1 **Variations in yield and gluten proteins in durum wheat varieties under**

2 **late-season foliar *vs.* soil application of nitrogen fertilizer in a northern**

3 **Mediterranean environment**

4

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17 **Running title:** Effects of late-season foliar nitrogen fertilisation in durum wheat

18

1   Abstract

2   BACKGROUND: With the increasing demand for high-quality foodstuffs and concern for

3   environmental sustainability, late-season nitrogen foliar fertilization of common wheat

4   is now an important and widespread practice.

5   RESULTS: We investigated the effects of late-season foliar vs. soil N fertilization on

6   yield and protein content of four varieties of durum wheat, Aureo, Ariosto, Biensur and

7   Liberdur, in a three-year field trial in northern Italy. Variations in LMW-GS, HMW-GS

8   and gliadins were assessed by SDS-PAGE. We found that N applied to the canopy did

9   not improve protein rate compared with N application to the soil (general mean: 138

10   mg g^{-1}), but moderately increased productivity in the high-yielding varieties Liberdur

11   and Biensur (three-year means: 7.23 vs. 7.13 t ha^{-1} and 7.53 vs. 7.09 t ha^{-1}, in two

12   varieties respectively). Technological quality was mainly related to variety choice,

13   Aureo and Ariosto having higher protein rates and glutenin/gliadin ratios. We also

14   found a strong 'variety $\times$ N application method' interaction in the proportions of

15   protein sub-units within each class, particularly LMW-GS and gliadins. A promising

16   result was the higher N uptake efficiency, although as apparent balance, combined

17   with higher HMW/LMW-GS ratio in var. Biensur.

18   CONCLUSION: Late-season foliar N fertilization allows N fertilizer saving, potentially

19   providing environmental benefits in the rainy climate of the northern Mediterranean

20   area, and also leads to variety-dependent up-regulation of essential LMW-GS and

21   gliadins. Variety choice is a key factor in obtaining high technological quality, although

22   it is currently associated with modest grain yield. We provide evidence of high quality

23   in the specific high-yielding variety Biensur, suggesting its potential as a mono-varietal

24   semolina for pasta production.

1

2 **Key words:** durum wheat varieties, foliar nitrogen fertilization, gliadins, HMW-GS,

3 LMW-GS, sustainable agriculture, technological quality in pasta production.

4

1 **INTRODUCTION**

2

3 Durum wheat (*Triticum turgidum* L., var. *durum*) plays a major role in human diets, and

4 is used throughout the world, and particularly the Mediterranean region, to produce

5 essential foods, like pasta, couscous, bread and bulgur. The technological value of

6 durum wheat mainly depends on the quantity and quality of proteins and starch[1,2]. As

7 protein content and composition are highly dependent on genotype, variety choice is

8 essential for producing high-quality pasta.

9 The most important class of biochemical markers in determining wheat quality is the

10 polymorphic group of seed storage proteins, represented by gliadins and glutenins.

11 Gliadins are alcohol-soluble proteins, which can be classified into S-rich prolamins, i.e.,

12 $\alpha-\beta-\gamma-$gliadins (molecular weight 36-44 kDa), and S-poor prolamins, i.e., ω-gliadins

13 (molecular weight 44-78 kDa). Glutenins consist of different sub-units of high

14 molecular weight (HMW-GS, 80-140 kDa) and low molecular weight (LMW-GS, 31-51

15 kDa), which form large aggregates joined by disulfide bonds. Gluten properties

16 determine dough strength, which is greater when there are higher proportions of

17 HMW-GS than LMW-GS polymers, although a high glutenin/gliadin ratio is also

18 important in determining the functional proprieties of the gluten[3].

19 Environmental factors and agronomic management play an important role in

20 determining wheat quality characteristics. For example, temperature and precipitation

21 during grain filling, and N availability are key factors in seed protein accumulation[4].

22 Nitrogen fertilization can have a strong impact on yield and semolina quality, according

23 to dosage, source, application timing and dose split[5].

1   The rate of N fertilization of durum wheat has a greater influence on quality than on

2   yield[6,7], as the total available N required to obtain an appreciable protein content may

3   be considerably higher than that needed simply to maximize yield[6,8]. Nitrogen is more

4   effective in increasing grain proteins when applied late in the season[9,10], and foliar

5   spraying can be more beneficial than soil application at appropriate stages[11-13]. Applied

6   at flowering, N is allocated more efficiently to the grains, while a spray solution applied

7   to the flag leaf and underlying leaf allows faster access of N to seeds[14]. Nitrogen

8   uptake from foliar spraying has the advantage of being less dependent on soil moisture

9   and may be effective when root uptake is impaired in dry soils or at late growth stages

10   when there is less root activity[15]. Applied to the canopy, lower quantities of N are

11   required, thus minimizing phytotoxicity, while the high efficiency of this method can

12   reduce crop requirement[11,16,17], thereby lowering gaseous N emissions and nitrate

13   leaching[16,18,19], making this a valuable method in a context of increasing demand for

14   environmental sustainability.

15   Foliar N application is not yet a widespread practice and little information is available

16   about its effects on durum wheat, especially in the unusual agricultural region at the

17   northern limit of the Italian Mediterranean environment. There is a great need to

18   improve the efficiency of N fertilization of this wheat species, which has a high grain

19   protein rate and N requirement, in order to reach the required standards of quality

20   while avoiding damage to the environment.

21   As nowadays late-season nitrogen supply has become a common practice in modern

22   wheat cultivation, the aim of the present study was to analyze and compare the effects

23   of two methods of N supply at the heading stage, soil vs. foliar spraying, on grain yield

24   and gluten protein accumulation in four different commercial durum wheat varieties.

1 We characterized the gluten protein profiles of these varieties in order to identify

2 suitable configurations for high technological quality for pasta production and to

3 detect possible interactions between fertilization method and protein sub-unit

4 composition.

5

6 **MATERIALS AND METHODS**

7

8 **Field trial set-up**

9 The trial was carried out in north-eastern Italy at the "L. Toniolo" Experimental Farm of

10 the University of Padua at Legnaro (45°20' N, 11°56' E, 12 m asl) over 3 years, starting

11 with the 2010-2011 growing season. The soil is silty-loam with pH 8.0, 1.7% organic

12 matter, CEC of 11.4 cmol(+) kg^{-1}, and a total N content of 1.1 g kg^{-1} (arable layer,

13 beginning of experiment). Temperatures and precipitation in the 3-year period 2010-

14 2013 are reported in Fig. 1A. The first year was characterized by high temperatures

15 and low rainfall in the last stage of the crop cycle; the second year (2011-12) had the

16 driest growing season together with the highest maximum temperatures; the third

17 year (2012-13) was characterized by high rainfall, especially in winter and spring, and

18 low maximum temperatures.

19 The effects of the two methods of late-season N fertilization were investigated in 4

20 durum wheat varieties using a split-plot experimental design with three replicates. The

21 fertilization factor was set in large plots, and varieties in randomized subplots (3 m

22 wide × 8 m long). The previous crop had been sugar beet in all three years. Sowing

23 generally took place in late October at a density of 350 seeds m^{-2} after careful soil

24 tillage consisting of 30-cm deep ploughing and 15-cm deep disc harrowing.

1 Four different varieties were compared, two of them acknowledged as being of very

2 high quality in terms of grain protein content, i.e., Aureo (Produttori Sementi Bologna,

3 Italy, now Syngenta, Basel, Switzerland) and Ariosto (Apsovsementi, Voghera, Italy),

4 and two of medium-high quality, i.e., Biensur (Apsovsementi) and Liberdur (S.I.S.

5 Società Italiana Sementi, Bologna, Italy) (Table SI 1).

6 Varieties were factorially combined with the two methods of late-season N

7 fertilization: foliar vs. soil application at the heading stage. The overall N fertilization

8 rate was 162 kg N ha^{-1} for foliar treatment and 182 kg N ha^{-1} for soil treatment. Prior to

9 the late-season N supply, the same quantities of N were applied to the soil: 24 Kg at

10 sowing (as ternary fertilizer), 52 kg during tilling (end February, as ammonium nitrate),

11 and 71 kg at the beginning of stem elongation (mid-April, as urea). Foliar fertilization

12 consisted of 15 Kg N ha^{-1} as UAN (urea ammonium nitrate, NSZ 26, Cifo) divided into

13 two applications in order to avoid any possible phytotoxicity, half at heading and the

14 other half fourteen days later at flowering. The soil treatment consisted in applying N

15 as urea at the heading stage at a rate of 35 Kg ha^{-1}, roughly double that of the foliar

16 treatment, in order to take into account a ~50% efficiency.

17 Harvesting was carried out with a plot combine harvester (Wintersteiger, Ried, Austria)

18 at the beginning of summer: 21 June 2011, 29 June 2012, and 3 July 2013. Grain

19 moisture was measured for each plot and yield adjusted to 13% moisture.

