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Malt Barley Yield and Quality Response to Crop Water Stress Index

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Abstract: Malt barley is a crucial irrigated crop in the semi-arid Western United States, where the states of Idaho, Colorado, Wyoming, and Utah account for 92% of the irrigated production acreage and 30% of total U.S. production. In this region, spring malt barley's seasonal evapotranspiration ranges from 400 to 650 mm, and competition for limited water supplies, coupled with drought, is straining regional water resources. This study aimed to investigate the use of canopy temperature for deficit irrigation scheduling of malt barley. Specifically, the objectives were to use data-driven models to estimate well-watered (T_{LL}) and non-transpiring (T_{UL}) canopy temperatures, correlate the crop water stress index (CWSI) with malt barley yield and quality measures, and assess the applicability of CWSI for malt barley irrigation scheduling in a semi-arid climate. A 3-year field study was conducted with five irrigation treatments relative to estimated crop evapotranspiration (full, 75%, 50%, 25%, and no irrigation) and four replicates each. Continuous canopy temperature measurements and meteorological data were collected, and a feedforward neural network model was used to predict T_{LL}, while a physical model was used to estimate T_{UL}. The neural network model accurately predicted T_{LL}, with a strong correlation (R^2 = 0.99), a root mean square error of 0.89 °C, and a mean absolute error of 0.70 °C. Significant differences in calculated season-average CWSI were observed between the irrigation treatments, and relative evapotranspiration, malt barley relative yield, test weight, and plump kernels were negatively correlated with the season-average CWSI, while seed protein was positively correlated. The relationship between daily CWSI and fraction of available soil water was well described by an exponential decay function (R^2 = 0.72). These results demonstrate the applicability of data-driven models for computing CWSI of irrigated spring malt barley in a semi-arid environment and their ability to assess plant water stress and predict crop yield and quality response from CWSI.

Keywords: deficit irrigation; canopy temperature; infrared radiometers; evapotranspiration; irrigation management

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1. Introduction

Malt barley is an economically important crop in the western and northern great plain regions of the U.S. (CO, ID, MT, ND, OR, UT, WA, and WY). In 2023, these regions accounted for approximately 92% of total U.S. barley production, encompassing 954,000 hectares in 2023 [1]. Montana had the greatest total acreage, while Idaho had the greatest total production due to extensive irrigated production. Barley production in Idaho, Colorado, Wyoming, and Utah represented 30% of total U.S. production acreage but 92% of total U.S. irrigated acreage in 2017. The yield of irrigated barley surpasses dryland barley production by 2 to 3 times [1]. Currently, about three-quarters of the barley grown in the U.S. is utilized for malt production "https://www.agmrc.org/commodities-products/grains-oilseeds/barley-profile:" (accessed on 5 May 2024), with the remainder used for animal feed or human food production.

The quality of malt barley is important for the brewing industry, as it must meet specific established quality parameters based on its end-use. There are two primary brewing end-uses: adjunct brewing, where added starches such as other grains are used as a source of fermentable sugars, and all-malt brewing, where no additional starches are utilized [2]. For brewing, malt barley seed must be of pure variety, have a high percentage of plump kernels (>90%), have seed protein < 13% for adjunct brewing and 12% for all malt brewing, have vigorous, even germination (>98%), have a low percentage of skinned and broken kernels (<5%), and be free of disease "https://drive.google.com/file/d/1-jQkWtxc9vcTtraAeGTl5RIdyRnlrqxP/view" (accessed on 5 May 2024). Malt barley that does not meet these specifications is typically marketed as feed barley at a lower price.

Spring barley seasonal evapotranspiration (ET_c) is typically within the range of 400 to 650 mm, varying based on location-specific climatic conditions https://www.usbr.gov/pn/agrimet/ (accessed on 5 May 2024), https://www.usbr.gov/gp/agrimet/ (accessed on 5 May 2024). Barley is characterized by a moderately deep root zone of approximately 1 m in unrestricted soils, allowing it to effectively utilize stored soil moisture. While spring barley demonstrates some degree of drought tolerance due to its moderate rooting depth, careful consideration must be given to the impact of water stress on grain quality for successful malt barley production. In cereal crops, water stress has the potential to reduce yield by decreasing the number and average weight of kernels per plant [3–6]. Additionally, cereal grain quality parameters may be adversely affected by water stress [2,5,7,8]. Notably, barley protein content often increases under water stress, which can have negative implications for malt barley's end-use, depending upon the timing, magnitude, and duration of water stress [2,5,7,8]. However, there has been observed variation in genotype protein response to water stress [2,9].

The region is facing unprecedented demand for water resources, driven by urban growth and ecosystem restoration efforts, which is straining irrigation supplies. Prolonged regional drought, exceeding severity levels not seen since 800 CE [10], has depleted surface water storage. Climate models predict decreasing snowpack volume and duration [11,12], which may further reduce water storage reservoir levels. The combination of escalating water demand and anticipated climate change impacts will result in less water available for irrigated crop production in the region. This reduction in irrigation water can be addressed by either decreasing crop production area or implementing deficit irrigation on the same production area. Deficit irrigation (DI) is the preferred approach, as maintaining existing production areas could sustain the rural economies dependent on irrigated crops, despite the likelihood of reduced yields. In the case of malt barley, reduced yields may be tolerable, but significant quality losses could lead to a loss of market access and ultimately impact the regional brewing industry infrastructure.

Effective soil water-based DI management requires precise knowledge of daily ET_c and soil water holding characteristics. Daily soil water status, based on a soil water balance, is needed to project when it will be depleted to a predetermined level to trigger an irrigation event. Periodic soil water measurement is necessary to verify computed soil water status [13–16]. Implementing an effective DI program requires a thorough understanding of soil–water–plant relationships to determine soil water holding characteristics and interpret soil water content data. Many producers lack the expertise or time to perform daily soil water balance calculations or desire to invest in soil water sensors needed for monitoring of soil water content.

A plant-based method for DI management may be easier for producers to implement than soil water-based DI management [14] by eliminating tedious daily soil water balance calculations and costs and maintenance associated with soil water monitoring. Ideally, the plant-based measure would express plant water status directly, without the need for training to interpret the measurements. Canopy temperature is such a plant-based indicator that can readily be measured using infrared radiometers and has been used to estimate ET_c and plant water status in many crops [17–20]. Ref. [21] measured up to a 6 °C temperature difference between canopy and air temperature of water stressed barley under full sunshine and 1.2 kPa vapor pressure deficit. Canopy temperature can be expressed as a crop water stress index (CWSI) [18,19], which can be readily interpreted without the need for knowledge of plant–soil–water characteristics.

Malt barley yield and quality response to plant water stress in terms of CWSI is unknown. It is necessary to determine the maximum CWSI that can be tolerated during deficit irrigation (DI) scheduling without compromising the marketability of the crop. The aim of the research reported in this paper was to explore the feasibility of using canopy temperature, as indicated by the CWSI of [18,19], for the scheduling of malt barley DI. Our specific objectives were to utilize canopy temperature data collected from fully irrigated and DI plots with data driven models to estimate CWSI reference temperatures, establish a correlation between CWSI and malt barley seed yield and quality measures, and use the results to evaluate the suitability of CWSI for malt barley DI in a semi-arid climate.

