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RESEARCH ARTICLE

Nitrogen dose to maximize grain yield and quality of durum wheat depends on the water availability in Chilean Mediterranean environments

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ABSTRACT

Quality durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) van Slageren) has the highest performance in climates with dry and hot summers. Chilean durum wheat has a low protein content. This research was carried out in two growing seasons in two Chilean localities, under two water conditions. The aim was to analyze the impact of N rate and application timing over yield and quality of durum wheat grain in the Mediterranean climate of central Chile. The field experiment was carried out with two durum wheat genotypes. For each experiment, there were two N factors: three rate N applied in durum wheat vegetative phase (0, 90, 210 kg N ha^{-1}) and four rate N applied in the reproductive phase (0, 30, 60, 90 kg N ha^{-1}). Therefore, the treatments were 12 combinations of N. Grain yield, biomass, and harvest index were affected by N application in the vegetative phase only. Both quantity and distribution of rainfall was the environmental factor that triggered three types of grain yield response to N fertilization: Environments in which the yield responds positively to N applications, environments without yield response to N applications, and environments in which the yield responds negatively to N applications. In an environment which the yield responds positively to N applications, the highest mean grain yield was 6309 kg ha^{-1}, protein content reached 13% in the highest N applications. In an environment without yield response, grain yield, black point, and hectoliter weight did not change with N fertilization. In an environment in which the yield responds negatively to N applications, the lowest mean grain yield was 1960 kg ha^{-1}, protein content increased to 16%, and hectoliter weight decreased below 79 kg hL^{-1} with 90 kg N ha^{-1} rate or higher.

Key words: Black point, grain protein, hectoliter weight, nitrogen management, *Triticum turgidum* subsp. *durum*, yellowberry.

INTRODUCTION

Durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) van Slageren) is a key source of calories and nutrients for many regions of the world. Grain yield, nutritional value and end-use quality are the major target traits for durum wheat improvement (Saini et al., 2022). Grain quality characteristics are grain size, hectoliter weight, grain hardness, mottling, grain protein content and quality, pre-harvesting sprouting resistance, black point, pink stained grain, grain moisture and frost damage (Hare, 2017). According to international quality standards, Chilean durum wheat has a high quality: 85.0 kg hL^{-1} hectoliter weight, 7.3% yellowberry and 3.0% black point and low protein content (mean of 10.4%) (Acevedo and Silva, 2007).

Climate change has increased temperature in the last century and rainfall has decreased in recent years, during 2010-2018, Central Chile was affected by a mega drought (Aldunce et al., 2017). Moreover, it is projected that minimum and maximum temperatures in Chile will increase by 2 °C and precipitation will decrease over 40% by the end of the twenty-first century (Araya-Osses et al., 2020). The effects of environmental stresses have been poorly studied with respect to the nutritional and quality of durum wheat (Zingale et al., 2023).

Drought and low soil fertility are the most important limiting factors in grain yield and quality of durum wheat in Mediterranean climates (Boulelouah et al., 2022). Water supply is the principal limiting factor for grain yield (Chen et al., 2023). Wheat's most sensitive growth stages to water stress with respect to grain yield are stem elongation, booting and anthesis, the main component affected with water stress on that period is grain number (Blum and Pnuep, 1990). The main characteristic associated with grain quality in durum wheat is protein content (Kaplan Evlice, 2022). The highest protein content is associated with the highest N availability and lowest soil water availability during grain filling (Giunta et al., 2022). Nevertheless, in a water-limited environment, one study showed that increasing the N input levels promoted the early growth of biomass and consumed too much water early in the growing season resulting in decreasing yield (Chen et al., 2023).

There is scarce information available from Chile about the relative importance of rates and partition of N fertilization, genotype, environment, and interaction between these factors, to maximize grain yield and quality characteristics in durum wheat grown in Mediterranean areas. Adaptation management, such as optimizing N fertilization in terms of rate and time to maintain grain yield and quality, has the potential to lessen the negative effects of climate change and reduce the release of N into the environment (Zingale et al., 2023).

The current study shows the results of trials carried out in two Central Chilean sites: Santiago and Chillán. Both have a Mediterranean climate, but differ with respect to rainfall and soil type—variables that affect grain quality. Our aim was to analyze the impact of N rate and application timing over durum wheat grain yield and quality and analyze how the response is modified by environmental conditions in the Mediterranean climate of central Chile. The hypothesis was that N rates in the vegetative phase would increase grain yield, while N rates in the reproductive phase would improve durum grain quality.

MATERIALS AND METHODS

Environment's description

This study was conducted during two growing seasons (2006/2007 and 2007/2008) in Santiago (33°34′ S, 70°37′ W; 604 m a.s.l.) and Chillán (36°31′ S, 71°54′ W, 220 m a.s.l.) under two water conditions (rainfed and irrigated). Thus, the growing seasons × location × water conditions combination generated a total of eight environments. The climate in Santiago is semi-arid Mediterranean, with a mean maximum temperature of 28.7 °C, a mean minimum temperature of 3.4 °C, and mean annual rainfall of 330 mm (Uribe et al., 2012). The soil has alluvial origin (Mollisol) with a sandy clay loam textural classification and slight depth (CIREN, 1996). The climate in Chillán is humid Mediterranean, with a mean maximum temperature of 28.9 °C, mean minimum temperature of 5.2 °C, and mean annual rainfall of 1026 mm (Del Pozo et al., 2019). The soil in Chillán is originated from volcanic ash (Melanoxerands) with a silty loam soil classification (CIREN, 1999).