20 The thousand seed weight (TSW) was determined by weighting 1,000-kernel samples

21 obtained from a counting-machine (Numigral Seed Counter, Chopin Technologies,

22 Villeneuve-la-Garenne, France). The number of kernels per square meter was

23 calculated by dividing the grain yield in a 0.5-m^2 sampling area by TSW in each plot.

1   The crop harvest index (HI) was calculated as grain-to-total aboveground biomass (dry

2   matter) ratio in 0.5-m^2 sampling areas in each plot at harvest.

3

4   **Analysis of grain quality**

5

6   **Grain protein content**

7   The total grain protein content was determined by the Kjeldahl method (official

8   analytical method 2001.11)[20] as total N rate multiplied by the coefficient 5.7.

9

10   **Gluten protein extraction and quantification**

11   A sample of 35 g of dried seeds from each cultivar-treatment combination was milled

12   into fine flour with a KnifetecTM 1095 (Foss, Hillerød, Denmark). Gluten proteins,

13   gliadins, high–molecular-weight glutenin subunits (HMW-GS) and low–molecular-

14   weight glutenin subunits (LMW-GS) were determined using the modified sequential

15   extraction procedure of Singh et al[21]. A 30-mg flour sample was subjected to extraction

16   with 1.5 mL of 55% (v/v) propan-2-ol for 20 min with continuous mixing at 65 °C,

17   followed by centrifugation for 5 min at 10,000 rpm. This step was repeated three

18   times, and the supernatants were combined and dried in a vacuum centrifuge to

19   obtain the protein gliadin fraction. The remaining pellet containing the GS fraction was

20   suspended in a 400 μL solution of 55% (v/v) propan-2-ol, 0.08 M

21   tris(hydroxymethyl)aminomethane hydrochloric acid (Tris HCl) pH 8.3, and 1% (w/v)

22   1,4-dithio-threitol (DTT) as reducing agent, and incubated for 30 min at 60 °C with

23   continuous mixing. After centrifugation for 5 min at 14,000 rpm, the supernatant

24   containing the HMW-GS and LMW-GS fractions was transferred to a new tube. To

1   precipitate HMW-GS, acetone was added to obtain a final concentration of 40% (v/v),

2   which was then centrifuged for 10 min at 14,000 rpm. The LMW-GS fraction was

3   precipitated in the remaining supernatant by adding acetone to obtain a final

4   concentration of 80% (v/v), and this was then centrifuged for 10 min at 10000 xg. The

5   GS fractions and gliadins were dissolved in 50% (v/v) acetonitrile (ACN) with 0.1% (v/v)

6   trifluoroacetic acid (TFA); relative quantification was determined by colorimetric

7   Bradford assay (Biorad Hercules, CA). Three technical replicates were performed for

8   each sample.

9

10   **Protein separation by SDS-PAGE and densitometric analyses of gliadins and glutenins**

11   SDS-PAGE was performed on a Mini-PROTEAN Tetra Cell (Bio-Rad) on 8%, 12% and

12   15% acrylamide gel for the HMW-GS, LMW-GS and gliadin fractions, respectively. 2.5

13   µg each of dried HMW-GS, LMW-GS and gliadins were suspended in 20 µL of loading

14   buffer containing 2% (w/v) SDS, 0.02% (w/v) bromophenol blue,

15   0.1% β−mercaptoethanol, 0.05 M Tris-HCl pH 6.8, and 10% (v/v) glycerol, and boiled at

16   95 °C for 5 min before loading onto the gel. A ColorBurst™ Marker Electrophoresis High

17   Range (Mw 30,000-220,000) was used to detect HMW-GS, and a Molecular-Weight

18   Marker® (Mw 14,000-66,000; Sigma Aldrich, St. Louis, MO, USA) to detect LMW-GS

19   and gliadins. After electrophoretic separation at 40 mA, the gels were stained with

20   brilliant blue G-colloidal solution (Sigma Aldrich) fixed in 7% (v/v) acetic acid and 40%

21   (v/v) methanol, and de-stained in 25% (v/v) methanol. Each protein sample (HMW-GS,

22   LMW-GS, and gliadins) was analyzed in three technical replicates in all three

23   experimental years. IMAGE lab 4.5.1 (Bio-Rad) software was used to identify protein

1 molecular weights (MW) and for relative quantification of the gliadin, LWM-GS and

2 HMW-GS single protein sub-units on each gel.

3

4 **Statistical analyses**

5 Analysis of variance (ANOVA) of the agronomic data was run with the Statgraphics

6 Centurion XVII statistical software (Statpoint Technologies, Inc. Warrenton, Virginia,

7 USA). Significant differences among means were verified with the Newman-Keuls test

8 at $P \leq 0.05$.

9 To facilitate interpretation of the large dataset obtained from the three-year field trial,

10 factorial discriminant analysis (MDA, Multigroup Discriminant Analysis with Wilks'

11 lambda and Pillai's trace tests) and principal component analysis (PCA) were carried

12 out to describe yield components and quality with respect to variety choice and

13 method of late-season N supply. Multivariate data normality was first verified by

14 Shapiro test. The data were standardized before analysis by subtracting the mean and

15 dividing by the standard deviation within each variable. Analyses were performed with

16 MS Excel XLSTAT (Addinsoft, Paris, France).

17

18 **RESULTS AND DISCUSSION**

19

20 **Effects of N fertilization and variety choice on yield and protein content**

21

22 Grain yield was significantly affected by cultivar choice. The two high-yielding varieties,

23 Biensur and Liberdur, were found to have better potential (7.31 and 7.18 t ha^{-1} at the

24 commercial humidity of 13%, respectively) than Ariosto (6.46 t ha^{-1}, with the highest

kernel weight) and particularly Aureo (5.12 t ha^{-1}) (Fig. 1B). As the different varieties had very similar plant densities, grain yield was thought to be mainly related to spike fertility, as confirmed by the number of kernels per m^2 that was higher in Biensur than in Aureo (+36%) (Fig. 2A). The high-yielding varieties also had better harvest indexes vs. the high-quality ones (+7%, Fig. 2C), despite worse values of the thousand kernel weight (TKW, –14%) (Fig. 2B). There was no difference in yield between foliar and soil N application, although only slight, not significant, improvements were attributed to foliar fertilization, particularly in var. Liberdur (Fig. 1B). Considering that the amount of N applied in foliar spraying (two applications) was half that of the soil treatment, our data confirm previous work reporting the high level of efficiency and sustainability of foliar N application for crop requirements[11,16,17]. Recent studies referred to our agricultural region confirm that nitrogen use efficiency for granular soil-applied fertilizers may vary considerably, it depending on soil type and year, with an average value of 46% and maximum of 75%[22]. Again, grain protein content differed significantly across varieties: var. Aureo had the highest value (158 mg g^{-1}) followed by Ariosto (142 mg g^{-1}), Biensur (131 mg g^{-1}), and finally Liberdur with the lowest value (122 mg g^{-1}). While confirming the general rule that productivity is negatively correlated with grain protein content, we point out that the protein rates of three of the varieties tested were > 130 mg g^{-1}, a critical threshold for pasta processing. The method of late-season N application (foliar vs. soil) had no significant influence on protein content (Fig. 1B). There was a marked effect of cultivation year on yield and, to a lesser extent, on kernel protein content (Fig. 1C), suggesting that protein content has a strong genetic dependence[23]. The high rainfall in the third trial year (2012-13) reduced both grain yield and protein content.

1   In terms of apparent N balance (i.e., the difference between N supply and grain N),

2   foliar supply was more favorable (lower values) than soil application in all varieties,

3   particularly Biensur, so we can expect nutrient foliar applications to have a generally

4   lower environmental impact[24] (Fig. 3). Although incomplete, the apparent N balance is

5   a good estimator of N uptake as the grains generally contain more than 75% of the

6   total plant uptake, while straw has negligible N concentrations (~0.3%).

7   These data suggest that, besides Aureo and Ariosto, var. Biensur can also provide good

8   quality with high both yield and nitrogen uptake, and may therefore be profitably

9   considered for future use in pasta production. As regard the application method of N

10   fertilizer, small agronomic variations were detected in these varieties, probably

11   because similar plant N uptakes were achieved with the two methods and treatment

12   differentiation started late in the season. However, improved grain N recovery is

13   generally expected with foliar fertilization compared with soil application[25], with

14   benefits in yield and protein contents[26-28] mainly due to retarded senescence of the

15   flag leaf[7].

