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Perennial forages influence mineral and protein concentrations in annual wheat cropping systems

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Abstract

Agricultural land management may influence crop nutritional quality. However, few studies have explored potential connections between crop quality with different land management strategies. We analyzed mineral and crude protein concentrations in spring wheat grain (*Triticum aestivum* L.) samples from a study in Mandan, ND conducted from 2006 to 2014. The study introduced a perennial forage phase into an annual spring wheat cropping system, in three to four replicates, and previously found yield benefits and enhanced soil parameters in the perennial forage treatments. We determined whether integrating a perennial forage phase into continuous wheat would also affect crop nutritional quality by measuring wheat grain mineral and protein concentrations. Crude protein concentration was greater ($p < .05$) when wheat followed alfalfa (*Medicago sativa* L.) and increased linearly after 2–5 yr of established alfalfa. We observed comparable wheat grain crude protein and mineral concentrations between continuous annually fertilized wheat and unfertilized wheat following perennial forages. Negative correlations ($p < .001$) were observed between wheat grain yield and crude protein, potassium (K), magnesium (Mg), nickel (Ni), phosphorus (P), sulfur (S), and zinc (Zn) concentrations. Discriminate multivariate analyses showed, with 96% predictive accuracy, that differences in crude protein and mineral concentration were largely driven by year of wheat harvest. Differences between harvest years were likely due to timely precipitation at critical Growth Stage 3, during spikelet development. Study outcomes highlighted the important role of perennial forages and environmental factors to influence protein and mineral concentration in spring wheat grain.

Abbreviations: AFW, annually fertilized wheat; GDD, growing degree day; DW, dry weight; IWG, intermediate wheatgrass; MIX, alfalfa–IWG mixture; NDAWN, North Dakota Agricultural Weather Network; TKW, 1,000-kernel grain weight.

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1 | INTRODUCTION

There is increased interest in how agricultural land management influences the nutritional quality of food. This is especially the case for staple food crops like wheat (*Triticum aestivum* L.) which make meaningful contributions to human nutrient needs (Pfeiffer & McClafferty, 2007). Research connecting different land management strategies with plant biochemistry and subsequent food quality is limited. The decline of protein and/or mineral concentrations in the food supply resulting from land management practices have been suggested (Davis, 2009; Garvin et al., 2006; Mayer, 1997), yet few studies offer rigorous results from reliable data (Farnham & Grusak, 2014; Garvin et al., 2006).

Wheat grain mineral concentration is influenced by both genetic and environmental factors (Anglani, 1998; Zhao et al., 2009). Research evaluating minerals in wheat grain samples spanning 160 years found differences in wheat grain mineral concentration were associated with genetic factors, and not fertilizer treatments, between long- (grown from 1845 to 1967) and short-stem, high-yielding varieties (grown from 1968 to 2005), with decreased mineral concentrations in newly developed short-stem, high-yielding varieties (Fan et al., 2008). Murphy et al. (2009) also found differences due to genetics yet differences were between crosses of *Thinopyrum elongatum*, a perennial wheat variety, and a common annual wheat variety, showing greater mineral concentration in perennial varieties. Garvin et al. (2006) grew 14 different wheat varieties including both long- and short-stem cultivars, at two locations in Kansas (Manhattan and Hutchinson). Although they observed similar trends as Fan et al. (2008) of decreased mineral concentrations in short-stem varieties, differences in mineral concentrations between the two locations were more prominent, indicating environmental factors influenced wheat grain nutritional quality.

Under different fertilizer and tillage treatments, Shiwakoti et al. (2019a) found no differences in wheat grain mineral concentration except for manganese (Mn), which increased linearly with nitrogen (N) fertilizer rates. A different yet similar study demonstrated positive correlations between wheat grain Mn concentration and N fertilization, and greater N and Zn concentrations in wheat grain when fertilized with either farmyard manure or inorganic N (Shiwakoti et al., 2019b; Shiwakoti et al., 2020). Shiwakoti et al. (2020) also reported an increase in N and S concentrations in wheat grain over time, speculating this could be due to greater N concentration in wheat grain occurring in cases where less rainfall occurred during the growing season.

