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Durum wheat yield and protein influenced by nitrogen management and cropping rotation

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ABSTRACT

Nitrogen (N) is the major input for cereal grain production and nitrogen management is critical for an optimal grain yield and protein concentration of durum wheat (*Triticum turgidum* subsp. *durum*) and efficiently use of nitrogen fertilizer. A two-year study was conducted in the semi-arid region of the Northern Great Plains (NGP) of USA to investigate nitrogen input level and application method under fallow-durum and pea-durum systems. A durum wheat (cv. Joppa) was planted in the field following fallow or field pea with 65 and 135 kg ha^{-1} nitrogen (N) input levels and four application methods under each N input level. Results showed that water is the major limiting factor determined the grain yield and protein concentration. Grain yield was greater but with slightly lower protein concentration following fallow (1958 kg ha^{-1}, 16.7%) than following field pea (1754 kg ha^{-1}, 16.4%). Increasing N input level from 65 kg ha^{-1} to 135 kg ha^{-1}decreased grain yield from 1933 to 1779 kg ha^{-1} but improved protein concentration from 16.3 to 16.8%. Split-application of N did not significantly affect yield and protein under drought year or under higher N rate, but there was a trend of yield increase under lower N rate in a wetter year. This study demonstrated that excessive input of N in a water-limited environment may result in “haying-off” causing low grain yield, test weight, HI, and NUE.

Introduction

In the semi-arid of the Great Plains of USA, the predominant crop in dryland production is wheat (*Triticum aestivum* L.) following summer fallow (Lenssen et al. 2007; Sainju et al. 2013b). Nitrogen and water typically are the most limiting factors for dryland crop production (O'Leary and Conor 1997b). Summer fallow usually retains soil water and nitrate nitrogen for the subsequent crop (Lenssen et al. 2007a), but recent studies have showed that what-fallow system affects soil quality by increasing soil erosion, reducing soil organic matter, and increase nutrient loss through leaching which resulted in decrease in annual grain yield (Lenssen et al. 2007; Sainju et al. 2013b, Mohammed et al. 2018). Therefore, there is a need to include alternative crops to rotate with wheat for annual cropping to diversify crop production and eliminate summer fallow.

Field pea (*Pisum sativum*, L.) is an important pulse crop that can be added to existing crop rotations to sustain crop yields in the arid and semi-arid regions (Miller et al. 2003a; Lenssen et al. 2007; Sainju et al. 2013; Sainju et al. 2019). Studies have reported that spring wheat grain yield and protein increased following pulses compared to spring wheat following spring wheat (Gan et al. 2003; Chen et al. 2012; Lin and Chen 2014). Since 1970, harvested pea area has been steadily increased while fallow is decreased (Tanaka et al. 2010). The rotations are not only increased crop yields, but also reduced the risk of crop failure, enhanced biodiversity, improved soil fertility, and increased farm income (Randall et al. 1997; Nielson 2001; Zenntner et al. 2002; Varvel and Wilhelm 2003; Muramoto et al. 2011; Chen et al. 2012; Miller et al. 2015; Sainju et al. 2019). In addition, the benefit of having pea in the rotation with spring wheat in the dryland cropping systems is that pea crop requires less water than some other crops to grow (Tanaka et al. 2010; Miller et al. 2015; Lenssen et al. 2018). Dry pea has a short growing season and shallow root system, therefore, could leave some soil moisture in the profile after their harvest (Nielsen 2001; McVay and Khan 2011; Miller and Holmes 2012). Furthermore, pea residues added N to soil due to high N concentration from N fixation or lower C/N ratio than non-legumes, which increases N mineralization, thereby reducing N fertilization input (Stevenson and van Kissel 1996; Miller et al. 2003b). However, it is not well understood what is the optimal N management for durum wheat grown in the pea-durum continuous cropping system in the semi-arid environment of the NPG.

