated water in the plot area was maintained until each final irrigation timing was reached, at which time main-plot areas could be independently stopped or continue running. Irrigations were applied at 100% of crop evapotranspiration (ET_c) as shown in Equation 1:

$$ET_c = K_c ET_r \quad (1)$$

where alfalfa (*Medicago sativa* L.)-based reference evapotranspiration (ET_r) was calculated using the American Society of Civil Engineers standardized Penman-Monteith Equation as obtained from the United States Bureau of Reclamation AgriMet Cooperative Agricultural Weather Network station located within 1 km of the site (USBR, 2016). Alfalfa-based barley mean stage-specific coefficient (K_c) vary based on growth stage and ranged from an initial 0.20 at emergence, a plateau of 1.03 at full cover, and 0.30 at the end of harvest (Allen et al., 1998; Allen & Wright, 2002; USBR, 2016). Irrigation management was based on Qureshi and Neibling (2009) to avoid soil-water depletion below 40%. Three final irrigation-timing treatments were applied based on visual growth-staging of main plots, with one irrigation treatment terminated at each of the following stages: F10.0, F11.2, and +7F11.2. Our assumption was optimum crop yield, as well as quality, would occur if the last irrigation was applied at F11.2

near the recommended N rate. Final irrigation timings were determined based on field observations and growth staging within the research study. Total cumulative irrigation applied at three different growth stages, daily ET_c, and total precipitation for each site-year are summarized in Figure 1.

2.4 | Plant tissue and harvest sampling

Plant height was measured from all plots immediately prior to harvest as the height from the soil surface to the tip of the barley grains excluding awns. A 1-m row section of plant material was cut from the 2nd row from the outside at the soil surface and collected near one end of the individual sub-plot levels offset 1 m from the border immediately prior to harvest to estimate field export. This subsample was hand-threshed for grain yield and the straw collected for biomass yield. Sub-plot ends were trimmed to a uniform length (6 m) prior to harvest to remove the sections where tissue sampling occurred, and a single-row binder was used to remove rows one and seven to minimize border effects. Plots were harvested on 4 Aug. 2015, 10 Aug. 2016, and 10 Aug. 2017. Grain yield was measured using a combine equipped with a HarvestMaster grain-weight system (Juniper Systems), and final yields were corrected to a moisture content of 145 g kg^{-1}. An approximate 1,000-g subsample was collected from combine-harvested grain for these quality analyses. Following harvest, grain quality characteristics, including protein content, test weight, and percentage plumps, were measured on combine-harvested grain. Grain was de-awned and cleaned (Pfeuffer Sample Cleaner, Model SLN). Test weight (lb bu^{-1}) was determined based on USDA federal grain inspection standards and converted to g L^{-1} (USDA, 2013). Plumps were determined based on two-row malt barley guidelines (i.e., barley retained on a 6/64 inch screen using mechanical sieving; USDA, 1997). Total N was determined for grain and straw from hand-harvested areas based on the Dumas method via high temperature combustion on a Variomax CN analyzer (Elementar Americas), and grain N was determined on combine-harvested grain and converted to grain protein values (ISO, 2016).

2.5 | Malt analysis

Barley was malted by the USDA-ARS Cereal Crops Research Unit in Madison, WI. Barley grain was malted in custom stand-alone steep tanks, germinators, and kilns based on Schmitt et al. (2013), with equipment and schedules described by USDA-ARS (2020). Analyses were conducted based on ASBC (1992) protocols. Malt extract was determined using the Malt-4 procedure and specific gravity measured using a density meter (Anton Parr DMA5000); FAN was determined on a Skalar Sans + flow analyzer (Skalar Analytical B.V.) using the Wort-12 protocols; DP was determined on a Skalar Sans + analyzer by the Malt-6c ferricyanide procedure; and β-glucan was determined on a Skalar Sans + analyzer using the Wort-18 fluorescence method with calcofluor as the fluorescent agent.

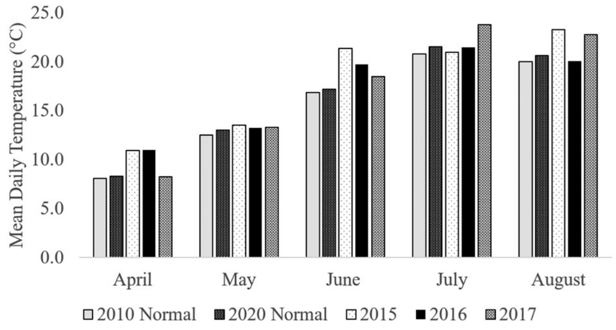

FIGURE 2 Mean daily temperature climate normals and measured values for 2015, 2016, and 2017 at the Kimberly Research and Extension Center, Kimberly, ID. Climate normal data retrieved from the National Oceanic and Atmospheric Administration (NOAA, 2021)

2.6 | Statistical analysis

Yield, quality, plant tissue, and malt characteristics (e.g., grain yield, grain protein, malt extract, etc.) were regressed against N rates where quadratic and linear terms and coefficients were allowed based on irrigation level and final irrigation timing using all replicates (Golden et al., 2009; Rogers et al., 2016). Sequential removal of model terms ($P \geq .05$) was conducted and the model refit until a satisfactory model was determined. Analyses were based on the split-plot design where final irrigation timing was the main-plot factor and N rate was the sub-plot factor. Block and year were treated as random effects in all models to allow inferences to be made across multiple environments (Carmer et al., 1989; Moore & Dixon, 2015). Statistical analyses were conducted using the PROC Mixed procedure in SAS Version 9.4 (SAS Institute), and where appropriate, mean separations were performed using Fisher's protected least significant difference at the $P = .05$ level. Pearson correlations and linear regression analyses were performed in SigmaPlot 14.0 (Systat) comparing selected grain and malt parameters from all final irrigation timings and N levels.