A no-till experiment in Mandan, ND assessed wheat yield differences between continuous annually fertilized spring wheat and unfertilized spring wheat planted after 2–5 yr of perennial forages (Franco et al., 2018). Spring wheat yield increased by 19 and 41% following 3 and 4 yr of alfalfa (*Medicago sativa* L.); respectively, and yield benefits persisted for 3 to 4 yr. Greater crop yields and enhanced soil parameters were also observed when wheat followed perennial systems with alfalfa and alfalfa–intermediate wheatgrass [*Thinopyrum intermedium* (Host) Barkw. & D.R. Dewey sbsp. *Intermedium*] mixtures compared to continuous annually fertilized wheat (Franco et al., 2018; Liebig et al., 2018). Since these treatments provided yield benefits and enhanced soil quality aspects (i.e., mitigated soil acidification, reduced soil bulk density, and increased particulate organic matter and water-stable aggregates), further analyses were pursued to assess potential crop nutritional quality effects from alfalfa and alfalfa–intermediate wheatgrass treatments. Our current objectives were to analyze wheat grain samples to determine whether integrating perennial forage phases into a wheat cropping system would enhance wheat grain mineral and crude protein concentrations. We also explored potential relationships between environmental factors and grain mineral and crude protein concentrations.

Core Ideas

- Perennial forages benefit annual cropping systems.
- Wheat grain samples were analyzed for mineral and protein concentration.
- Protein was greater when wheat followed alfalfa versus intermediate wheatgrass.
- Grain quality was similar between annual cropping and wheat following perennials.
- Grain mineral and protein concentrations were influenced by environmental factors.

2 | MATERIALS AND METHODS

2.1 | Plot establishment

The field experiment was conducted from 2006 through 2014 at the USDA-ARS Northern Great Plains Research Laboratory in Mandan, ND (46˚48’ 29“ N, 100˚54’ 56” W). The study was conducted on a Parshall fine sandy loam (coarse-loamy, mixed, superactive, frigid Pachic Haplustoll) in a Continental semiarid climate with mean annual precipitation of 456 mm and mean annual temperature of 4 ˚C. Main plot treatments (9.1 by 36.6 m) in four replicates (except the alfalfa treatment which had three replications due to spatial limitations) were established in 2006 in a conventionally prepared (intensively tilled with a tandem disc) seedbed and included; (a) intermediate wheatgrass (*Thinopyrum intermedium*,var. ‘Manska’; IWG) monoculture seeded at a rate of 3.6 kg ha^{-1}; (b) field pea (*Pisum sativum*, var. ‘Admi-

TABLE 1 Mean wheat grain yield and quality components at Mandan, ND, following 2–5 yr of perennial treatments: Alfalfa ($n = 48$), intermediate wheatgrass (IWG; $n = 64$), and alfalfa–IWG mixture (MIX; $n = 63$), with standard errors (SE), and combined treatment means of annually fertilized wheat (AFW; $n = 16$) during the same period for comparison. Mean values are combined treatments from 2011–2014 on a dry weight (DW) basis with four replications of IWG, MIX, and AFW, and three replications of alfalfa

	Treatment				
Wheat quality components	**Alfalfa**	**IWG**	**MIX**	**SE**	**AFW**
CP[a], g kg^{-1} DW	145a*	136b	140ab	0.97	139
TKW, g	27.1a*	26.6ab	26.4b	≤1.49	26.7
K, mg g^{-1} DW	4.13	4.20	4.17	≤0.06	4.39
Mg, mg g^{-1} DW	2.29	2.27	2.29	0.05	2.18
Mn, µg g^{-1} DW	39.1	39.1	36.4	≤1.51	42.2
P, mg g^{-1} DW	4.79	4.78	4.85	0.23	4.72
S, mg g^{-1} DW	1.54	1.53	1.49	0.08	1.52
Zn, µg g^{-1} DW	36.0a**	39.0b	37.8ab	≤4.34	32.9

Note: Values not sharing a common letter are significantly different at X according to Y test.
*Significant at the .05 probability level;
**Significant at the .01 probability level.
[a]CP, crude protein; TKW, thousand kernel grain weight.

ral') seeded at a rate of 72.9 kg ha^{-1} as a legume monoculture which was then planted to alfalfa (*Medicago sativa*, var. 'Beaver') in 2007 at a rate of 1.2 kg ha^{-1}; (c) intermediate wheatgrass and field pea (planted to alfalfa in 2007) binary mixture (MIX) at a rate of 1.8 and 72.9 kg ha^{-1}, respectively, and (d) fertilized spring wheat (var. 'Amidon'; AFW) seeded at a rate of 100.9 kg ha^{-1}. Plots were seeded with a John Deere 750 no-till drill (Deere & Company, Moline, IL) on 19-cm-spaced rows, and no tillage was used for the remainder of the study.

