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Spring wheat yield and grain quality response to nitrogen rate

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Abstract

Nitrogen (N) is the most limiting nutrient in cereal production, yet its use efficiency remains very low at only 35%. Nutrient use efficiency (NUE) is crucial for increasing crop yield and quality while reducing fertilizer inputs and minimizing environmental damage. Optimum N rates that maximize yield without reducing NUE have been found to vary from location to location. This field study assessed the effect of N rates on the yield and quality of spring wheat (*Triticum aestivum* L.) at five locations in southern Idaho in 2015–2017. Nitrogen was applied as urea (46–0–0) immediately after planting at five rates: 0, 84, 168, 252, and 336 kg ha^{-1}. Nitrogen application improved grain quality (increased protein) even when no increase in yield was noted. Nitrogen use efficiency and N uptake were affected by N rate at only 2 and 4 of 14 site-years, respectively. These observations highlight the challenging task of pinpointing the appropriate N rates for optimizing wheat yield, grain protein, N uptake and NUE; and the importance of adjusting N rates based on location, year, and prevalent environmental conditions.

1 | INTRODUCTION

Worldwide wheat (*Triticum aestivum* L.) production was estimated at 765.77 Mg in 2019, with an average grain yield of 3,546.8 kg ha^{-1}. Wheat production in the United States reached 52.26 Mg, with an average yield of 3,474.8 kg ha^{-1} in 2019 (FAOSTATS, 2021). Many producers rely on nitrogen (N) fertilizers to optimize yields (Raun et al., 2002), with total fertilizer N consumption for all agricultural crop production in 2019 estimated at 11.67 and 107.74 Mg in the United States and worldwide, respectively (FAOSTATS, 2021). According to Omara et al. (2019), only 35% of all applied N is taken up by the crops worldwide, with overapplication of fertilizer as a major factor resulting in low nitrogen use efficiency (NUE) values (Raun & Johnson, 1999). Avoiding excess N application is one way to increase NUE (Ma et al., 2019). Therefore, applying the right rate of fertilizer is key to attaining high yields while reducing environmental impact.

There are a number of methods that can be used when determining the correct rate of fertilizer to be applied including soil sampling, yield goal based and response index (RI). Soil sampling prior to planting is critical because it provides knowledge about the residual soil N, which can be used to ensure adequate supply without excess (Davis et al., 2002) to improve NUE. Bundy and Andraski (2004) found the amount of N applied decreased when N rate recommendations were based on pre-plant soil NO_3^-N content in 11 out of 21 sites, which resulted in economic gains.

Abbreviations: NDVI, Normalized Difference Vegetation Index; NUE, nitrogen use efficiency; RI, response index.

Yield goal was defined by some authors as yield per hectare that you hope to grow (Dahnke et al., 1988). Zhang and Raun (2006) noted that other yield goals in areas like the Midwest were determined by averaging yields from the past 5 yr and adding 20%. Nitrogen-response trials and historical yields, however, are not always helpful in accurately estimating N (Walsh & Walsh, 2020). According to Raun et al. (2001), the application requirement of a crop can be determined by combining the yield potential and soil test NO_3^-N for an estimate of the total N required. Yield potential can vary from location to location depending on soil moisture, field management history, and previous maximum yields (Rehm & Schmitt, 1989).

Other authors have argued that N rate should be based on the response index of a crop. Mullen et al. (2003) reported that there is potential to determine the crop N requirement using the response index RI calculated by using the in-season GreenSeeker sensor readings (Normalized Difference Vegetative Index [NDVI]) from the N-rich strip divided by NDVI from the unfertilized check. The RI reflects the likelihood of crop response to applied N fertilizer. When no differences exist between the N-rich strip and the unfertilized check, it means one of two things: (a) enough N had been mineralized from soil organic matter or deposited in the rain/snow to meet crop need for N, (b) crop growth was likely limited by other variable(s) that concealed the ability to detect N deficiencies (Walsh, 2015).