3 | RESULTS AND DISCUSSION

3.1 | Growing season conditions

Spring barley is commonly planted in early to mid-April in the region and harvested in August. Monthly mean daily average normal temperatures during the growing season ranges from 8.3 to 21.6 ˚C with a mean of 16.2 ˚C (Figure 2; NOAA, 2021).

TABLE 2 ANOVA *P*-values for final fitted models for grain yield, grain N uptake, straw biomass, and straw-N uptake as affected by final irrigation timing (irrigation) and fertilizer N application rates at the Kimberly Research and Extension Center, Kimberly, ID

Source of variation	Grain yield	Grain N uptake	Straw biomass	Straw N uptake
	P-value			
Irrigation	.004	.004	.005	<.0001
Linear N rate	<.001	<.0001	<.0001	NS
Linear N rate × irrigation	.040	NS	NS	NS
Quadratic N rate	.002	<.001	.012	NS
Quadratic N rate × irrigation	NS	NS	NS	NS

Note. NS, not significant ($P \geq .05$).

Temperatures were generally similar or greater than the climate normal (NOAA, 2021) during the 2015, 2016, and 2017 growing seasons (Figure 2). Mean daily temperatures in June and July, when crop evapotranspiration is greatest, were particularly high in June 2015 and July 2017 compared with the climate normal for the region. Total normal precipitation during this time frame averages nearly 100 mm with more than 80% of this coming in the months of April, May, and June and less than 20 mm in July or August (NOAA, 2021). Precipitation levels in 2015, 2016, and 2017 were all below average at 78, 72, and 57 mm, respectively (Figure 1). Mean cumulative precipitation plus irrigation for 2015, 2016, and 2017 was 230, 365, and 420 mm for the F10.0, F11.2, and +7F11.2 treatments, respectively (Figure 1). Total seasonal ET_c from planting until harvest averaged for 2015, 2016, and 2017 was 487, 529, and 529 mm for the F10.0, F11.2, and +7F11.2 treatments, respectively.

3.2 | Grain and straw yield and N uptake

Grain yield was described by a nonlinear (quadratic) function of N rate where differences in the quadratic coefficient were not observed, and both the linear and intercept portion of the function were dependent on final irrigation timing (Table 2). Measured grain yield increased with increasing fertilizer N application for the F11.2 and +7F11.2 final irrigation timings (linear = 23.5 and 22.1, respectively), where grain yield increased for the F10.0 (linear = 19.4), but only the highest N rate of 168 kg N ha^{-1} resulted in a grain yield increase compared with no fertilizer for the F10.0 timing (Table 3; Figure 3). Measured grain yields were greatest from the final irrigation timings of F11.2 and +7F11.2 at fertilizer N rates of 56 kg N ha^{-1} and greater with an average of 6,439 kg ha^{-1} where no difference was measured based on increased N applications.

Current University of Idaho Extension N guidelines have several sources of uncertainty. First, as no soil tests have been shown to accurately predict mineralization, an estimation of 50 kg N ha^{-1} is used despite a wide range of mineralization rates occurring (Rogers et al., 2018). Second, malt barley rates are reduced between approximately 22 and 45 kg ha^{-1} compared with those reported for feed barley (Robertson & Stark, 2003). The current fertilizer N recommendation would incorporate the 93 kg N ha^{-1} measured as inorganic N and would be between 157 and 180 kg N ha^{-1}, or an application of 64–87 kg N ha^{-1} of applied N, for a difference of 8–31 kg N ha^{-1} compared with the calculated value in this study based on adjustments for malting barley (Table 1). However, the production guide indicates rates as low as 112 kg N ha^{-1} of inorganic N plus applied N have maximized yield for malting barley. The 56 kg N ha^{-1} application rate is slightly below the current recommendations but not outside the range of expectations. It is likely that N mineralization was greater than the mean value used for the production guide, where recent work has indi-

TABLE 3 Final fitted model coefficients for grain yield, grain N uptake, straw biomass, and straw N uptake as affected by final irrigation timings (irrigation) and fertilizer N application rates at the Kimberly Research and Extension Center, Kimberly, ID

Irrigation	Intercept	Linear	Quadratic
Grain yield			
F10.0	3,834	19.4	−.08
F11.2	5,160	23.5	−.08
+7F11.2	4,874	22.1	−.08
Grain N uptake			
F10.0	65.0	.53	−.0016
F11.2	88.2	.53	−.0016
+7F11.2	79.8	.53	−.0016
Straw biomass			
F10.0	2,924	19.1	−.053
F11.2	3,554	19.1	−.053
+7F11.2	3,338	19.1	−.053
Straw N uptake			
Averaged across irrigation	20.6	.19	NS†

Note. +7F11.2, +7 d Feekes 11.2; F10.0, Feekes 10.0; F11.2, Feekes 11.2; NS, not significant ($P \geq .05$).

