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Yield and Grain Quality Response of Spring Wheat Varieties to Irrigation and Fertility Management

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Abstract

Experiments were conducted in 2020 and 2021 in North Dakota to determine the effects of foliar and soil applied fertilizers, variety and irrigation on yield and grain quality of spring wheat. Foliar application of N did not consistently increase yield and protein indicating the soil N levels were adequate to optimize yield. The variety Bolles had higher protein content than Faller. Zinc (Zn) content in the grain was greatest when applied at either flowering or post anthesis. It was also found to be correlated with grain protein content. Yield and grain protein content were negatively related. There was no consistent effect of phosphorous or Zn when applied to the soil on yield, protein, gluten, or Zn content in the grain. Zinc concentration in the grain was significantly correlated with the protein, gluten and P content of the grain. The timing of Zn application was critical to the success of translocating Zn to the grain. Grain Zn concentration increased with most late season foliar Zn applications to both varieties indicating potential for enriching spring wheat nutrient content through production management practices already common in areas that grow spring wheat.

Keywords

Zinc, Gluten, Fertilizer Timing, Nitrogen, Phosphorus

1. Introduction

After maize (*Zea mays* L.), wheat (*Triticum aestivum* L.) is the most important crop globally in terms of total production [1]. However, for many regions of the world, wheat is the most important crop in terms of calories and protein in the human diet. Of the three major cereals, wheat has the highest protein content [2]. The quality of the protein from wheat is relatively low when compared to other plant sources as it typically has sub-optimal levels of some of the essential amino acids, most particularly lysine [3]. Nevertheless, gluten, one of the primary protein types in wheat grain, is highly valued as it imparts functional qualities that are required for making popular foods such as raised breads and noodles. Of the wheat classes, hard red spring wheat has the highest protein content and most of the varieties that are currently grown have proteins that have high gluten strength which gives doughs the desired viscoelastic properties. For this reason, hard red spring wheat as a class is sold at a premium to most other classes. Furthermore, protein content can play an important role when marketing this class of wheat and is therefore strictly measured when sold. Given the value of protein in spring wheat, variety selection and fertility management can significantly impact the value of the crop at harvest.

Wheat and other cereals in general have a relatively low zinc (Zn) concentration in their grain, particularly in areas of the world where soils are deficient in zinc. Therefore, there is concern that people in areas of the world where a large proportion of the calories consumed come from wheat may become deficient in Zn. Zinc deficiencies in humans affect the skin, the central nervous system and can impair the immune system increasing the risk of respiratory, gastrointestinal, or other infections. Zinc deficiencies in children can delay growth and cause stunting and reduced brain function. Agronomic and breeding approaches have recently been employed to improve Zn content in wheat grain as a means of reducing the Zn deficiency in humans in areas of the world of highest risk to this deficiency [4].

Nitrogen and phosphorus are the two plant essential nutrients that are most likely to be limiting to wheat production in the northern great plains of North America. Chemical fertilizers containing these nutrients are commonly applied every cropping season to fields not under organic production. Nitrogen availability to the plant can have a big impact on both the yield and the protein content of the wheat crop, with deficiencies early in the season having the greatest impact on yield and deficiency later in the season having the greatest impact on protein content. Except on sandy soils, most N fertilizer is applied prior to planting in the northern great plains [5]. However, nitrogen in the soil can be lost to leaching and denitrification, resulting in a global average nitrogen fertilizer efficiency of only 33% [6]. Split applications have the potential to improve fertilizer use efficiency in seasons and soils where N losses may be significant [7]. A post-anthesis foliar application of the nitrogen fertilizer urea ammonium nitrate (UAN) diluted with water to reduce leaf burn has the potential for increasing grain protein. This application, however, has been found to only be profitable when yields and the protein premiums are high [8]. Milling and baking analysis has shown that augmenting the protein in the grain in this way did not diminish its functionality [9].

Though phosphorus (P) is not a significant component of grain protein, P fertilization can indirectly impact grain quality. When P is limiting yield an application that increases grain yield may reduce protein content as the plant may add additional starch to the kernel, diluting the protein in the grain especially if N availability cannot match the increased need to maintain a favorable balance between protein and starch [10]. Applications of phosphorus fertilizers can reduce the Zn concentration in the grain of wheat [11].

Zinc is used by the wheat crop in only very small amounts and is generally not yield-limiting in wheat production in North Dakota [7]. However, applying zinc in excess of what is needed to optimize yield may be beneficial to improving its concentrations in the grain and thereby help reduce Zn deficiency in humans in regions where this is problematic. Zinc has shown a benefit when applied to crops by seed priming (imbibed into the seed prior to planting), as a chelate or as $ZnSO_4$ to the soil before planting, or as a foliar application [12]. In deficient soils, soil applications were more effective in increasing yield and the combination of soil and foliar applied zinc were the most effective in increasing its concentration in the grain [13]. Other research [14] has recommended a foliar application over a soil application to augment zinc in the grain. Two foliar applications of zinc were found to be needed to increase zinc levels in the grain above the desired threshold of 40 $mg \cdot kg^{-1}$ [15] and farmers are unlikely to adopt this system of increasing zinc in the grain without a price incentive.

Experiments were conducted in 2020 and 2021 to investigate effects of nitrogen, phosphorus, and zinc fertilization practices on yield and grain quality, including zinc concentration, in hard red spring wheat.