Overall, environment is a key factor essential in determining the appropriate N rate for optimizing wheat yield and quality. Walsh et al. (2020) found that N fertilization may increase wheat grain quality (protein content) even when grain yield is not increased. Spiertz and De Vos (1983) emphasized that N rate recommendations for wheat should be determined based on the amount of residual soil N and the typical crop N response for a particular growing environment. Omara et al. (2020) found that nonresponsiveness of wheat to N fertilizer accounted for 29 and 23% of grain yield at two locations, where yield at maximum N application rate did not significantly differ from yield of the unfertilized check. This highlights the need to treat each location differently when prescribing N rates. Mamo et al. (2003) noted that economically optimal nitrogen rate (EONR) varied from one field to the other; varying N rates by location has also resulted in decreased N fertilizer consumption compared with a uniform N rate application across locations.

Raun et al. (2011) did not find any relationship between wheat yield response to N and growing season (year) at any site in long-term field trials. They concluded that: (a) wheat yield potential and wheat responsiveness to N are independent of one another, and (b) yield potential is specific to the growing season. Girma, Freeman, et al. (2007) and Girma, Holtz, et al. (2007) found that wheat yield potential changes from 1 yr to the next due to temporal variability in rainfall,

Core Ideas

- Application of all N fertilizer at planting is not efficient for wheat.
- Nitrogen fertilizer rates for wheat should account for site- and year-specific conditions.
- When prescribing N rates to wheat, yield potential and responsiveness to N should be considered.
- Higher N rates resulted in enhanced grain protein content, but low N use efficiency.

temperature, and relative humidity that can vary greatly from year to year. McKenzie et al. (2008) found that wheat yields were optimized when available N was >26 kg N Mg^{-1} of grain yield. Mohammed et al. (2013) also observed increased wheat grain yield and protein content with increase in fertilizer N rates. They noted, however, that there were large differences in yields at different locations with the same N application rate. Similarly, Walsh et al. (2018) found a strong relationship between applied N rates and spring wheat grain yield at each site-year, but the relationship varied between growing locations and years. These findings suggest that N fertilizer recommendations should be site and year specific.

Entz and Fowler (1989) found a significant increase in wheat grain yield due to applied N and water, even with considerably high amounts of residual soil N; they noted that 62% of the increase in wheat yield was due to applied N. Walsh et al. (2018) found that there was a significant effect of climate, N application rate, and time on the wheat yield performance.

In general, environment plays a major role in shaping the optimum N rate for a particular crop. Several authors have demonstrated that higher/uniform N rates do not necessarily translate into higher yields (Arnall et al., 2013; Dhital & Raun, 2016). This is likely because the demand for N varies from location to location with each subsequent year. Based on research conducted at multiple locations, Arnall et al. (2013) reported that economically optimum N rates varied widely from year to year and from location to location. Raun et al. (2019) showed how unpredictable the environment can be in determining the final grain yield and N demand. Indeed, crop response is conditioned by climate and agronomic practices (Pampana & Mariotti, 2021).

Thus, multiple authors have found that ideal N rates required for optimized grain yield and quality have varied dependent on location. One of the biggest challenges for cereal producers is finding the right rate of N fertilizer appropriate for their growing area and climate. Therefore, the main objective of this study was to assess whether a single specific optimum N rate (or a range of N rates) can be pinpointed

for optimizing grain yield and quality of spring wheat while maximizing NUE in southern Idaho. We hypothesized that site-specific and year-specific N recommendations is the best approach to N fertilization, and that application of all N fertilizer at the time of planting is not efficient for Idaho spring wheat.

2 | MATERIALS AND METHODS

2.1 | Experimental locations

Field trials were conducted at five locations in southern Idaho (Aberdeen, Ashton, Parma, Rupert, and Soda Springs) during 2015 (except Parma), 2016, and 2017 growing seasons, resulting in a total of 14 site-years.

