



Impact of Nitrogen and Water on Barley Grain Yield and Malting Quality

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Abstract

Barley is among the most important crops in northern latitudes especially for malting and distilling. Inter-annual weather variability in terms of rainfall and temperature patterns can impact crop uptake of soil water and nitrogen, which influences the crop growth and development. The present study shows the effects of nitrogen and water applied on: (i) specific grain quality traits necessary for distilling; (ii) plant biomass, nitrogen, and yield; and (iii) farmer's marginal net return. The experiment was conducted during the growing seasons of 2018 and 2019 at the James Hutton Institute (UK) with two nitrogen fertilizers and two irrigation levels. During the growing season soil mineral nitrogen and soil water content and plant biomass and nitrogen were measured. At harvest yield, yield component, and grain quality traits were determined. 2018 was a very dry growing season, as opposed to the wetter 2019 respect to the long-term growing season rainfall (1974–2017). Grain yield in 2018 was higher for the irrigated treatment, but in 2019 the irrigation, due to high rainfall, had lower yield. Environmental conditions impacted grain quality, and the patterns of soil water and mineral N affecting the final quality traits. Despite variable weather conditions the grain quality requirements from the industry of either beer or whisky are met.

Keywords Cereal · Grain Quality · Rainfall · Drought

1 Introduction

Barley (*Hordeum vulgare* L.) is among the oldest cultivated crops and it is grown from areas close to the equator up to the arctic circle, in both high and low input cropping systems (Newton et al. 2011; Dawson et al. 2015). Barley is mainly used as livestock feed and human food or for alcohol

production like beer and whisky (Cammarano et al. 2021). In northern latitudes, both winter- and spring-sown barley are cultivated; and in countries like Scotland, where the malting industry is one of the most economically important, barley is mostly spring-sown. This is because it is used for whisky production as it meets the quality standard requirements for distilling. This means that spring-sown barley represents an important economic crop for the Scottish economy (O'Connor 2018) and, it also means that farmers need to produce enough yield but with the right quality requirements.

In fact, production for malting (e.g., for whisky or beer) is challenging because the aim should be to keep the farm a profitable enterprise but at the same time provide the right amount of grain nitrogen (N)% required by the distilling industry. Usually, a premium is paid to farmers if their barley grain N% ranges between 1.45 and 1.85% (UK Malt 2021). The specific grain N content for malting barley differs according to the exact end use. For example, most whisky malt requires low protein barley because the lower N% the more starch is present. On the other hand, brewers use malt made from a wide range of grain N% levels (e.g., from 1.44

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to 1.90%) depending on the type of beer being brewed, and the brewing equipment, and a higher protein content of the grain reduces friability (Gianinetti et al. 2005, 2013).

This is a relevant aspect for farmers because higher grain N% is the most frequent reason for rejecting barley for malting quality (UK Malt 2021). The optimization of such tradeoff (yield vs. quality) is obtained by farmers by changing agronomic management such as sowing date, fertilizer rate, and plant density. For example, in Scotland spring-sown barley could potentially be sown at earlier times (e.g., March) which will increase growing season length; but frost can cause poor soil conditions for tillage and seedling emergence. In fact, mid-April is the usual sowing date for spring barley, or it is delayed if some exceptional weather event does not allow sowing. The N fertilization optimal amount is, to some extent, harder to achieve on spring-sown barley because its rate impacts the grain N concentration. Experimental evidence in such environments show that N fertilization amount rate has larger effect on grain N% than timing (Jesse et al. 2018). However, some findings indicate that agronomic management like cultivar choice and seeding rate interact with environmental conditions (rainfall and temperature) to have a greater impact on grain quality respect to the N fertilization rates and fertilizer type (McTaggart and Smith 1995; Sainju et al. 2013).

Another issue to consider in terms of optimal N response is the weather/climate variability. Despite being famous for being a high rainfall country, the eastern regions (where most of the barley is cultivated) of Scotland have average annual rainfall of about 700 mm and are subject to some dry spells and high spatial and inter-annual variability (Cammarano et al. 2016). For example, long-term growing season rainfall (defined as the period between April and September) is highly variable with 215 mm at one site (Cammarano et al. 2019) compared to 396 mm at another field site only 30 km away (Cammarano et al. 2021). Cammarano et al. (2019) showed that environment monthly rainfall shifts effect both barley yield and quality production and, that the long-term rainfall record showed has decreased by 20 mm in May over the last two decades with respect to the long-term (40 year) average. Under such environmental conditions the current warming trends and the projected temperature changes indicate a potential benefit for the expansion of

barley production for malting industry. However, the spatial patterns of rainfall might affect the production, and prolonged dry spells early in the growing seasons (e.g., May) will limit the benefits of the warming trends (Martin et al. 2017; Werritty 2002). Triboi and Triboi-Blondel (2002) concluded that the combination of the timing of the drought was an important parameter determining grain N% values.

Even in such environments trade-offs between N or water is not desirable and an understanding on how crop growth, grain yield and quality traits vary with different levels of water and N are needed to avoid negative environmental and economic impacts. Previous research has used crop growth modelling to optimize N management and its tradeoffs (Giménez et al. 2016; Basso et al. 2012; Cammarano et al. 2020, 2021). An economic perspective of trade-offs between quality and N can help explain the response of farmers to decisions on N management (Pannell 2017).

In light of projected changes in climate patterns and variability, there is a need for improving the understanding on how soil-plant-weather impacts nitrogen uptake, grain yield and quality, and the economic feasibility. Our hypothesis states that also at northern latitude, where staple crops are grown in rainfed environment without drought stress, the interaction between nitrogen and irrigation can have impacts on grain yield and quality. Hence, the objectives of this study were to evaluate the effectiveness of nitrogen and irrigation water applied on: (i) specific grain quality traits necessary for distilling; (ii) plant biomass, nitrogen, and yield; and (iii) farmer's financial marginal net return.

2 Materials and Methods

2.1 Experimental Site

The experiment was done at the James Hutton Institute (Invergowrie, U.K., 56°27' N 03°04' W, 27 m a.s.l.) on a Brown Forest Soil – Carpow Association of loamy texture (Bell and Hipkin 1988). The average soil organic matter up to 60 cm was 1.9%, and the average silt, clay and sand content was 44.5, 14.4, and 41.1%, respectively (Table 1). Daily weather data were obtained from an in-situ weather station for the period 1974–2019 for daily solar radiation

Table 1 Basic Soil Physical and Chemical Properties at six depth intervals (0–60 cm) prior to the beginning of the experiment in May 2018

Depth (cm)	Silt (%)	Clay (%)	Sand (%)	Bulk Density (g cm ⁻³)	Organic Matter (%)	Nitrate-N (mg kg ⁻¹)	Ammonium-N (mg kg ⁻¹)	Mineral N (mg kg ⁻¹)
0–10	40.13	12.85	47.02	1.39	2.5	13.6	2.2	15.8
10–20	41.02	12.74	46.24	1.57	2.6	17.6	2.1	19.7
20–30	42.04	13.15	44.81	1.55	2.5	22.0	2.2	24.2
30–40	44.12	14.96	40.92	1.65	1.7	10.6	2.1	12.7
40–50	55.59	17.73	26.68	1.95	1.2	9.1	2.0	11.1
50–60	44.32	14.95	40.73	1.70	1.1	9.3	1.8	11.1

(MJ m⁻² d⁻¹), rainfall (mm), maximum and minimum air temperatures (°C), as reported in Fig. 1a-d. The long-term growing season rainfall (Apr-Sep) was 290 mm, while in 2018 was 195 mm, and in 2019 was 379 mm (Fig. 1a). The growing season maximum temperature was 16.3, 19.0, and 17.0 °C for 1974–2019, 2018, and 2019, respectively. While the growing season minimum temperature was 8.2 °C for 1974–2019, 8.6 °C for the growing season 2018, and 8.7 °C for the growing season 2019 (Fig. 1c, d).