Treatments and experimental design

The field experiment was carried out with two durum wheat (*Triticum turgidum* L. subsp. *durum* (Desf.) van Slageren) genotypes 'Llareta INIA' and 'Corcolén INIA'. For each experiment, there were two N factors: Three N rates applied in the durum wheat vegetative phase (0, 90, 210 kg N ha^{-1}) applied as sodium nitrate (15% N) 1/3 at sowing and 2/3 in the first node stage, and four N rates applied in the reproductive phase (0, 30, 60, 90 kg N ha^{-1}) applied as sodium nitrate at boot stage.

The experimental design was a randomized complete block design with a split-plot structure. The main plot was N rates in the vegetative phase, and the sub-plot was N rates in the reproductive phase. The blocking factors were slope and soil depth. The experimental unity was a plot of 25 m^2 (5 m width × 5 m length), with four replicates.

Crop management

Table 1 describes the physical and chemical properties of the soil and phenological dates, such as sowing, heading, and physiological maturity. Information is available for every season and site. Wheat was sown at a seeding rate of 220 kg ha^{-1} using a conventional seed drill of 20 cm wide rows, leaving 395 seeds m^{-2}. Every experiment was fertilized with 120 kg P_2O_5 ha^{-1} at sowing through triple phosphate super fertilizer and 90 kg K_2O ha^{-1} at pre-sowing through potassium sulfate. Diseases, weeds, and pests were controlled to ensure good crop growth.

Table 1. Sowing date, physical and chemical characteristics of the soil in the evaluated environments. Env.: Environment; Irrig.: irrigation; FC: Field Capacity; PWP: permanent wilting point; OM: organic matter; Physiol.: physiological.

Env.	Locality	Year	Rain	Irrig.	Soil depth	FC	PWP	Soil bulk density	pH	OM	N	P	K	Sowing date	Heading date	Physiol. maturity date
			—mm—		cm	—%—		g cm^{-3}		%	—ppm—					
1	Santiago	2006	306	240	50	20.6	11.2	1.42	8.1	1.5	28	19	141	22 Jun	10 Oct	20 Nov
2	Santiago	2006	306	15	50	20.6	11.2	1.42	8.1	1.5	28	19	141	22 Jun	10 Oct	19 Nov
3	Chillán	2006	196	52	40	39.9	25.2	0.89	6.0	8.4	23	20	177	30 Aug	10 Nov	12 Dec
4	Chillán	2006	196	0	100	25.7	13.3	1.49	6.0	8.5	17	34	338	30 Aug	12 Nov	11 Dec
5	Santiago	2007	80	270	50	19.9	8.4	1.34	8.1	1.6	10	10	147	29 Jun	29 Oct	26 Nov
6	Santiago	2007	80	45	50	19.9	8.4	1.34	8.1	1.6	10	10	147	29 Jun	24 Oct	21 Nov
7	Chillán	2007	97	161	40	40.8	23.5	1.16	6.2	10.0	10	23	179	11 Sep	19 Nov	19 Dec
8	Chillán	2007	97	0	40	40.8	23.5	1.16	6.3	8.6	10	18	99	11 Sep	16 Nov	16 Dec

Measurements

Four central rows (1 m length) were harvested at physiological maturity. Fifty stems were weighed and dried at 70 °C for 48 h in an oven to obtain yield and yield components. The remaining material was harvested, weighed, and threshed in a stationary threshing machine. Biomass, grain yield, and harvest index were measured in the whole sample. The N content was determined using the Kjeldahl method. Protein percentage was calculated multiplying the result of Kjeldahl method by a factor of 5.7. Hectoliter weight was obtained by weighing grains in a volume of 100 L (kg hL^{-1}). The percentage of yellowberry and black point grains were evaluated in each sample using visual inspection of 200 grains randomly chosen. Meteorological data, such as rainfall, maximum and minimum temperature were obtained from the INIA La Platina Climatological Station, located 700 m from the trial in Santiago, and the INIA Quilamapu Climatological Station at the Chillán experimental site.

Statistical analysis

Data were analyzed using a mixed linear model. The first model used genotypes, and evaluated the environment effect, N treatments, genotypes, and their interactions. This analysis showed that the genotype and N treatments interaction was nonsignificant for any studied variable. Thus, a second analysis was done using the genotypes as replicates and separating N treatments into two factors (vegetative phase N rate and reproductive phase N rate). In the mixed linear model, fixed effects were the environment, vegetative phase N, reproductive phase N, and their interactions, while random effects were the environment, block (nested within the environment), and vegetative phase N (nested in the block).