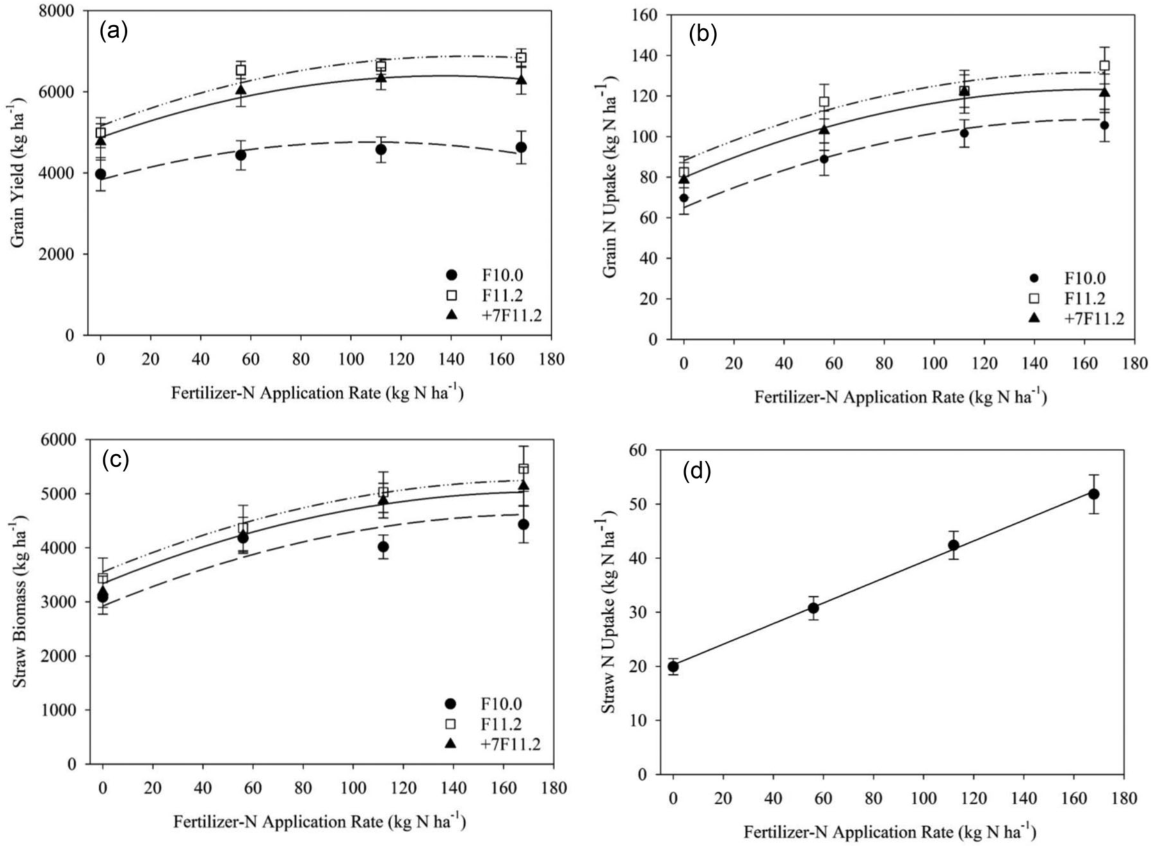

FIGURE 3 Malt barley (a) grain yield, (b) grain N uptake, (c) straw biomass yield, and (d) straw N uptake as affected by final irrigation timing [Feekes 10.0 (F10.0), Feekes 11.2 (F11.2), and +7 d Feekes 11.2 (+7F11.2)] and fertilizer N application rate (equation coefficients are listed in Table 3), where 93 kg N ha^{-1} of additional soil inorganic N was measured

TABLE 4 ANOVA *P*-values for final fitted models for grain yield, protein, plumps, test weight, and plant height as affected by final irrigation timing (irrigation) and fertilizer N rates at the Kimberly Research and Extension Center, Kimberly, ID

Source of variation	Grain yield	Protein	Plumps	Test weight	Plant height
	P-value				
Cutoff	.004	NS†	<.001	<.001	NS
Linear N rate	<.001	<.001	<.001	<.001	<.001
Linear N rate × cutoff	.040	<.001	.019	NS	NS
Quadratic N rate	.002	NS	NS	NS	<.001
Quadratic N rate × irrigation	NS	NS	NS	NS	NS

Note. NS, not significant ($P \geq .05$).

cated a wide range of N mineralization in the region (Rogers et al., 2018). Additionally, barley fertilizer guides currently indicate that sugar beet residue is accounted for in the recommendations by soil testing (Robertson & Stark, 2003); however, Minnesota guidelines indicate that up to a 79 kg ha^{-1} credit should be provided for lush and green sugar beet tops (Kaiser, 2018). It is not evident at this time that a credit for sugar beet tops would be more accurate than current soil testing in Idaho, but it is an area that could be considered for further research in an attempt to refine fertilizer N recommendations. Losses to the environment also could have decreased the system efficiency where leaching and denitrification are typically small when synthetic fertilizer is used (Dungan et al., 2017; Rogers & Loomis, 2021), and ammonia volatilization is likely the source of the most N loss (Dari & Rogers, 2021). However, urea was managed to reduce ammonia volatilization by incorporating it by tillage to a depth greater than 5 cm, which has been shown to reduce N losses as ammonia (Dari

& Rogers, 2021; Jones et al., 2013). Calculated maxima from the quadratic functions indicated that N applications of 121, 147, and 138 kg N ha^{-1} would be the maximum of the modeled quadratic functions with grain yields of 5,010, 6,886, and 6,400 for F10, F11.2, and +7F11.2, respectively. Yields within the study were within a similar range as those seen in cereal variety trials in the region (Marshall et al., 2019). Historic yield goals and production factors play a critical role, and thus, yields at all locations are not expected to necessarily reach these levels.