Durum wheat, also called pasta wheat, is a tetraploid species of wheat, which is an ideal wheat for making pasta and higher protein durum wheat produced high cooked pasta firmness and low cooked pasta weight and cooking loss (Moayedi et al. 2021). Therefore, durum market demands a higher protein concentration in the grain and farmers normally apply a higher rate of N in durum production (Chen personal communication with farmers). Most wheat farmers in the Northern Great Plains apply fertilizer-N in the fall or early spring as one application before plating, which may result in low nitrogen use efficiency (NUE) or is subjected to a potential loss of N. Therefore, there is a need to study alternative N application method and timing for improved durum wheat yield and protein. Fertilizer-N applied as banded has greater benefits compared broadcast fertilization. Coulter-injection of urea ammonium nitrate (UAN) has showed less volatilization loss than broadcast application of urea (Mueller and Vyn 2017). But the most appropriate N application strategy for a farmer will depend on location, equipment, and weather during the growing season (Otteson et al. 2007). Split-application of N between fall banding and spring broadcast has been reported producing the maximum winter wheat yield and protein in Canada prairies (Beres et al. 2018).

The objectives of this study were (i) to investigate durum wheat yield and protein affected by replacing fallow with pea in water-limited environment, and (ii) to study durum wheat yield and protein in response to N input level and application method, as well as N use efficiency under fallow-durum and pea-durum.

Materials and methods

The experiment site was located at the dryland farm of the Eastern Agricultural Research Center (47°46'55" N, 104°14'52" W, elevation 691 m above sea level), about 12 km NW of Sidney, Montana, USA. Weather data were collected from a weather station located on-site and operated by North Dakota Agricultural Weather Network Center. The frost-free period at this site is between May 15th through September 21st. Soils is Williams loam (Fine-loamy, mixed, superactive, frigid Typic Argiustolls; 0-4% slope), which consists of very deep, well drained, moderately slow or slowly permeable soils predominantly formed in calcareous glacial till.

The study was established in the spring of 2017 and continued to 2018. The experiment consisted of two annual crop rotations in which a durum wheat (cv. Joppa) was planted following fallow (fallow-durum) or field pea (pea-durum). Fertilizer-N was applied at the rate of 65 and 135 kg N ha^{-1} for durum wheat phases under each rotation in four different methods and timings, i.e. 1) 100% applied by banding at planting, 2) 100% applied by broadcasting after seedling emergence, 3) 50% applied by banding at planting and 50% applied by broadcasting at seedling emergence, and 4) 50% applied by banding at planting, 30% by broadcasting at seedling emergence, and 20% by foliar application at stem elongation (Table 1). Prior to planting, soil samples were taken to test the background soil NO_3 concentrations. The initial soil N was 28 and 30 kg ha^{-1} after fallow and 25 and 28 kg ha^{-1} after pea in 60 cm soil profile in 2017 and 2018, respectively. Durum wheat was planted at 78 kg ha^{-1} using a plot planter at 22cm row spacing at a seeding depth of 3.8 to 5.0 cm on April 26, 2017 and May 8, 2018.

The experimental design was a randomized complete block in a split-split-plot arrangement with rotations as main plots. Within each main plot, two fertilizer-N rates and four application methods were randomly assigned. Each plot was 6.1 m long and 1.52 m wide and all treatment combinations were replicated three times. A blend of monoammonium phosphate (110-520-0 g kg^{-1} N-P_2O_5-K_2O) and urea (460-0-0) g kg^{-1} N-P_2O_5-K_2O) was used for soil-applied N. Urea-ammonium nitrate (280-0-0 g kg^{-1} N-P_2O_5-K_2O) was used for foliar N application. Initial soil test results indicated P deficiency and 50 kg P_2O_5 ha^{-1} was applied each year before durum and spring wheat planting in a form of 11-52-0 blend of N-P_2O_5-K_2O). Soils at this site are naturally high in K, and soil tests recommended no K fertilization. Other management practices such as weed and pest control for all crops were done according to Montana State University recommendations. Herbicide LV-6 (2,4-dichlorophenoxyacetic acid, 2-ethylhexyl ester) at 0.77 kg a.i. ha^{-1} and Discover (Clodinafop-propargyl) at 0.06 kg a.i. ha^{-1} were applied at tillering stage for controlling broadleaf and grass weeds.