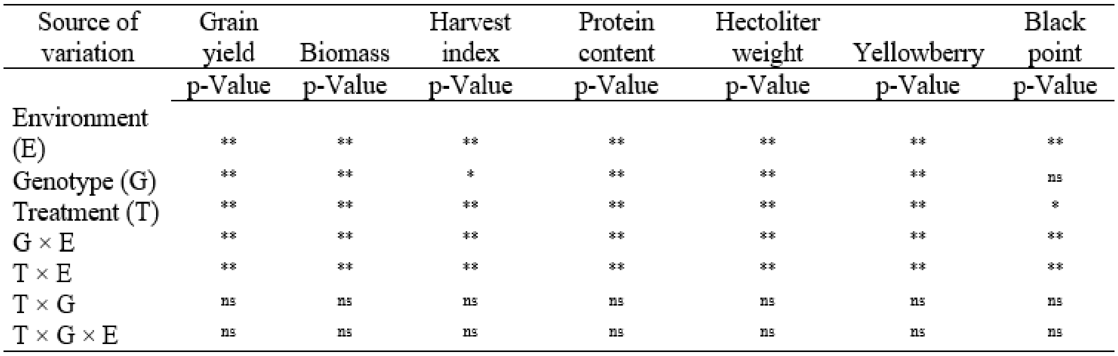
Multiple comparisons test DGC 5% ($\alpha = 0.05$) was used for the comparison of means. The DGC is a partition test method (no overlap of letters between means) recommended to compare five or more means (Di Rienzo et al., 2002).

RESULTS

The mixed linear model provided the significance of the different variation sources analyzed (treatment, genotype, environment, and their interactions) over grain yield, biomass, harvest index, protein content, hectoliter weight, yellowberry, and black point (Table 2). There was no Treatment × Genotype × Environment interaction for any variables. The Treatment × Environment interaction was significant ($p < 0.01$) for all variables. No Treatment × Genotype interaction was found, which allowed for the averaging of genotype information. This simplified the analysis and enabled the separation of N treatment into two factors in a new model.

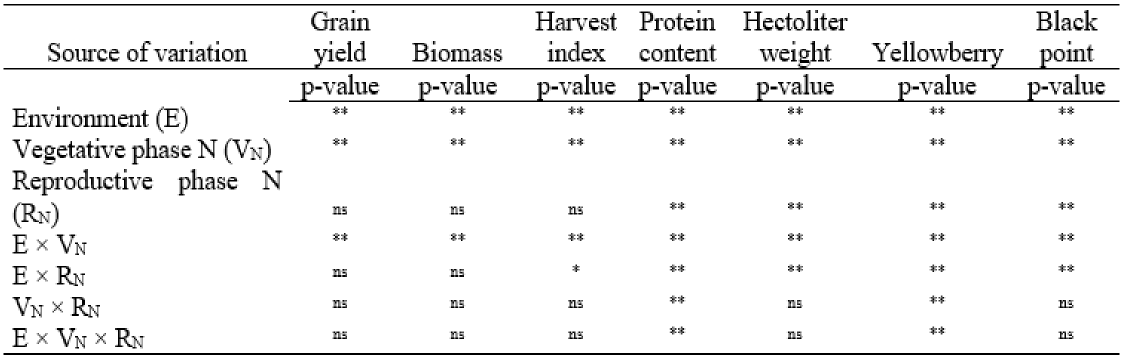
Table 3 summarizes the results of the second mixed linear model, including: environment, vegetative phase N, reproductive phase N, and their interactions over grain yield, biomass, harvest index, and quality variables. The Environment × Vegetative phase N × Reproductive phase N interaction was significant for protein content and yellowberry only. Vegetative phase N × Environment had a significant effect in all evaluated variables. Reproductive phase N × Environment was significant for harvest index (HI) and all quality variables.

Table 2. Variation source and significance for grain yield, biomass, harvest index, protein, hectoliter weight, yellowberry and black point, corresponding to two genotypes growing in eight environments with different N treatments. $^{*}P \leq 0.05$; $^{**}P \leq 0.01$; ^{ns}: nonsignificant.



Source of variation	Grain yield	Biomass	Harvest index	Protein content	Hectoliter weight	Yellowberry	Black point
	p-Value	p-Value	p-Value	p-Value	p-Value	p-Value	p-Value
Environment (E)	**	**	**	**	**	**	**
Genotype (G)	**	**	*	**	**	**	ns
Treatment (T)	**	**	**	**	**	**	*
G × E	**	**	**	**	**	**	**
T × E	**	**	**	**	**	**	**
T × G	ns	ns	ns	ns	ns	ns	ns
T × G × E	ns	ns	ns	ns	ns	ns	ns

Table 3. Variation source and significance for grain yield, biomass, harvest index, protein, hectoliter weight, yellowberry and black point, corresponding to two genotypes growing in eight environments with two factors of N fertilization (fertilization during the vegetative phase and fertilization during the reproductive phase). $^{*}P \leq 0.05$; $^{**}P \leq 0.01$; ^{ns}: nonsignificant.