Research in Wyoming reported yields from furrow-irrigated malt barley increased from N application rates of 0–202 kg N ha^{-1} ranging from 3,900 to over 5,000 kg N ha^{-1} (Lauer & Partridge, 1990). Slight reductions or no effects were noted for grain yield when comparing final irrigation timings following anthesis with continued irrigations during grain fill (Lauer & Partridge, 1990). Work by Qureshi and Neibling (2009) under optimal N rates reported yield losses when irrigation was terminated either prior to F11.2 or continued after F11.2, noting that F11.2 was an optimal timing to complete irrigations when optimal N rates were available. Results from the current study indicated no effect to yield by stopping irrigation at F11.2 compared with +7F11.2 (Figure 3). Application of N under drought stress, as found in the F10.0 timing, would indicate that N application only had an effect at the extreme end, which is a practice that is unlikely to be agronomically or environmentally sound. Grain N uptake was described by a nonlinear (quadratic) function (Table 2). Grain N uptake ranged from 70 to 135 kg N ha^{-1} (Figure 3). Data from the F11.2 and +7F11.2 final irrigation timings with N applications of 56 and 112 kg ha^{-1} were similar to those reported by Rogers & Loomis (2021) where 123 kg N ha^{-1} was measured at maturity in irrigated production in Idaho.

Straw biomass yield was described by a nonlinear (quadratic) function (Table 2). Nitrogen application had a greater effect on straw biomass than did final irrigation timing because irrigation terminations occurred at the end of the stem-extension phase or during grain fill, allowing sufficient vegetative growth to occur (Figure 3). However, termination at F10.0 when the grain head is in the boot phase did have reductions in straw biomass yield compared with the F11.2 and +7F11.2 final irrigation timings. Finally, straw N uptake increased with greater N rates but was not affected by final irrigation timing (Table 2). Maximum N uptake is typically measured at F11.2 in irrigated production in southern Idaho (Rogers et al., 2019; Rogers & Loomis, 2021), where N is partitioned from the vegetative tissue into the grain between F11.2 and harvest with the majority of N found in the grain at harvest. Thus, grain N removal is the main net export from barley fields where grain straw is typically retained and recycled in the soil or removed from the field in bales. In terms of nutrient cycling, soil returns or exports of N from the remaining straw residue would be similar regardless of final irrigation timing, and thus, differences in N balances would be largely controlled by the grain where the F10.0 final irrigation timing had reduced grain N uptake.

TABLE 5 Final fitted model coefficients for grain protein concentration, plumps, test weight, and plant height as affected by final irrigation timing (irrigation) and fertilizer N application rate at the Kimberly Research and Extension Center, Kimberly, ID

Irrigation	Intercept	Linear	Quadratic
Protein			
F10.0	110	.24	NS
F11.2	103	.12	NS
+7F11.2	101	.12	NS
Plumps			
F10.0	692	−1.10	NS
F11.2	911	−0.35	NS
+7F11.2	924	−0.40	NS
Test weight			
F10.0	633	−.14	NS
F11.2	676	−.14	NS
+7F11.2	671	−.14	NS
Height			
Averaged across irrigation	54	−1.10	3.3×10^{-4}

Note. +7F11.2, +7 d Feekes 11.2; F10.0, Feekes 10.0; F11.2, Feekes 11.2; NS, not significant ($P \geq .05$).

TABLE 6 ANOVA *P*-values for final fitted models for malt quality parameters of malt extract, free amino nitrogen (FAN), diastatic power (DP), and β-glucan as affected by final irrigation timing (irrigation) and fertilizer N rates at the Kimberly Research and Extension Center, Kimberly, ID

Source of variation	Malt extract	FAN	DP	β-glucan
	P-value			
Irrigation	<.0001	NS	.005	<.0001
Linear N rate	<.0001	<.001	<.0001	<.0001
Linear N rate × cutoff	<.0001	NS	<.0001	.03
Quadratic N rate	NS	NS	NS	NS
Quadratic N rate × irrigation	NS	NS	NS	NS

Note. NS, not significant ($P \geq .05$).