Grain was harvested using a self-propelled Wintersteiger Classic plot combine (Wintersteiger, Utah, USA). Prior to combine harvest a biomass bundle sample was cut by hand from 3 rows x 1 m long area. The biomass was weighed and grain was threshed. The grain samples from bundle samples and combine harvest were placed in the drying room for two weeks at 35°C, cleaned, and weighed to estimate grain yield, and the straw samples were dried at 60 °C to get the dry biomass weight. Grain moisture, test weight, and protein content were measured using a Foss Infrared Grain Analyzer (Foss North America, Eden Prairie, MN). Grain

Analyzer. The reported grain yields were adjusted to 120 g kg^{-1} moisture content. The protein yield is calculated by

Protein yield = Grain yield × protein concentration ……………………………….[1]

Residual soil NO_3-N was determined by taking composite soil samples of 3 cores from each plot at 60 cm depths in two increments, 0-30 and 30-60 cm depths, air dried and ground to pass a 2 mm sieve. Soil NO_3-N was extracted with 1 M KCl solution and quantified by a Flow Injection Auto-analyzer (LACHAT, 1994).

Nutrient use efficiency (NUE) was calculated for the four fertilizer-N application methods when 135 kg N ha^{-1} was applied compared with 65 kg N ha^{-1}. The NUE is calculated by,

$$\text{NUE} = \frac{Biomass\ yield\ \left(@\ 135\ kg\ N\ ha^{-1}\right) - biomass\ yield\ (@35\ kg\ N\ ha-1)}{\Delta\ N\ rates} \ldots\ldots\ldots\ldots\ldots\ldots[2]$$

$$\text{NUE} = \frac{Grain\ yield\ \left(@\ 135\ kg\ N\ ha^{-1}\right) - grain\ yield\ (@35\ kg\ N\ ha-1)}{\Delta\ N\ rates} \ldots\ldots\ldots\ldots\ldots\ldots[3]$$

$$\text{NUE} = \frac{Protein\ yield\ \left(@\ 135\ kg\ N\ ha^{-1}\right) - Protein\ yield\ (@35\ kg\ N\ ha-1)}{\Delta\ N\ rates} \ldots\ldots\ldots\ldots\ldots\ldots[4]$$

Where, ΔN = difference between higher and lower N rates.

Statistical analysis was performed using SAS software (version 9.4, SAS Institute Inc. Cary, NC, USA, 2012). Analysis of variance was performed by considering year, rotation, N rate, application methods and their interactions. Treatment replications were considered as random effect. If the analysis indicated a significant interaction, least square means were investigated using the SLICE option in the LSMEANS statement to determine the effect of year, rotation, N rate, and application methods. Differences among treatment means for all variables were assessed using the LINES option in the LSMEANS statement which were denoted by letters in the figures. Effects were considered significant at the $P \leq 0.05$ probability level.

Results

Weather

Soil moisture at the experiment site relied on only annual precipitation. Mean annual precipitation (1949-2018) at this experimental site was 349 mm, with about 269 mm occurring from April through September (Figure 1). Both years were characterized by cooler than 78 yrs normal. Average monthly temperatures in 2017 were 1.0 to 2.0 °C cooler than normal during the entire growing season except for July (Figure 1a). Average monthly temperatures in 2018 were 1.0 to 5.0 °C cooler than normal during the entire growing season except for May. Compared to 2017, temperatures were a little warmer in during germination and early emergence growth in 2018.

The weather conditions resulted in varied levels of precipitation during the two growing seasons (Figure 1b). Compared to normal growing season precipitation in this area, year 2017 was considered a drought year. In 2017, crops received below average rainfall from April to July and then exceeded in August through September. In 2018, except May, total monthly rainfall during the growing season was slightly lower than 78-year average. However, higher than normal precipitation (41 mm) in May brought the season-long precipitation near normal (272 mm).