2. Materials and Methods

2.1. Variety, Water Management and Fertilizer Study

Experiments were conducted in 2020 and 2021 at the NDSU Carrington Research Extension Center in North Dakota, USA. Experiments consisted of factorial combination of three factors in a randomized complete block design with four replications. The factors consisted of varieties (two levels), water management (two levels) and fertilizer treatments (six levels). The two spring wheat varieties were Bolles, a variety with high grain protein content and moderate to low yield potential compared to other commonly grown commercial varieties, and Faller, a high yielding variety with lower-than-average protein content. The water management treatments were dryland (only rainfall as the source of water) and irrigated. Natural rainfall totals were 188 and 140 mm in 2020 and 2021, respectively. Water was applied as recommended for best management practices for irrigated wheat production on the footprints which received irrigation. The fertilizer treatments were as follows: 1) nitrogen (N) at 33 $kg \cdot ha^{-1}$ applied at the 3 leaf stage, 2) N at 33 $kg \cdot ha^{-1}$ plus zinc at 1.12 $kg \cdot ha^{-1}$ applied at the 3-leaf stage; 3) a foliar application of the commercial fungicide Prosaro™ which contains equal parts of prothioconazole and tebuconazole at the rate 0.35 kg/ha of the combined active ingredients at the flowering stage; 4) Prosaro at rate 0.35 kg/ha of active ingredients combined with 1.12 $kg \cdot ha^{-1}$ Zn was applied at flowering stage; 5) N at 33 $kg \cdot ha^{-1}$ at the post-anthesis stage (7 days after flowering); and 6) N at 33 $kg \cdot ha^{-1}$ plus Zn at 1.12 $kg \cdot ha^{-1}$ post-anthesis (7 days after flowering). The nitrogen in this experiment was from a 28% solution of urea ammonium nitrate (UAN). The zinc was supplied from the commercial product called Blue Tsunami^{TM} that contained 10% chelated zinc.

Wheat was sown at a rate of 430 $plants \cdot m^{-2}$. Individual plots were 125 m^2. Protein content was obtained from a 100-gm subsample of each plot using a calibrated NIR analyzer. Leaf nutrient concentration was determined using the nitric acid tissue digest method coupled with detection by inductively coupled plasma atomic emission spectroscopy (ICP-AES) [16]. Thousand kernel weight was determined by calculating the number of kernels in a 10 g sample and converting data to the weight of 1000 kernels.

Data were subject to an analysis of variance (ANOVA) using Statistic® (version 8.0 for Windows). The least significant difference (LSD) at $P < 0.05$ was used to compare means of the variables measured. Correlation analysis was used to detect significant relationships between variables of interest using the Pearson correlation, with $P < 0.05$ considered significant.

2.2. Basal Fertilization Study

Field experiments were conducted in 2020 and 2021 at the NDSU Carrington Research Extension Center. The experiments were arranged using a randomized complete block design with four replications. Treatments consisted of eight different fertilizer treatments: Treatments 1 was the control where no P or zinc was applied; Treatments 2 - 4 were three different rates (28, 56 and 112 $kg \cdot ha^{-1}$) of the fertilizer 10-40-0-1-0 which contains 10, 40, 0, 1 and 0 percent by weight of nitrogen, phosphorus, potassium, sulfur and zinc, respectively. In the tables, treatments 2 - 4 are identified as MES 25, MES 50 and MES 100, respectively. Treatments 5 - 7 were three different rates (28, 56 and 112 $kg \cdot ha^{-1}$) of the fertilizer 10-40-0-1-1 which contains 10, 40, 0, 1 and 1 percent by weight of nitrogen, phosphorus, potassium, sulfur, and zinc, respectively. In the tables, treatments 5 - 7 are identified as MESZ 25 MESZ 50, MESZ 100, respectively. Finally, treatment 8 received 1.58 kg $ZnSO_4$ ha^{-1} and no P. All fertilizers were applied prior to planting as in-furrow treatments. Spring wheat was sown at a rate of 430 seeds per m^2. Was this no-till? The area of each plot was 125 m^2.

Protein and gluten content was obtained from a 100-gm subsample of each plot using a calibrated NIR analyzer. The same method as described above for determining the nutrient content of plant tissues was used for determining N and Zn content in the grain. Thousand kernel weight was determined by calculating the number of kernels in a 10 g sample and converting data to the weight of 1000 kernels.

Data were subject to an analysis of variance (ANOVA) using Statistic (version 8.0 for Windows). The least significant difference (LSD) at $P < 0.05$ was used to compare means of the variables measured. Correlation analysis was used to detect significant relationships between variables of interest using the Pearson correlation, with $P < 0.05$ considered significant.

3. Results and Discussion

3.1. Variety, Water Management and Fertilizer Study

Conditions were generally more favorable for wheat production in 2021 than in 2020 due to better rainfall and more cooler temperatures during the season. There was a significant interaction for variety, water management, and cropping year for thousand kernel weight ($P < 0.01$) (**Table 1**). In 2020, the 1000-kernel weights of Bolles and Faller were 35.9 and 36.2 g, respectively. These values were 8.8% less in Bolles and 10.8% less in Faller when grown with irrigation compared to when grown under dryland conditions. In contrast, in 2021, the 1000-kernel weights of Bolles and Faller were 35.6 and 37.0 g, respectively. Under irrigation in 2021, these values were 10.2% and 16.2% higher than when grown under dryland conditions. Thousand kernel weight is not always correlated with yield as yield is a product of both kernel numbers and kernel weight. Conditions were less favorable for developing high kernel numbers in 2020 so that during grain filling there was less competition for photosynthates on a per kernel basis resulting in the kernels becoming slightly larger as conditions that season allowed for good grain fill. In 2021, the higher yield under irrigation compared to dryland conditions can be partially explained by the higher 1000-kernel weight suggesting that moisture during grain-fill could have limited the amount of photosynthate that was available to established kernels this season.