16

17

18   **Characterization of gluten proteins**

19

20   In accordance with other findings that N plays a key role in wheat plant nutrition and

21   grain quality[29], we found a significant correlation between N accumulation in the

22   kernels and the final total gluten protein content measured by quantifying the various

23   protein fractions (HMW-GS, LMW-GS and gliadins) across the three experimental years

24   (R^2 = 0.75). Nitrogen fertilization has been reported to enhance the synthesis of GS,

resulting in a higher GS/gliadin ratio, due to different expressions of the gluten gene families[30-34-28]. However, modulation of the gluten content by N fertilizers is also expected to be cultivar dependent[31]. In this regard, var. Aureo and Ariosto had higher total protein contents, while Biensur exhibited the highest HMW/LMW-GS ratio under both N treatments, and a higher GS/gliadin ratio than Liberdur (Fig. 4). Foliar fertilization slightly increased, although not significantly, the GS/gliadins ratio in all varieties, a part from Biensur, and the HMW/LMW-GS ratio in Ariosto only.

Previous studies have found a positive correlation between the GS/gliadin ratio and dough strength[34,35]. Edwards and collaborators[36] showed that addition of a glutenin-rich fraction consisting of HMW-GS and LMW-GS to the base semolina increases the mixograph dough strength. In common wheat, improvements of bread-making quality of flour by late foliar N supply have already been demonstrated[37]. Studies have also suggested that foliar N is mainly incorporated in storage proteins[38].

Principal component analysis

PCA was conducted on the whole dataset of the three-year trial in order to establish the relevance of each variable and treatment. PCA identified two synthetic variables, which explained an overall variability of 91.4%, mainly represented by F1 (78.87%) (Fig. 5). Most of the relevant variables (loadings > |0.5|) were assigned to the F1 variable, such as total grain protein rate, HMW-GS and LMW-GS content, and the GS/gliadin ratio, while the F2 variable included the HMW/LMW-GS ratio as a significant variable. The vector direction of the variables enabled us to establish a general strong negative correlation between yield and quality parameters (i.e., total gluten proteins, and both HMW-GS and LMW-GS), which highlights the difficulty in obtaining high yield and high

1 quality together. A positive correlation was found between yield and the polymeric-to-

2 monomeric protein ratio (i.e., HMW/LMW-GS), a selection criterion for pasta

3 production[2].

4 Marked differences between the varieties were found, as clearly evidenced by the

5 separate plotting of groups in the MDA chart (circles and centroids; Fig. 5). Results

6 confirmed var. Ariosto and particularly Aureo as superior-quality varieties with high

7 levels of total proteins and HMW-GS and LMW-GS, while Biensur exhibited a high

8 HMW/LMW-GS ratio, and, along with Liberdur, high yield. Regarding fertilization

9 method, foliar application constantly diverged from soil application, improving yield in

10 Liberdur, Biensur, and, unexpectedly, Ariosto, and further improved the already good

11 technological value of Aureo.

12

13 **Protein indicators for wheat quality**

14 Varieties Biensur and Ariosto had HMW-GS compositions typical of the allelic

15 configuration Bx7 and By8 at locus *Glu-B1* (Fig. 6), in accordance with published data[39].

16 The HMW-GS of var. Aureo had the typical configuration Bx6 and By8 at the same

17 locus. It has been suggested that both HMW-GS configurations make a favorable

18 contribution to the technological quality of gluten in durum wheat[40]. Liberdur

19 exhibited only the Bx20 allele expression while By was null (Fig. 6). There is scientific

20 evidence that durum wheat with this protein profile is weak[41,42], while Shewry and

21 collaborators[43] used wheat transformation to confirm that HMW-GS Bx20 is associated

22 with lower dough strength. Lower overall strength of this protein subunit is thought to

23 depend on lower density of intermolecular disulfide bonds (fewer cysteine residues at

24 the N-terminal), resulting in lower polymeric protein content.

1   In all the varieties tested, LMW-GS protein patterns showed the typical configuration

2   of the LMW-2 protein groups, which are coded at the locus *Glu-B3* (Fig. 6). This

3   configuration is characterized by a 42 kDa LMW-GS, the most abundant GS of this

4   class[44]. An additional band was present in var. Biensur, suggesting a putative LMW-2

5   allelic variant[42]. Lastly, Figure 6 also shows the gliadin configurations of all the

6   varieties; the γ-45 gliadin group is associated with the LMW-2 GS pattern due to

7   genetic linkage[45].

8   Var. Biensur had the best HMW-GS configuration for high gluten strength and an

9   optimal response in term of the GS/gliadin ratio, both of which are associated with

10   significant differences in the dough strength of durum wheat[2,35,44,46].

11   Members of the gliadin, LMW-GS and HMW-GS families were quantified by

12   densitometric analysis to examine varietal differences and possible up-regulation by

13   the late nitrogen supply method. Statistical analysis of the data from the three

14   experimental years revealed significant differences among varieties with respect to the

15   relative abundances of all the members of each gluten protein class (Table 1).

16   Significant differences between the N fertilization methods (foliar vs. soil treatment)

17   were also observed in all the LMW-GS and gliadin classes, with the exception of gliadin

18   35 kDa, while HMW-GS were not affected (Table 1). The most important result was the

19   significant 'cultivar x N supply method' interaction found in all gluten protein classes

20   (Table 1). Variations in HMW-GS composition can be mainly ascribed to variety choice,

21   while the effect of fertilization method was very low. On average, var. Aureo contained

22   ~50% subunit Bx6 and ~50% sub-unit By8, while varieties Ariosto and Biensur

23   contained ~65-70% Bx7 and ~30-35% By8 (Fig. 7). Liberdur was not included in the

1   densitometric analysis for HMW-GS as it exhibited only the Bx20 sub-unit, while By was

2   a null allele.

3   Regarding the LMW-GS, there are evident differences among cultivars, particularly in

4   the 42 kDa and 37 kDa sub-units, which are the most abundant ones (Fig. 8) and were

5   generally up-regulated by N foliar treatment (main effect +0.8% and +0.3%,

6   respectively, compared with N supply to the soil). The less abundant sub-units 32 and

7   31 kDa were instead generally down-regulated by N foliar treatment (Fig. 8). Aureo, in

8   particular, responded better than the other varieties to foliar N treatment, up-

9   regulating both LMW-GS 42 kDa and LMW-GS 37 kDa (up to 2%). LMW-GS 37 kDa also

10   improved in Ariosto and Biensur, although to a lesser extent (Fig. 8). Var. Liberdur had

11   the highest relative abundance of LMW-GS 42 kDa (> 50% of the total LMW-GS) and

12   exhibited a significant increase in this sub-unit under foliar N treatment (up to 1%).

13   Biensur had the highest relative abundance of LMW-GS 37 kDa (> 35% of the total

14   LMW-GS) and the greatest increase due to N foliar treatment (up to 2%).

15   Regarding the gliadins, we carried out relative quantification of the fractions in the

16   MW range 28-35 kDa, which corresponded to the overlapping $\alpha/\beta-$ and γ-gliadin MWs.

17   These gliadins account for up to 64% of total gliadin content and are those mainly

18   involved in gluten technological proprieties due to the presence of six ($\alpha/\beta-$) and eight

19   ($\gamma-$) cys residues in the C-term domain[47]. In particular, γ-gliadins can form intra- and

20   inter-chain disulfide bonds interacting with the HMW and LMW polymers[47]. In the

21   range of 39-35 KDa, where most of the γ-gliadins usually occur, var. Biensur had the

22   highest content of 39 kDa gliadin under both N fertilization methods, but it was slightly

23   lower with foliar N; although this sub-unit is less abundant in Aureo and Liberdur, it

24   was significantly up-regulated by foliar N (+1 and +2%, respectively) (Fig. 9). The 35 kDa

gliadin was also positively regulated by foliar N supply in varieties Aureo, Biensur and

Liberdur (average increase of 1,5-2%), but the opposite pattern was found with var.

Ariosto. In the range of 31-28 kDa, in which most of the α/β gliadins fall, the 30 kDa

gliadin was up-regulated by foliar N treatment in Biensur (up to 2%), and in Ariosto (up

to 3%); in the latter variety this protein band accounted for more than 40% of gliadins

(Fig. 9). Gliadins 31 kDa and 28 kDa were both less modulated by the N supply method.