Biomass and Grain Yield

The year and rotation effects were significant on durum biomass and grain yield, and N rate had a significant effect on grain yield, but not on biomass (Table 2). Durum biomass and grain yields were much higher in 2018 (6623 and 2645 kg ha^{-1}) than in 2017 (5232 and 1066 kgha^{-1}), and the fallow-durum produced more biomass and grain (6544 and 1958 kg ha^{-1}) than the pea-durum rotation (5310 and 1754 kgha^{-1}) (Figure 2 and Figure 3). While N rate and application method did not significantly affect the biomass yield in this study (Table 2, Figure 3), the N rate had a significant impact on grain yield (Table 2, Figure 2). With the N rate increasing from 65 to 135 kg ha^{-1}, the grain yield decreased from 1933 to 1779 kg ha^{-1}. Split application did not significantly affect biomass and grain yield (Table 2), but there was a trend of increasing grain yield in 2018 under 65N input level (Figure 4).

Protein

Year and N rate had a significant effect on durum protein, but the rotation effect was not statistically significant (Table 2, Figure 5). Durum grain protein concentration was greater in 2017 (172 g kg^{-1}) than in 2018 (159 g kg^{-1}). Protein concentration was greater in 135 kg N ha^{-1} (168 g kg^{-1}) than in 65 kg N ha^{-1} treatment (163 g kg^{-1}). Although the differences were not statistically significant, the pea-durum rotation (167 g kg^{-1}) tended to produce slightly higher protein concentration than the fallow-durum rotation (164 g kg^{-1}). The N application method did not significantly affect protein concentration (Table 2). The effects of year, rotation, and N rate were opposite to grain yield, treatments that had higher yields tended to have lower protein concentrations.

Nitrogen Use Efficiency

In this study, lower N rate had higher grain yields which resulted in negative NUE values. When N rate was increased from 65 to 135 kg ha^{-1}, the NUE was 1.06 kg kg^{-1} based on biomass yield, -2.21 kg kg^{-1} based on grain yield, and -0.23 kg kg^{-1} based on protein yield calculated using Equation 3, 4, and 5.

Discussion

Water is the major limiting factor in dryland agriculture. Results from this study clearly demonstrated the effects of available water on yield and protein. The year 2017 was a dry year when compared to 2018 (Figure 1) which resulted in higher grain yield but lower protein concentration (Figure 3 and 4). The effects of moisture were also demonstrated in rotation treatment; durum wheat biomass and grain yields were greater following fallow than following field pea. Summer fallow has been used to store precipitation water in semi-arid and arid area to reduce the risk of crop failure (Aase and Pikul 2000). Researchers calculated the available water threshold for cereal grain production in Pacific Northwest inland area and Northern Great Plains.

Crop yield response to nitrogen input is also affected by available soil moisture plus precipitation during the growing season. In this study, durum biomass increased from 5890 to 5964 kg ha^{-1}, but the grain yield decreased from 1779 to 1933 kg ha^{-1} (Figure 2 and 3). This is because excessive N input promoted the early vegetative growth of durum wheat and consumed excessive stored soil moisture resulting water shortage during the grain filling and “haying-off”. Haying-off is a negative grain yield response of dryland wheat to nitrogen fertilizer input (Herwaarden et al., 1998). Herwaarden et al. (1998) studied wheat response to N application at three locations in southern New South Wales, Australia. They found grain yield decreased 24% at highest N input treatment compared to control. Application of N increased biomass at anthesis, but kernel weight and harvest index decreased remarkably. The authors concluded that haying-off was associated with reduced post-anthesis assimilation due to lack of soil water and reduction in post-anthesis assimilation and retranslocation of pre-anthesis reserved assimilation. A study using a wheat model to assess impact of the expected future climate with elevated CO2, lower growing season rainfall and higher temperature on the incidences of haying off of wheat grown in south-eastern Australia. They found that the impact of climate on crop haying off may be reduced by agronomic practices, such as sowing crop early.