There was a significant three-way interaction between variety, water management, and cropping year for grain yield ($P < 0.01$) (**Table 1**). In 2020, the grain yields of Bolles and Faller grown without irrigation were 2369 $kg \cdot ha^{-1}$ and 2855 $kg \cdot ha^{-1}$, respectively, which was 57.2% and 66.1% of the yield when they were grown under irrigation. In 2021, however, Bolles and Faller when grown without irrigation had similar yields and were only 28.3 and 36.8% higher when grown with irrigation. The relative performance for yield of the varieties was surprising in 2021, as Faller typically has much higher yield than Bolles regardless of the environment.

Table 1. Kernel weight and yield of two wheat varieties grown under different water management in 2020 and 2021.

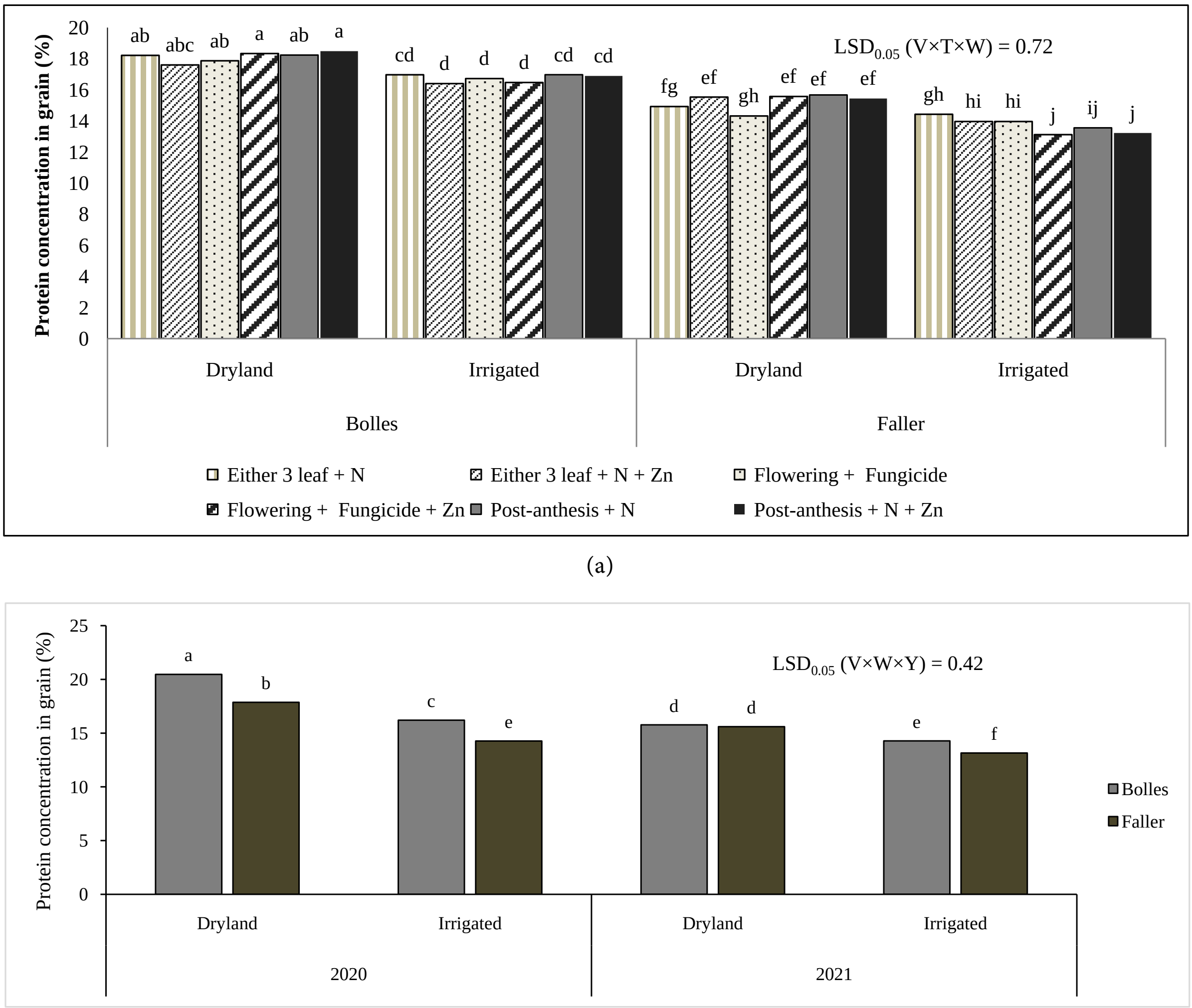
	Kernel weight (g 1000 kernels^{-1})				Yield ($kg \cdot ha^{-1}$)			
	2020		2021		2020		2021	
Variety	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Bolles	35.9	33.0	30.5	33.6	2369	4141	3784	4857
Faller	36.2	32.7	32.8	36.9	2855	4319	3594	4920
LSD 0.05 (VxWxY)	1.0				97			