These data indicate that the proportions of the different members of each GS-protein

class is a varietal trait, although it is possible to obtain a significant positive effect of N

foliar treatment on the most abundant LMW-GS sub-units and the gliadin fractions in

the range 39 to 30 kDa. Nitrogen uptake from foliar spraying can be more efficient

than from soil supply when root activity is reduced, as in the case of late growth stages

(post-anthesis), and increases protein accumulation in developing grains. Previous

studies demonstrated that late-season urea spraying of wheat consistently resulted in

higher yield and a cultivar-dependent increase in protein content[48]. In this study,

technological quality was mainly related to variety choice, but our data support the

important influence of the method of N fertilizer supply on durum wheat gluten

protein sub-unit composition, and consequently on grain quality. The amount of N and

the method of late-season application, even when the amount of N taken up by the

plant is similar, are key factors in determining wheat productivity and quality. PCA and

MDA of our 3-year dataset did not support the significance of rainfall and temperature

recorded during grain filling, although agronomically important, probably because our

experimental site is located at the northern border for durum wheat in the

Mediterranean area, where water deficits and heat stress are unusual events. In this

regard, both air temperature and humidity affect the effectiveness of foliar N supply

and phytotoxicity, but not in this trial probably because of the small amount of fertilizer supplied and the favorable (i.e., moderate temperature, high air humidity) climatic conditions at heading. Nonetheless, modulation of HMW-GS, LMW-GS, and α-gliadins, γ-gliadins, and ω-gliadins in response to high temperatures, drought and also nitrogen fertilization are documented in the literature[31,46,49-51-44]. In particular, Hurkman and collaborators[30] demonstrated that the proportions of ω-gliadins and HMW-GS, and a few α-gliadins and LMW-GS were modified in developing endosperm in response to fertilizer and high temperature during anthesis, while most of the γ-gliadins and LMW-GS were unchanged. Gluten protein accumulation is a complex process subject to spatial and temporal regulation as well as environmental signaling. Individual proteins within each gluten protein class accumulate to different levels and can be influenced by environmental changes to different extents, suggesting that the corresponding genes have different basal levels of expression and possibly different N response regulatory elements in the promoter sequences.

CONCLUSIONS

This study demonstrates that N fertilizer applied to the canopy of durum wheat at heading-flowering guarantees faster N access to seeds, has appreciable effects on grain quality and gives moderate improvement in yield. Foliar treatment is of environmental importance as lower amounts of N need to be applied to the crop and greater N uptake is expected; this has potential benefits in terms of reducing nitrate leaching in the rainy climate of NE Italy, which lies at the northern Mediterranean border for durum wheat cultivation. This study demonstrates that an amount of at

least 20 kg N ha^{-1} can be saved in the fertilization plan with foliar supply compared with soil fertilization, and that the greater amount of N taken up by the crop (varietal mean: +19 kg ha^{-1}) may reduce further the leaching risk.

Among the genotypes, the high-yielding var. Biensur was, unexpectedly, found to have high protein quality, acceptable total gluten protein content, high GS/gliadin and HMW/LMW-GS ratios, and an optimal allelic GS configuration (Bx7 and By8), suggesting that high productivity can be combined with good quality through suitable breeding programs. Aureo, followed by Ariosto, were confirmed as being high-quality varieties with high contents of total proteins, HMW-GS, and LMW-GS, supporting their current use as mono-varietal semolina for pasta production. Although each variety has a specific protein fingerprint, late-season foliar N supply can positively up-regulate important LMW-GS and gliadins, although the effect is variety-dependent. This suggests that fine-tuning of grain quality, especially in weak genotypes, would require assessment of their individual responses to late foliar N supply. Future work will require to evaluate dough rheological and pasting properties of semolina obtained from cv. Biensur cultivated in Northern Italy for its possible use as monovarietal source in pasta production.

1

2 **REFERENCES**

3 (1) Saaman J, El-Khayat GH, Manthey FA, Fuller MP, Brennan CS, Durum wheat quality:

4 II. The relationship of kernel physicochemical composition to semolina quality and end

5 product utilization. *Int J Food Sci Tech* **41:** 47-55 (2006).

6 (2) Sissons M, Role of durum wheat composition on the quality of pasta and bread.

7 *Food* **2:** 75-90 (2008).

8 (3) Varzakas T, Kozub N, Xynias IN, Quality determination of wheat: genetic

9 determination, biochemical markers, seed storage proteins-bread and durum wheat

10 germplasm. *J Sci Food Agric* **94:** 2819-2829 (2014)**.**

11 (4) Lopez-Bellido L, Lopez-Bellido R-J, Castillo JE, Lopez-Bellido FJ, Effects of long-term

12 tillage, crop rotation and nitrogen fertilization on bread-making quality of hard red

13 spring wheat. *Field Crop Res* **72:** 197–210 (2001).

14 (5) Grant CA, Brown KR, Racz GJ, Bailey LD, Influence of source, timing and placement

15 of nitrogen on grain yield and nitrogen removal of durum wheat under reduced and

16 conventional tillage management. *Can J Plant Sci* **81:** 17–27 (2001).

17 (6) Garrido-Lestache E, Lopez-Bellido RC, Lopez-Bellido L, Durum wheat quality under

18 Mediterranean conditions as affected by N rate, timing and splitting, N form and S

19 fertilisation. *Eur J Agron* **23:** 265-278 (2005).

20 (7) Blandino M, Pilati A, Reyneri A, Effect of foliar treatments to durum wheat on flag

21 leaf senescence, grain yield, quality and DON contamination in North Italy. *Field Crops*

22 *Res* **114:** 214-222 (2009).

1   (8) Bown B, Westcott M, Christensen N, Pan B, Stark J, Nitrogen management for hard

2   wheat protein enhancement. Pacific Northwest Extension publication, PNW578.

3   (2005). http://www.cals.uidaho.edu/edComm/pdf/pnw/pnw0578.pdf

4   (9) Brown BD, Petrie S, Irrigated hard winter wheat response to fall, spring, and late

5   season applied nitrogen. *Field Crops Res* **96***:* 260–268 (2006).

6   (10) Ottman MJ, Doerge TA, Martin EC, Durum grain quality as affected by nitrogen

7   fertilization near anthesis and irrigation during grain fill. *Agron J* **92:** 1035–1041 (2000).

8   (11) Gooding MJ, Davies WP, Foliar urea fertilization of cereals: A review. *Nutr Cycl*

9   *Agroecosys* **2:** 209-222 (1992).

10   (12) Arif M, Chohan MA, Ali S, Gul R, Khan S, Response of wheat to foliar application of

11   nutrients. *J Agric Biol Sci* **61:** 30-34 (2006).

12   (13) Khan P, Memon MY, Imtiaz M, Aslam M, Response of wheat to foliar and soil

13   application of urea at different growth stages. *Pak J Bot* **41:** 1197-1204 (2009).

14   (14) Wuest S B, Cassman K G, Fertilizer-nitrogen use efficiency of irrigated wheat: II.

15   Partitioning efficiency of preplant versus late-season application. *Agronomy J* **4***:* 689-

16   694 (1992).

17   (15) Zhao-Hui W, Sheng-Xiu L, Sukhdev M, Effects of fertilization and other agronomic

18   measures on nutritional quality of crops. *J Sci Food Agric* **88:** 7- 23 (2008).

19   (16) Edwards JT, Arnall DB, Zhang H, Nitrogen fertilization timing and source affected

20   hard red winter wheat yield but application method does not. *Crop Manag* **8** doi:

21   10.1094/CM-2009-0511-01-RS (2009).

22   (17) Woolfolk CW, Raun WR, Johnson GV, Thomason WEC, Mullen RW, Wynn KJC,

23   Freeman KW, Influence of late-season foliar nitrogen applications on yield and grain

24   nitrogen in winter wheat. *Agron J* **94:** 429–434 (2002).

1 (18) Basso B, Cammarano D, Troccoli A, Chen D, Ritchie JT, Long-term wheat response

2 to nitrogen in a rained Mediterranean environment: field data and simulation analysis.

3 *Eur J Agron* **33:** 132-138 (2010).

4 (19) Robertson GP, Goffman P, Nitrogen transformations, E.A. Paul (Ed.). Soil

5 Microbiology, Ecology, and Biochemistry (3rd ed.), Academic/Elsevier, New York, pp.

6 341–364 (2007).

7 (20) Association of Official Analytical Chemists (AOAC). Official Methods of Analysis,

8 17th ed., 2000 AOAC International, Washington, DC, USA.

9 (21) Singh KN, Shepherd WK, Cornish BG, A simplified SDS-PAGE procedure for

10 separating LMW subunits of glutenin. *J Cereal Sci* **14:** 203-208 (1991).

11 (22) Morari F, Zanella V, Sartori L, Visioli G, Berzaghi P, Mosca G, Optimising durum

12 wheat cultivation in North Italy. Understanding the effects of site-specific fertilization

13 on yield and protein content. *Precis Agric* in press (2017) doi: 10.1007/s11119-017-

14 9515-8

15 (23) Rharrabti Y, Villegas D, Garcia del Moral LF, Aparicio N, Elhani S, Royo C,

16 Environmental and genetic determination of protein content and grain yield in durum

17 wheat under Mediterranean conditions. *Plant breeding* **120:** 381–38 (2001).

18 (24) Lotfollah M, Malakout MJ, Effects of N-fertilizers on wheat grain protein through

19 foliar application. *Develop. Plant Soil Sci* **86:** 115-117 (1999).

20 (25) Gooding MJ, Gregory PJ, Ford KE, Ruske RE, Recovery of nitrogen from different

21 sources following applications to winter wheat at and after anthesis. *Field Crops Res*

22 **100:** 143-154 (2007).

1 (26) Peltonen J, Peltonen P, Effect of apical-timed urea spraying on yield components

2 and quality properties of spring wheat (*Triticum aestivum* L.) in greenhouse

3 experiments. *Acta Agric Scan* **40:** 33-43 (1990).