Although protein concentration increased from 16.3 to 16.8% when N input increased from 65 to 135 kg ha^{-1} (Fig. 4). The NUE was negative 0.23 kg kg^{-1} based on protein yield. This is because the grain yield decreased when high rate of fertilizer N was applied. In dryland production systems, NUE remains very low (Raun and Johnson 1999). Therefore, the N input should be budgeted based on the amount of stored soil moisture plus the predicted rainfall during the growing season. Excessive input of N fertilizer not only lower crop NUE, but also left a substantial amount of residual N in the soil profile. In this study, soil NO3-N was 37% greater when higher rate (135 kg N ha^{-1}) of N fertilizer used in the top 30 cm of soil. To avoid excessive residual N left in the soil profile and to improve NUE, fertilizer should be split-applied. In this study, Split-application of N did not significantly affect yield and protein under drought year and at higher N rate, but there was a trend of yield increase under lower N rate in a wetter year. This indicated 135 kg ha^{-1} of N has exceeded the crop demand in this low rainfall area, and 65 kg ha^{-1} is sufficient for durum production. The trend of yield increase with split application of 65 kg N ha^{-1} suggest farmers should split-application of N fertilizer to improve NUE.

CONCLUSIONS

In this study, water is the major limiting factor affecting durum wheat yield and protein concentration. Under the water limited environment, increasing N input level promoted the early growth of biomass and consumed too much water from soil profile in the early growing stage, which resulted in decreased grain yield, lower HI, and negative NUE. Results from this study suggest nitrogen input rate should be budgeted based on available soil moisture and the predicted rainfall amount in the growing season. Nitrogen should also be split-applied according the amount of water received or predicted to reduce the risk of haying-off.

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TABLES

Table 1. Description of fertilizer-N application strategies for the 65 and 135 kg N ha^{-1} rate applied to durum and spring wheat plots after either fallow or pea phases of the rotation.

Treatment name	N rate (kg ha^{-1})	Method of N fertilization
100Band	65 or 135	All fertilizer banded at planting
100Broad	65 or 135	All fertilizer broadcast two weeks after emergence
50P50E	65 or 135	50% banded at planting + 50% broadcast two weeks after emergence
50P30E20F	65 or 135	50% banded at planting + 30% broadcast two weeks after emergence + 20% foliar at elongation (Feekes 10.5)

Table 2. Summary statistics (*P* > F) for dependent variables for durum wheat assuming fixed effects of year, crop rotations, and fertilizer-N treatments and their interactions and random block effects.

Source	Grain yield	Test weight	Protein conc.	Protein yield	Biomass	Harvest index
				--- *P* > F ---		
Year (Y)	***	***	***	***	***	***
Rotation (R)	**	0.85	0.20	**	***	**
N rate (N)	*	0.22	**	0.20	0.78	0.12
Split (S)	0.19	0.65	0.66	0.23	0.20	0.57
Y×R	0.22	0.07	0.22	0.68	0.37	0.39
Y×N	0.52	0.84	0.99	0.79	0.18	0.67
Y×S	0.51	0.44	0.54	0.61	0.83	0.92
R×N	0.31	0.86	0.72	0.38	0.89	0.56
R×S	0.71	0.50	0.94	0.72	0.45	0.84
N×S	*	0.85	0.58	0.11	0.47	0.10
Y×R×N	0.12	0.86	0.72	0.15	0.82	*
Y×R×S	0.29	0.31	0.25	0.68	0.99	0.53
R×N×S	0.49	0.86	0.93	0.47	0.90	0.22
Y×R×N×S	0.37	0.93	0.98	0.47	0.96	0.13

* Significance at the 0.05 probability level.