2.2 Agronomic Management

The spring barley cultivar “*Concerto*” was planted on 4 May 2018 and 15 Apr 2019 at 360 seeds m⁻² on a 12.2 by 12 m plots for both growing seasons in the same experimental field. The cultivar *Concerto* was the first ever non-glycosidic-nitrile producer variety and has become the “*benchmark variety*” for the malting and distilling industry (<https://www.limagrain-europe.com/en/barley>). The cultivar is a two-row barley, released in 2009 and adapted to medium to heavy soils. Spring-sown barley in 2018 was

followed by fallow and then another spring-sown barley in 2019. The crop was managed in a way to avoid pest and diseases. The experimental design (completely randomized) was kept the same for both years and consisted of 2 levels of nitrogen fertilization (N) and two irrigation levels. Each treatment was replicated 3 times.

The two N fertilizer levels were unfertilized (0 N) and 120 kg N ha⁻¹ (+N). The N fertilizer was applied at emergence, following a common practice in Scotland to apply fertilizer either at sowing or up to emergence for malting barley.

The irrigation levels were no irrigation (+RF) and irrigation (+IRR); the irrigation was done with sprinklers to provide water for 3 days a week (Monday, Wednesday and Friday) for a total of 45 min per day with a coverage of 5 mm of water per h⁻¹.

Hence, the experiment consisted of 3 replicates of 2 levels of N and 2 levels of water irrigation combined in the following 4 treatments: N-Fertilization and Irrigation (+N-IRR); N-Fertilization and no Irrigation (+N-RF); no

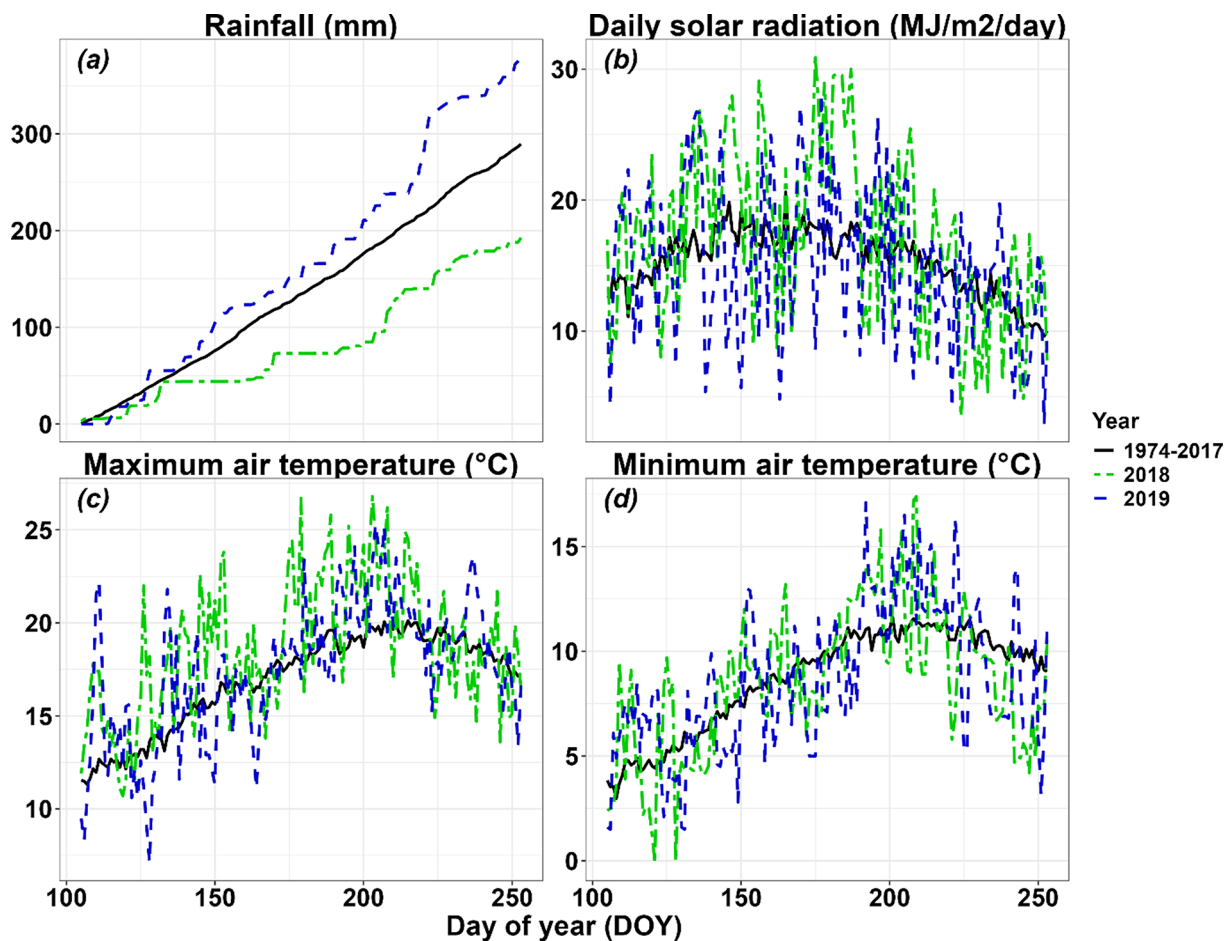


Fig. 1 Daily weather data for growing season (average sowing date to average harvest date) for: *a*) cumulative rainfall; *b*) daily solar radiation; *c*) minimum air temperature; and *d*) maximum air temperature at

the experimental site at Invergowrie, U.K. for the growing season 2018 (green dash-dot line); 2019 (blue dashed line); and as a 1974–2017 average (full black line)

Fertilization and Irrigation (0 N-IRR); no Fertilization and no Irrigation (0 N-RF).

2.3 Recorded Data

The experiment was sampled one day prior to sowing (3 May 2018 and 14 April 2019) for soil water content and soil mineral N. In 2018 the soil was also sampled on the 3rd of May for soil texture, bulk density and organic carbon (Table 1). The samples were analyzed by Yara Analytical Service for soil texture, organic matter and mineral N. Gravimetric soil water content (g g^{-1}) was done by weighing 40 g of soil samples and oven-dried at 105 °C for 48 h according to McKenzie et al. (2002). Volumetric soil water content was determined by multiplying gravimetric soil water content by the soil bulk density.