4 (27) Bly AG, Woodard HJ, Foliar nitrogen application timing influence on grain yield and

5 protein concentration of hard red winter and spring wheat. *Agron J* **95:** 335-338

6 (2003).

7 (28) Woodard HJ, Bly A, Relationship of nitrogen management to winter wheat yield

8 and grain protein in South Dakota. *J Plant Nutr* **21:** 217-233 (1998).

9 (29) Schipper A, Modifications of the dough physical proprieties of various wheat

10 cultivars by environmental influences. *Agrobiological Res* **44:** 114-132 (1991).

11 (30) Hurkman WJ, Tanaka CK, Vensel WH, Thilmony R, Altenbach SB, Comparative

12 proteomic analysis of the effect of temperature and fertiliser on gliadin and glutenin

13 accumulation in the developing endosperm and flour from *Triticum aestivum* L. cv.

14 Butte 86. *Proteome Sci* **11**:8. (2013) ,http://www.proteomesci.com/content/11/1/8.

15 (31) Wan Y, Shewry RP, Hawkesford J, A novel family of γ-gliadin genes are highly

16 regulated by nitrogen supply in developing wheat grain. *J Exp Bot* **64:** 161-168 (2013).

17 (32) Visioli G, Galieni A, Stagnari F, Bonas U, Speca S, Faccini A, Pisante M, Marmiroli N,

18 Proteomics of durum wheat grain during transition to Conservation Agriculture. *PLoS*

19 *ONE* **11(6):** e0156007 (2016).

20 (33) Galieni A, Stagnari F, Visioli G, Marmiroli N, Speca A, Angelozzi G, D'Egidio S,

21 Pisante M, Nitrogen fertilization of durum wheat: a case of study in Mediterranean

22 area during transition to Conservation Agriculture. *Italian J Agron* **662:** 12-23 (2016).

23 (34) Wasik RJ, Bushuk W, Relation between molecular-weight-distribution of

24 endosperm proteins and spaghetti making quality. *Cereal Chem* **52:** 322-328 (1975).

(35) Dexter JE, Matsuo RR, The effect of gluten protein fractions on pasta dough rheology and spaghetti-making quality. *Cereal Chem* **55:** 44-57 (1978).

(36) Edwards NM, Mulvaney SJ, Scanlon MG, Dexter JE, Role of gluten and its components in determining durum semolina dough viscoelastic proprieties. *Cereal Chem* **80:** 755-763 (2003).

(37) Fageria NK, Filho MPB, Moreira A, Guimarães CM, Foliar fertilization of crop plants. *J Plant Nutr* **32:** 1044-1064 (2009).

(38) Tea I, Genter T, Naulet N, Boyer V, Lummerzheim M, Kleiber D, Effect of foliar sulfur and nitrogen fertilization on wheat storage protein composition and dough mixing properties. *Cereal Chem* **81:** 759-766 (2004).

(39) Martinez MC, Ruiz M, Carrillo MJ, Effects of different prolamin alleles on durum wheat quality proprieties. *J Cereal Sci* **41:** 123-131 (2005).

(40) Gianibelli MC, Larroque OR, MacRitchie F, Wringley W, Biochemical, genetic, and molecular characterization of wheat glutenin and its component subunits. *Cereal Chem*, **78:** 635-646 (2001).

(41) Ammar K, Kronstad WE, Morris CF, Breadmaking quality of selected durum wheat genotypes and its relationship with high molecular weight glutenin subunits allelic variation and gluten polymeric composition. *Cereal Chem* **77:** 230-336 (2000).

(42) Brites C, Carrillo MJ, Influence of high molecular weight (HMW) and low molecular weight (LMW) glutenin subunits controlled by Glu-1 and Glu-3 loci on durum wheat quality. *Cereal Chem* **78:** 59-63 (2001).

(43) Shewry PR, Gilbert SM, Savage AWJ, Tatham AS, Wan YF, Belton PS, Wellner N, D'Ovidio R, Bekes F, Halford NG, Sequences and proprieties of HMW subunit 1Bx20

from pasta wheat (*Triticum durum*) which is associated with poor end use proprieties. *Theor Appl Genet* **106:** 744-750 (2003).

(44) D'Ovidio R, Masci S, The low-molecular-weight glutenin subunits of wheat gluten. *J. Cereal Sci* **39:** 321-339 (2004).

(45) Payne PI, Jackson EA, Holt LM, The association between gamma-gliadin and gluten strength in durum wheat varieties: a direct casual effect or the result of genetic linkage. *J Cereal Sci* **2:** 73-81 (1984).

(46) Sissons MJ, Ames NP, Hare RA, Clarke JM, Relationship between glutenin subunit composition and gluten strength measurements in durum wheat. *J Sci Food Agric* **85:** 2445–2452 (2005).

(47) Wieser H, Chemistry of gluten proteins. *Food Microbiol* **24:** 115–119 (2007).

(48) Varga B, Svečnjak Z, The effect of late-season urea spraying on grain yield and quality of winter wheat cultivars under low and high basal nitrogen fertilization. *Field Crop Res* **96:** 125-132 (2006).

(49) Dupont FM, Hurkman WJ, Vensel WH, Tanaka C, Kothari KM, Chung OK, Alternbach SB, Protein accumulation and composition in wheat grains: effects of mineral nutrients and high temperature. *Eur J Agron* **25:** 96-107 (2006).

(50) Majoul T, Bancel E, Triboï E, Ben Hamida J, Branlard G, Proteomic analysis of the effect of heat stress on hexaploid wheat grain: characterisation of heat responsive proteins from total endosperm. *Proteomics* **3:** 175-183 (2003).

(51) Flagella Z, Giuliani MM, Giuzio L, Volpi C, Masci S, Influence of water deficit on durum wheat storage protein composition and technological quality. *Eur J Agron* **33:** 197-207 (2010).

1 **Table 1**: Significance of main effects of 'variety' and 'nitrogen fertilization method' (late-season foliar vs.

2 soil supply) and their interaction (Newman-Keuls Test) on proportions of HMW-GS, LMW-GS, and

3 gliadins in each protein class.

4

Protein class	KDa	Variety (P level)	N supply method (P level)	Interaction (P level)
HMW-GS	X-type	0.0000 ***	0.1350 n.s.	0.0120 *
	Y-type	0.0000 ***	0.1350 n.s.	0.0120 *
LMW-GS	42	0.0000 ***	0.0126 **	0.0000 ***
	37	0.0000 ***	0.0000 ***	0.0000 ***
	32	0.0000 ***	0.0000 ***	0.0000 ***
	31	0.0000 ***	0.0007***	0.0000 ***
Gliadins	39	0.0000 ***	0.0027 ***	0.0000 ***
	35	0.0000 ***	0.2267 ns	0.0000 ***
	31	0.0000 ***	0.0010 **	0.0003 ***
	30	0.0000 ***	0.0001***	0.0000 ***
	28	0.0000 ***	0.0000 ***	0.0000 ***