Perennial forages were cut, baled, and removed at least once annually. Harvest management was based on heading stage in grass monocultures, and alfalfa development for alfalfa monocultures and mixtures. Two cuttings were taken in 2008 and 2009 as growth allowed. All plots were fertilized with 67 kg N ha^{-1} yr^{-1} (146 kg ha^{-1} urea; 46–0–0) after planting in 2006. In 2007, fertilization continued at the same rate in all plots except alfalfa monocultures which were not fertilized for the remainder of the study. From 2008 to 2011, one quarter (9.1 by 9.1 m) of each main plot was converted annually from perennial forage to unfertilized spring wheat. Therefore, by 2011, the whole plot was seeded to spring wheat. The perennial forage strip was terminated by spraying glyphosate (*N*-[phosphonomethyl] glycine isopropylamine salt) in the fall and again the following spring on converted plot areas to ensure successful wheat stands. Perennial forage strips that were converted to spring wheat were not fertilized for the remainder of the study. Spring wheat samples included treatments after 2, 3, 4, and 5 yr of perennial culture. Spring wheat was planted 17 May 2011; 3 May 2012; 24 May 2013; and 20 May 2014; then harvested 26 Aug. 2011; 17 Aug. 2012; 3 Sept. 2013; and 4 Sept. 2014. Further experimental details are reported in Franco et al. (2018) and Liebig et al. (2018).

2.2 | Wheat grain analysis

Wheat grain was harvested using a Hege plot combine (Hege Maschinen, Niederlassung, Germany) equipped with a Grain Gage (Harvest Master, Logan, UT). Wheat was cleaned using a Carter Day grain cleaner (Carter Day International, Minneapolis, MN), and grain moisture and test weight assessed using the Seedburo grain tester (Seedburo Equipment Company, Des Plaines, IL). Wheat grain samples were air dried and 1,000-kernel weight (TKW) was determined using ESC-1 (Electronic Seed Counter, Agriculex, Canada), then stored at 20 ˚C. For mineral analysis, wheat grain samples were mill-ground, weighed (500-mg dry weight [DW]) into Teflon digestion vessels with 10-ml ultrapure nitric acid and an iridium internal standard (50 µg), and heated in sealed pressurized Teflon vessels with a microwave digestion system (MARS6; CEM Corporation, Matthews, NC). The iridium standard was used to correct for potential loss of volume during microwave digestion. After cooling, samples were diluted (30-fold) with distilled water, then elemental concentration determined using inductively coupled plasma–optical emission spectrometry (ICP-OES; iCAP 7000; Thermo Electron North America LLC, Madison, WI). The instrument was calibrated daily with certified standards. Crude protein was assessed by analyzing nitrogen via the Kjeldahl method using the FOSS instrument (Kjeltec 8400 analyzer, Hillerøed, Denmark), and using 6.25 for the conversion factor from N to crude protein percentage, then converting to g kg^{-1}.

2.3 | Data analysis

Initial statistical analysis of wheat mineral and crude protein concentration was performed as detailed in Franco et al.