** Significance at the 0.01probability level.

*** Significance at the 0.001 probability level.

LIST OF FIGURES

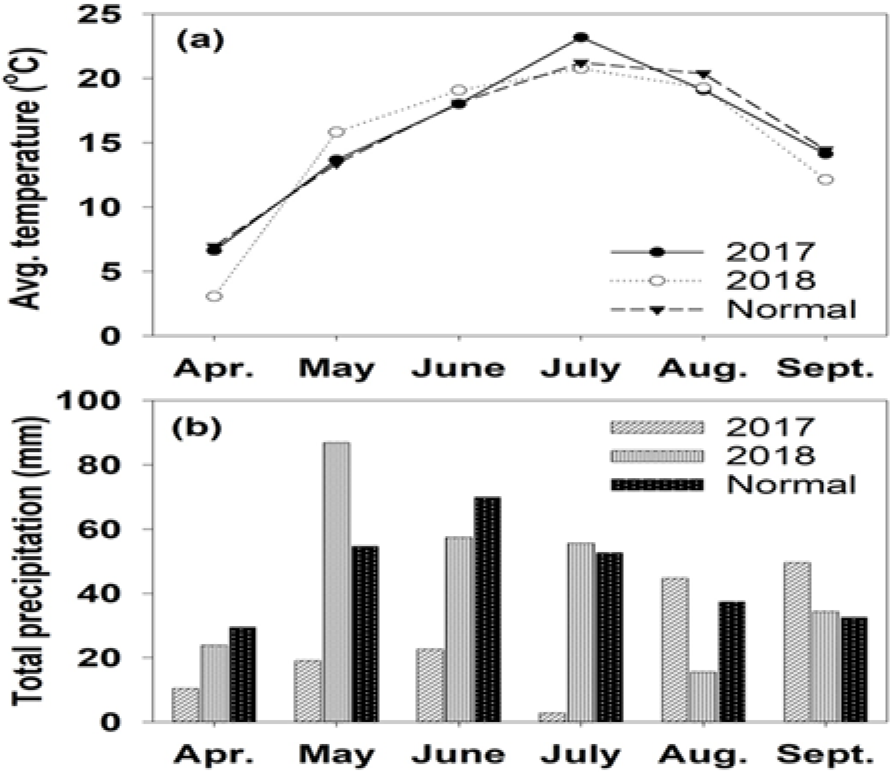
Fig. 1: Growing season measured (2017 and 2018) and long-term average (1949-2018) monthly average temperature (a) and monthly total precipitation (b) at the experiment site.

Fig. 2: Durum wheat biomass yield as affected by year, crop rotation, and N rate. Biomass yield is on dry mass basis. Different letters on top of the bars represent significant difference between the means at $P \leq 0.05$. Error bars represents standard errors of the means.

Fig. 3: Durum wheat grain yield as affected by year, crop rotation, and N rate. Grain yield was adjusted to 120 g kg^{-1} moisture content. Different letters on top to the bars represent significantly different between the means at $P \leq 0.05$. Error bars are standard errors of the means.

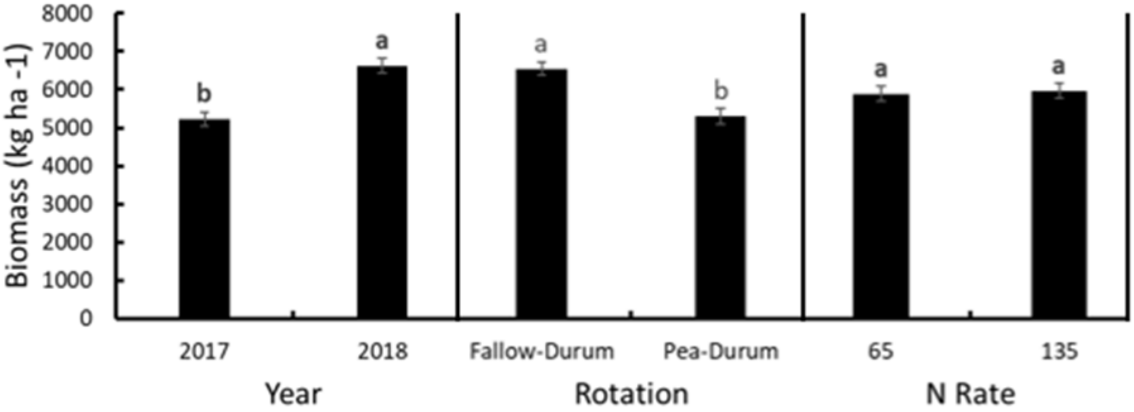
Fig. 4: Durum grain yield as affected by split application of fertilizer-N at 65 kg ha^{-1} input level in 2017 and 2018 growing seasons. Error bars are standard errors of the means.

Fig. 5: Durum wheat protein concentration as affected by year, crop rotation, and N rate. Different letters on top of the bars represent significantly different between the means at $P \leq 0.05$. Error bars are standard errors of the means.



(a)
Avg. temperature (°C)
25
20
15
10
5
0
2017
2018
Normal
Apr.
May
June
July
Aug.
Sept.
(b)
Total precipitation (mm)
100
80
60
40
20
0
2017
2018
Normal
Apr.
May
June
July
Aug.
Sept.