5 * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$

6

1 **A**
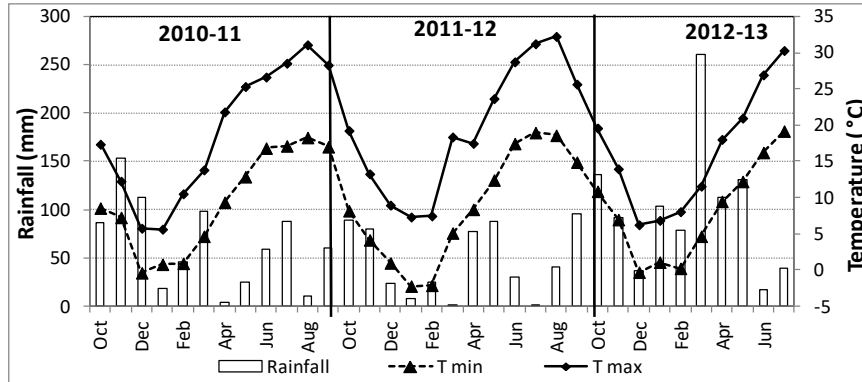
2
3 **B**
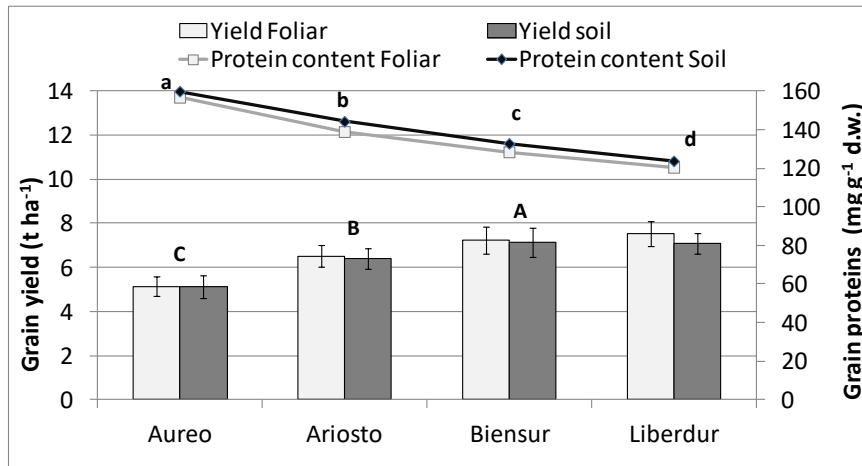
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6 **C**
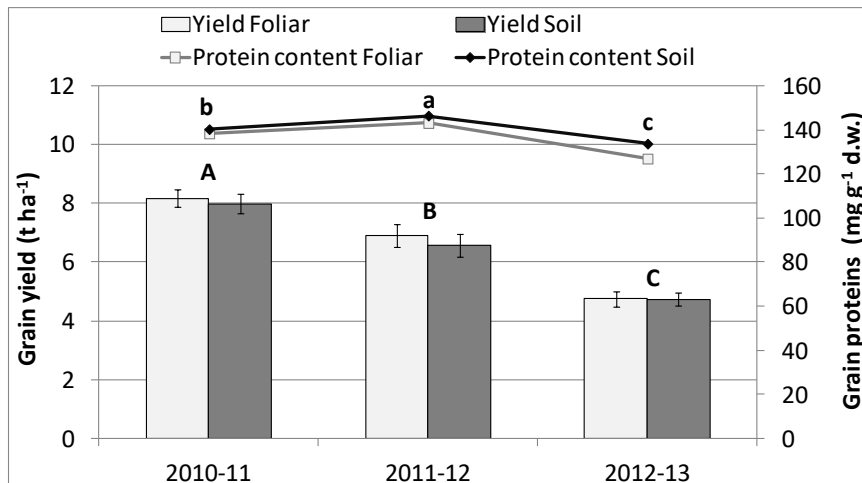
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8 **Figure** 1. (A) Monthly rainfall and mean temperatures; (B) grain yield (at 13% moisture) and protein

9 content (mg g^{-1} DW) (3-year means ± S.E.; n=9) in four varieties of durum wheat and (C) across three-

10 year trial under late-season foliar vs. soil N fertilization. Lower case letters: differences in grain protein

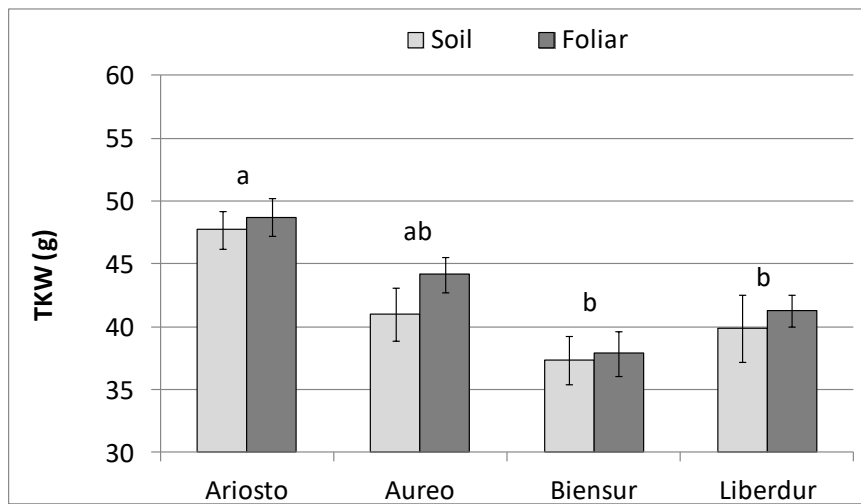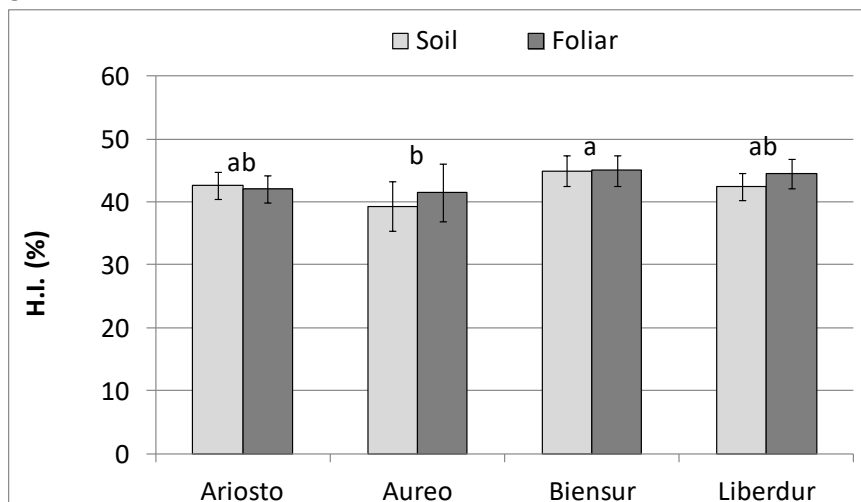11 contents among varieties/years. Capital letters: differences in yield among varieties/years (Newman-

12 Keuls test, *P* <0.05).

13

1 A
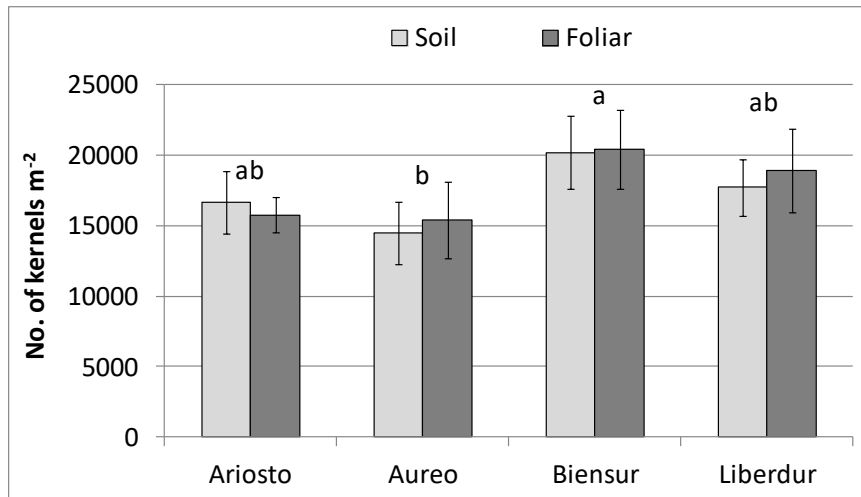
2
3 B

4
5 C

6
7 **Figure 2**. Three-year means (± S.E.; n=9) of yield components, i.e., number of kernels per unit surface

8   area (A) and thousand kernel weight TKW (dry weight) (A) and harvest index H.I (C) in four varieties of

9   durum wheat. Letters: differences among varieties (Newman-Keuls test, *P* < 0.05).

10
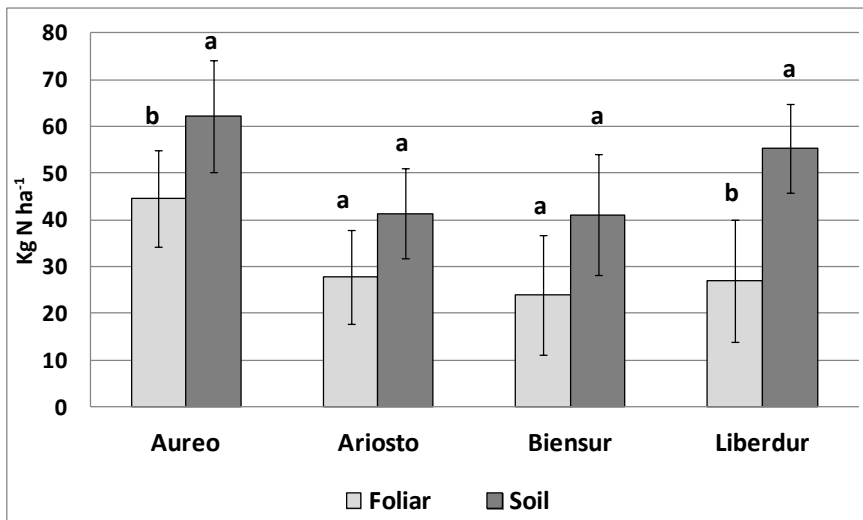
Figure 3. Apparent N balance (3-year average; $\pm$ S.E.; n=9) calculated as the difference between total N fertilization (foliar or soil application) and grain N content in four durum wheat varieties. Letters: differences between late-season foliar vs. soil nitrogen fertilization within same variety (Newman-Keuls test, $P < 0.05$). Note that smaller values indicate greater N uptake efficiency.
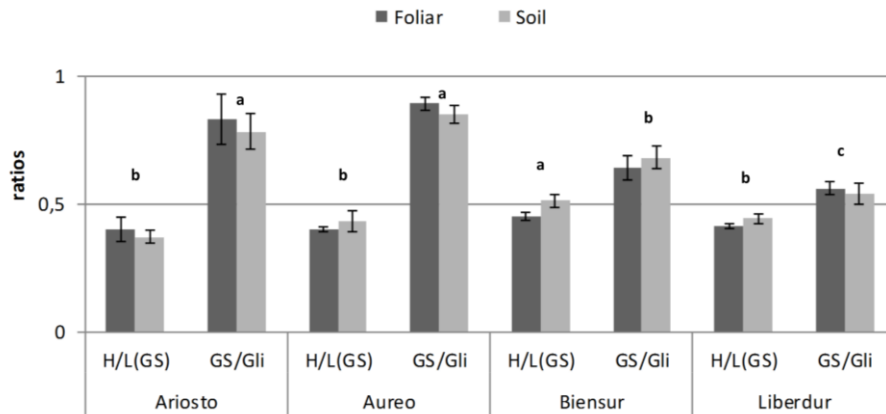
Figure 4. HMW-to-LMW-GS (H/L) and glutenin-to-gliadin (GS/Gli) ratios (3-year average; ± s.ᴇ.; n = 9) in four durum wheat varieties under late-season foliar vs. soil N fertilization. Letters: differences among varieties within each parameter (Newman-Keuls test, *P* < 0.05).