3.3 | Barley grain quality and plant height

Grain protein and plumps were described by a linear function of N rate and final irrigation timing where quadratic factors were nonsignificant ($P \geq .05$; Table 4). Test weight was

TABLE 7 Final fitted model coefficients for malt quality parameters of malt extract, free amino nitrogen (FAN), diastatic power (DP), and β-glucan as affected by final irrigation timing (irrigation) and fertilizer N rate at the Kimberly Research and Extension Center, Kimberly, ID

Irrigation	Intercept	Linear	Quadratic
Malt extract			
F10.0	77.5	−.024	NS
F11.2	80.3	−.009	NS
+7F11.2	80.3	−.007	NS
FAN			
Averaged across Irrigation	225.3	.132	NS
DP			
F10.0	125.1	.379	NS
F11.2	120.6	.097	NS
+7F11.2	105.1	.147	NS
β-glucan			
F10.0	52.3	.466	NS
F11.2	63.4	.401	NS
+7F11.2	59.4	.248	NS

Note. +7F11.2, +7 d Feekes 11.2; F10.0, Feekes 10.0; F11.2, Feekes 11.2; NS, not significant ($P \geq .05$).

described by a linear function where intercepts differed based on final irrigation timing, but linear coefficients did not differ. Plant height was described based on a quadratic function where no differences in coefficients were determined based on final irrigation timing. Grain protein rate of increase was linear with the greatest slope under the most water restriction at the F10.0 final irrigation timing where the linear coefficient was 0.24 compared with 0.12 for F11.2 and +7F11.2 (Table 5). Within an N rate, F11.2 and +7F11.2 did not differ, and both had protein content less than those from the F10.0 final irrigation timing with the exception of the 0 kg N ha^{-1} rate (Figure 4). Protein content was above generally acceptable levels of 130 g kg^{-1} for F10.0 when fertilizer was applied above the 0 kg N ha^{-1} rate, and thus, quality specifications would not have been met with fertilizer applications. Protein for the F11.2 and +7F11.2 were all below 130 g kg^{-1}. The rate of increase across the N concentrations in the F11.2 and +7F11.2 was less in the current study (linear coefficient = 0.12) compared with Stark and Brown (1987) where it was 0.17. The previous work of Stark and Brown (1987) noted a much wider range of protein content (80–140 g kg^{-1}) across their studies. Difference in protein content is likely related to improved breeding lines in the current study that have targeted low protein for malting purposes, and thus, compared with previous work, the tested cultivar responded less per unit of added N. This variation in N response to protein warrants further investigation to determine if increased yields can occur by additions of fertilizer N without risking excess protein content.

Response of grain plumpness to N and final irrigation timing was well-fit by a linear model where the linear coefficients and intercepts varied based on final irrigation timing (Table 4). Similar to reports from Stevens et al. (2015) on the effects of increased N on barley grain plumpness, we also observed a negative relationship between N application rate and grain plumpness in the study where linear coefficients were −.35 and −.40 for F11.2 and +7F11.2, respectively (Table 5; Figure 4). No difference was measured for either the F11.2 or +7F11.2 at any N rate. The F10.0 final irrigation timing resulted in greatly decreased plump kernels compared with the F11.2 and +7F11.2 treatments and were well below the 900 g kg^{-1} target for adjunct two-row barley (AMBA, 2021). Test weights had a similar and negative linear coefficient (−.14) where only the intercept varied based on final irrigation timing (Figure 4). Generally, the F10.0 final irrigation timing had slightly reduced test weights, but overall, test weights were above average with only slight reductions with increasing N rate and with the early F10.0 final irrigation timing. No difference in plant height was measured based on final irrigation timing, but a positive quadratic relationship of height was determined based on N rate (Tables 4 and 5).

3.4 | Malting characteristics

Malt extract was described by a linear function of N rate and final irrigation timing (Table 6). Despite statistical differences, reductions in malt extract were small for the F11.2 and +7F11.2 where the linear coefficients were -.009 and -.007, respectively (Table 7). This reduction indicates that increased N applications resulted in relatively small reductions in malt extract under the conditions described in the study. Decreases in malt extract with increased N applications were observed similar to Blazewicz et al. (2017) but to a much lesser extent. The F10.0 sample linear rate of decrease was more than double that of the F11.2 or +7F11.2 final irrigation timings as noted by the linear coefficient of -.024. This was a reduction from 78 to 74%, indicating that final irrigation timing was a greater factor than N rate (Figure 5). Malt extract was at or near the 81% criteria for F11.2 and +7F11.2 that is ideal for malt as described by AMBA (2021), but with added N, the F10.0 dropped to below optimal levels.

Free amino N was described by a linear function of N rate that did not differ based on final irrigation timing whereas both DP and β-glucans were described by linear functions of N rate and final irrigation timing (Table 6). Free amino N increased with added N regardless of final irrigation timing where the linear coefficient was .132 (Table 7; Figure 5). Diastatic power was slightly below the 140° target for F11.2 and +7F11.2 and differed based on final irrigation timing and