Source of variation	Grain yield	Biomass	Harvest index	Protein content	Hectoliter weight	Yellowberry	Black point
	p-value	p-value	p-value	p-value	p-value	p-value	p-value
Environment (E)	**	**	**	**	**	**	**
Vegetative phase N (V_N)	**	**	**	**	**	**	**
Reproductive phase N (R_N)	ns	ns	ns	**	**	**	**
E × V_N	**	**	**	**	**	**	**
E × R_N	ns	ns	*	**	**	**	**
V_N × R_N	ns	ns	ns	**	ns	**	ns
E × V_N × R_N	ns	ns	ns	**	ns	**	ns

Response of grain yield to vegetative phase applied N in different environments

The effect of Environment × Vegetative phase N rate interaction over grain yield had three different responses (Figure 1). There was a positive response in which grain yield increased according to higher N fertilization in the crop vegetative phase (environments 1, 3, 4, and 7). A neutral response was obtained when there were no grain yield changes to increasing N rates during the crop vegetative phase (environments 2 and 8). The negative response implies that grain yield decreased with the higher N rates in the vegetative state (environments 5 and 6). Every response was considered as one mega-environment, which was related to environmental conditions, particularly water availability.

The analysis of grain yield, biomass, and HI in the three mega-environments showed different patterns (Table 4). The mega-environment that had a positive response to N application in the vegetative phase had higher values of grain yield, biomass, and HI. The mean grain yield increased from 3319 to 6309 kg ha^{-1}. Similarly, biomass and HI increased from 8786 to 15 525 kg ha^{-1} and 0.39 to 0.42, respectively. The mega-environment without response to N application in the vegetative phase had a mean grain yield of 2546 kg ha^{-1}, the biomass reached a maximum value (7675 kg ha^{-1}) with applications of 90 and 210 kg N ha^{-1} and the HI decreased only with a dosage of 210 kg N ha^{-1}. The mega-environment with a negative response showed a decrease in grain yield from 3174 to 1960 kg ha^{-1} with increasing applications of N during the crop vegetative phase. Nonetheless, the biomass increased (mean 12253 kg ha^{-1}) with applications of 90 and 210 kg N ha^{-1}. The HI declined from 0.28 to 0.14 with N fertilization.

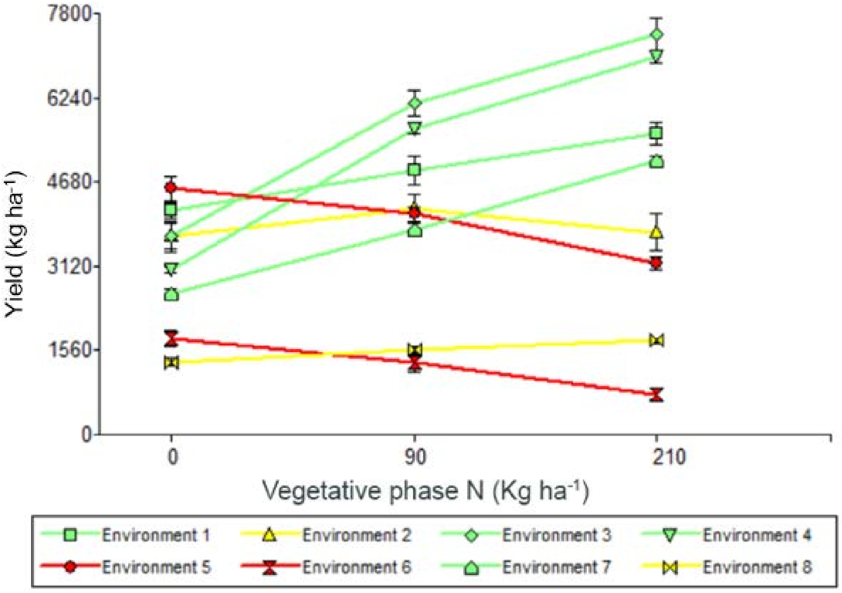


Figure 1. Effect of N rates applied during the vegetative phase on grain yield. Vertical bars correspond to standard error.

Table 4. The effect of N rates in the vegetative phase on grain yield, biomass, and harvest index, according to the three mega-environments. Means with common letter are nonsignificant according to DGC test ($p > 0.05$).

N rates	Grain yield	Biomass	Harvest index
kg N ha^{-1}	kg ha^{-1}	kg ha^{-1}	
Positive response			
0	3319^{c}	8786^{d}	0.39^{b}
90	5143^{b}	12808^{b}	0.41^{a}
210	6309^{a}	15526^{a}	0.42^{a}
Without response			
0	2340^{d}	6304^{e}	0.39^{b}
90	2699^{d}	7580^{d}	0.37^{b}
210	2600^{d}	7769^{d}	0.36^{c}
Negative response			
0	3174^{c}	10498^{c}	0.28^{d}
90	2704^{d}	12497^{b}	0.20^{e}
210	1960^{e}	12008^{b}	0.14^{f}

Influence of environmental parameters in grain yield expression

The environments had similar mean temperatures during grain filling (15.3-16.6 °C). The main differences were associated with the amount and distribution of rainfall during the spike active-growing phase and grain filling. Those factors explained the different grain yield responses to N fertilization during the vegetative phase.

The mega-environment with a positive response includes the environments irrigated in Santiago in 2006 (Figure 2a), irrigated and rainfed in Chillán in 2006 (Figure 2b), and irrigated in Chillán in 2007 (Figure 2d). The rainfed experiment in Chillán in 2006 was set in a deep soil profile (100 cm), and it was a rainy year (1434 mm) with 173 mm recorded during October, November, and December. Thus, it can be considered as a high-water availability mega-environment.