There was a significant interaction between varieties, fertilizer treatment and water management ($P < 0.01$) (**Figure 1(a)**) for grain protein. Bolles had greater protein content than Faller regardless of water management treatment with the highest protein obtained with Bolles when grown without irrigation (**Figure 1(b)**). For both varieties, protein content declined significantly when grown under irrigation. Protein levels for Bolles varied from 17.7% to 18.5% and from 16.4% to 17.0%, without and with irrigation, respectively. The decline in protein under irrigation can be expected if irrigation results in an increase in yield because as yield increases, the protein in the kernel is diluted by the extra carbohydrate deposited in the kernel. The reduction in grain protein content in Faller was much more pronounced compared to Bolles under irrigation. There was no consistent difference in grain protein concentration among the various foliar treatments within each of the water management treatments (**Figure 1(a)**). Only with Faller and with irrigation were there significant differences between foliar treatments. In this treatment combination, the lowest protein was recorded when no nitrogen was included in the foliar treatments, or when it was applied after flowering.

There was also a significant three-way interaction between variety, water management and cropping year for grain protein concentration ($P < 0.01$) (**Figure 1(b)**). In 2021, Bolles and Faller had 26.3% and 17.9% more grain protein in the dryland conditions when compared to irrigated conditions. In 2021, however, the difference in protein between dryland and irrigated for Bolles and Faller was only 10.4% and 18.6%, respectively.

The grain N concentration was significantly affected by water management, fertilizer treatment and cropping year ($P < 0.01$) (**Figure 2(a)**). In 2020, the averaged of N concentration in dryland condition (3.0%) was higher than that of irrigated treatments (2.7%). Furthermore, the foliar treatments under dryland conditions were consistently higher than under irrigation except for the fungicide treatment with no N, and when N was applied post anthesis without Zn. Foliar treatments did not differ in grain N when irrigated in 2020 and ranged from 2.8% to 3.0% but were on average significantly lower than N levels for similar treatments under rainfed conditions which ranged from 2.9% to 3.0%.

Fertilizer treatment and water management also affected grain Zn concentration, and the responses differed between the two wheat varieties ($P < 0.01$) (**Figure 2(b)**). In Bolles grown in dryland condition, the highest grain Zn concentration (58.3 $\text{mg}\cdot\text{kg}^{-1}$) was found when Zn was applied post-anthesis (N + Zn), while applying Zn at flowering (fungicide + Zn) and the post-anthesis (N + Zn) in irrigated conditions produced the highest grain Zn concentrations of 65.4 and 54.6 mg/kg, respectively. With Faller when grown in dryland conditions, applying fungicide at flowering and N post-anthesis resulted in the highest Zn concentrations of 57.9 and 50.8 $\text{mg}\cdot\text{kg}^{-1}$, respectively, while grain Zn concentration did not differ among fertilizer treatments in irrigated conditions and ranged from 39.0 mg/kg to 49.5 mg/kg.



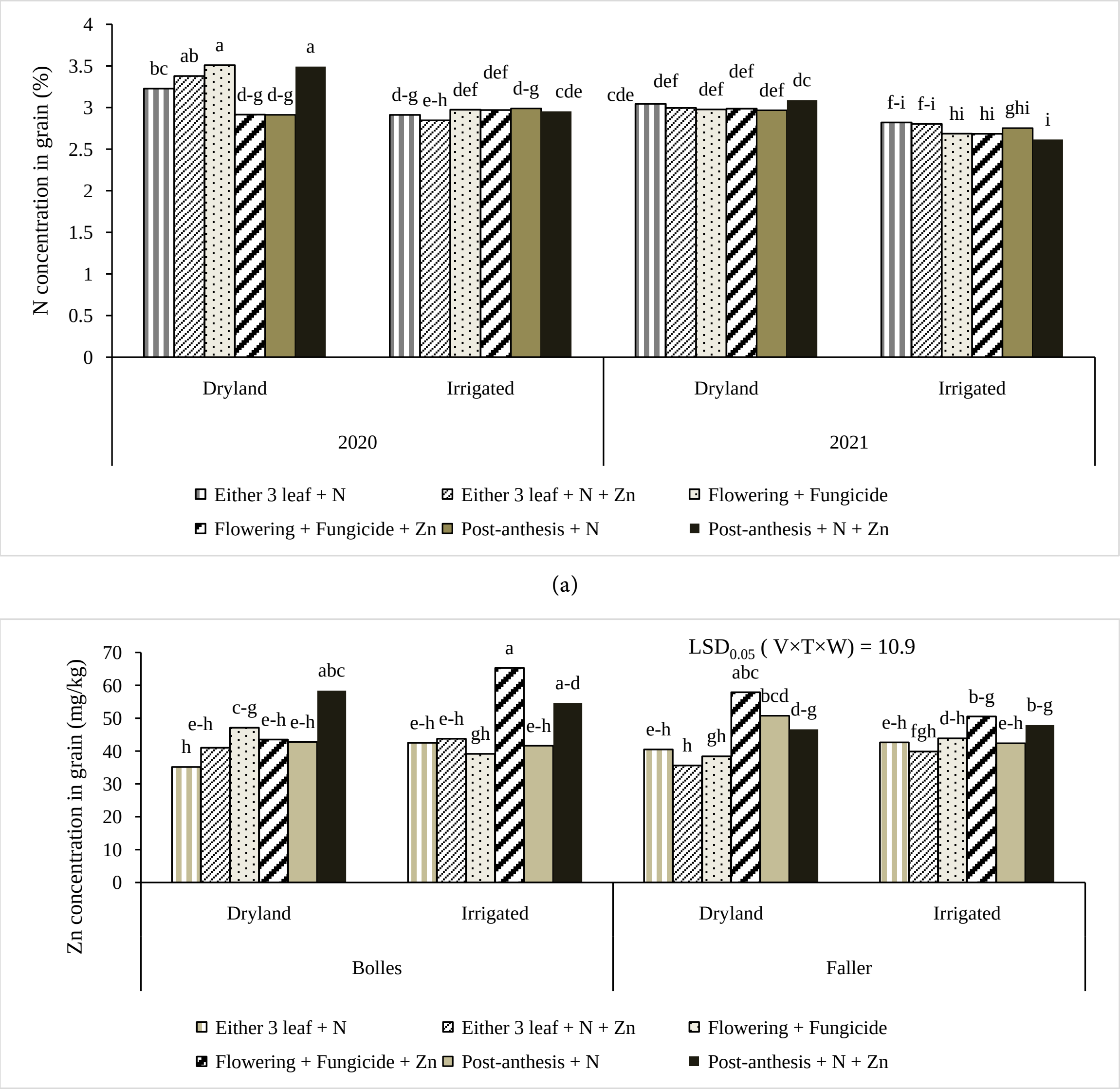
(a)