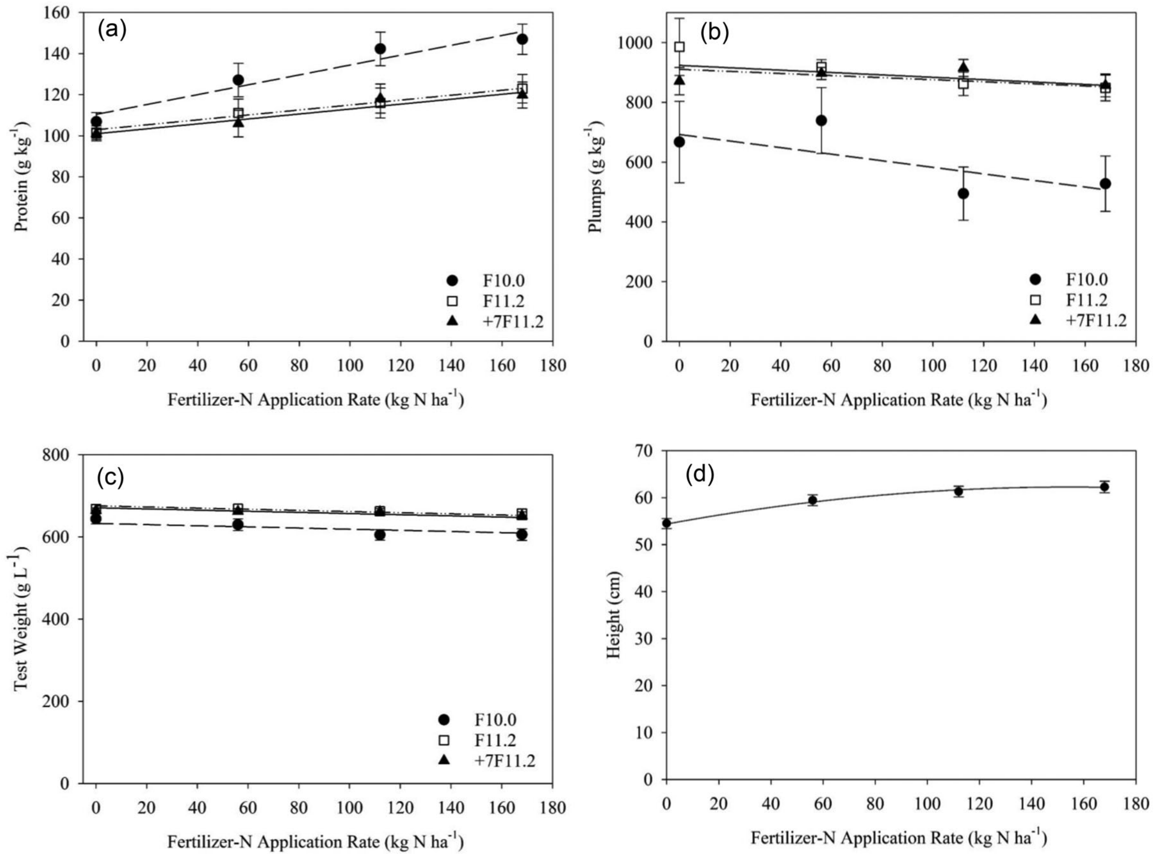

FIGURE 4 Malt barley (a) grain protein concentration, (b) plumps, (c) test weight, and (d) plant height at harvest as affected by final irrigation timing [Feekes 10.0 (F10.0), Feekes 11.2 (F11.2), and +7 d Feekes 11.2 (+7F11.2)] and fertilizer N application rate (equation coefficients are listed in Table 5), where 93 kg N ha^{-1} of additional soil inorganic N was measured

N rate linearly, where DP was greatly increased in the F10.0 final irrigation timing when fertilizer N was applied (AMBA, 2021). The only malt response where F11.2 and +7F11.2 did not closely track was for β-glucan where the F10.0 and F11.2 treatments did not differ, and the +7F11.2 was decreased at higher N rates. Ideal malt characteristics strive for β-glucans below 100 mg kg^{-1}, which was surpassed for the two highest N rates for both the F10.0 and F11.2 final irrigation timing (AMBA, 2021). Similar to the current study, previous work has reported increased β-glucan under increased N rates and at greater precipitation or irrigation amounts (Anker-Nilssen et al., 2008; Güler, 2003; Oscarsson et al., 1998). These results indicate that late-season irrigations can reduce β-glucan content even at higher N rates, indicating an important factor to consider when developing irrigation and N recommendations for barley.

Pearson correlation analysis using data from all final irrigation timings and N levels indicated that grain protein at harvest was better correlated to malting parameters compared with grain yield (Table 8). Grain protein was negatively correlated to malt extract (r = -.838), positively correlated to β-glucan (r = .524), positively correlated to FAN (r = .792), and positively correlated to DP (r = .902), where the malting parameters were correlated to varying degrees among themselves. Investigation of regression relationships further confirmed that grain protein described malt characteristics, where R^2 ranged from .27 to .70; malt extract decreased with increased protein; and FAN, DP, and β-glucans increased as grain protein increased (Figure 6). These relationships will prove important during fertilizer guideline development, particularly if malting parameters are unavailable.