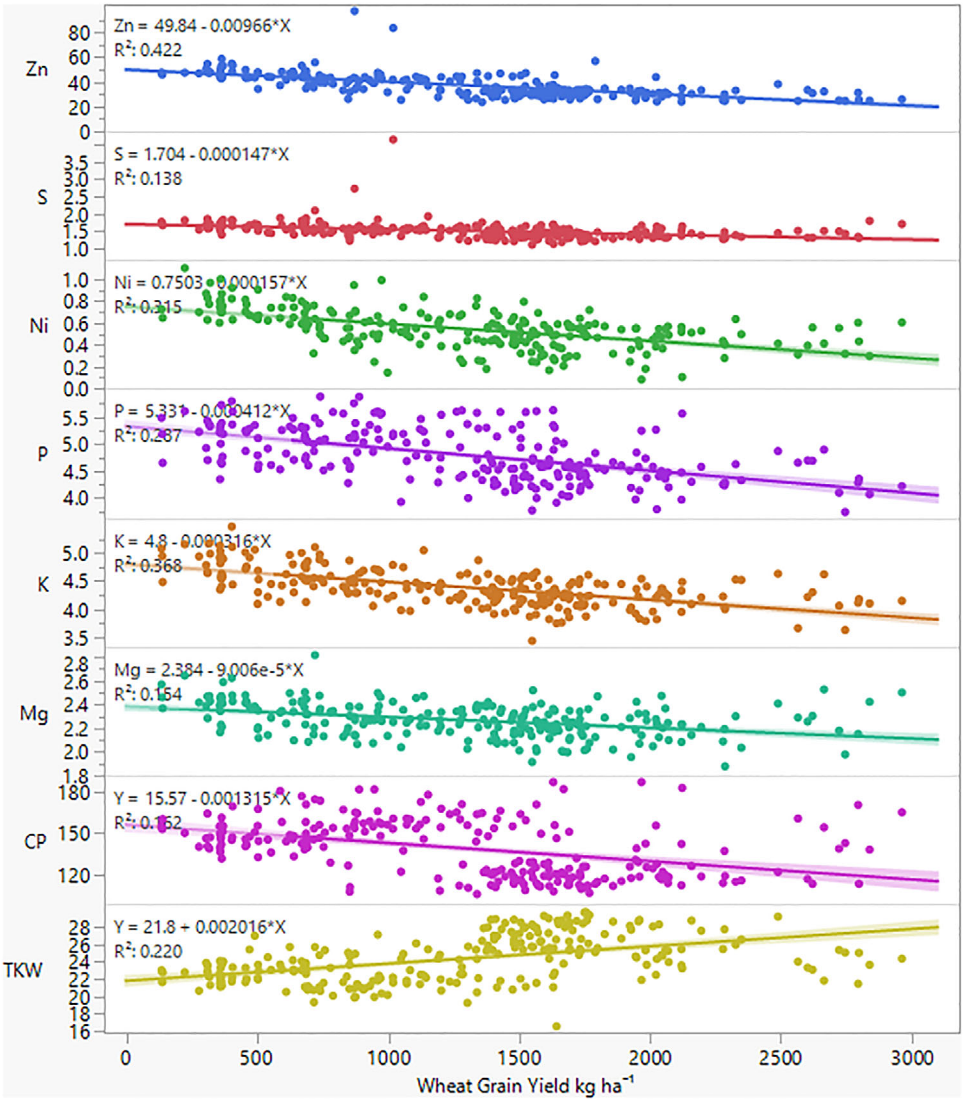

FIGURE 1 On a dry weight (DW) basis, correlations showing increasing yield (kg ha^{-1}) with decreasing crude protein (CP; g kg^{-1}) and mineral concentrations: Ni and Zn, in μg g^{-1} DW; and K, Mg, P, and S in mg g^{-1} DW; and positively corelated 1,000-kernel weight (TKW). Data shows combined treatments from 2011 to 2014. Coefficient of determination (R^2) is the square of coefficient of correlation (r)

(2018). Briefly, the experimental design consisted of a split-plot randomized complete block design with a staggered start of unfertilized spring wheat in plots under sequential years in perennial forage crops (all plots had four replications except alfalfa plots, which had three replications due to space limitations). Whole plots were perennial forage treatments within each block, and strips were the lateral conversion to unfertilized spring wheat across all treatment plots, creating split subplots. The subplot experimental unit was modeled as a repeated measure using AR(1) covariance structure. In a mirrored analysis, the model was adjusted, and perennial phase duration was used as a continuous variable. This allowed combined means of data from 2011 to 2014 to assess the effect of perennial culture longevity on wheat grain quality. Our model was a subset of the original Franco et al. (2018) dataset and did not assess the effect of years after perennial culture termination. Therefore, our data was limited to a smaller set of experimental factors. As grain mineral and crude protein concentrations were distinctly different between harvest year but with homogeneous variance within year, wheat grain mineral and crude protein concentration data were analyzed as a mixed model; year and block were modeled as G-side random effects; the perennial crop and the number of years the experimental units had been in perennial (‘years in perennial’) were modeled as fixed effects; the experimental units were modeled as repeated measures with compound symmetry covariance structure. Multiple comparisons were adjusted with Tukey–Kramer method in SAS Mixed procedure (SAS 9.4, 2017 SAS Institute, Cary, NC). Exploratory data analysis (Tukey, 1977) methods were used to determine whether other patterns existed in the data not associated with the experimental design but associated with yearly climatic variables.