(b)

Figure 1. Protein content of two wheat varieties (Bolles and Faller) as affected by water management, foliar fungicide and fertility treatments averaged over cropping seasons (a) and the main effects of variety and water management for 2020 and 2021 separately (b).

The N concentration in the leaf was significantly affected by variety, fertilizer treatment and cropping year ($P < 0.01$) (**Figure 3(a)**). In 2020, application of N at the 3-leaf stage produced the highest leaf N concentration in Bolles (5.2%), while leaf N in Faller variety was the highest with the N + Zn applied at the 3-leaf stage (5.0%). In 2021, the applications of N and N + Zn at the 3-leaf stage resulted in the highest N concentration in both varieties compared with other treatments, however, the N concentration was statically similar for these two treatments in both varieties. In addition, the leaf N concentration was significantly affected by water management, fertilizer treatment and cropping year ($P < 0.01$) (**Figure 3(b)**). In 2020, there was no difference in leaf N concentration among fertilizer treatments under dryland conditions and averaged 4.0%, while under irrigated conditions applying the N with and without Zn at the 3-leaf resulted in the highest leaf N concentrations. In 2021, like 2020, applying N with or without Zn at the 3-leaf stage resulted in the highest N leaf concentration. However, there was an increase recorded in leaf N concentration when the N was applied post-anthesis, though not as pronounced.

There was a significant interaction between water management, foliar treatment, and cropping year for leaf Zn content ($P < 0.05$) (**Figure 3(c)**). The highest leaf Zn concentration of 273 mg·kg^{-1} was achieved in 2021 under irrigated conditions when Zn was applied post anthesis with N. Expect under dryland conditions in 2020, the highest leaf Zn concentration in both years was achieved when Zn was applied with N at the post-anthesis stage. This was followed by the Zn application at flowering.



(a)

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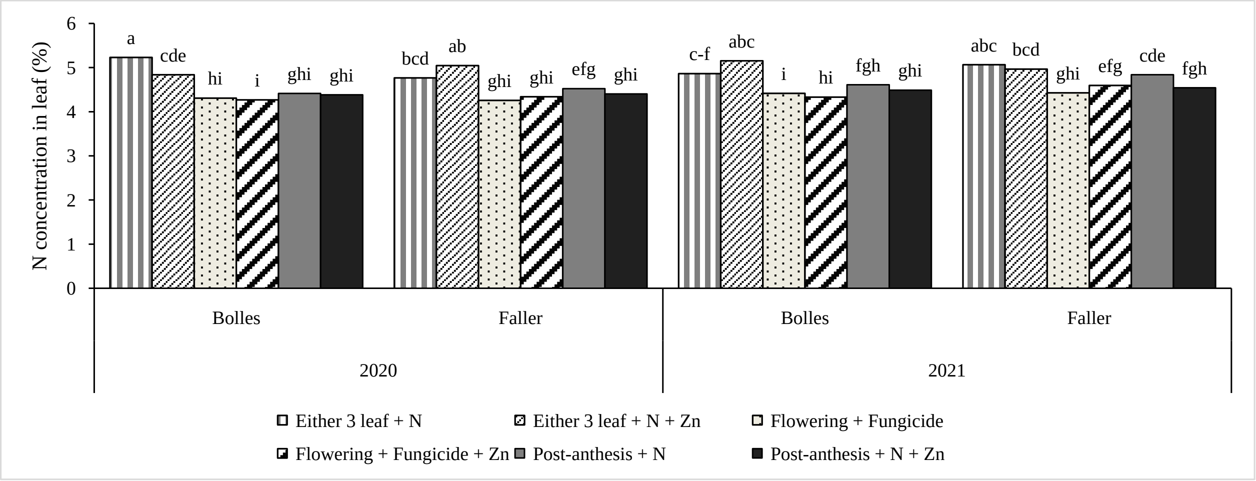
Figure 2. Effect of foliar treatments and water management in 2020 and 2021 on N concentration in the grain (a) and the effect of foliar treatments, water management and variety averaged over seasons on Zn concentration in the grain (b).