1

F1 + F2 = 91.40 %

F1 + F2 = 91.40 %
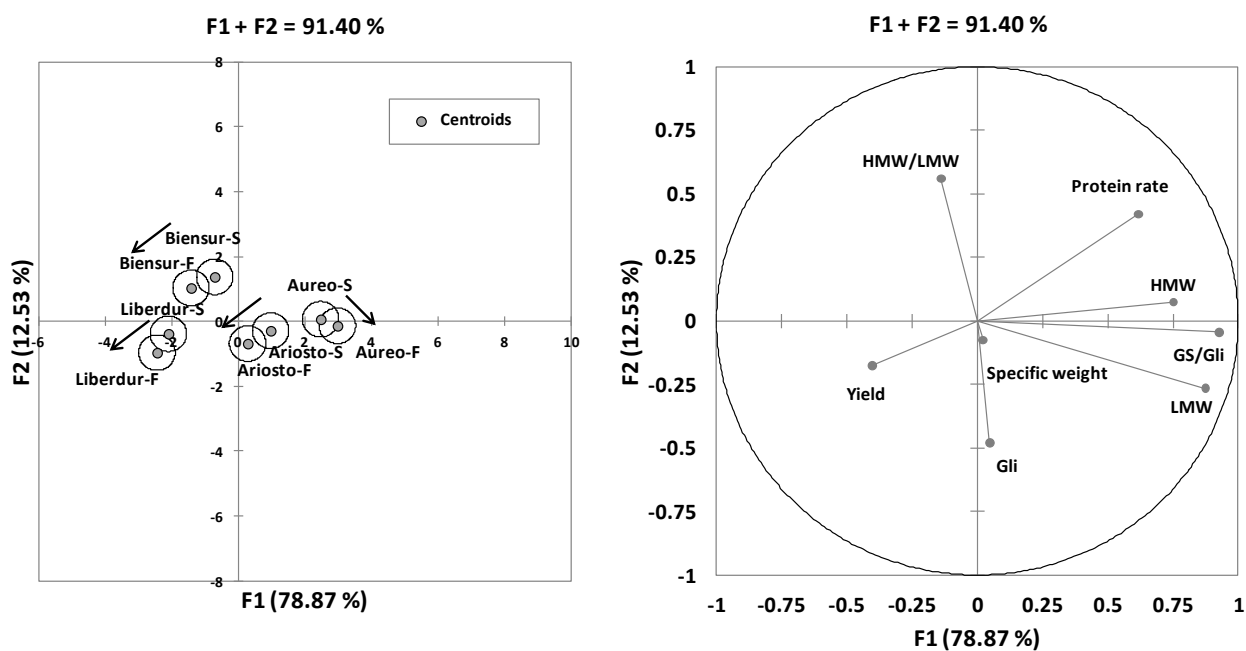
2

Variables	F1	F2
Yield	-0.401	-0.175
Specific weight	0.022	-0.075
Protein rate	0.618	0.420
HMW	0.752	0.075
LMW	0.875	-0.265
HMW/LMW	-0.139	0.561
Gli	0.047	-0.481
GS/Gli	0.929	-0.045

3

4

5 **Figure 5:** PCA with F1 and F2 loadings (highlighted values > |0.5|) and DA for variety classification

6 considering yield, specific weight of kernels, protein content, gluten proteins [HMW-GS, LMW-GS and

7 gliadins (Gli)], and HMW/LMW-GS and GS/Gli ratios. In DA arrows indicate variations from late foliar (F)

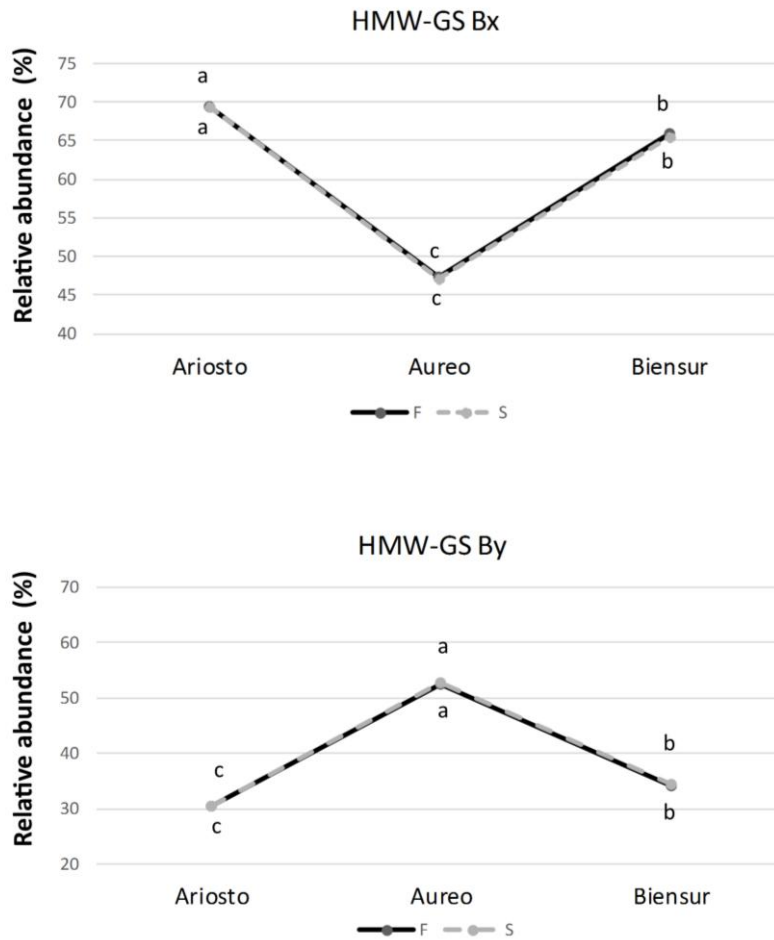8 to soil (S) nitrogen fertilization within same variety.