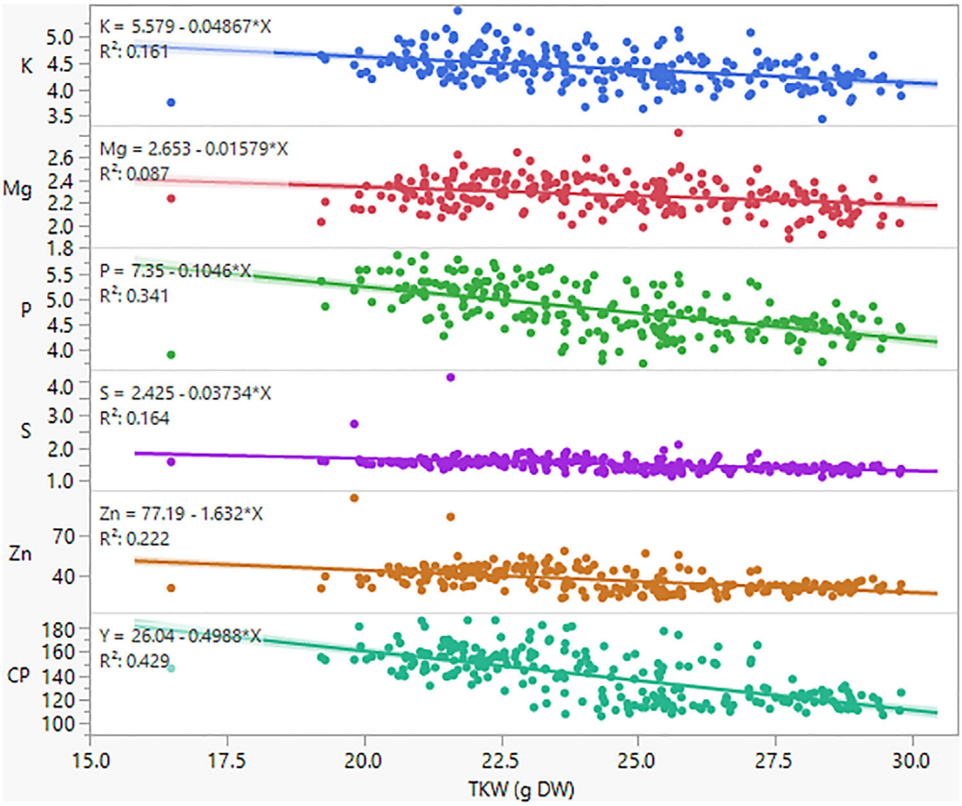

FIGURE 2 On a dry weight (DW) basis, correlations showing increasing 1,000-kernel weight (TKW in g DW) with decreasing crude protein (CP; g kg^{-1}) and mineral concentrations: K, Mg, P, and S in mg g^{-1} DW, and Zn, in μg g^{-1} DW, Data shows combined treatments from 2011 to 2014

TABLE 2 Actual (rows) vs. predicted (columns) confusion matrix of the canonical plot using training accuracy for wheat grain yield and quality components following perennial forages at Mandan, ND. The misclassification rate is 4.2%, thus 95.8% of the datapoints were accurately predicted to their actual year

Score Summaries					
Source	**Count**	**# misclassified**	**% misclassified**	**Entropy R^2**	**−2 Log Likelihood**
Model	1,190	50	4.20	.88	382.93

Year of Wheat Harvest				
Actual Year	**Predicted Year**			
	2011	**2012**	**2013**	**2014**
2011	265	0	30	0
2012	5	285	0	5
2013	0	0	300	0
2014	0	10	0	290

Given the multivariate nature of the data and expected correlation among grain minerals, principal components analysis and canonical discriminate analysis were used to identify variables driving annual variation. Simple correlation analysis and descriptive statistics were also used.

Weather data were analyzed to determine similarities between 2011 and 2013, then 2012 and 2014, as the odd and even years of harvest showed similar patterns of mineral and crude protein concentrations in the discriminate multivariate analysis. Weather data were obtained from North Dakota Agricultural Weather Network (NDAWN, 2020a). Growing degree days (GDD) were determined using maximum and minimum temperatures, and corresponding wheat growth stages determined using NDAWN (2020b), via the Bauer et al. (1984) and Haun (1973) methods, respectively. Number of days from planting to wheat grain