4 | SUMMARY AND CONCLUSIONS

Nitrogen fertilization and final irrigation timing affected the majority of barley grain, straw, and malt characteristics. Little to no differences in resulting grain quality were measured between the F11.2 and +7F11.2 final irrigation timing, indicating that irrigations past F11.2 were not generally beneficial. For the F11.2 and +7F11.2, N applications of 56 kg N ha^{-1} maximized yield in the study, but greater predicted yields were determined from the fitted model that resulted in only small grain or malt quality characteristics outside of the range acceptable for malting. Results indicate that the magnitude of detrimental quality response to fertilizer N applications may

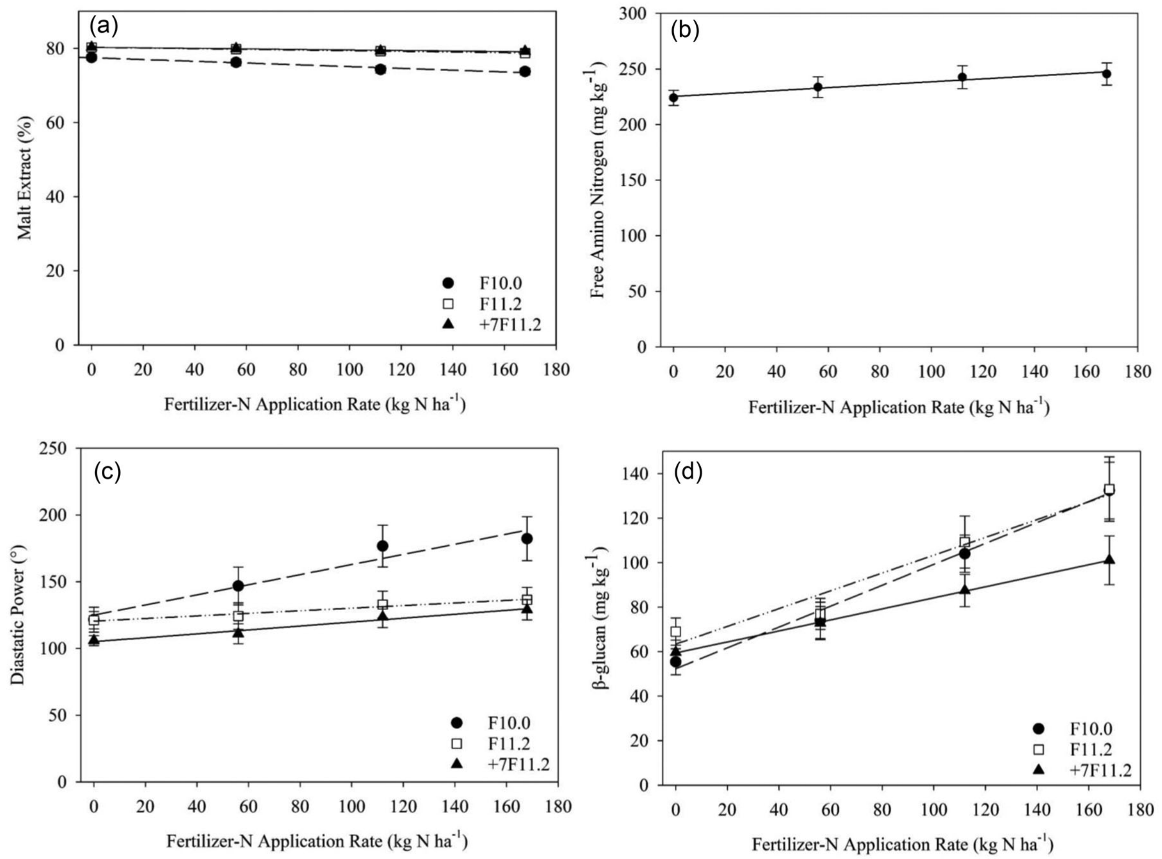

FIGURE 5 Malt barley (a) malt extract percentage, (b) free amino nitrogen (FAN), (c) diastatic power (DP), and (d) β-glucan concentrations as affected by final irrigation timing [Feekes 10.0 (F10.0), Feekes 11.2 (F11.2), and +7d Feekes 11.2 (+7F11.2)] and fertilizer N application rate (equation coefficients are listed in Table 7), where 93 kg N ha^{-1} of additional soil inorganic N was measured

TABLE 8 Pearson correlation *r*-values between grain protein, grain yield, malt extract, free amino nitrogen (FAN), diastatic power (DP), and β-glucan at the Kimberly Research and Extension Center, Kimberly, ID

	Grain protein	Malt extract	Malt β-glucan	FAN	DP
Grain yield	−.021	.381***	.074	.099	−.179*
Grain protein		−.838***	.524***	.792***	.902***
Malt extract			−.389***	−.588***	−.872***
Malt β-glucan				.398***	.444***
FAN					.788***

*Significant at the $P \geq .05$ probability level.
**Significant at the $P \geq .01$ probability level.
***Significant at the $P \geq .001$ probability level.

be reduced in modern cultivars. Achievement of higher yields through increased fertilizer N applications could be further investigated as quality may stay within limits at higher fertilizer N application rates. Of note in the study were slightly low DP and elevated β-glucan values at the F11.2 final irrigation timing at the two highest N rates, which would be above ideal levels for malting but may be beneficial to barley for human consumption because β-glucans are desirable for their ability to lower cholesterol. Additionally, grain protein was well-correlated to malt characteristics under varying N rates and final irrigation timing, indicating the potential for its use as a proxy for selection factors when establishing fertilizer recommendations. The results of this study provide evidence of grain yield and quality, barley straw, and malt characteristics that are critical for establishing appropriate fertilizer N recommendations on malt barley in Idaho and irrigated production in the western United States. Response trends from the study are likely similar for all-malt breeding lines, but the