2. Materials and Methods

2.1. Site Description

The USDA-ARS Northwest Irrigation and Soil Laboratory near Kimberly, Idaho, served as the site for the field study conducted from 2021 to 2023. The region has a borderline arid-semiarid climate, with an average annual precipitation of 253 mm and an average annual alfalfa-reference evapotranspiration (ET_r) of 1479 mm over the past 20 years. Approximately 45% of the annual precipitation and 83% of the annual ET_r occur during the April through mid-October growing period. The study site soil is a well-drained Portneuf silt loam classified as very deep [22].

2.2. Experimental Design

The field study employed a randomized block experimental design to evaluate five different irrigation treatments, each with four replications. The five irrigation treatments included: fully irrigated (FIT), 75% FIT, 50% FIT, 25% FIT, and zero irrigation. Each treatment plot measured 4.6 m wide by 9.1 m long and was surrounded by a 3 m or 9 m wide bare border to facilitate plot access and accommodate irrigation system components. The FIT treatment represented a condition where the crop was irrigated weekly with a cumulative depth equal to the estimated weekly spring grain evapotranspiration (ET_c). Irrigation was applied using a solid-set sprinkler system, with all plots receiving water on the same day but with varying durations to achieve the desired application depths.

2.3. Cultural and Harvest Practices

The tillage regimen was consistent across all study years, involving tandem discing in the fall prior to the growing season and roller harrowing in the spring before planting. Spring forage oats was the preceding crop each year. The precise spatial location of the experimental plots changed annually, but they were situated adjacent to the previous year's study area. The tillage practices reflected those commonly used by regional producers for spring grain production.

Prior to spring planting, four soil cores were collected from each experimental block and combined into composite samples representing two depth increments: 0–30 cm and 30–60 cm. The composite soil samples were analyzed for concentrations of nitrate nitrogen, ammonium nitrogen, sodium bicarbonate-extractable phosphorus, and exchangeable potassium. The study sites were then uniformly fertilized based on University of Idaho Extension recommendations [23].

The spring malt barley cultivar Moravian 69 was planted on 10 April 2021, 28 April 2022, and 25 April 2023, at a depth of 3 cm. A 26-row tractor-mounted grain drill with 18 cm row spacing was used to plant the barley at a rate of 2 million seeds per hectare. Full crop emergence occurred on 11 May 2021, 10 May 2022, and 11 May 2023. Herbicides were applied by ground sprayer in 2021 and by drone in 2022 and 2023, using the maximum labeled rates to control weeds. Additionally, a growth regulator was applied to reduce lodging, following standard regional producer practices.

The harvest area within each plot was 0.9 m (5 rows) wide and 9.1 m long, adjacent to the center line of the plot, to minimize non-uniform water application due to sprinkler pattern edge effects. Plots were harvested on 8 August 2021, 9 August 2022, and 6 August 2023, using a small plot combine, where grain yields were subsequently measured and corrected to a dry weight. For each plot, a 1000 g barley seed subsample was collected, de-awned, and cleaned (Plueffer, Sampler Cleaner Model SLN, Kitzingen, Germany) for use in subsequent seed quality analysis.

2.4. Grain Quality Analysis

Barley test weight was determined according to USDA standards and reported in lb bu^{-1}, then converted to g L^{-1} [24]. Plump kernels were identified using a 6/64″ slotted screen and mechanical sieving, per USDA guidelines [25]. Seed nitrogen content was measured by combustion using an Elementar Vario Max CN analyzer (Elementar Americas, Inc., Ronkonkoma, NY, USA) and then converted to protein concentrations based on ISO [26] standards.

2.5. Irrigation System

A fixed solid set sprinkler system described by [27] was used for irrigation. Application intensity of the sprinkler system was 25 mm h^{-1}. The surface water supply was filtered through a 130 µm screen. Manual ball valves were used to control treatment water application. All irrigations occurred in the morning (6:00 to 12:00 MST) to minimize wind drift and evaporation losses. Rain gauges centered in each plot verified water application and rainfall amounts weekly.

In the 2023 study, a portable solid set system with 12.1 m sprinkler spacing was used immediately after planting to apply 50 mm of water in multiple small irrigations, ensuring seed germination. These R2000 WF sprinklers (Nelson Irrigation Corp., Walla Walla, WA, USA) had 3.9 mm nozzles. The portable system was then removed, and the fixed solid set system was used for the remainder of the season.

2.6. Field Measurements and Instrumentation

Canopy temperature was continuously measured in three replications of each irrigation treatment using infrared radiometers. Solar radiation, air temperature, relative humidity, and wind speed at 2 m height were also measured adjacent to the experimental plots. Details of sensors and their installation, sensor sampling rate, and data storage rate are provided by [27].

2.7. Calculation of CWSI

The CWSI was calculated using 15 min average measured canopy temperature values and the empirical formula developed by [18,19] as:

$$\mathrm{CWSI} = (T_c - T_{LL})/(T_{UL} - T_{LL}) \quad (1)$$

where T_{LL} = lower reference temperature (°C), which represents the canopy temperature of well-watered malt barley, T_{UL} = upper reference temperature (°C), which represents the canopy temperature of non-transpiring malt barley, and T_c = measured canopy temperature (°C). The lower reference temperature was estimated using a neural network model, and the upper reference temperature was estimated using a plant-atmosphere energy balance equation for a non-transpiring canopy. The specific details of the methods used to estimate the reference temperatures are provided by [27]. A spreadsheet detailing calculation of CWSI is provided as Supplementary Material to this manuscript.

2.8. Irrigation Scheduling and Soil Water Measurement

The irrigation schedule for the FIT was based on a weekly soil water balance to maintain soil water content between 50 and 100% available throughout the growing season. Estimated daily malt barley evapotranspiration (ET_c) was calculated using the ASCE standardized reference evapotranspiration equation [28] and daily small spring grain crop coefficients [29] from a nearby AgriMet (U.S. Bureau of Reclamation, "https://www.usbr.gov/pn/agrimet/" (accessed on 5 May 2024)) weather station within 100 m of the study site. Precipitation data were also obtained from the same AgriMet station. Irrigation was applied once a week on the same day for all treatments.

Soil moisture was measured weekly in 0.15 m increments from 0.15 to 2.3 m in 2021 and 0.15 to 1.7 m in 2022–2023 at the center of each plot using a neutron probe. The neutron probe was calibrated to the experimental site soil using the methods of [30], with separate calibrations for the 0.15 m depth and deeper depths.

Seasonal ET_c (mm) was calculated using a soil water balance between emergence and harvest as described [27].

2.9. Statistical Analysis

PROC MIXED in SAS version 9.4 (SAS Institute Inc., Cary, NC, USA) was used for statistical data analysis to test for treatment differences. Least squares means (LSMEANS) to determine the significance of treatment and interaction effects. Unless otherwise noted, treatment differences and interactions were considered statistically significant at $p < 0.05$.