Latitude/longitude, planting and harvesting date, precipitation, and average temperature, from planting to harvest for each site-year is reported in Table 1. Elevation was 1,342, 1,603, 680, 1,67, and 1,760 m for Aberdeen, Ashton, Parma, Rupert, and Soda Springs, respectively. All sites have semi-arid climates with long, cold, and moderately snowy winters and hot and dry summers. Soil type and characterization of the top 60-cm soil before planting for each site-year is shown in Table 2.

Soft white spring wheat (*Triticum aestivum* L. 'Alturas') was planted at Parma using H&N Equipment research plot drill. Hard red spring wheat (cultivar Cabernet) was planted using a Hege 500 series drill at all other locations. Spring wheat varieties used in this study were widely grown varieties for the area where the experimental locations were located. Plant density was approximately 3.9 million seed ha^{-1} (106.5 kg seeds ha^{-1}). Row spacing was set at 17.78 cm using double disk openers. The plots were 1.52 m wide by 4.27 m long, and then reduced to 3.05 m using glyphosate herbicide and rototiller. Granular urea (46–0–0) was surface broadcasted immediately after planting at five different rates (0, 84, 168, 252, and 336 kg N ha^{-1}). Each treatment was replicated four times in a randomized complete block design, resulting in a total of 20 plots at each location. All sites were irrigated every 7–10 d using sprinkler irrigation systems, except for Soda Springs, which is a dryland site.

2.2 | Post-harvest data analysis

At maturity, yield was determined by harvesting wheat with a Wintersteiger Delta small plot research combine equipped with a mini-Grain Analysis Computer (GAC) plus moisture tester Harvest Master Classic GrainGage HM800 (Juniper Systems, Inc.) powered by Mirus software (Juniper Systems, Inc.). The plot weights were extrapolated to yield on kilogram per hectare basis adjusted to 13.5% moisture.

Grain N content was measured using near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIR analyzer (Perten Instruments, Inc.). Spring wheat grain protein content was calculated by multiplying grain N content by 5.7 (Fowler et al., 1990) expressed in percentage. Wheat grain N uptake was calculated by multiplying yield by total N concentration of the grain. Nitrogen use efficiency was determined using the difference method (Varvel & Peterson, 1990) by deducting the total N uptake in wheat from the N-unfertilized treatment (check plot) from total N uptake in wheat from fertilized plots and then divided by the rate of N fertilizer applied.

2.3 | Statistical analysis

The effects of N rate on spring wheat grain yield, grain protein content, grain N uptake, and NUE were assessed. Data were analyzed by ANOVA using PROC GLM in SAS 9.4 (Littell et al., 1996). Data were also analyzed using the GLIMMIX procedure to compare the least-square means, main effects, and assess interactions of the experimental factors. Year was treated as a fixed effect to determine the Location × Year × N rate association. Block within a Year, Location × Block within a Year, and N rate × Block within a Year were considered as random effects. Due to the presence of Location × Year × N rate interaction for grain yield, grain protein, and grain N uptake, the data is reported by site-year. Grain yield, grain protein, and grain N uptake was significantly different between years and locations. Figures and regressions were generated using Excel (Microsoft Corp.).

3 | RESULTS AND DISCUSSION

3.1 | Grain yield and grain protein content

Spring wheat grain yield and grain protein content values for 2015, 2016, and 2017 are reported in Tables 3, 4, and 5, respectively.