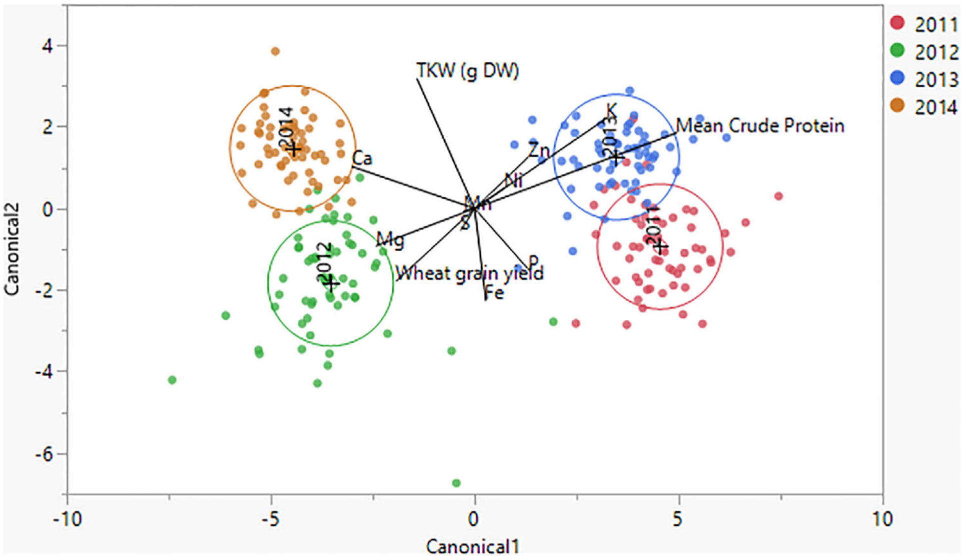

FIGURE 3 Canonical plot showing a linear discriminant analysis of each year (2011–2014) as a group. Details calculated from the overall pooled within-group covariance matrix. TKW, 1,000-kernel weight

maturity was 102, 108, 103, and 108 d for 2011–2014, respectively.

3 | RESULTS AND DISCUSSION

Our primary objective was to utilize spring wheat samples and determine whether integrating perennial forages in annual cropping systems influences grain crude protein and mineral concentrations. Combined means from 2011 to 2014 showed wheat grain had greater crude protein concentration when wheat followed alfalfa versus IWG treatments (Table 1), and crude protein concentration increased linearly at 135, 142, 149, and 154 g kg^{-1} after 2–5 yr of alfalfa culture, respectively. The increased crude protein in wheat grain following 5 yr of alfalfa was greatest during the first year of wheat (174 g kg^{-1}), declining over the subsequent years of wheat (Year 2, 3, and 4 having 150, 162, and 128 g kg^{-1} crude protein, respectively), yet still greater than AFW (117 g kg^{-1}) 5 yr after alfalfa termination. However, the data points for each year after alfalfa termination contain only three observations. Wheat following alfalfa had greater grain weight (measured in TKW) than MIX treatments, yet lower Zn concentration than when wheat followed IWG (Table 1). Combined treatment means of S concentration increased ($p = .05$) from 1.45 mg g^{-1} DW after 2 yr of perennials to 1.61 mg g^{-1} DW after 4 years of perennials.

Due to sample size differences, the analysis did not allow direct comparison of AFW to alfalfa, IWG, and MIX treatments. However, by using the mixed model described in the data analysis section, we observed differences in crude protein concentrations by evaluating specific comparisons of interest adjusted for multiple comparisons. Wheat planted after 5 yr of alfalfa showed greater wheat grain crude protein concentration ($p < .05$) than AFW. We also noted greater Zn concentration ($p \leq .05$) in wheat grain when wheat followed IWG and MIX treatments than in AFW, yet wheat grain had greater ($p \leq .05$) Mn in AFW than when wheat followed 2, 3, and 5 yr of MIX perennials. Aside from these differences, we observed comparable wheat grain crude protein and mineral concentrations between continuous annually fertilized wheat and wheat following perennial forage (Table 1), suggesting integrating perennial forage phases in annual cropping systems may replace some fertilizer inputs.

Combined results from this study and previous data reported by Franco et al. (2018) were similar to Davis et al. (2012), showing comparable or improved grain yields under diverse cropping systems compared to conventional systems that rely more heavily on agrichemical inputs. In addition to increased crop yield (Entz et al., 2002; Franco et al., 2018) and increased wheat grain Zn and protein concentration, integrating perennial forages in annual cropping systems may improve soil nutrient cycling and enhance soil carbon sequestration potential by increasing particulate soil organic matter (Franzluebbers et al., 2014; Liebig et al., 2018; Stewart et al., 2016).