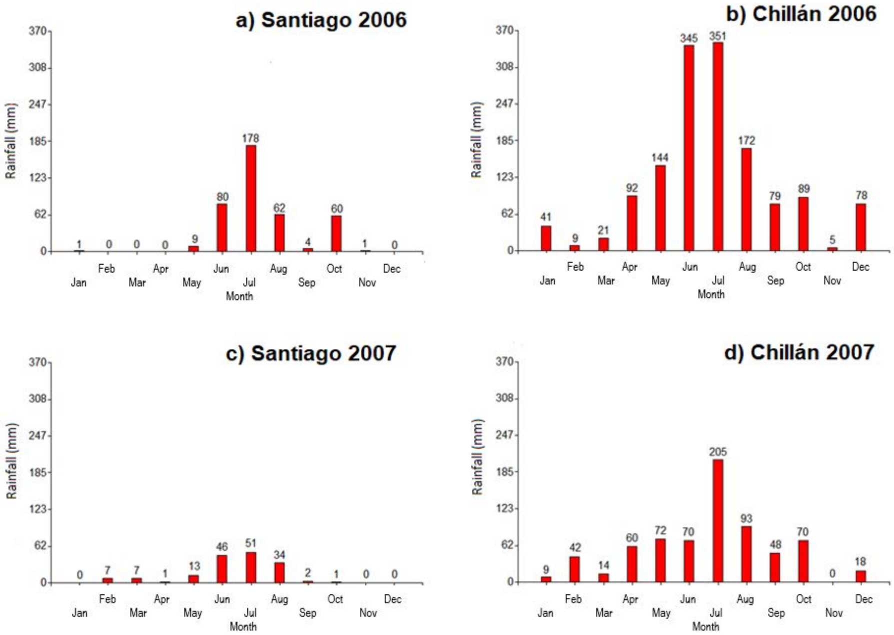


Figure 2. Distribution of annual rainfall in Santiago and Chillán: 2006 and 2007.

The mega-environment without grain yield response to increasing N fertilization during the vegetative phase contains the environments rainfed in Santiago in 2006 (Figure 2a) and Chillán in 2007 (Figure 2d). In Santiago, the rainfall during September and October was 64 mm. While the precipitation in Chillán during October and November was 70 mm. This mega-environment faced a slight drought, producing low grain yield and biomass.

The mega-environment with negative response included the environments irrigated and rainfed in Santiago in 2007 (Figure 2c). Rainfall was low during September and October; the spike active-growing phase received only 3 mm and there was no rainfall during the grain filling. Due to a failure in the irrigation system for the irrigated trial during September and October, the experiment faced a drought period from the spike active-growing phase until the beginning of grain filling, so this mega-environment was exposed to severe drought.

Grain quality response to N rates and partitioning

Protein content. In the mega-environment with severe stress, where grain yield responded negatively to N fertilization, protein content increased markedly with increasing applications of N made in both the vegetative and reproductive phases, achieving 12% protein only with 30 kg N ha^{-1} in the reproductive phase. The maximum protein content (16%) was obtained with the highest N rates (210 kg N ha^{-1} applied in vegetative phase and 90 kg ha^{-1} applied in reproductive phase). On the other hand, in those mega-environments with a positive and neutral response, grain protein content increased with increasing N rates, but at a lower magnitude, showing response to N application only in the reproductive phase and when the fertilization in the vegetative phase was low (0 and 90 kg N ha^{-1}). There were no detectable effects in the reproductive phase when applications in the vegetative phase were 210 kg N ha^{-1}. The maximum protein content was 13% applying rates equal to or higher than 180 kg N ha^{-1} independently of the N partition in both mega-environments (Figure 3).

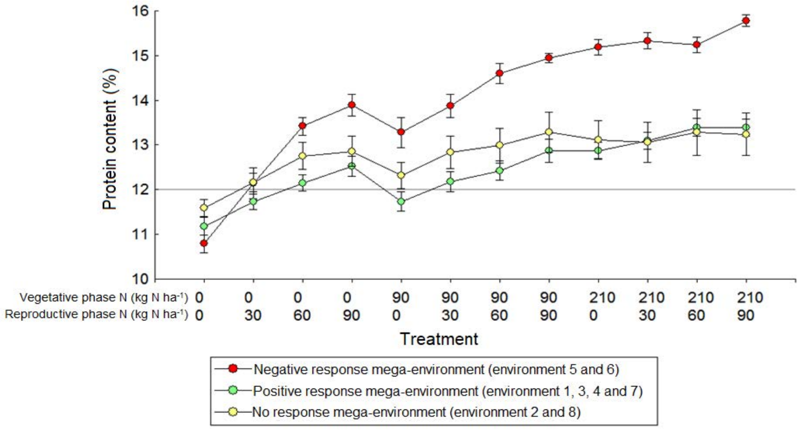


Figure 3. Effect of N treatments on protein content in three mega-environments. The 12% line represents the percentage above which the Chilean pasta industry gives a bonus on grain production. Bars represent the standard error of the mean.