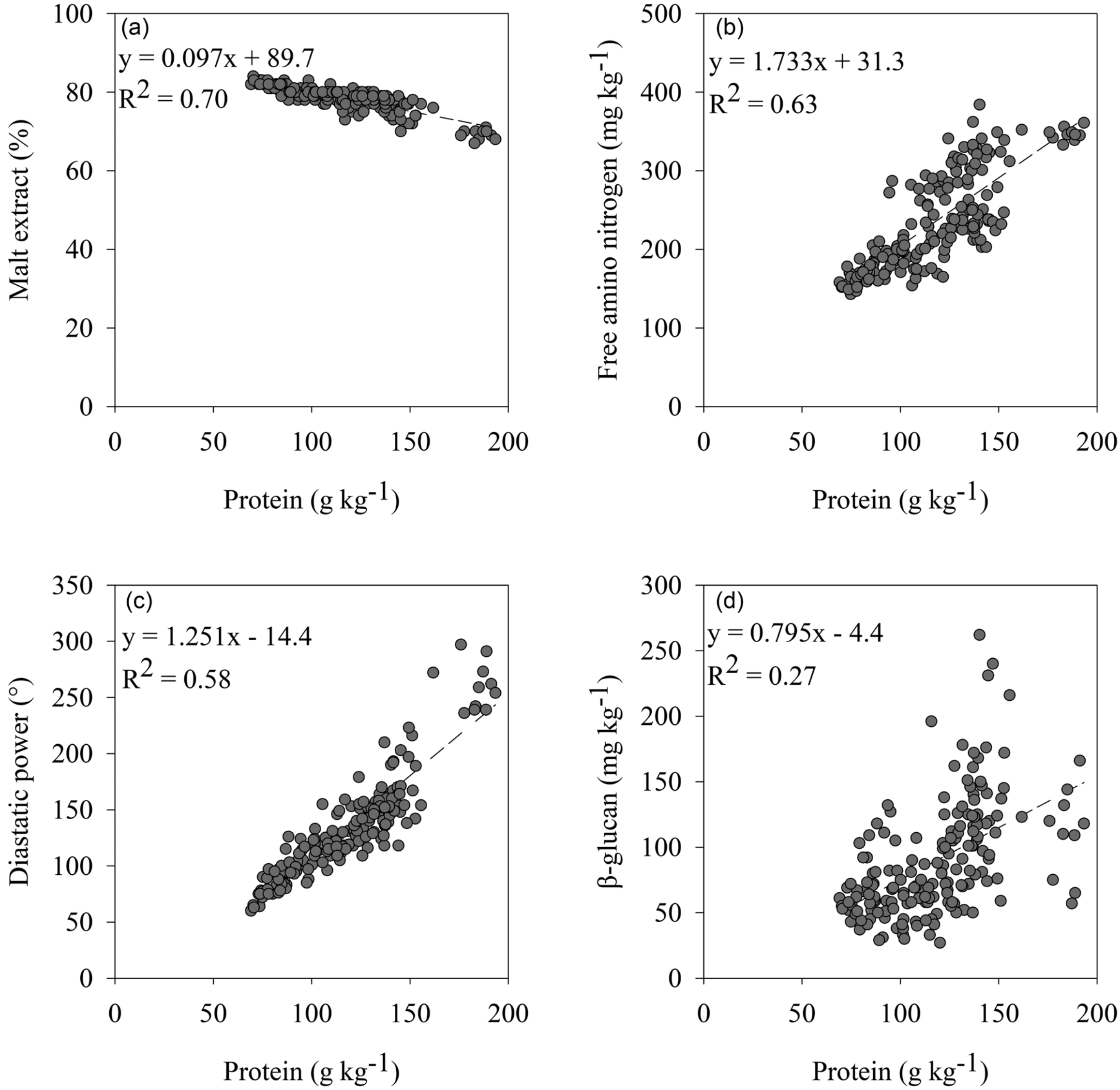

FIGURE 6 Regression analyses of grain protein and malt characteristics (a) malt extract percentage, (b) free amino nitrogen (FAN), (c) diastatic power (DP), and (d) malt β-glucan concentrations at the Kimberly Research and Extension Center, Kimberly, ID

magnitude of response is not known at varying N and irrigation levels as the current cultivar response may not be indicative of those lines bred for lower grain protein and, thus, use in all-malt brewing. Further studies on varying cultivars and locations would provide an increased understanding of responses across genotypes and environments. Thus, final irrigation timing and proper N management are critical factors for maximizing barley agronomic productivity alongside malt quality in the western United States.

ACKNOWLEDGMENTS

Support for this research was provided by Molson Coors Beverage Company and the Idaho Barley Commission. The authors thank Scott Pristupa, Irene Shackelford, and Chris Martens for laboratory and field assistance; Dr. Juliet Marshall, Chad Jackson, and Tod Shelman for assistance with planting and harvest; and Dr. Howard Neibling's field crew for irrigation management.

AUTHOR CONTRIBUTIONS

Christopher W. Rogers: Conceptualization; Data curations; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – review & editing. Biswanath Dari: Data curation; Formal analysis; Writing – review & editing; Howard Neibling: Investigation; Methodology; Project administration; Resources; Supervision. Jason Walling: Investigation; Methodology; Writing – review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Rogers, C. W., Dari, B., Neibling, H., & Walling, J. (2022). Barley yield and malt characteristics as affected by nitrogen and final irrigation timing. *Agronomy Journal*, 1–14. https://doi.org/10.1002/agj2.21036