Mean yield values varied substantially by year and location, with the lowest yielding site-year in Soda Springs in 2016 (2,085 kg ha^{-1}), and the highest yielding site-year in Rupert in 2016 (8,452 kg ha^{-1}). Mean yield values ranged from 3,015 to 6,851 kg ha^{-1} in 2015, from 2,085 to 8,452 kg ha^{-1} in 2016, and from 2,241 to 6,671 kg ha^{-1} in 2017. In general, the growing conditions at all 14 site-years have progressed from substantially higher precipitation and cooler air temperatures in 2015, to lower precipitation and warmer air temperatures in 2016 and 2017 (Table 1). Grain yields at Soda Springs were lower compared with other locations, which could be related to lower water and nutrient availability at this dryland site (Table 1). As reported by Pampana and Mariotti (2021),

TABLE 1 Latitude/longitude, planting and harvesting date, precipitation, and average temperature, from planting to harvest for 14 site-years in Idaho

Site-year	Latitude/Longitude	Planting date	Harvest date	Precipitation, planting to harvest	Average temperature, planting to harvest
				mm	˚C
Aberdeen, ID					
2015	42˚57′48.19″ N, 112˚49′15.30″ W	15 Mar.	17 Aug.	119	14.7
2016	42˚57′39.36″ N, 112˚49′17.37″ W	8 Apr.	18 Aug.	81	16.2
2017	42˚57′8.83″ N, 112˚49′32.74″ W	12 Apr.	18 Aug.	78	16.2
Ashton, ID					
2015	44˚04′28.82″ N, 111˚22′51.26″ W	16 Apr.	27 Aug.	164	14.6
2016	44˚03′25.66″ N, 111˚19′53.75″ W	2 May	1 Sept.	86	15.6
2017	44˚04′15.25″ N, 111˚23′59.26″ W	4 May	31 Aug.	55	16.1
Parma, ID					
2016	43˚80′47.33″ N, 116˚94′42.40″ W	23 Mar.	1 Aug.	90	17.7
2017	43˚80′48.18″ N, 116˚94′69.43″ W	5 Apr.	1 Aug.	62	18.4
Rupert, ID					
2015	42˚43′14.70″ N, 113˚29′16.21″ W	20 Mar.	13 Aug.	104	15.0
2016	42˚44′41.75″ N, 113˚37′50.61″ W	7 Apr.	9 Aug.	46	16.2
2017	42˚43′12.28″ N, 113˚30′23.04″ W	12 Apr.	11 Aug.	78	16.4
Soda Springs, ID					
2015	42˚43′13.17″ N, 111˚34′47.48″ W	1 May	25 Aug.	211	16.5
2016	42˚47′10.95″ N, 111˚35′37.63″ W	4 May	31 Aug.	86	17.3
2017	42˚45′45.98″ N, 111˚36′13.94″ W	10 May	5 Sept.	61	17.7

Note. Sources: Marshall et al. (2015, 2016, and 2017) and Bureau of Reclamation.

TABLE 2 Soil type, and soil characterization of the top 60-cm soil before planting for 14 site-years in Idaho

Site-year	Soil type[a]	pH	OM	Soil residual total N	P	K	SO_4^2–S
			%	kg ha^{-1}	mg kg^{-1}		
Aberdeen, ID							
2015	Declo L, a	8.1	1.1	240	22	303	50
2016		8.1	0.9	195	25	260	45
2017		8.1	0.9	194	15	260	44
Ashton, ID							
2015	Greentimber-Marystown-Robinlee SiL, b	6.0	2.1	57	50	241	47
2016	Marystown SiL, b	6.4	2.9	117	12	205	25
2017	Greentimber-Marystown-Robinlee SiL, b	6.4	2.9	119	12	205	25
Parma, ID							
2016	Green leaf-Owyhee SiL, a	8.0	1.9	100	98	319	30
2017		8.1	2.1	65	59	283	33
Rupert, ID							
2015	Portneuf SiL, b	8.1	1.2	73	35	332	38
2016		8.0	1.2	100	16	243	21
2017	Sluka SiL, b	8.0	1.2	101	16	243	21
Soda Springs, ID							
2015	485BB Foundem-Kackley complex, c	6.3	1.9	81	28	402	12
2016	705AA Lostine-Foundem complex, b	6.1	2.5	65	49	449	18
2017	225AA Ririe-Lostine complex, c	6.1	2.5	64	49	404	18

Note. L, loam; OM, organic matter; SiL, silt loam. Sources: Marshall et al. (2015, 2016, and 2017) and Walsh (personal communication, 2021).