3. Results

3.1. Cumulative Water Application and Fraction of Available Soil Water

The cumulative estimated crop evapotranspiration (ET_c) and total water application (rainfall + irrigation) for each irrigation treatment are shown in Figures 1A, 2A and 3A for study years 2021, 2022, and 2023, respectively. In 2021 and 2022, the cumulative water application of the full irrigation treatment (FIT) closely approximated estimated ET_c. However, in May and June of 2023, the cumulative water application exceeded the estimated ET_c of the FIT. This was due to water application inefficiencies and the need to maintain soil water depletion below 50% of available soil water. The seasonal water applied (rainfall + irrigation) amount for each treatment is provided in Table 1. Rainfall between emergence and harvest was 30, 53, and 50 mm in 2021, 2022, and 2023, respectively.

Table 1. Water applied (irrigation + rainfall), soil water extraction, and soil water balance-based malt barley evapotranspiration (ET_c) between crop emergence and harvest, season crop water stress index between the first week in June and Mid-July and malt barley yield, average fraction of available soil water (*f*ASW), yield, seed protein, percent plump kernels, and test weight in each study year. Values followed by the same letter in a study year are not significantly different ($p \leq 0.05$).

Year	**Treatment**	**Water Applied (mm)**	**Soil Water Extraction (mm)**	**Season Average *f*ASW**	**ET_c (mm)**	**Season CWSI**	**Yield (kg ha^{-1})**	**Protein (g kg^{-1})**	**Plump Kernels (%)**	**Test Weight (g L^{-1})**
2021	FIT	506	15 a	0.65 a	522 a	0.21 a	8251 a	95 a	94 a	645 a
	75%FIT	395	85 b	0.41 b	481 b	0.31 ab	7000 a	117 b	91 a	641 a
	50%FIT	284	96 b	0.37 b	382 c	0.47 b	4901 b	146 c	83 a	626 a
	25%FIT	186	85 b	0.32 b	272 d	0.71 c	1794 c	182 d	42 b	604 b
	None	62	116 b	0.33 b	179 e	1.06 d	1111 c	169 d	31 b	600 b
2022	FIT	393	43 a	0.61 a	474 a	0.01 a	7033 a	104 a	88 a	631 a
	75%FIT	308	95 b	0.52 b	431 b	0.10 a	6015 b	121 a	78 a	612 ab
	50%FIT	223	106 b	0.46 bc	348 c	0.30 b	4285 c	145 b	62 b	600 bc
	25%FIT	138	112 b	0.42 c	259 d	0.50 c	2151 d	174 c	16 c	576 c
	None	53	107 b	0.38 c	160 e	0.72 d	1164 e	187 c	17 c	574 c
2023	FIT	440	54 a	0.66 a	493 a	−0.01 a	8988 a	102 a	96 a	677 a
	75%FIT	348	80 a	059 a	428 b	0.03 ab	8351 a	102 a	92 a	675 a
	50%FIT	257	113 b	0.47 bc	370 c	0.21 bc	6621 b	120 b	72 b	645 a
	25%FIT	166	113 b	0.39 cd	278 d	0.34 cd	4273 c	152 c	28 c	603 b
	None	74	124 b	0.38 d	197 e	0.48 d	2758 d	170 d	17 c	589 b

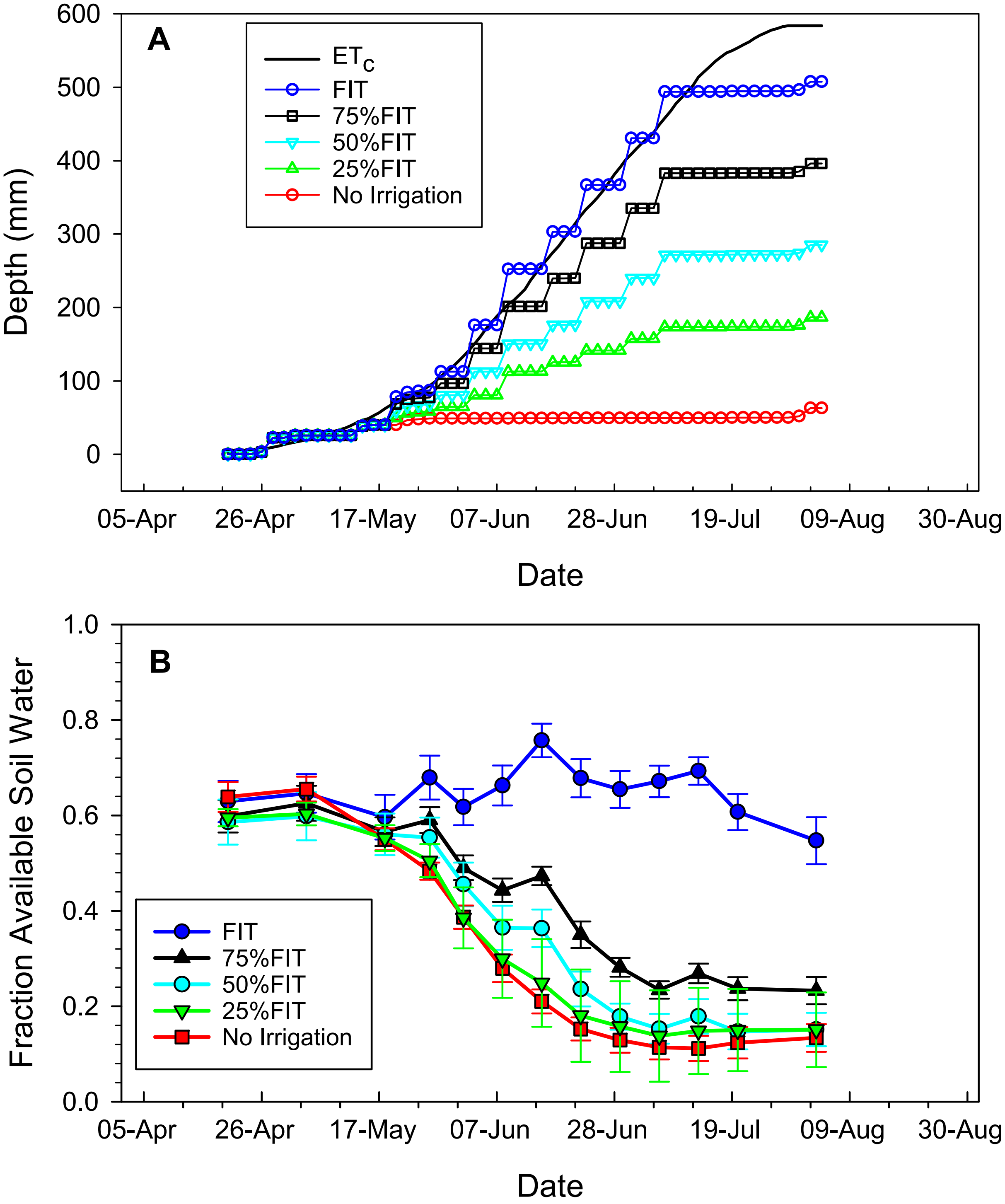

Figure 1. Study year 2021 (**A**) estimated malt barley evapotranspiration (ET_c) and cumulative water (rainfall + irrigation) applied; (**B**) fraction of available water in each irrigation treatment (full irrigation (FIT), 75% FIT, 50% FIT, 25% FIT and no irrigation). Bars represent the standard error of the measurements.