In addition, soil water content and soil mineral N were sampled at different crop growth stages during each growing season (7 Jun, 2 July, 17 August 2018, and 5 July, 10 September 2019). Each plot was sampled up to 60 cm at 10 cm intervals of depth.

On the dates reported above, and for both growing seasons, in each treatment three replications of plant samples were made for determination of aboveground biomass (kg DM ha^{-1}) and plant N%. Plant N% was determined at the Yara Analytical Service while aboveground biomass was determined by oven-drying plants at 65 °C until constant weight was reached and then weighted. After harvest (17 August 2018 and 10 September 2019) straw biomass was done in Dundee, while grain dry mass, grain protein, thousand grain weight (TGW), hot water extract (HWE), viscosity, caliber (percentage of grains > 2.5 mm, which is a measure of the grain size) and friability were determined

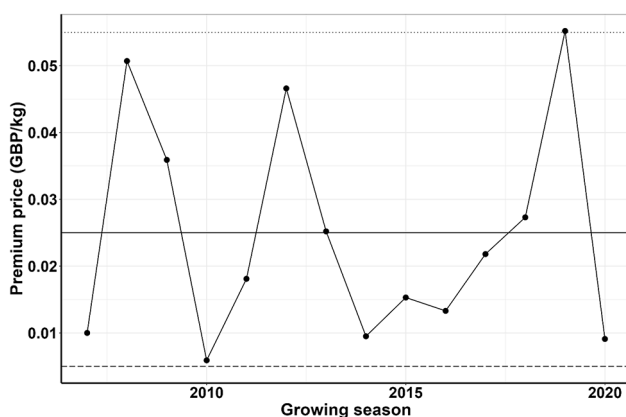


Fig. 2 Premium paid to farmers for malting quality barley during the period 2007–2020 in GBP kg^{-1} as reported by AHDB (2021). The dashed lower line represents the minimum level of premium considered in the marginal net return calculation ($0.005 \text{ GBP kg}^{-1}$), the solid horizontal line corresponds to the mean value ($0.025 \text{ GBP ha}^{-1}$) and the dotted upper line correspond to the maximum level of premium considered in the marginal net return calculation ($0.055 \text{ GBP ha}^{-1}$)

at the CREA-GB Laboratory (Fiorenzuola d'Arda, Italy). Barley was malted with an Automatic Micromalting System (Phoenix Biosystems, Adelaide, South Australia) and the methodology was described in details in Gianinetti et al. (2005). The grain protein content was converted in grain N% by dividing it by 6.25.

In terms of quality traits, Scottish farmers are paid a premium based on the grain N%. The quality parameters required by the industry varies for the different usages, for cask ale the grain N% should be between 1.45 and 1.55%; for distilling between 1.5 and 1.6%; and for export between 1.7 and 1.85% (UK Malt 2021). The observed grain yield (reported as dry weight), the N fertilization, and the grain N% were used to calculate the marginal net return (MNR) for each treatment for the two years. The price paid for barley yield was $0.157 \text{ GBP kg}^{-1}$, the cost of N fertilizer was 0.25 GBP kg^{-1} as an indicative cost in 2019 values (Redman 2019).

The premium price for malting barley grain was determined if grain N% was between 1.45 and 1.85% and then this was added in the calculation of the MNR (UK Malt 2021). The premium was considered in two different ways in the calculation. Firstly, the actual premium values paid for the year being considered (2018 and 2019) was 0.0273, and $0.0552 \text{ GBP kg}^{-1}$ for 2018 (Pr_{2018}) and 2019 (Pr_{2019}), respectively (AHDB 2021). Second, the historical premium paid to farmers was evaluated. There was a high variability between years and 14 years of premium price data were used to show yearly trends (Fig. 2). From the historical premium data, a minimum, an average, and a maximum premium price was chosen to reflect such inter-annual variability. The premium values were 0.005, 0.25, and $0.055 \text{ GBP kg}^{-1}$, for the minimum (Pr_{min}), mean (Pr_{av}), and maximum (Pr_{max}) levels, respectively. The MNR (Eq. 1) was then calculated as follow:

$$MNR = (Y_{i,j} * Price + Pr_k) - (N_{fert} * Cost) \quad (1)$$

where MNR is the Marginal Net Return, $Y_{i,j}$ is the observed yield for the treatment i , and the growing season j , Pr_k is the premium level based on the Pr_{2018} , Pr_{2019} , Pr_{min} , Pr_{av} , Pr_{max} as defined above, and N_{fert} is the N fertilizer applied to the experiments (120 kg N ha^{-1}).

2.4 Statistical Analysis

Given the available experimental material, the models for the data were considered as follows: for a three-factors (treatment, year and timing of sampling) with fixed effect of year and all factors as random for plant nitrogen and crop aboveground biomass parameters; while a two-factors

(treatment and year) with fixed effect of year and treatment as random for caliber, friability, hot water extract (HWE), grain N, thousand grain weight (TWG), viscosity and yield parameters. Normality of distribution and homogeneity of variance were verified using Levene test and Mauchly's sphericity test.

Analysis of Variance (ANOVA) was made using Genstat V (Payne et al. 1987) and Duncan's test for comparing pairs of means was performed.

All the Figures were done using the ggplot2 package in R environment (Wickham 2016).

3 Results

3.1 Agronomic and Quality Aspects

The observed volumetric soil water content results were reported in Fig. 3. The first sample for both growing seasons was taken before sowing and in both cases the soil water content values were similar for both growing seasons with average values of $0.30 \text{ m}^3 \text{ m}^{-3}$ across depths and growing seasons (Fig. 3). During the growing season 2018 the irrigated treatments had the greatest soil water content during the period Jun/Jul, which was particularly evident for the sampling made the Day of Year (DOY 158, corresponding to 7th of Jun 2018) when in the top 40 cm of soil there were an additional 0.5 to $0.15 \text{ m}^3 \text{ m}^{-3}$ of water respect to the rainfed treatments (Fig. 3). During the 2019 growing seasons the differences between the treatments were small and there were very similar patterns of soil water content observed.

The soil mineral N showed some distinct patterns for the growing seasons 2018 and 2019. One day before sowing, the values were 20 kg N ha^{-1} higher for the growing season 2019 in the first 20 cm of soil, at deeper soil profile the differences were less marked (Fig. 4). During the growing season 2018, the N treatments showed higher values at the second sampling point (DOY 158) and in the first 10 cm of soil where it was sampled 80 and 50 kg N ha^{-1} for the +N+IRR and +N+RF, respectively (Fig. 4). In the subsoil there was very little difference between treatments, except at 40–50 cm where the +N+RF had about 20 kg N ha^{-1} more N than the other treatments. In 2019 soil mineral N patterns and values were similar for all the treatments, except at the 40–50 cm where the 0 N+RF showed a peak of 50 kg N ha^{-1} while the other treatments reported 20 kg N ha^{-1} (Fig. 4). Overall, the initial (before sowing) and final (at harvest) soil mineral N content for both growing seasons showed similar values (Fig. 4).