[a]a denotes slopes of 2–2%; b denotes slopes of 3–7%, and c denotes slopes of 8–15%. Detailed methods for soil laboratory analysis described in Yang et al. (2018).

TABLE 3 Effect of N rate on spring wheat grain yield and protein content, for four locations in Idaho, 2015

	Aberdeen		Ashton		Rupert		Soda Springs	
Fertilizer N rate	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	3,530	9.3	4,849	10.6	7,208	11.1	3,339	10.5
84 kg ha^{-1}	3,771	10.4	5,281	11.2	6,764	13.1	3,822	11.2
168 kg ha^{-1}	3,269	10.3	5,125	13.4	7,379	9.9	3,813	13.0
252 kg ha^{-1}	2,593	12.3	5,503	15.5	6,838	11.6	3,598	14.0
336 kg ha^{-1}	1,910	13.1	5,989	13.4	6,064	10.8	4,010	14.2
F test	**	**	ns†	**	ns	ns	ns	**

**Significant at the .01 level.
†ns, not significant at $P < .05$.

TABLE 4 Effect of N rate on spring wheat grain yield and protein content, for five locations in Idaho, 2016

	Aberdeen		Ashton		Parma		Rupert		Soda Springs	
Fertilizer N rate	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	5,859	12.4	4,393	12.2	5,047	8.7	7,135	8.9	1,971	13.5
84 kg ha^{-1}	6,230	13.2	3,842	13.3	5,488	9.1	8,650	9.8	2,073	13.1
168 kg ha^{-1}	6,391	15.5	4,035	14.4	6,237	11.1	8,496	10.1	1,956	13.7
252 kg ha^{-1}	5,701	15.7	3,708	15.1	6,171	11.5	9,028	11.5	2,069	14.9
336 kg ha^{-1}	5,954	16.4	3,115	15.3	5,192	12.3	8,950	12.4	2,354	14.7
F test	ns†	***	ns	***	ns	***	**	***	ns	ns

**Significant at the .01 level.
***Significant at the .001 level.
†ns, not significant at $P < .05$.

TABLE 5 Effect of N rate on spring wheat grain yield and protein content, for five locations in Idaho, 2017

	Aberdeen		Ashton		Parma		Rupert		Soda Springs	
Fertilizer N rate	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein	Grain yield	Grain protein
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	2,922	12.5	5,354	16.5	4,652	9.1	6,373	11.8	2,012	11.8
84 kg ha^{-1}	3,051	12.4	5,136	16.4	4,746	9.6	6,794	12.1	2,021	10.0
168 kg ha^{-1}	3,630	13.2	5,636	16.5	5,315	10.5	7,439	12.5	2,087	11.4
252 kg ha^{-1}	2,983	13.5	4,968	17.0	5,530	11.3	6,744	12.8	2,522	11.4
336 kg ha^{-1}	2,627	14.8	5,294	17.2	5,167	11.0	6,002	13.3	2,566	11.0
F test	ns†	**	ns	ns	ns	**	ns	**	ns	ns

**Significant at the .01 level.
†ns, not significant at $P < .05$.

precipitation amount and patterns tend to substantially influence not only N availability, but also crop N uptake.