The fraction of available soil water (*f*ASW) for the 0 to 0.9 m soil profile is shown in Figures 1B, 2B and 3B for study years 2021, 2022, and 2023, respectively, for each irrigation treatment. At emergence, the *f*ASW was less than 0.7 in all three study years. The *f*ASW of the irrigation treatments began to diverge soon after the irrigation treatments were imposed. The relative *f*ASW values corresponded with the relative amounts of irrigation applied for each treatment in all study years. In all years, the *f*ASW of the FIT remained above 50% available soil water from emergence to mid-July, the time of the last irrigation. In 2023, the water applied exceeded the estimated crop ET_c through May (Figure 3A), and the *f*ASW increased accordingly (Figure 3B).

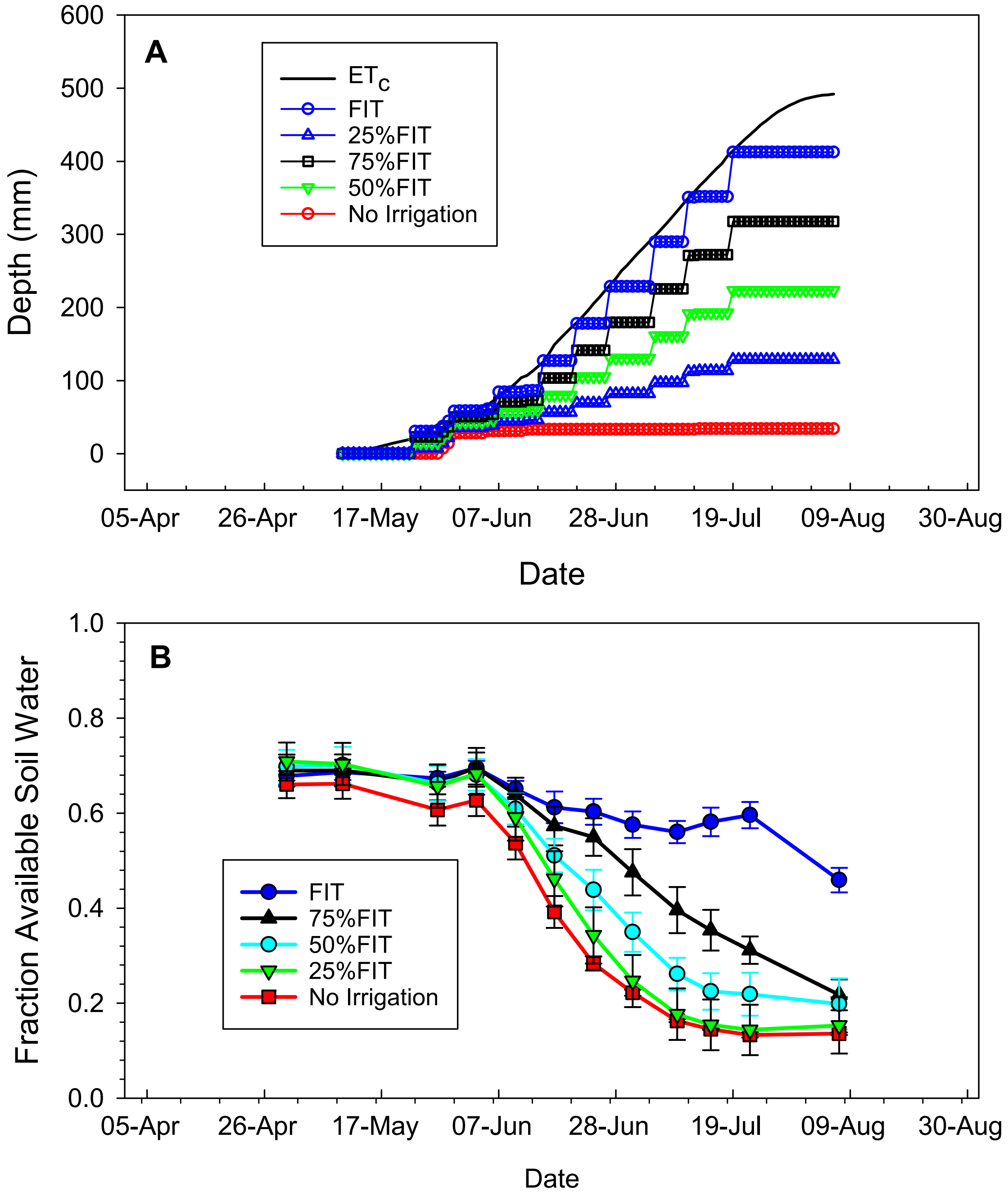

Figure 2. Study year 2022 (**A**) estimated malt barley evapotranspiration (ET_c) and cumulative water (rainfall + irrigation) applied; (**B**) fraction of available water in each irrigation treatment (full irrigation (FIT), 75% FIT, 50% FIT, 25% FIT, and no irrigation). Bars represent the standard error of the measurements.