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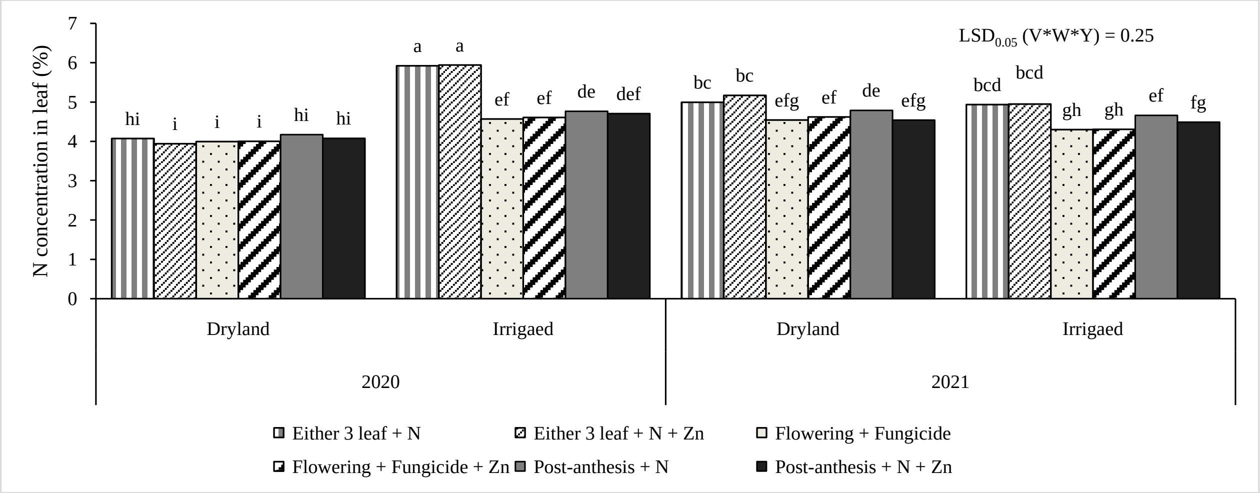

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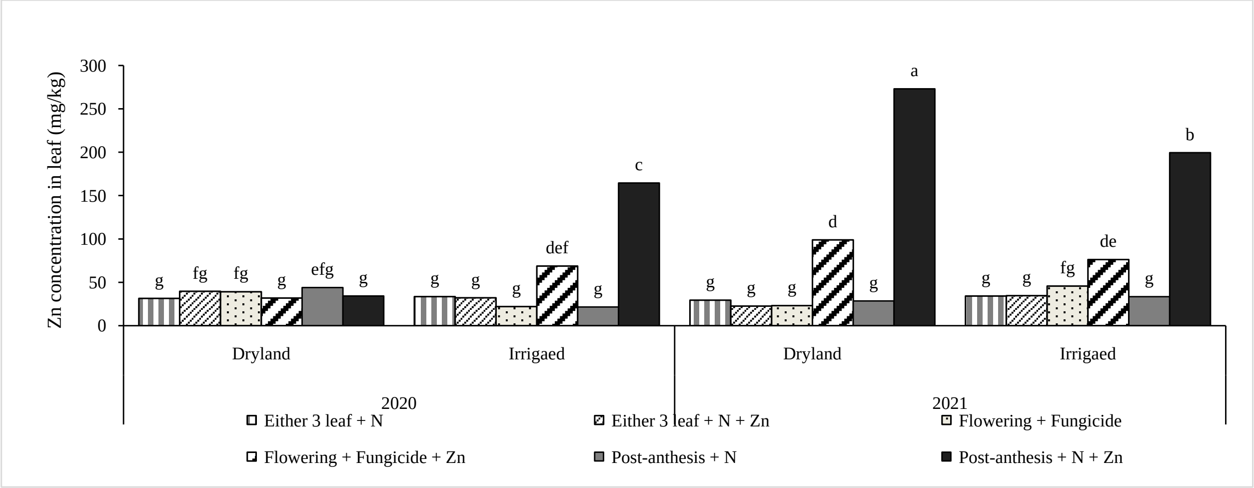
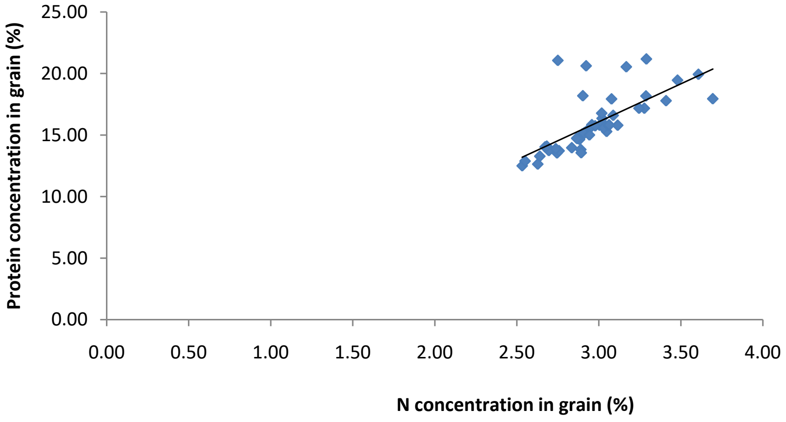


(c)

Figure 3. Nitrogen concentration in the leaf as affected by variety, foliar treatment and year (a); variety, water management and year (b); and Zn concentration in the leaf as affected by foliar treatment, water management and year (c).