The treatment effects for the crop aboveground biomass (dates reported in the methodology, plant N concentration (N%), grain yield, and quality parameters) are given

in Table 2. Overall, the year by the treatment interaction showed statistically significant effects ($P < 0.05$) for most of response variables measured (Table 2). Hot Water Extracts (HWE) did not show any statistically significant effects. For plant N% the interaction between year and timing (< 0.001) showed statistically significant difference of the effects. Aboveground biomass showed statistically significant differences that were reported for the timing (< 0.001), and the interactions between treatments and year (< 0.001). The caliber showed significant differences for the year (0.003), while friability for the interactions between treatments and years (< 0.001). Grain N% showed significant differences for the treatments (0.024), and for the year (0.001), and viscosity, thousand grain weight and grain yield showed significant difference for the interaction between treatment and year (0.013).

The values of plant N% and aboveground biomass at flowering (DC 65) (Zadoks et al. 1974) and at maturity (DC 90) for the growing seasons 2018 and 2019 and for all the four treatments is showed in Fig. 5a-d and Table S1. During the growing season 2018, the aboveground biomass at flowering (DC 65) was 3342, 3263, 1483, and 1402 kg DM ha^{-1} for the +N+IRR, +N+RF, 0 N+IRR, and 0 N+RF, respectively (Fig. 5a and Tab. S1). At harvest (DC 90) the +N+IRR had 5059 kg DM ha^{-1} while the other treatments were at 2500 kg DM ha^{-1} , except for the 0 N+RF which had 1800 kg DM ha^{-1} (Fig. 5a and Supplemental Table 1). The values of the aboveground biomass for the growing season 2019 were overall higher than 2018 and at flowering (DC 65) this was more evident for the 0 N treatments, independently of the irrigation levels (Fig. 5b and Supplemental Table 1). At maturity (DC90) the +N+IRR showed similar values among the two growing seasons, but the rest of the treatments had about 3000 kg DM ha^{-1} more biomass in 2019 than in 2018 (Fig. 5b). Plant N% showed marked differences for the growing season 2018 with respect to 2019. At flowering (DC 65) the values of plant N% were about 1.3% for the fertilized treatments (+N) and 1% for the non-fertilized ones (0 N), while for the 2019 growing season those values were slightly higher for the irrigated treatments (IRR) than the rainfed ones (RF) (Fig. 5c-d). At harvest (DC 90), the values of plant N% for the 2018 growing season were slightly lower for the fertilized treatments (0.54%) respect to the non-fertilized ones (0.63%); while in 2019 the values were not too dissimilar among treatments ranging between 0.72 and 0.89% (Fig. 5c-d).

The results of the grain yield, yield components, and grain quality are shown in Fig. 6a-g. Grain yield showed a distinct pattern for the drier growing season, 2018, with respect to the wetter one (2019). The +N+IRR in 2018 had the highest grain yield with 2529 kg DM ha^{-1} , while the lowest yield was reported for the 0 N+RF with 1042 kg

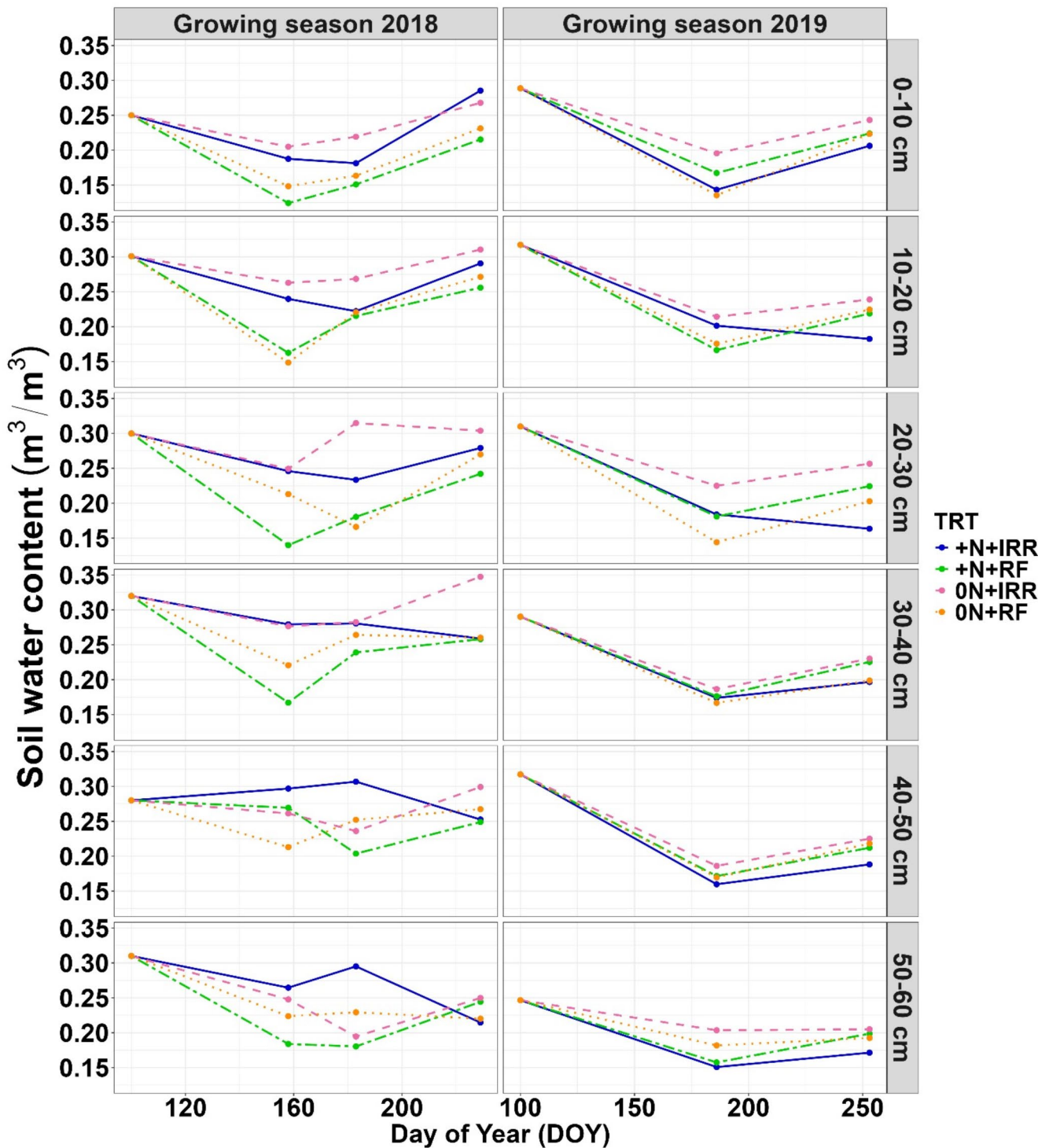


Fig. 3 Volumetric Soil water content ($\text{m}^3 \text{m}^{-3}$) measured from sowing to harvest at six depth intervals (0–60 cm) (each row of the Figure represents a soil depth) during the growing season 2018 (left-hand side) and 2019 (right-hand side) for the full irrigated and fertilized

(+N+IRR; full blue line); fertilized and non-irrigated (+N+RF; dash-dot green line); non fertilized and irrigated (0 N+IRR; dashed pink line); and non-fertilized and non-irrigated (0 N+RF; dotted orange line) treatments