Hectoliter weight. In the mega-environment with water availability, where grain yield responded positively to N application, hectoliter weight was high (mean value 84.1 kg hL^{-1}) independently of N treatment. In the mega-environment with slight stress, without N response, the hectoliter weight was 82.4 kg hL^{-1}, independent of N treatment. On the other hand, in the severe stress mega-environment, the hectoliter weight decreased from 82.5 to 68.0 kg hL^{-1} with N fertilization. Rates of 90 kg N ha^{-1} or higher resulted in values below 79 kg hL^{-1}, penalized by the Chilean pasta industry and rates of 210 kg N ha^{-1} or higher resulted in values below 71 kg hL^{-1}, the rejection limit by industry (Figure 4).

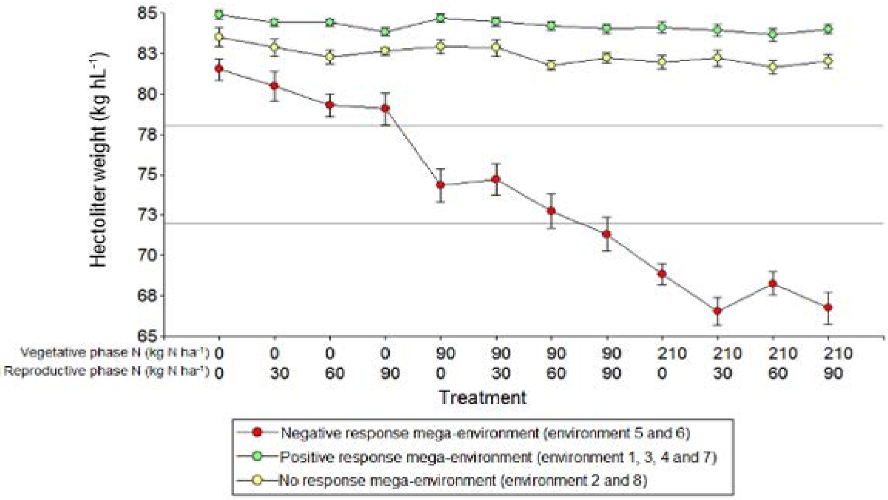


Figure 4. Effect of N treatments on the hectoliter weight in three mega-environments. The line at 72 kg hL^{-1} indicates the rejection limit in the Chilean pasta industry, while the line at 79 kg hL^{-1} indicates the penalty limit. Bars represent the standard error of the mean.

Yellowberry of wheat grains. The mega-environments with some degree of water stress (negative and neutral responses) had a low percentage of yellowberry (0.4% and 1.4%, respectively) (Figure 5). In addition, they showed a similar response pattern to the N treatments, although the mega-environment without response had slightly higher yellowberry percentages. On the other hand, in the mega-environment with water availability there were higher yellowberry percentages, 20% without N fertilization, but this value decreased with N applications during the vegetative and reproductive phases. Nonetheless, applications during the reproductive phase did not have an effect when the rate was 210 kg N ha^{-1} in the vegetative phase.

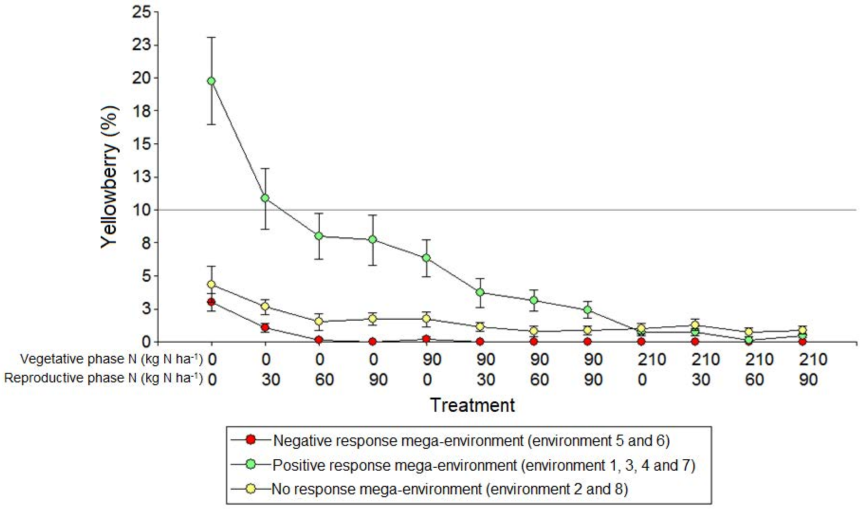


Figure 5. Effect of N treatments on yellowberry percentage in three mega-environments. The 10% line represents the percentage below which the Chilean pasta industry bonus begins. Bars represent the standard error of the mean.

Black point. As in the previous case the mega-environments with some degree of water stress (negative and neutral responses), black points were near 0% (0.0% and 0.1% respectively) independent of N rate (Figure 6). The mega-environment with water availability had a higher percentage of black points. The increasing N rates in the vegetative and reproductive phases increased the black point percentages from 1.6% to 3.1%.