There was a positive correlation between grain protein concentration and grain N (r = 0.69, P < 0.01) (**Figure 4(a)**) and between grain protein concentration and grain Zn (r = 0.48, P < 0.01) (**Figure 4(b)**). Grain Zn concentration was not significantly correlated with grain N, however. In contrast, the protein concentration in grain was significantly and negatively correlated with N concentration in the leaf (r = −0.44, P < 0.01) (**Figure 4(c)**), while it was not correlated with grain N. Furthermore, no correlation was observed between grain yield, Zn concentration and N concentration in the leaf.

The difference between flowering and post-anthesis treatments was only four days on average. Yet physiologically zinc did not translocate out of the flag leaf with the post-anthesis application compared to the flowering treatment. Grain zinc concentration was often higher with the flowering treatment as well compared to post-anthesis. In three of four environments grain zinc concentration increased following application at flowering compared to no zinc application, making that application timing more reliable than the post-anthesis timing for increasing grain zinc concentration. No grain zinc concentration increase occurred with early season zinc applications.



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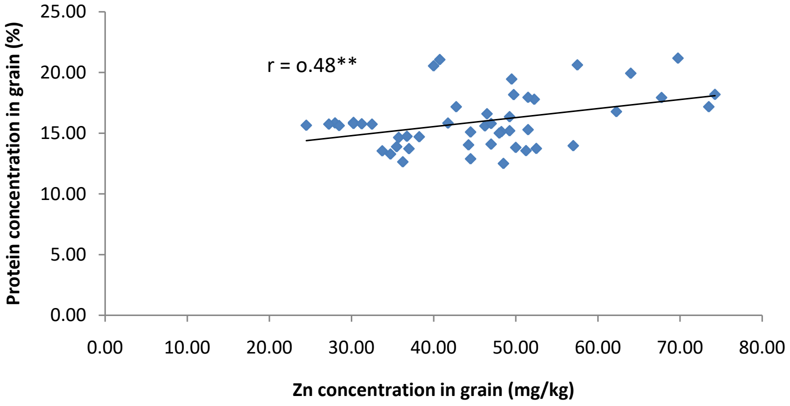

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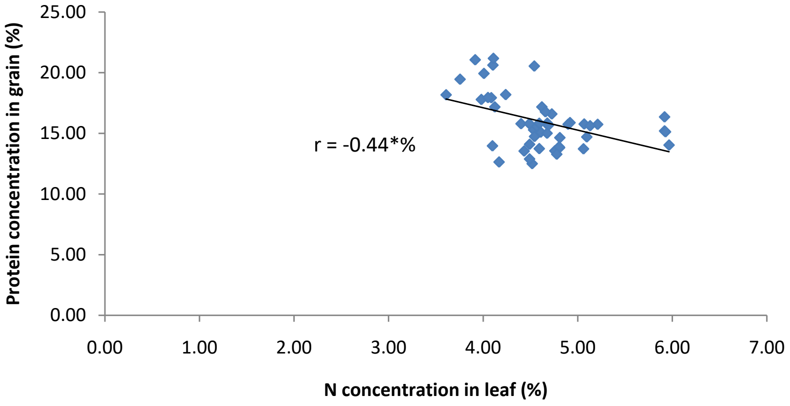

(a)

Figure 4. Relationship between grain protein and nitrogen concentration in the grain (a), Zn concentration in the grain (b), and nitrogen concentration in the flag leaf (c) in two spring wheat cultivars grown with differing fertilizer treatments over two cropping years (2020 and 2021).

3.2. Basal Fertilization Study

Plant stand and kernel weight differed significantly ($P < 0.05$) between the two seasons. There were 20.7% more plants·ha^{-1} in 2021 than in 2020 (Table 2) indicating that there was better emergence and seedling survival in 2021. Furthermore, kernel weight was 14.2% greater in 2021 than in 2020 probably due to slightly better conditions for grain development and higher yields in 2021. There were no significant differences between the fertilizer treatments when averaged across years but there was a significant interaction between fertilizer treatment and cropping year for grain yield ($P < 0.05$) (Table 2). In 2020, applying MESZ25 and MESZ100 increased yield by 17.1% and 16.0%, respectively, compared to the unfertilized control, while the remaining fertilizer treatments did not differ significantly from the control. Whereas in 2021, grain yield was not affected by any of the fertilizer treatments relative to the control.

Gluten and P concentration were affected by cropping year ($P < 0.01$) (Table 2). In 2020, the grain had 2.9% and 37.1% higher gluten and P concentration, respectively, than in 2021. There was a significant interaction between fertilizer treatment and cropping year on the concentration of protein and Zn in the grain ($P < 0.01$) (Table 2). Applying MES50, MES100, MESZ25 and MESZ100 reduced protein concentration compared to the control by 2.9%, 2.2% and 1.8% and 2.4%, respectively, while the other treatments were not significantly different from the control (Table 3). However, there was no significant difference in protein concentration among treatments in 2021. Compared to the control treatment, the application of MESZ 50 decreased Zn concentration in the grain by 35.0% in 2021, while other treatments were not significantly different from the control. However, there was no effect of fertilization treatments on grain Zn concentration in 2020. The gluten concentration was significantly and positively correlated with protein ($r = 0.79$, $P < 0.01$), P concentration ($r = 0.68$, $P < 0.01$) and Zn concentration ($r = 0.75$, $P < 0.01$) (Table 4). The protein concentration in grain was also correlated with P concentration ($r = 0.93$, $P < 0.01$), and Zn concentration ($r = 0.98$, $P < 0.01$). In addition, there was a significant correlation between P and Zn concentration ($r = 0.95$, $P < 0.01$).