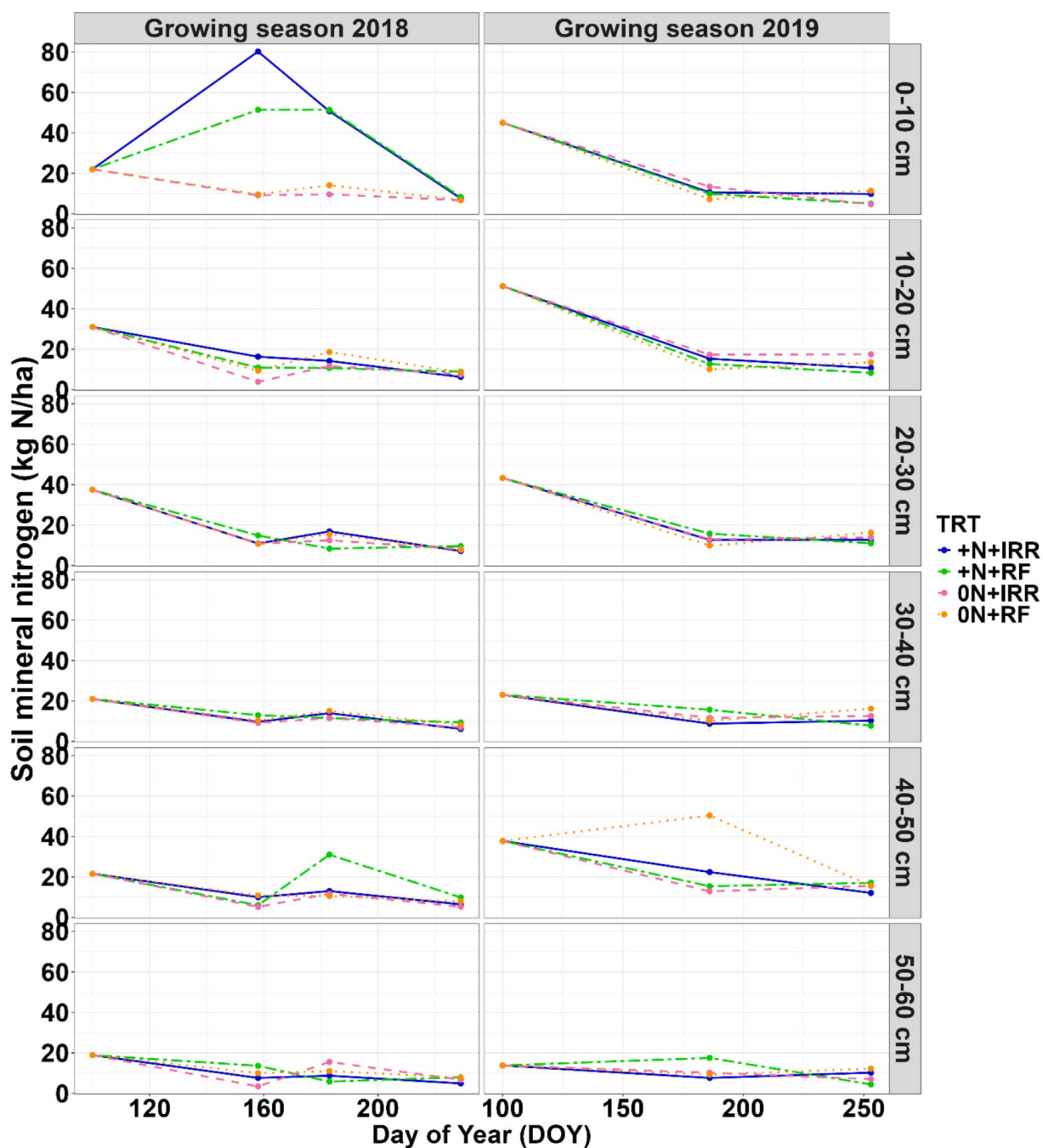


Fig. 4 Soil mineral nitrogen (kg N ha^{-1}) measured from sowing to harvest at 10 cm intervals up to 60 cm (each row of the Figure represents a soil depth) during the growing season 2018 (left-hand side) and 2019 (right-hand side) for the full irrigated and fertilized (+N+IRR; full

blue line); fertilized and non-irrigated (+N+RF; dash-dot green line); non fertilized and irrigated (0 N+IRR; dashed pink line); and non-fertilized and non-irrigated (0 N+RF; dotted orange line) treatments

DM ha^{-1} (Fig. 6a and Supp. Table 1). However, in 2019 the grain yield levels were overall higher with the lowest yield recorded for the +N+IRR with $2849 \text{ kg DM ha}^{-1}$ and the highest yield was recorded for the 0 N+RF with $3599 \text{ kg DM ha}^{-1}$ (Fig. 6a and Supp. Table 1). The TGW averaged 45 g in 2018 and 42 g in 2019, with the +N+IRR, +N+RF, and 0 N+RF having higher values

in the first growing season. But, for both growing seasons the 0 N+IRR showed the lowest TGW number with 41 g respect all the other treatments (Fig. 6b). The rainfed treatments showed 5% more grain N% respect to the irrigated, especially for the 0 N+RF, and in 2018 for the +N+RF (Fig. 6c). HWE and viscosity did not show any noticeable differences with only little variation among treatments and

Table 2 The Treatment effects for the Crop Aboveground Biomass, Plant N concentration (n%), Grain Yield, and Malting Quality parameters. Anova Test performed on each of the measured variable replicated in the Field. Significant results at $p < 0.05$ are bold and underlined for simplicity. The used is a three-factors randomized complete design with fixed effect of year and all factors as random for plant nitrogen and crop aboveground biomass; while a two-factors with a randomized complete design with fixed effect of year and treatment as random for caliber, friability, hot water extract (hwe), grain n, thousand grain weight (twg), viscosity and yield. ^atrt: treatment (fertilized and irrigated (+n+irr); fertilized and non-irrigated (+n+rf); non fertilized and irrigated (0n+irr); and non-fertilized and non-irrigated (0n+rf)); ^adegrees of freedom; ^bprobability; gs: sampling at two growth stages, flowering and maturity; year: 2018 and 201

Variable	Source of variation	DF ^a	Fpr ^c
Plant Nitrogen	+TRT	3	0.313
	Year	1	0.143
	<u>GS</u>	1	<0.001
	TRT*Year	3	0.78
	TRT*GS	3	0.349
	<u>Year*GS</u>	1	<0.001
	TRT*Year*GS	3	0.188
	Residual	32	
	Total	47	
	Crop aboveground biomass	TRT	3
<u>Year</u>		1	<0.001
<u>GS</u>		1	<0.001
<u>TRT*Year</u>		3	<0.001
TRT*GS		3	0.084
Year*GS		1	0.182
TRT*Year*GS		3	0.360
Residual		32	
Total		47	
Caliber		TRT	3
	<u>Year</u>	1	0.003
	TRT*Year	3	0.328
	Residual	16	
	Total	23	
Friability	<u>TRT</u>	3	<0.001
	Year	1	0.148
	<u>TRT*Year</u>	3	<0.001
	Residual	16	
	Total	23	
HWE	TRT	3	0.148
	Year	1	0.12
	TRT*Year	3	0.226
	Residual	16	
	Total	23	
Grain N	<u>TRT</u>	3	0.024
	<u>Year</u>	1	0.001
	TRT*Year	3	0.099
	Residual	16	
	Total	23	
TGW	<u>TRT</u>	3	<0.001
	<u>Year</u>	1	<0.001
	<u>TRT*Year</u>	3	0.023
	Residual	16	
	Total	23	