9
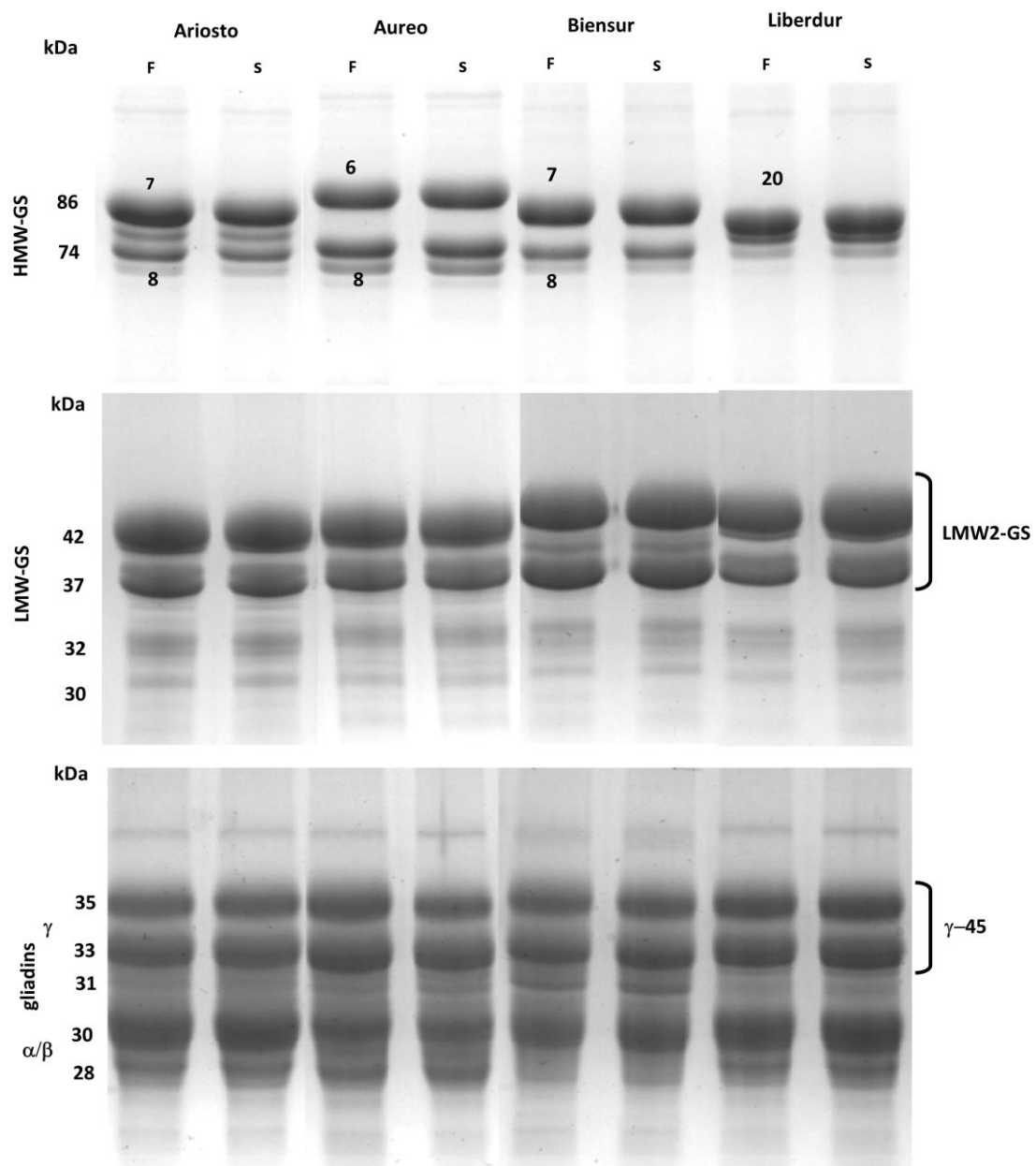
Figure 6. SDS-PAGE of HMW-GS (top), LMW-GS (middle) and gliadins (bottom) with their molecular weights of four durum wheat varieties under late-season foliar (F) vs. soil (S) nitrogen fertilization.
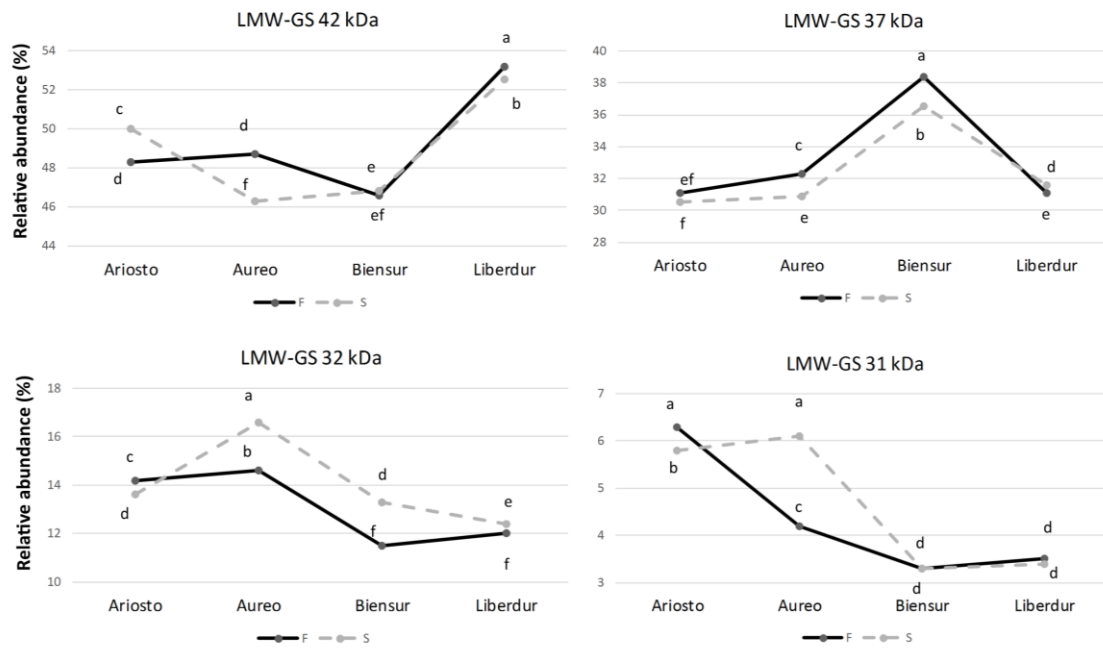
HMW-GS Bx

HMW-GS By

1

2   **Figure 7.** Relative abundances (%) of HMW-GS sub-units in three durum wheat varieties obtained by

3   densitometric analysis. Data are means of three replicates and three years (n = 9). Letters: differences

4   between late-season foliar (F) and soil (S) nitrogen fertilization within same variety (Newman-Keul test,

5    $P < 0.05$). Variety Liberdur is not included as By expression was null.
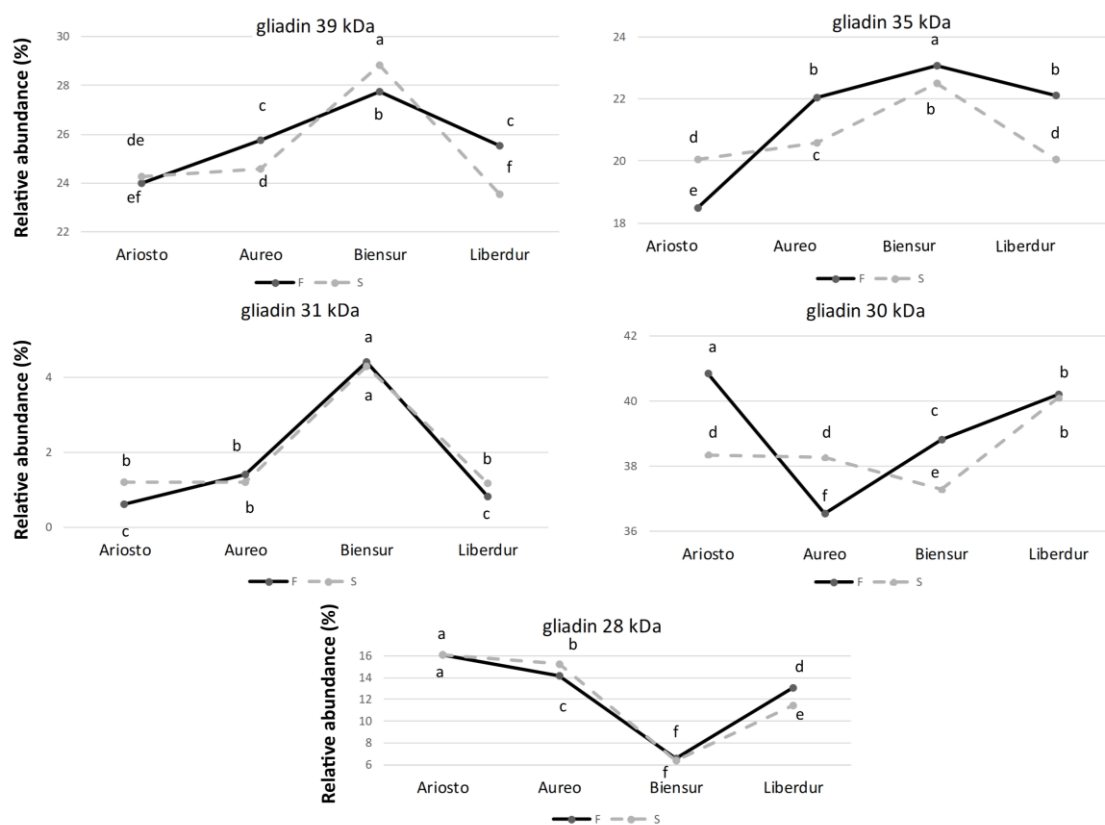
6

Figure 8. Relative abundances (%) of LMW-GS in four durum wheat varieties obtained by densitometric

analysis. Data are means of three replicates and three years (n = 9). Letters: differences between late-

season foliar (F) and soil (S) nitrogen fertilization within same variety (Newman-Keul test, $P < 0.05$).

3   **Figure 9.** Relative abundances (%) of γ and $\alpha-\beta$ gliadins in four durum wheat varieties obtained by

4   densitometric analysis. Data are means of three replicates and three years (n = 9). Letters: differences

5   between late-season foliar (F) and soil (S) nitrogen fertilization within same variety (Newman-Keuls test,

6   *P* < 0.05).