We pursued exploratory data analyses, combining data from all years of the experimental treatments. Combined data showed negative pairwise correlations (r; $p < .001$) between wheat yield and crude protein concentration ($r = -.40$) and minerals K ($r = -.61$), Mg ($r = -.39$), Ni ($r = -.56$), P ($r = -.54$), S ($r = -.37$), and Zn ($r = -.65$) concentrations, and a positive pairwise correlation to TKW ($p < .0001$; $r = .47$). Trends showing goodness of fit adapted to axis scale for wheat grain yield correlations (R^2) are shown in Figure 1. Our results support other studies showing negative

TABLE 3 Growth stages shown for each year of wheat harvest (2011–2014), precipitation (mm) and solar radiation (MJ m^{-2}) accumulated at each growth stage, growing degree days (GDD) at each growth stage, and number of days to reach each growth stage at Mandan, ND

Growth stages	Year	Precipitation	Solar Rad	GDD	Number of days
		mm	MJ m^{-2}		
0	2011	50	224	177	14
	2012	15	320	168	14
	2013	98	185	176	13
	2014	11	249	180	11
.5	2011	2	107	72	5
	2012	13	100	72	5
	2013	17	115	76	5
	2014	1	63	58	4
1	2011	42	171	142	10
	2012	16	256	148	13
	2013	19	199	130	8
	2014	23	203	150	11
2	2011	32	154	138	9
	2012	11	221	141	9
	2013	20	182	143	8
	2014	15	189	148	9
3	2011	20	163	138	8
	2012	46	212	143	9
	2013	3	242	155	9
	2014	58	148	137	8
4	2011	42	170	143	8
	2012	0	211	139	8
	2013	2	170	126	7
	2014	9	201	137	8
5	2011	21	143	146	8
	2012	37	179	142	8
	2013	2	174	149	8
	2014	0	221	150	9
6	2011	45	159	148	8
	2012	0	202	150	8
	2013	9	202	141	9
	2014	11	181	143	8
7	2011	6	69	71	4
	2012	3	62	58	3
	2013	7	101	82	5
	2014	0	83	64	4
7.5	2011	52	81	75	4
	2012	8	104	80	4
	2013	2	72	68	4
	2014	49	97	86	5
8	2011	20	139	134	8
	2012	4	173	145	8
	2013	5	200	144	9
	2014	11	143	139	8

(Continues)

TABLE 3 (Continued)

Growth stages	Year	Precipitation	Solar Rad	GDD	Number of days
9	2011	45	158	150	9
	2012	10	143	135	8
	2013	2	168	147	8
	2014	17	120	132	7
10	2011	0	132	118	7
	2012	33	160	147	9
	2013	28	118	134	7
	2014	55	98	142	9
11	2012	0	47	28	2
	2013	0	52	49	3
	2014	28	68	63	4
11.4	2014	0	41	30	2
11.6	2014	0	19	14	1

correlations between yield and wheat grain mineral concentrations (Garvin et al., 2006; Smith et al., 2017), and although this inverse relationship is generally thought to be a dilution effect, it is not well understood.

Thousand-kernel weight differed ($p < .0001$) among years of harvest, with greater TKW in 2014 (30.6 g), followed by 2012 (27.4 g), 2013 (25.3 g), and 2011 (23.4 g), with no effect from years in perennial culture. Although wheat grain yield was positively correlated with TKW, combined treatment means of wheat grain yield were 1,120, 1,850, 530, and 1,670 kg ha^{-1}, for 2011, 2012, 2013, and 2014, respectively, indicating yield was not strictly due to increased TKW. Thousand-kernel weight showed negative pairwise correlations (r; $p < .001$) with crude protein concentration ($r = -.66$) and grain mineral concentrations K ($r = -.40$), Mg ($r = -.30$), P ($r = -.58$), S ($r = -.40$), and Zn ($r = -.47$). Trends showing goodness of fit adapted to axis scale for wheat grain yield correlations (R^2) are shown in Figure 2.

A discriminate multivariate analysis showed differences in crude protein and mineral concentration were largely driven by the year in which wheat samples were harvested (Figure 3; Table 2). These results support other observations showing greater differences between winter wheat grain mineral concentration as affected by calendar year of harvest, rather than treatments such as tillage or N fertilization (Shiwakoti et al., 2019a). Differences between years of harvest were so distinct that the discriminate multivariate model predicted, with 96% accuracy, which year a sample was collected (Table 2). Combined treatment means of wheat grain yield are previously noted, and combined treatment means of crude protein concentration were 165, 133, 155, and 120 g kg^{-1} across all treatments from 2011 to 2014, respectively. The lower yield in 2013 was due to a crop-damaging hailstorm and sawfly (*Cephus cinctus*) infestation in early August.