Table 2 (continued)

Variable	Source of variation	DF ^a	Fpr ^c
Viscosity	TRT	3	0.754
	<u>Year</u>	1	0.013
	<u>TRT*Year</u>	3	0.013
	Residual	16	
	Total	23	
Yield	TRT	3	0.136
	<u>Year</u>	1	<0.001
	<u>TRT*Year</u>	3	><0.001
	Residual	16	
	Total	23	

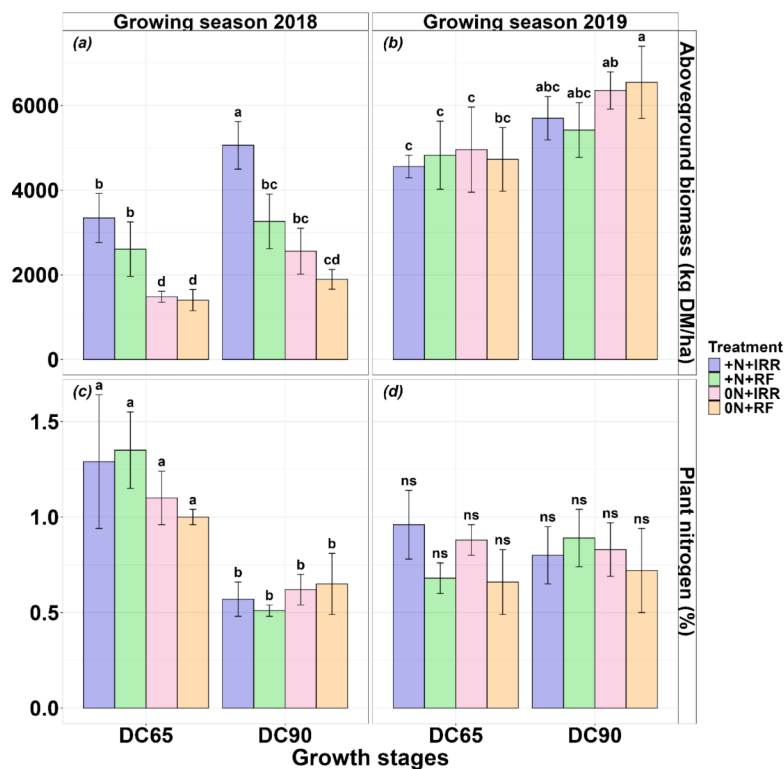
years, while the caliber was slightly more variable during the wetter growing season of 2019 respect to the 2018, especially for the 0 N + RF (Fig. 6d, e,g). The Friability was low for the +N + RF in 2018 with 80%, while the other treatments showed values of 90%, but in 2019 all the treatments showed values of about 87% (Fig. 6f).

The relationship between grain N% and the water supply (rainfall plus irrigation) showed the general patterns of decreasing grain N% at increased water supply. Grain N% decreased from 1.65 to 1.45% as water supply increased from 140.5 to 631.1 mm (Fig. 7). In both growing seasons there was a decrease in grain N between the +RF and the +IRR treatments. but there was a difference in terms of N response with the fertilization effects showing an increase of grain N% in 2018 and a decrease in 2019 (Fig. 7).

3.2 Economic Aspects

The patterns of the different levels of MNR, calculated using the premium for 2018 and 2019 (MNR), using the long-term average premium values (MNRav), long-term maximum premium values (MNRmax) and minimum premium values (MNRmin) for the different treatments and years are shown in Fig. 8 and Supplemental Fig. 1. Overall, a common pattern is observed showing the MNR to decrease for the 2018 growing season and for the MNR to increase for the 2019 growing season. The +N + IRR for both growing season showed similar levels of MNR which was the greatest MNR at any premium level for the 2018 and the smallest in 2019, with values ranging from about 380 GBP ha⁻¹ for MNRmin to 506 GBP ha⁻¹ for MNRmax, decreasing for the 0 N + RF with values ranging between 159 and 191 GBP ha⁻¹ for the MNRmin and Max in 2018, respectively (Fig. 8). The situation is opposite in 2019 when the lowest MNRs are obtained with the +N + IRR treatments and the highest values with the 0 N + RF treatments. It is worth noticing that the +N + RF treatments obtained MNR values that were constant for both growing seasons, with values ranging from 204 GBP ha⁻¹ to 260 GBP ha⁻¹ for MNmin to MNmax, respectively (Fig. 8). Using the matching premium

Fig. 5 Aboveground biomass (kg DM ha^{-1}) (*a, b*) and plant nitrogen (%) concentration (*c, d*) for the growing season 2018 (*a, c*) and 2019 (*b, d*) collected at two different Zadok's growth stages (DC65: Flowering; and DC90: maturity) for the full irrigated and fertilized (+N+IRR; blue bar); fertilized and non-irrigated (+N+RF; green bar); non fertilized and irrigated (0 N+IRR; pink bar); and non-fertilized and non-irrigated (0 N+RF; orange bar) treatments. The error bars represent the standard deviation of the measurements ($n=3$). The letters represent the statistical significance for the growth stage and treatment (for one full panel); the statistical significance is also shown in Table 2



values for the growing seasons (e.g. in 2018 the premium paid for the 2018) the +N+RF had similar MNR with 235 GBP ha^{-1} , while the MNR for the 0 N+RF increased from 162 GBP ha^{-1} in 2018 to 351 GBP ha^{-1} in 2019 (Fig. 8).

4 Discussions

In light of projected changes in climate patterns and variability, there is a need for improving the understanding on barley nitrogen uptake, grain yield and quality, and the economic feasibility. The interannual variability in rainfall patterns (Fig. 1a) and the different fertilization/irrigation combinations impacted on the grain quality and production (Fig. 6a, c) showing how at those higher latitudes the tactical choice of nitrogen fertilization and amount can be critical to optimize grain quality traits.