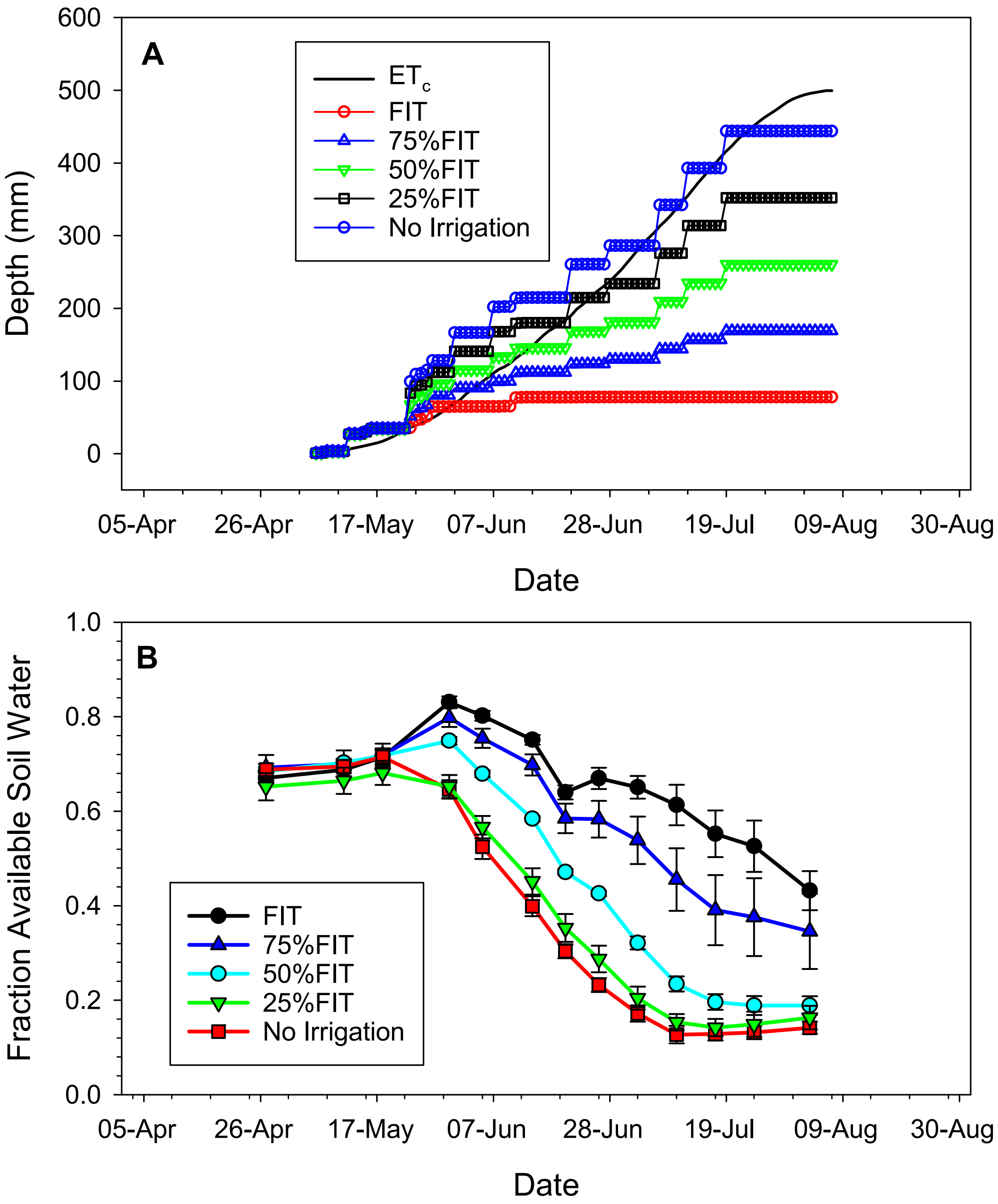

Figure 3. Study year 2023 (**A**) estimated malt barley evapotranspiration (ET_c) and cumulative water (rainfall + irrigation) applied; (**B**) fraction of available water in each irrigation treatment (full irrigation (FIT), 75% FIT, 50% FIT, 25% FIT, and no irrigation). Bars represent the standard error of the measurements.

The seasonal average *f*ASW differed significantly ($p < 0.001$) between irrigation treatments in each study year (Table 1). Furthermore, study year and the interaction between irrigation treatment and study year were also significant ($p < 0.001$), so the data were analyzed separately for each year. The FIT (full irrigation treatment) had comparable seasonal average *f*ASW values across all study years. However, there were no significant differences in seasonal average *f*ASW between the 25% FIT (25% full irrigation) and no irrigation treatments in any of the study years.

3.2. Crop Water Stress Index

The neural network model for estimating T_{LL} achieved excellent predictive accuracy, with a coefficient of determination of 0.99, a root mean squared error (RMSE) of 0.89 °C, and a mean absolute error (MAE) of 0.70 °C. Data from the 2021 study year was excluded from model development, as the measured canopy temperatures that year were significantly higher compared to 2022 and 2023. This discrepancy was likely due to poor crop emergence in the first year, leading to increased bare soil visibility that may have influenced the canopy temperature sensor readings.

A daily CWSI was calculated as the mean 15 min CWSI between 13:00 and 15:00 MDT. A seasonal CWSI was calculated as the average daily CWSI between the second week of June and mid-July. The season summary excluded days when the canopy was wet or when solar radiation was less than 200 W m^{-2}. The season CWSI values are shown in Table 1 for each irrigation treatment and study year.

Season CWSI differed significantly ($p < 0.001$) between irrigation treatments in each study year (Table 1). Furthermore, study year and the interaction between irrigation treatment and study year were also significant ($p < 0.001$), so the data were analyzed separately for each year. As irrigation amount, ET_c, and season average *f*ASW decreased, the season CWSI increased (Table 1). No significant difference in season CWSI was observed between the FIT and 75% FIT irrigation treatments in any study year.

The relationship between daily CWSI and *f*ASW for the 0 to 0.6 m soil profile across the three study years is shown in Figure 4. A two-parameter exponential decay function fit the data well, with a coefficient of determination of 0.76. According to [31], the common limit for allowable soil water depletion (1-*f*ASW) without adversely affecting barley yield is 0.55 (>0.45 available). Based on the relationship depicted in Figure 4, this allowable 0.55 depletion level corresponds to a daily CWSI of approximately 0.2. This correlation suggests that an irrigation scheduling strategy using a mean daily CWSI threshold of 0.2 could be an effective irrigation management approach.