A secondary objective was to explore potential relationships between environmental factors and spring wheat grain crude protein and mineral concentrations. The discriminate multivariate analysis showed similarities in wheat grain mineral and crude protein data between 2011 and 2013, then 2012 and 2014. To expand on possibilities explaining these differences, we sought similarities in the weather data between the even, then odd years. To distinguish between years of wheat harvest and subsequent effects on wheat grain mineral and crude protein concentrations, we assessed available weather data and determined GDD with corresponding growth stages of wheat (Table 3).

The most notable similarities between the even, then odd years are during Growth Stage 3 where precipitation was greater in 2012 and 2014 than in 2011 and 2013. Research evaluating wheat grain nutritional quality has largely focused on wheat growth stages from anthesis to maturity (Li et al., 2015; Waters et al., 2009; Zhao et al., 2009). Wheat spikelet formation begins between Growth Stages 3 and 4, when Leaf 3 has developed and tillering begins (Frank & Bauer, 1982; Frank et al., 1988), and is a critical phase during wheat growth and development as this is when spikelet number is determined (Rawson, 1970). Frank et al. (1987) found that water-stressed wheat plants during early growth stages (0–4) rendered reduced spikelet numbers per spike. Water stress influences wheat development in later growth stages as well, reducing time until anthesis in plants mildly water-stressed, whereas severe water stress prolonged anthesis (Angus & Moncur, 1977). Our data show total accumulated precipitation from Growth Stages 0–3 at 145.9, 101.4, 156.4, and 108.0 mm from 2011, 2012, 2013, and 2014, respectively (Table 3). Wheat yield was greater in 2012 and 2014, which had less precipitation during early growth stages (0–3) than 2011 and 2013, yet during Growth Stage 3 (i.e., ending at

Growth Stage 4) precipitation was greater in 2012 and 2014 (Table 3). This stage of development is critical in determining yield, and greater precipitation during Growth Stage 3 likely enhanced spikelet numbers, subsequently increasing yield in 2012 and 2014.

Crop quality is a function of genetics, ontogenetic factors, and soil conditions. Several species transport minerals from mature tissues to newly developing tissues (Watanabe Maejima et al., 2016; Wolswinkel, 1992). Allocation of minerals to wheat grain occurs throughout seed development, as assimilation of minerals such as boron (B), chlorine (Cl), copper (Cu), iron (Fe), Mn, molybdenum (Mo), Ni, and Zn improve seed quality and aid in resiliency to diseases, pathogens, and pests (Dimkpa & Bindraban, 2016). Stress also influences nutrient assimilation, and water-stressed plants typically have decreased accumulation of nutrients (Bista et al., 2018; Nieves-Cordones et al., 2019). From our study, total precipitation from seeding to harvest date was 376, 197, 213, and 287 mm from years 2011 to 2014, respectively. It is not clear from our data that 2012 and 2014 were water-stressed. More likely, greater precipitation in 2012 and 2014 during the critical Growth Stage 3 increased spikelet formation, rendering greater yield which has negative correlations to mineral concentration.

4 | CONCLUSION

We observed comparable wheat grain crude protein and mineral concentrations between continuous annually fertilized wheat and wheat following perennial forages, suggesting incorporating perennial forage phases into annual cropping systems may replace the need for fertilizers. Our results also show that incorporating perennial forages such as alfalfa may enhance protein in wheat grain after 5 yr of established alfalfa, yet lower Zn concentration.

Precipitation during early growth stages influences wheat yield, which is negatively correlated with wheat grain mineral and crude protein concentrations. Thus, a low yield harvest of wheat may contain greater mineral and crude protein concentrations.

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AUTHOR CONTRIBUTIONS

Andrea K. Clemensen: Data curation; Writing-original draft. Michael A. Grusak: Data curation; Formal analysis; Investigation; Methodology; Writing-review & editing. Sara E. Duke: Data curation; Formal analysis; Writing-review & editing. John R. Hendrickson: Conceptualization; Investigation; Methodology; Supervision; Visualization; Writing-review & editing. José G. Franco: Writing-review & editing. David W. Archer: Conceptualization; Methodology; Visualization; Writing-review & editing. James N. Roemmich: Writing-review & editing. Mark A. Liebig: Investigation; Writing-review & editing

CONFLICT OF INTEREST

The authors report no conflict of interest.

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