The rainfall patterns for the two growing seasons were very contrasting, with 95 mm less rainfall in 2018 and 89 mm more rainfall in 2019 with respect to the mean growing season (Apr-Sep) rainfall that was 290 mm (based on 1974–2019). Despite having only two growing seasons the fact that were contrasting respect to the long-term averages makes the experiment unique in this sense. Drier years (especially during late spring) are becoming common at such latitudes and can negatively affect crop responses (Cammarano et al. 2019). After Day of Year (DOY) 125, the rainfall occurred in the 2018 growing season (dry growing

season) was lower both compared to both the historical data (1974–2017) and the 2019 growing season. In addition, both the daily solar radiation and maximum air temperature were higher in the 2018 respect to the 2019 growing season. In both the growing seasons, all the treatments started with the same soil water content due to wet winters, but during the driest growing season (2018) the irrigated treatments (+IRR) had greater soil water content through the soil profile. This was evident during flowering and grain filling stages compared to the rainfed ones (Fig. 3). In 2018 the grain yield of +N-IRR treatment (2529 kg DM ha^{-1}) produced greater yield, while for the other treatments (0 N-IRR and +N-RF) there was no difference in yield. In contrast, the wetter growing season of 2019 did not show any treatment effect on yield (Fig. 6a). These results are well explained by the effects of N deficiency and availability on barley growth and development (Chapin et al. 1988). During the 2018 growing season treatments under water stress and fertilized did not uptake mineral soil N with consequent negative impact on photosynthesis and plant growth confirming the results of Garstang and Vaughan (1992) and Bardehji and coauthors (2021) on barley. On the other hand, the higher rainfall occurred during the 2019 growing season could have caused greater N leaching, and the treatments with additional irrigation and fertilization would definitely cause more N leaching. In fact, the yield response in 2019 shows lower yields for the fertilized respect to the non-fertilized treatments. It is interesting to note that the treatment

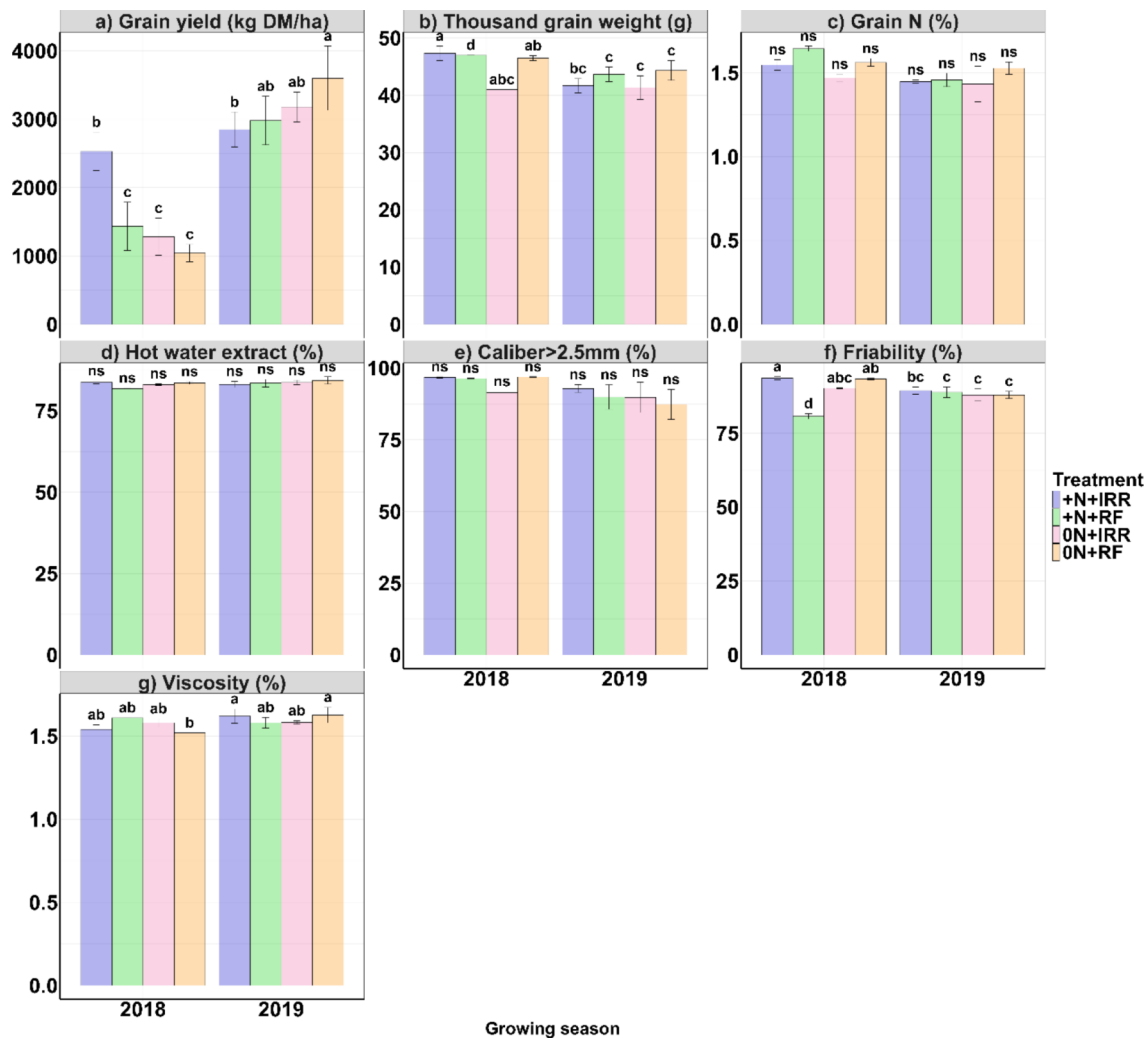


Fig. 6 Grain yield (kg DM/ ha) (a) and grain quality (b-g) parameters of spring barley for the growing season 2018 and 2019 for the full irrigated and fertilized (+N+IRR; blue bar); fertilized and non-irrigated (+N+RF; green bar); non fertilized and irrigated (0 N+IRR; pink

bar); and non-fertilized and non-irrigated (0 N+RF; orange bar) treatments. The letters represent the statistical significance for the growth stage and treatment (for one full panel); the statistical significance is also shown in Table 2

0 N-RF (which is non-fertilized and rainfed) had over the growing season higher soil mineral N in the 30–40 cm of the soil profile causing the treatment to produce higher yield and so more grain N than the +N-RF (Fig. 7).

The current N fertilizer applications by barley farmers in Scotland is about 120 and 160 kg N ha⁻¹, which guarantees that the N% for malting barley market requirements is satisfied (UK Malt 2021). It is well reported that the combination (and timing) of rainfall (e.g. drought effects) and temperature (e.g. in the terms of heat stress) affects grain N% (Triboi and Triboi-Blondel 2002). The drier growing season showed a very dry spell during the vegetative stage (-95 mm of rainfall respect to the long-term growing season rainfall (1974–2017) and N is applied around emergence when the soil water is still optimal because of the wet winter. Therefore, a 120 kg N ha⁻¹ applied followed by

a drier period caused plants to uptake the fertilizer N and then reduce the amount of soil water (e.g., left-hand side of Fig. 3) impacting the expansive growth processes during the period of spikelet/floret initiation.

Combinations of growing season rainfall distribution and the amount of mineral soil N and water impacts grain N% amount (Prystupa et al. 2018; de Ruiter and Brooking 1994). This study shows that grain N% differs (Table 1) between two years and these differences correspond with contrasting patterns of soil water and soil mineral N content.