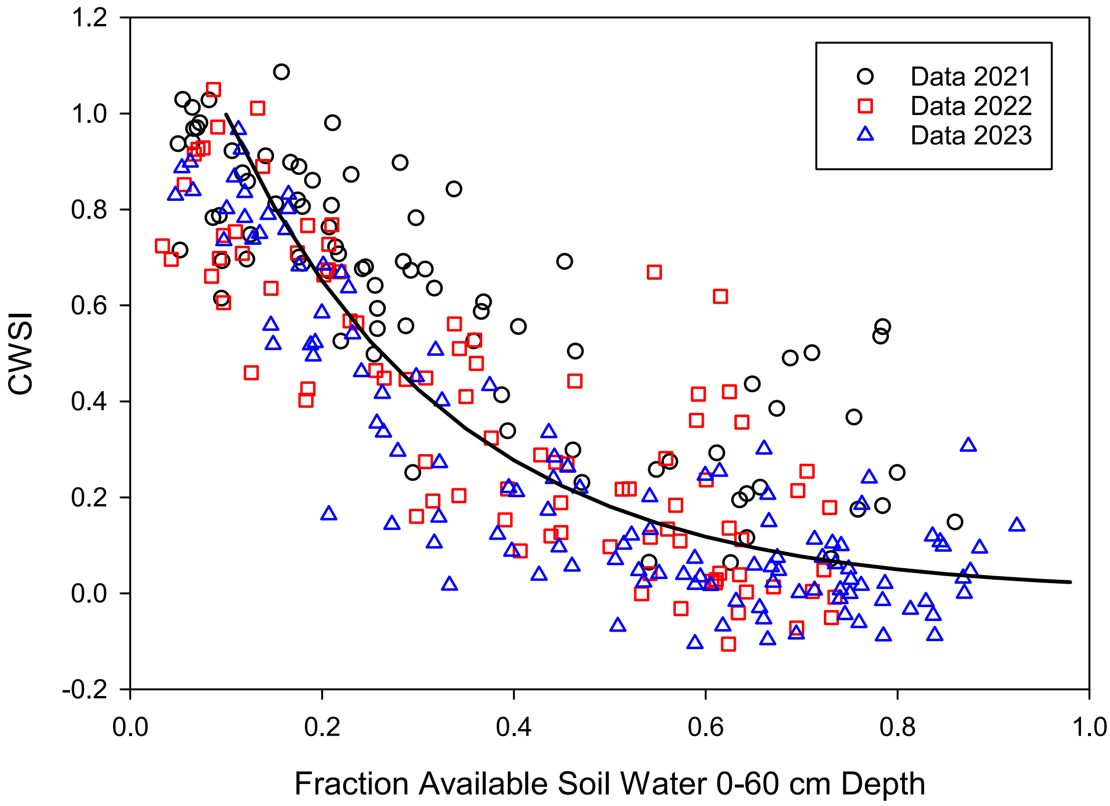

Figure 4. Relationship between daily crop water stress index (CWSI) and fraction of available soil water in the 0 to 0.6 m soil profile for the three study years combined (n = 294).

3.3. Evapotranspiration

Crop ET_c differed significantly ($p < 0.001$) between irrigation treatments in each study year (Table 1). Furthermore, study year and the interaction between irrigation treatment and study year were also significant ($p < 0.001$), so the data were analyzed separately for each year. In every study year, the ET_c was significantly different among the irrigation treatments. Averaged across the three study years, the fraction of ET_c for the deficit irrigation treatments relative to the full irrigation treatment (FIT) was 0.90 for 75% FIT, 0.74 for 50% FIT, 0.54 for 25% FIT, and 0.36 for the no irrigation treatment.

The relationship between season CWSI and relative ET_c is shown in Figure 5A. Relative ET_c was calculated as the ratio of soil water balance-based ET_c for each treatment replicate to the maximum ET_c of any treatment replicate in a given study year. This relationship was well represented by a negative linear correlation, with a coefficient of determination of 0.74. Several data points in Figure 5A plot above the regression line, and these correspond to the 2021 study year. This is likely due to measured canopy temperatures being greater in 2021 compared to 2022 and 2023, potentially caused by bare ground visibility for the canopy temperature sensors resulting from crop emergence issues in some plots that year.

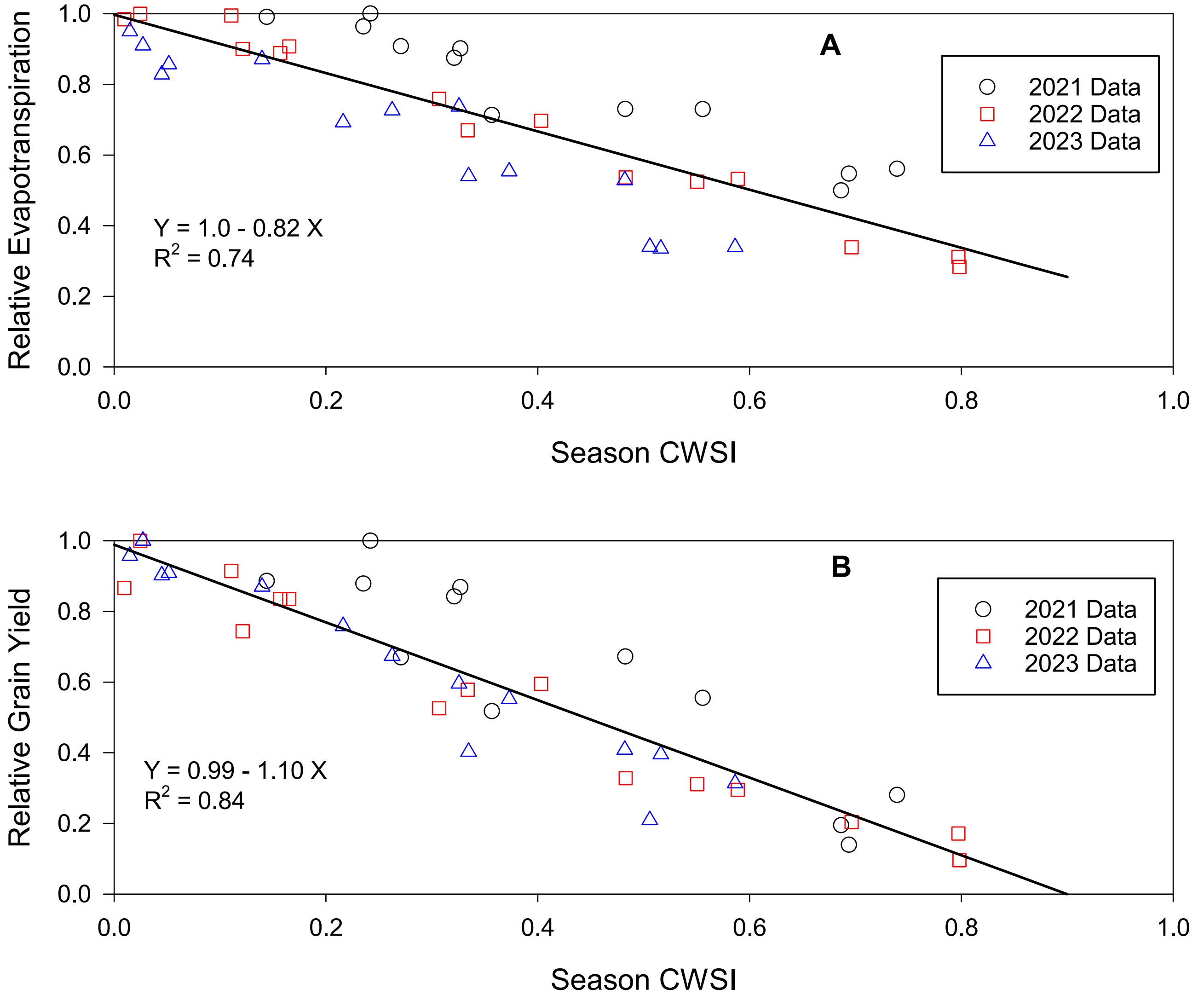

Figure 5. Relationship between season crop water stress index (CWSI) and (**A**) relative evapotranspiration; (**B**) malt barley relative grain yield for the three study years combined.

3.4. Malt Barley Yield

Malt barley yields showed highly significant differences ($p < 0.001$) between the irrigation treatments in each study year (Table 1). The study year was also highly significant ($p < 0.001$), and the interaction between irrigation treatment and study year was significant. Given the significance of study year, the data were analyzed separately for each year. In 2021 and 2023, there was no significant difference in yields between the FIT and 75% FIT irrigation treatments. Yields of the FIT, 75% FIT, and 50% FIT irrigation treatments were greatest in those two years compared to 2022.