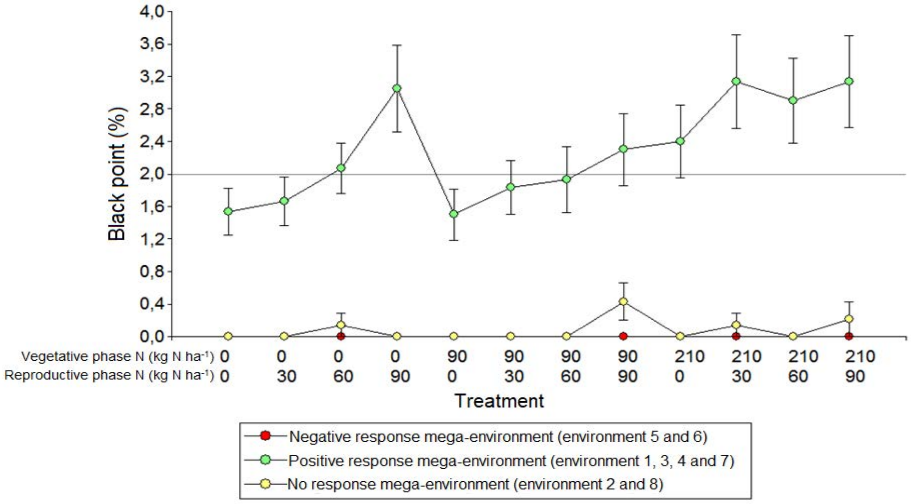


Figure 6. Effect of N treatments on black point percentage in three mega-environments. The line at 2% indicates the penalty limit in the Chilean pasta industry. Bars represent the standard error of the mean.

DISCUSSION

Amount of N applied to maximize grain yield depends on water availability

The environments with N applications during the vegetative phase had grain yield differences associated with irrigation, amount and distribution of rainfall in the spike active-growing phase and grain filling. Wheat grain yield was highly influenced by the environment. The environmental effects on yield are reflected in the significant contrasts between water management conditions (Schulthess et al., 2013). The main factor that influences the N fertilizer rate to maximize grain yield is the amount of water available in the environment (Boulelouah et al., 2022).

The mega-environment with a positive response to fertilization included environments with water availability; thus, these environments showed an effect in yield with N fertilization. In environments where the rainfall was high and homogeneously distributed, grain yield increased until rates of 150 kg N ha^{-1}, being grain yield 5400 kg ha^{-1} (Ayadi et al., 2022). Yield response to N rate was observed when the rainfall amount exceeded 450 mm during the growing season (Tedone et al., 2018). The economical grain yield was achieved maintaining root zone soil depletion below 45% (Mon et al., 2016), this could explain the positive response to N rate with lower amount of rainfall in the growing season due to the depth of the soil obtained in this study. The increment in grain yield is explained by the increment in the number of grains per square meter and the number of spikes per square meter (Boulelouah et al., 2022).

In Chile, durum wheat is produced from Valparaíso region to Los Lagos region. The national average grain yield during the season 2021/2022 was 7100 kg ha^{-1} (ODEPA, 2022). The national durum wheat production supplies 95% of the total needs of the Chilean pasta industry (Farías Pérez et al., 2019). The regions that produce better grain quality are Metropolitan Region and Biobío Region (Acevedo and Silva, 2007).

In the Metropolitan Region the average grain yield during the season 2020/2021 was 5830 kg ha^{-1} considering the normal humidity which the grain is commercialized (ODEPA, 2022). In Santiago, grain yield ranged from 2502 kg ha^{-1} (under lower irrigation conditions) to 6475 kg ha^{-1} (under high irrigation conditions) (González-Ribot et al., 2017). In the case of this experiment the grain yield was similar than the average grain yield in the region.

In Chillán, yield ranged from 7400 to 7920 kg ha^{-1} without any water restriction and sowing early in the season (Hirzel et al., 2021), values normal for the area of study which is associated with the low effective soil depth (Hirzel et al., 2020). The grain yield in this experiment in Chillán was lower than the normal values due to a delay of the sowing.

The mega-environment without response to N fertilization during the vegetative phase included rainfed environments with a slight drought and environments with rainfall between 60 and 70 mm during the spike growing phase. This mega-environment had low grain yield and biomass due to the limited rainfall. Yield was water-limited and greater N additions did not help to increase yield (Afshar et al., 2021).

The mega-environment with a negative response to N fertilization had a low rainfall (162 mm). From September until October, the period of spike growing, the rain was 3 mm, while in November, the period of grain filling, there was no rainfall. The grain yield and HI decreased with N applications- from 3174 to 1960 kg ha^{-1} and from 0.28 to 0.14 respectively. This decline could be explained by the "haying off" phenomenon, which consists of the reduction of grain yield as a response to vigorous vegetative growth promoted by N fertilization during the rainy season, whereas during spring, the crop uses available water, triggering a low soil water content. This process may coincide with the spike active-growing phase and grain filling (Chen et al., 2023).

Protein content increased with N dose in environments with lower water availability

Protein content depends on genotype, environment, and water availability (Colecchia et al., 2013). The mega-environment with lower water availability had 2.5% more protein than moderate and high-water availability environments, other research has shown a mean of 3% more protein content in water stress trials compared with those irrigated trials (Kiliç and Yağbasanlar, 2010). Under non-limiting water conditions, the starch and protein are accumulated in the grain simultaneously. Split N application improved wheat grain protein by 2.4% (from 12.5% to 12.8%). Late season N supply can shift N remobilization to later grain filling stages and increasing grain N uptake (Giordano et al., 2023). In a water limited environment, increasing the N input levels promoted the early growth of biomass and consumed the water from the soil profile resulting in the shortening of the grain filling period and a reduction of carbohydrates, allowing for the accumulation of more protein per unit of starch and an increase in the protein content (Ozturk et al., 2022; Chen et al., 2023). In Chile, high temperatures and drought stress during grain filling increase protein content (Acevedo and Silva, 2007). In Chillán protein content ranged from 13.6% to 14.4% (Hirzel et al., 2020). Grains over 11.5% protein content could be used for pasta (Hare, 2017) and, in the Chilean pasta industry, there is a bonus when grains exceed 12% (Acevedo and Silva, 2007).