The results of this study agree with the findings of another study in the same agro-environment in which it was found that monthly rainfall shifts significantly changed in the last decade, in particular during April-May period (Cammarano et al. 2019) affecting the barley yield and quality production as shown in this study. Despite Scotland is known to

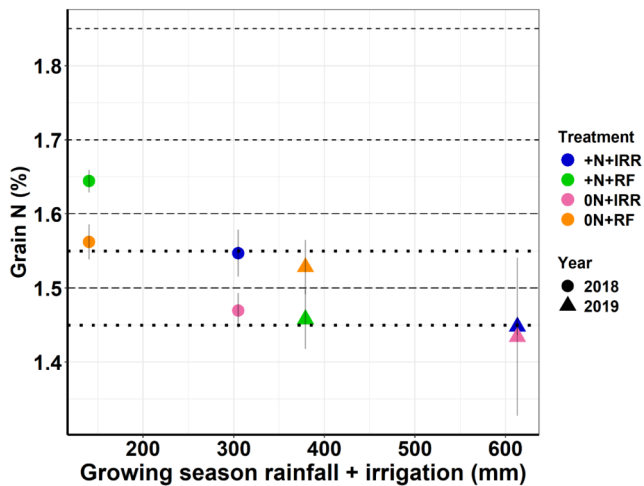


Fig. 7 Relationship between grain N (%) and growing season (sowing to harvest) rainfall for the treatments fertilized and irrigated (+N+IRR; blue symbols), fertilized and rainfed (+N+RF; green symbols), non-fertilized and irrigated (0 N+IRR; pink symbols), and non-fertilized and rainfed (0 N+RF; orange symbols) for the growing season 2018 (circles) and 2019 (triangles). The error bars represent the standard deviation of the measurements ($n=3$). In the irrigated treatments the amount of irrigation water was added to the total sum. The dotted lines (1.45 to 1.55 grain N%) represents the optimal grain N% for cask ale production, the long-dashed lines (1.5 to 1.6%) represents the optimal N% for distilling, and the dashed lines (1.7 to 1.85%) represents the optimal N% for export quality

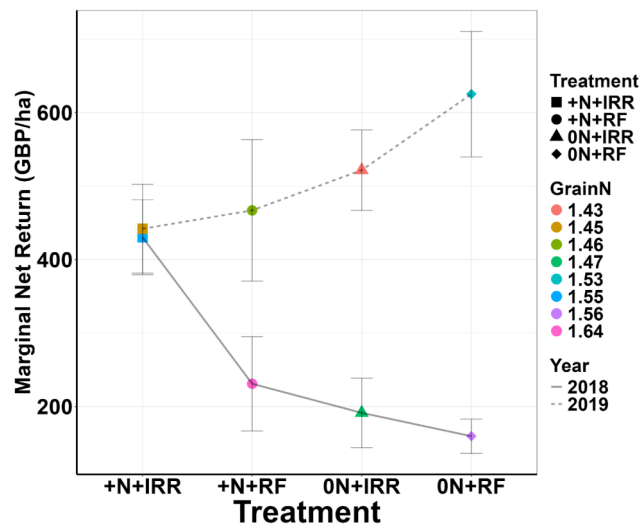


Fig. 8 Marginal net return (MNR) (GBP/ha) calculated for the treatments fertilized and irrigated (+N+IRR; squares) fertilized and rainfed (+N+RF; circles), non-fertilized and irrigated (0 N+IRR; triangles), and non-fertilized and rainfed (0 N+RF; diamonds) for the growing season 2018 (full line) and 2019 (dashed line). The color of the symbols is the grain N (%) content. The error bars represent the standard deviation of the measurements ($n=3$)

be a country with high rainfall, the spatial variability of its distribution can be high (Cammarano et al. 2016). The changes in temporal rainfall distribution, associated to the spatial variability means that it could be a limiting factor in future expansion of spring barley in Scotland while the current projected warming indicates a potential benefit to expand barley production for malting industry (Martin et al. 2017; Werritty 2002).

The calculation of the marginal net return is an important economic perspective that has helped explaining the response of farmers to decisions fertilizing (Pannell 2017). Gourevitch, Keeler, and Ricketts (2018) proposed the concept of socially optimal fertilization rates which are reduced rates that offer social benefits. In the current study we did not explore the effects of fertilization on N losses but rather on grain quality and net marginal return. The wrong fertilization management strategies will mean negative consequences for the environment (more N leaching) or the farmer (rejection according to malting barley quality criteria).

The specific grain N content for malting barley differs according to the exact end use. As stated in the introduction most whisky malt requires low protein barley because the lower N% the more starch is present. And, depending on the type of beer being brewed, and the brewing equipment, a higher protein content of the grain reduces friability (Gianinetti et al. 2005, 2013). So, if the barley produced in this study was used for beer production the requirements would be higher friability and lower grain N contents. Different malting quality traits are associated with quantitative trait loci (QTL) that have been identified in barley. Among these loci, QTL2 accounts for 37.6% of the variation for the malt extract (Han et al. 1997). In fact, the quality traits in terms of HWE and grain N content indicate that given the environmental and management conditions the barley produced is suitable for beer production and for distilling for both growing seasons irrespective of the treatment levels (Fig. 6c and d).

In addition, malt extract is a complex quantitative trait that is controlled by multiple genes (Iqbal et al. 2023). This information can explain the no effect of the investigated treatment as well as no year effect on the HWE.

Friability gives an indication related to the physically disintegration of the grain, allowing the separation of friable constituents from the hard ones and giving the degree of accessibility to enzymes (Gebeyaw 2021). Our results are in agreement with those of Gianinetti et al. (2013) showing that the treatment with higher protein content of the grain reduces friability.

Pardo et al. (2022) suggested that the minimum total weight% of grains with a caliber higher than 2.5 mm must be 90%, in our study this percentage was obtained for all investigated treatments and years apart of treatment

0 N + RF suggesting the important role of soil water content and N for caliber. Similar results were reported by Clarke and coauthors (2004) who studied the effect of the nitrogen fertilizer and irrigation on grain size of winter wheat.

Viscosity is a parameter related to the dissolution of polysaccharides and filtration speed of the malt wort, and a low viscosity value is an important indicator of high-quality malt (Fang et al. 2019). However, in the present study viscosity did not show any noticeable differences with only little variation among treatments and years.

Future work should include quantification of environmental losses in terms of N leaching and greenhouse gas emissions and longer time span in order to identify the tradeoffs between production, quality requirements, and mitigation strategies.

5 Conclusions

The environmental conditions for growing barley in a high rainfall region of north-western Europe can greatly impact grain quality traits. In addition, considering projected changes in climate patterns and variability, the present study provides evidence from Scotland with two growing seasons with contrasting rainfall and temperature patterns. These environmental factors impacted the crop use, of soil water and soil mineral N affecting the final yield as well as the grain quality traits. These results have implications both for farmers, distilleries and policymakers and there is a need to evaluate the quantity of N fertilization to achieve the grain quality requirements under climate change constraints. In view of this scenario crop modelling and digital agriculture are useful approaches to overcome these issues and hence a strong multidisciplinary approach will be required.

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Author Contributions DC, DR contributed to conception and design of the study. DC, DR organized the database and performed the statistical analysis. DC wrote the first draft of the manuscript. JH, AG, MB and DR wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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Data Availability The datasets generated during and/or analyzed during the current study are not publicly available due an agreement between partners but are available from the corresponding author on reasonable request.

Declarations

Conflict of Interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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