The relationship between season CWSI and relative yield (RY) is shown in Figure 5B. Relative yield was calculated as the ratio of each treatment's yield to the maximum yield of any treatment replicate in a given study year. The data exhibit a strong negative linear relationship between season 5 CWSI and RY, with a coefficient of determination of 0.84. Several data points plotting above the regression line are from the 2021 study year, potentially due to bare ground visibility by the canopy temperature sensors resulting from crop emergence issues in some plots that year.

3.5. Malt Barley Seed Protein

Malt barley seed protein content showed highly significant differences ($p < 0.001$) between irrigation treatments in each study year (Table 1). Furthermore, study year and the interaction between irrigation treatment and study year were also significant ($p < 0.001$), so the data were analyzed separately for each year. In 2022 and 2023, there was no significant difference in seed protein between the 75% FIT and FIT irrigation treatments. Across all study years, seed protein increased as crop water use (ET_c) decreased, with the non-irrigated treatment resulting in the highest seed protein levels.

Figure 6A illustrates the positive linear relationship between the season CWSI and malt barley seed protein across the three study years, with a coefficient of determination of 0.81. Notably, the seed protein remained below the 130 g kg^{-1} industry limit for malt barley, with one exception, when the seasonal average daily CWSI was less than 0.2.

3.6. Malt Barley Plump Kernels

Irrigation treatment had a highly significant effect on the percentage of plump kernels across all study years ($p < 0.001$, Table 1). Study year and the interaction between irrigation treatment and study year were also significant ($p < 0.001$), so the data were analyzed separately for each year. In no year there was a significant difference in the percent of plump kernels between the 75% FIT and FIT irrigation treatments. Similarly, the 25% FIT irrigation and no irrigation treatments did not differ significantly in any year. However, percent plump kernels consistently decreased with lower irrigation levels, with the no irrigation treatment producing the least plump kernels each study year. Notably, the percent plump kernels fell below the malt industry's 90% desired threshold in 2022 across all irrigation treatments. The reason for this anomalous drop is uncertain, as there were no apparent differences in climate or soil water availability in the fully irrigated plots that year compared to other study years.

The relationship between season CWSI and percent plump kernels is shown in Figure 6B for study years 2022 and 2023. However, the 2021 data deviated from the 2022 and 2023 trends, likely due to higher measured canopy temperatures in 2021. This was potentially caused by some bare ground visibility detected by the canopy temperature sensors resulting from crop emergence issues in certain plots that year. A sigmoid function (Figure 6B) provided an excellent representation of the relationship between season CWSI and percent plump kernels, with a coefficient of determination of 0.92.

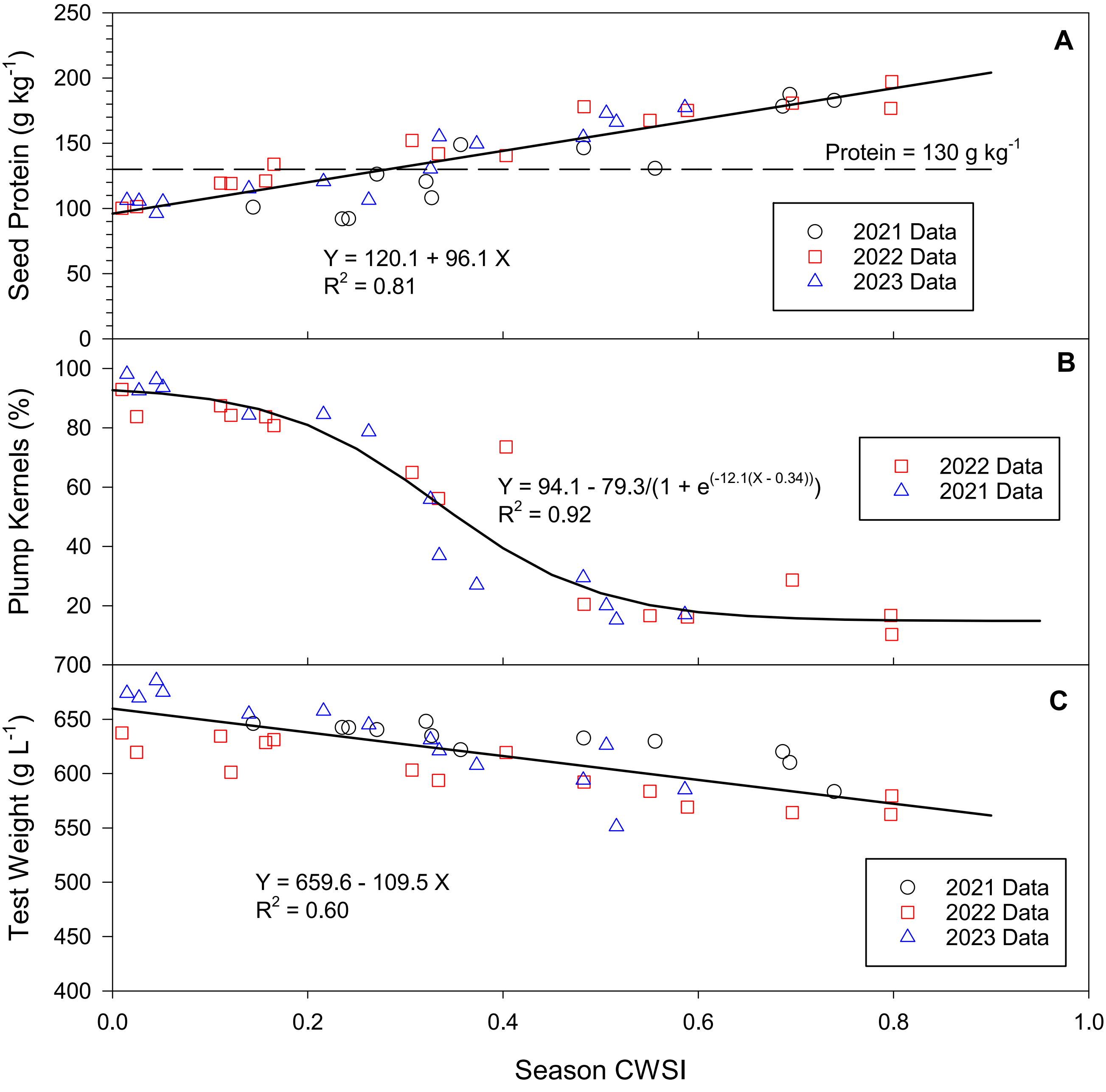

Figure 6. Relationship between season crop water stress index (CWSI) and (**A**) malt barley seed protein for the three study years combined; (**B**) percent plump kernels for study years 2022 and 2023 only; (**C**) seed test weight for the three study years combined.

3.7. Malt Barley Seed Test Weight

Malt barley seed test weight differed significantly across irrigation treatments ($p < 0.001$) in each study year (Table 1). Also, study year and the interaction between irrigation treatment and study year were also significant ($p < 0.01$), so the data were analyzed separately for each year. There was no significant difference in test weight between the 75% FIT and FIT irrigation treatments in any study year. Similarly, there was no significant difference between the 25% FIT and no irrigation treatments. However, test weight decreased with lower levels of evapotranspiration (ET_c), with the no irrigation treatment having the lowest test weight across all study years. As depicted in Figure 6C, the combined three-year data show a strong negative linear relationship between season CWSI and malt barley seed test weight, with a coefficient of determination of 0.60.