Fig. 1



Biomass (kg ha -1)
8000
7000
6000
5000
4000
3000
2000
1000
0
b
a
a
b
a
a
2017
2018
Fallow-Durum
Pea-Durum
65
135
Year
Rotation
N Rate

Fig. 2

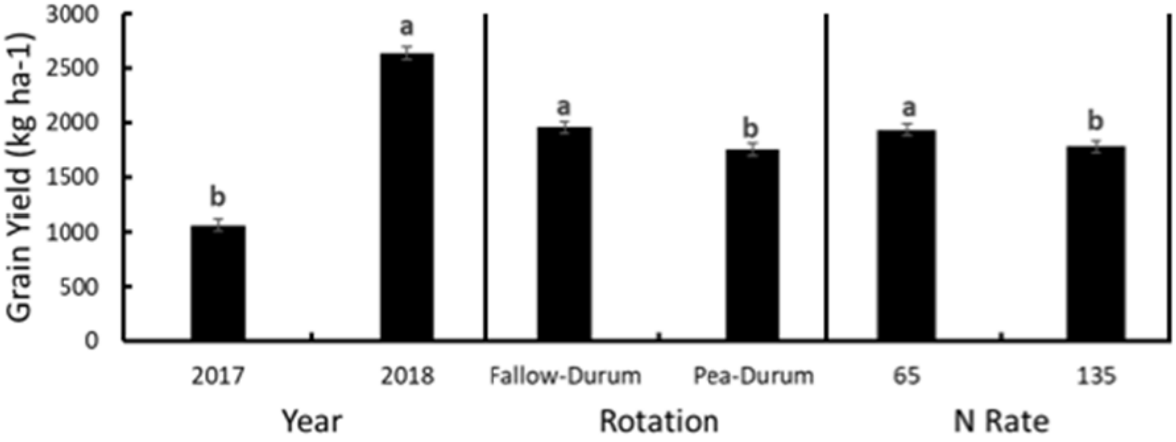

Grain Yield (kg ha-1)
3000
2500
2000
1500
1000
500
0
b
a
a
b
a
b
2017
2018
Fallow-Durum
Pea-Durum
65
135
Year
Rotation
N Rate

Fig. 3

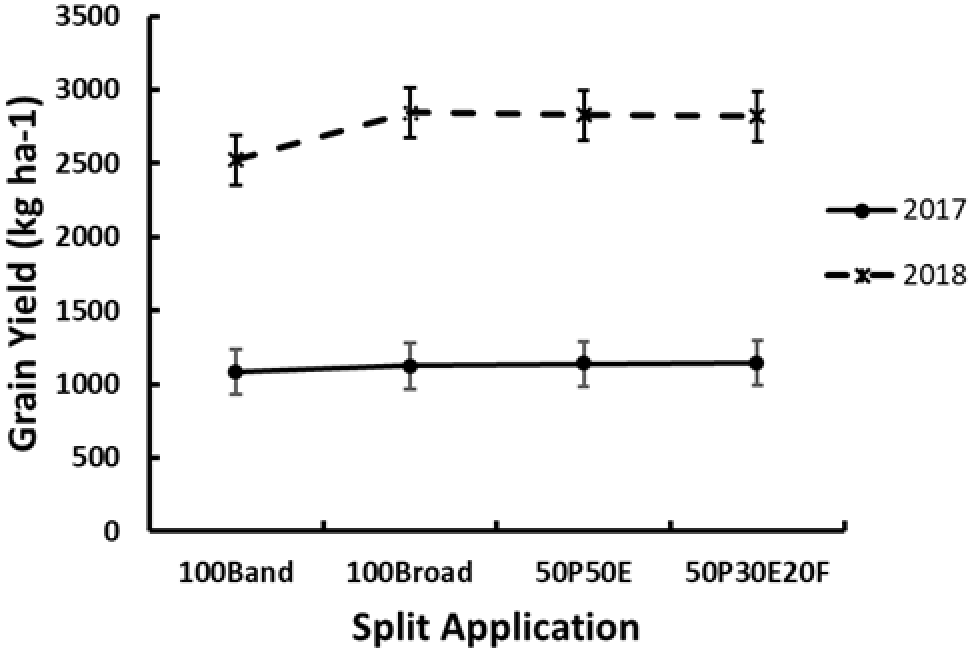

Grain Yield (kg ha-1)
3500
3000
2500
2000
1500
1000
500
0
2017
2018
100Band
100Broad
50P50E
50P30E20F
Split Application