Nitrogen dose reduced hectoliter weight in environments with lower water availability

Hectoliter weight is a measure of the grain packing density (kilogram by hectoliter), affected by both size and shape. A hectoliter weight over 76 kg hL^{-1} is desirable (Hare, 2017). In Chilean mills, penalties begin when the hectoliter weight goes below 79 kg hL^{-1} (Acevedo and Silva, 2007). Chilean average hectoliter weight is 84.96 kg hL^{-1}(Acevedo and Silva, 2007), and in Chillán hectoliter weight was 82.2 kg hL^{-1} (Hirzel et al., 2020). Hectoliter weight is clearly modified by water stress (Erice et al., 2019). Under severe drought conditions, increasing N applications led to the hectoliter weight reduction from 81.5 to 66.8 kg hL^{-1}. Similarly, Gerba et al. (2013) documented that the hectoliter weight was reduced with N fertilization in rainfed and terminal-drought environments. This is because in water limited environments high N input level promoted the early growth of biomass and consumed water from soil profile early in the growing season resulting in decreased hectoliter weight (Chen et al., 2023). On the other hand, hectoliter weight has been shown to be higher in mega-environments with positive and neutral response to N fertilization, as detailed by Houshmand et al. (2014), who concluded that the hectoliter weight was higher in absence of water stress. Water stress accelerates phenology, shortens the grain filling period and hectoliter weights are positively associated with longer grain filling period (Ozturk et al., 2022).

Nitrogen dose reduced yellowberry incidence only in environments with high water availability

The mega-environment with a positive response showed the highest percentages of yellowberry, reaching 20% without N fertilization and 1% with 210 kg N ha^{-1}. Therefore, this mega-environment had a continuous decrease in yellowberry with increasing N rates. A similar pattern was reported by Gerba et al. (2013), where there was a 30% decrease in yellowberry grains with N applications and the highest percentages in non-limiting environments. Low fertilization rates and high-water availability increased yellowberry incidence (Mon et al., 2016). In Chile, environments with lower temperatures and high-water availabilities during grain filling increase the incidence of yellow berry (Acevedo and Silva, 2007). In this study, N doses below 60 kg N ha^{-1} on reproductive stage increased over 10% yellowberry in high-water availability environment, this is important because in the Chilean mill industry, a bonus is provided when the percentage of yellowberry is below this value (Acevedo and Silva, 2007).

Higher black point incidence in environments with high water availability

The black point was registered in the mega-environment with high water availability only. Black point appears in environments where there is higher crop moisture caused by either irrigation or rainfall during heading and grain filling (Fernandez and Conner, 2011; Li et al., 2019). The N fertilization in the vegetative and reproductive phases significantly increased percentages of black point. These results are consistent with trends observed by Fernandez and Conner (2011), where higher N applications increase black point percentage due to the highest rates, with foster denser canopies that provide a favorable microclimate for the development of this disease. In Chile, cold and wet environments during grain filling presents higher incidence of black points (Acevedo and Silva, 2007). Penalties for the grain quality start at 3% (Hare, 2017). In Chilean mills, penalties are given when the percentage of black point is over 2% (Acevedo and Silva, 2007). In this study N doses over 150 kg N ha^{-1} exceeded the limit, meaning that those grains could receive penalties.

CONCLUSIONS

The N fertilization to produce durum wheat in Chile depends on the environment, distribution, and amount of water in the season. Environments lower than 320 mm of water could provoke a neutral or negative yield response depending on the distribution of water amount. If the amount of water is not available in the critical period, the response of N application will reduce grain yield. If the amount of water is not available for grain filling, the response of N application will not affect grain yield. Environments with neutral yield response could have beneficial effect on grain quality applying only 90 kg N ha^{-1} at vegetative stages. Environments higher than 330 mm water (including water available in the soil profile at sowing) and well distributed in season increased grain yield with the rate of N applications. The protein content also increased with the amount of N applied. Therefore, only 210 kg N ha^{-1} per ha applied at the vegetative stage maximizes grain yield and protein quality in these environments. This study concludes that a site-specific recommendation for durum wheat in N management in Chilean environments is necessary to produce higher quality and grain yield for the pasta industry to reduce unnecessary N application and economic losses.

Author contribution

Conceptualization: P.S. Methodology: P.S., E.A. Software: P.A. Validation: P.S., E.A. Formal analysis: P.A. Investigation: P.A., P.S. Resources: P.S., I.M., E.A. Data curation: P.S. Writing-original draft: P.A. Writing-review & editing: P.S, E.A., I.M. Visualization: P.A. Supervision: P.S., E.A. Project administration: P.S., I.M. Funding acquisition: P.S. All co-authors reviewed the final version and approved the manuscript before submission.

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