4. Discussion

Decreased irrigation amount resulted in greater seasonal soil water extraction up to the limit of malt barley's capability. The seasonal soil water extraction of the 75% FIT treatment was significantly greater than the FIT treatment in two out of three study years (Table 1). However, the seasonal soil water extraction of the 50% FIT, 25% FIT, and no irrigation treatments was not significantly different in any study year. This is because only 55 to 70% of available soil water was present in the root zone at emergence. This limited the crop's ability to extract much additional water from the soil profile for irrigation deficits greater than 50% of ET_c. Greater soil water availability at crop emergence would have allowed the crop to extract more water from the root zone in the deficit irrigation treatments.

As the amount of irrigation water applied decreased, the season average fASW also decreased. Lower seasonal average fASW values indicate greater severity and duration of crop water stress, with no values below 0.3 in any study year. The season average fASW differed significantly between the FIT and 75% FIT irrigation treatments in two out of the three study years. However, the season average fASW for the 50% FIT, 25% FIT, and no irrigation treatments were not significantly different in 2021 and 2022. Additionally, the 25% FIT and no irrigation treatments had similar season average fASW each year, suggesting equivalent water stress severity and duration.

As the amount of irrigation water applied decreased, the season CWSI increased (Table 1). There were no significant differences in season CWSI between the FIT and 75% FIT irrigation treatments in any study year, despite significant differences in season fASW in 2021 and 2022. This is due to the nonlinear relationship between daily mean CWSI and fASW (Figure 4), where daily CWSI remains near zero until fASW decreases to a critical level, resulting in crop water stress. In contrast, there were significant differences in season CWSI between the 50% FIT, 25% FIT, and no irrigation treatments in 2021 and 2022, despite no significant differences in season average fASW. This indicates that season CWSI is a better indicator of the severity and duration of crop water stress than fASW alone. Furthermore, season CWSI was well correlated with relative malt barley yield (Figure 5B), seed protein (Figure 6A), percent plump kernels (Figure 6B), and seed test weight (Figure 6C), suggesting that season CWSI is a good predictor of the effects of water stress on malt barley yield and quality.

As the amount of irrigation water applied decreased, ET_c also decreased (Table 1). Significant differences in ET_c were observed between each irrigation treatment across all study years. Although ET_c differed significantly between the FIT and 75% FIT irrigation treatments in all years, there were no significant differences in seasonal CWSI or malt barley yield and seed protein in two out of three study years. This suggests that modest reductions in ET_c due to water stress may not adversely impact malt barley yield or seed protein when sufficient soil moisture is available.

Reducing irrigation amounts adversely affected malt barley yield and quality parameters. Specifically, decreasing irrigation and associated reductions in evapotranspiration led to lower barley yields, consistent with findings from previous studies [2,4,8,32–34]. While water stress can increase barley seed protein [2,7], mild deficits can maintain protein below malt quality requirements [4,35]. In this study, the 75% irrigation treatment kept protein levels below the 130 g/kg malt barley target across all years. However, unpredictable climatic conditions could still raise protein beyond acceptable limits under deficit irrigation. Nonetheless, reductions of 25% or less showed potential, as yield losses were small and protein remained below thresholds, as also observed in a prior regional study [2]. Developing cultivars with less negative response to water stress could further improve the feasibility of deficit irrigation for malt barley production.

Daily CWSI Threshold for Irrigation Scheduling

The relationship between daily CWSI and fASW shown in Figure 4 indicates that a fASW of 0.45 (55% depletion) corresponds to a daily CWSI of approximately 0.2. This suggests that a daily CWSI threshold of 0.2 would be comparable to an irrigation threshold of 55% soil water depletion, which is needed to avoid yield reduction. A daily CWSI of 0.2 as an irrigation threshold would result in a season CWSI of less than 0.2, as the daily CWSI would cycle between 0 and 0.2 over time. However, in the study years 2022 and 2023, a season CWSI of 0.13 resulted in significant malt barley yield reductions, as well as increases in seed protein and decreases in percent plump kernels that exceeded malt barley targets (Table 1). This indicates that while a *f*ASW of 0.45 (55% depletion) corresponds to a daily CWSI of approximately 0.2, a season CWSI of 0.1 was still detrimental to malt barley production. The actual season CWSI value would depend on how rapidly the CWSI increases after an irrigation event, which can be influenced by the amount of water applied. Additional research is needed to determine a CWSI threshold for irrigation scheduling that would not result in malt barley seed protein and percent plump kernels exceeding targets.

While current irrigated malt-barley germplasm should be approached with caution for deficit irrigation, genetic variation exists in barley response to drought. Breeding for high-yield and low protein response alongside irrigation stress may be necessary to develop cultivars capable of retaining desirable traits under water-stressed conditions. Furthermore, animal feed and human food barley do not have the strict limitations on protein and plumps that malt barley producers face, which could lead to an easier path of implementation of CWSI-based deficit irrigation scheduling for these alternative barley uses.

5. Conclusions

Malt barley canopy temperature response was measured across five irrigation treatments in a three-year field study. A neural network model predicted the lower reference temperature with a high degree of accuracy, exhibiting a linear coefficient of determination of 0.99 with the measured FIT canopy temperatures and low RMSE (0.89 °C) and MAE (0.70 °C).

The CWSI was calculated for malt barley at 15 min intervals between 13:00 and 15:00 MDT from early June through mid-July. A daily CWSI value was then computed as the average of these 15 min CWSI measurements taken during that 2 h window. To calculate the season CWSI, the daily CWSI values were averaged from early June through mid-July, excluding any days when the canopy was wet from irrigation or rainfall, as well as days with solar radiation less than 200 w m^{-2}. This season CWSI was found to be well correlated with several malt barley parameters: evapotranspiration (ET_c), seed yield, seed protein, percentage of plump seed kernels, and seed test weight. As the season CWSI increased, malt barley's relative ET_c, relative seed yield, and seed test weight decreased linearly. Conversely, malt barley seed protein increased linearly with higher season CWSI. Malt barley percentage of plump kernels decreased in a nonlinear, sigmoid function pattern as the season CWSI increased.

The relationship between daily CWSI and *f*ASW was well represented by a two-parameter exponential decay function, with a coefficient of determination of 0.76. This indicates that an allowable soil water depletion of 0.55 corresponds to a daily CWSI of approximately 0.2. This suggests that irrigation scheduling based on a daily CWSI threshold of 0.2 could be an effective water management strategy. However, increasing the season CWSI would adversely affect malt barley yield components. These adverse effects are less problematic for feed and food barley, where acceptance criteria are less strict, so water reductions have less impact on desired end-use quality. Further field research is needed to evaluate the feasibility of using a daily CWSI threshold for irrigation scheduling of malt barley.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14122897/s1, MS Excel Spreadsheet S1: Barley CWSI Calculator.

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