Fig. 4

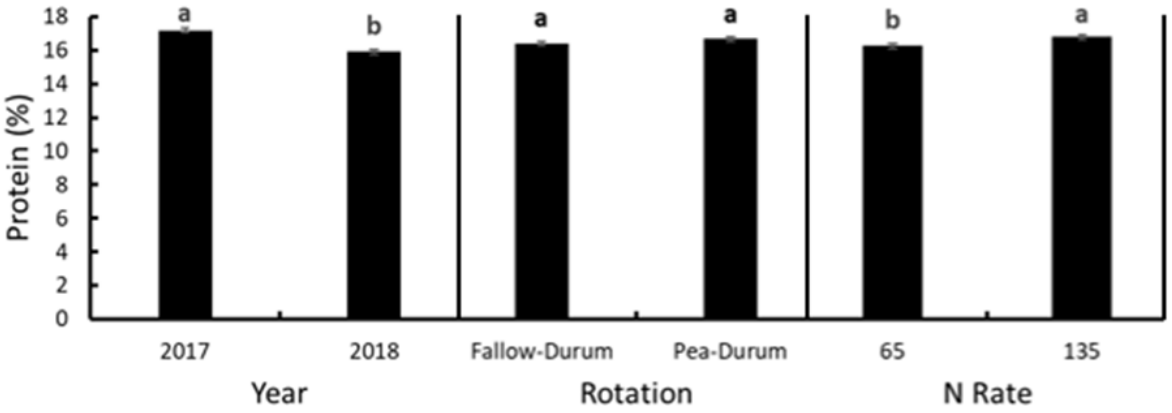

Protein (%)
0
2
4
6
8
10
12
14
16
18
a
b
a
a
b
a
2017
2018
Fallow-Durum
Pea-Durum
65
135
Year
Rotation
N Rate

Fig. 5

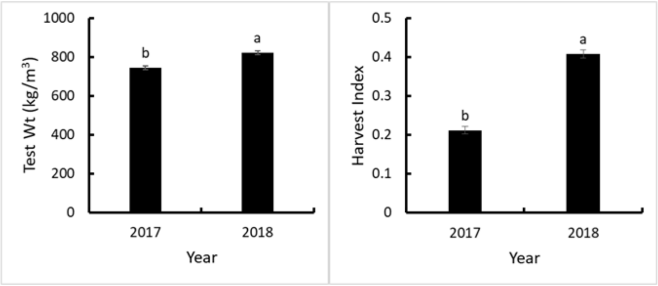

Test Wt (kg/m³)
0
200
400
600
800
1000
b
a
2017
2018
Year
Harvest Index
0
0.1
0.2
0.3
0.4
0.5
b
a
2017
2018
Year

Fig. 6

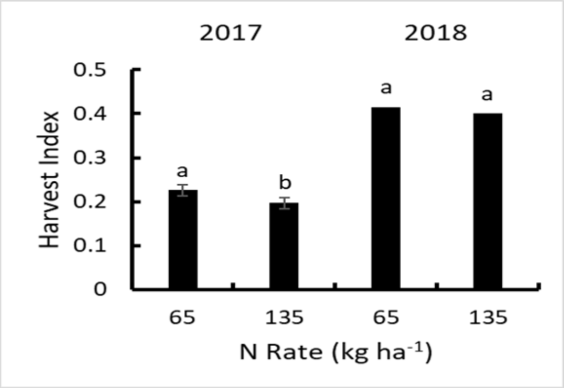

2017
2018
0.5
0.4
0.3
0.2
0.1
0
Harvest Index
a
b
a
a
65
135
65
135
N Rate (kg ha-1)

Fig. 7