Table 2. Plant stand, kernel weight and yield of wheat grown under different fertilizer treatment over two cropping years (2020 and 2021).

Year	Treatment	Plant Stand (no. × 10^6)	1000 Kernel Weight (g)	Yield ($kg \cdot ha^{-1}$)[a]	
2020	Control	2.18	26.8	2106	fgh
	MES 25	2.42	27.4	1897	h
	MES 50	2.26	27.5	2253	d-g
	MES 100	2.43	26.8	2096	gh
	MESZ 25	2.51	28.4	2466.	a-d
	MESZ 50	2.42	27.5	2140	e-h
	MESZ 100	2.36	28.3	2444	a-d
	$ZnSO_4$	2.41	27.8	2269	c-g
2021	Control	2.50	31.3	2480	a-d
	MES 25	3.18	30.9	2580	ab
	MES 50	2.74	31.3	2389	b-f
	MES 100	2.69	30.5	2669	ab
	MESZ 25	3.15	32.3	2540	abc
	MESZ 50	3.16	31.2	2664	ab
	MESZ 100	2.67	30.4	2712	a
	$ZnSO_4$	2.77	31.3	2394	b-e
Mean cropping year					
	2020	2.37	27.6	2209	
	2021	2.86	31.5	2553	
F-test					
Cropping year (Y)		**	***	***	
Treatment (T)		ns	ns	*	
(Y × T)		ns	ns	*	
LSD values					
$LSD_{0.05}$ (Y)		0.36	0.56	100.5	
$LSD_{0.05}$ (T)		-	-	201.0	
$LSD_{0.05}$ (Y × T)		-	-	284.2	

**$p < 0.01$, ***$p < 0.001$, ns = not significant at $P < 0.05$. [a] means followed by the same letter are not significantly different using LSD at $P < 0.05$.

Table 3. Gluten, protein, P and Zn concentration in grain wheat grown under different fertilizer treatment over two cropping years (2020 and 2021).

Year	Treatment	Gluten (%)	Protein (%)	P (%)	Zn ($mg \cdot kg^{-1}$)
2020	Control	42.0	18.0	0.45	70.0
	MES 25	41.5	18.1	0.47	74.5
	MES 50	40.8	17.5	0.50	68.5
	MES 100	41.5	17.6	0.46	71.0
	MESZ 25	41.5	17.7	0.49	71.0
	MESZ 50	41.9	17.9	0.48	76.0
	MESZ 100	41.6	17.6	0.48	68.3
	$ZnSO_4$	42.3	17.9	0.52	71.5
2021	Control	40.6	16.0	0.34	41.5
	MES 25	40.1	15.8	0.36	43.0
	MES 50	41.2	16.1	0.35	41.0
	MES 100	39.4	15.7	0.36	38.8
	MESZ 25	41.0	16.0	0.38	41.0
	MESZ 50	40.1	15.8	0.33	30.8
	MESZ 100	40.0	15.8	0.37	40.0
	$ZnSO_4$	41.5	16.0	0.34	40.5
Mean crop year					
	2020	41.6	17.8	0.48	71.3
	2021	40.5	15.9	0.35	39.6
F-test					
Crop year (Y)		***	***	**	***
Treatment (T)		ns	*	ns	ns
(Y × T)		ns	*	ns	*
LSD values					
$LSD_{0.05}$ (Y)		0.44	0.1	0.02	2.7
$LSD_{0.05}$ (T)		-	0.2	-	-
$LSD_{0.05}$ (Y × T)		-	0.3	-	7.5

**$p < 0.01$, ***$p < 0.001$, ns = not significant at $P < 0.05$, ^{a} means followed by the same letter are not significantly different using LSD at $P < 0.05$.

Table 4. Relationship between gluten and protein, P, and Zn concentration in grain wheat grown under different fertilizer treatment over two cropping years (2020 and 2021).

	Gluten	Protein	Phosphorous
Protein	0.79**	-	-
Phosphorous	0.68**	0.93**	-
Zinc	0.75**	0.98**	0.95**

4. Conclusion

Yields were higher in 2021 than in 2020 due to more favorable rainfall and a more favorable temperature regime for yield development. Irrigation significantly increased yield in both seasons indicating that water was limiting in the rainfed treatments. Foliar applications of nitrogen did not consistently improve yield regardless of timing suggesting that N levels in the soil were adequate to optimize yield. In only one season and under irrigation did foliar N impact grain protein content with applications earlier in the season being more beneficial than later ones. The variety Bolles consistently had higher grain protein content than Faller and is recommended if high grain protein is a major requirement when marketing the crop. The Zn content in the grain was most responsive to foliar applications at flowering or later. Applications of P with or without Zn did not consistently improve yield, protein or Zn content in the grain suggesting that these nutrients were not limiting at the yield levels achieved in these experiments. Higher rates of P also did not antagonistically affect grain zinc concentration. There were significant correlations between Zn concentrations and protein, gluten and P, implying that grain with higher protein levels may also be a better source of Zn and P if these are limiting in the diet.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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