Crop yield potential and crop responsiveness to N (significant increase in wheat yield due to applied N fertilizer) both affect the demand for fertilizer. In this study, residual soil N varied from 57 to 240 kg N ha^{-1} for 14 site-years, with a mean value of 112 kg N ha^{-1} (Table 2). Grain yield was significantly affected by fertilizer N rate at only 2 (Aberdeen in 2015, and Rupert in 2016) of 14 site-years (Tables 3–5). Aberdeen in 2015 had the highest residual soil N (240 kg N ha^{-1}), which may have resulted in a step-wise decrease in grain yields with increased fertilizer N application rates. On

the other hand, Rupert in 2016 had residual soil N comparable to other site-years (100 kg N ha^{-1}); all N rates resulted in comparable yields that were significantly higher compared with unfertilized treatment. The lack of yield response to N agrees with findings by Walsh et al. (2020) who conducted studies in the same wheat production areas. They reported that N rate was not correlated with wheat yield at any of the site-years. Acknowledging that limited response of yield to N fertilization could have been due to relatively high residual soil N levels, the authors highlighted that water availability (irrigation and precipitation) was a primary source of variation in yield and grain protein. These results are not surprising because water availability has a major effect on wheat production in semi-arid growing environments such as Idaho. The lack of yield response to applied N at higher N fertilizer rates is well documented. Even in production areas without a long-standing record of excessive N fertilization (and thus, relatively low residual soil N), such as Nepal, Rawal et al. (2022) reported that wheat grain yield was statistically the same for medium (125 kg ha^{-1}) and high (150 kg N ha^{-1}) N rates.

These results emphasize the complexity of wheat yield response to applied N fertilizer and agrees with findings by Raun et al. (2011) that yield potential and N response are independent of one another. They did not find any relationship between applied N rate and wheat grain yield at any site-years. Our results agree with a report by Pampana and Mariotti (2021) that seasonal variations in climate impact wheat yields.

Mean grain protein values varied substantially from 1 site-year to another (Tables 3–5), with the lowest value at Parma in 2017 (10.3%), and the highest value at Ashton in 2017 (16.7%). Mean grain protein values ranged from 11.1 to 12.8% in 2015, from 10.5 to 14.6% in 2016, and from 10.3 to 16.7% in 2017. Soft white spring wheat was planted in Parma and hard red spring wheat was planted at all other locations; grain protein in soft white spring wheat is typically not as responsive to N compared with hard red spring wheat. In general, grain protein values were lower at Parma; this makes sense due to the fact that this was a soft white spring wheat variety where the protein levels are genetically lower compared with hard red spring wheat varieties.

In this study, grain protein content was significantly affected by fertilizer N rate at 10 of 14 site-years (Tables 3–5). For these site-years, grain protein content increased with increase in applied fertilizer N rates up to 336 kg N ha^{-1} (up to 252 kg ha^{-1} at Ashton in 2015, and at Parma in 2017). This agrees with work done by Woodard and Bly (1998) where they found an increase in grain protein with application of N with rates ranging from 55 to 165 kg N ha^{-1}. Similarly, Walsh et al. (2018) observed that wheat grain protein was increased with increased fertilizer N rates.

In general, in 2015, Ashton had higher grain protein values compared with other locations. In 2016, Rupert (hard red spring wheat) and Parma (soft white spring wheat) had the lowest levels of grain protein recorded regardless of the N rate, while in 2017, grain protein content was highest at Ashton at the highest N rate of 336 kg N ha^{-1}.

Similar to the findings of Abad et al. (2004) and Pampana and Mariotti (2021), we found that wheat yield reached a plateau at lower N rates compared with grain protein content. This indicates that N fertilization can be effective in increasing grain protein without negatively affecting grain yields. A study conducted in Idaho by Walsh et al. (2020) has shown that N rate of 150 kg N ha^{-1} (residual soil N + N applied as fertilizer) optimized yield and grain protein content.

In this study, across all site-years, grain protein content increased with N rate. This agrees with findings by Walsh (2020), who reported that wheat grain protein content may be enhanced with N application even if grain yield is not increased. Several authors have also found a positive relationship between N rate and grain protein (Fiez et al., 1994; Kindred et al., 2008; Terman et al., 1969; Vaughan et al., 1990). Fiez et al. (1994) pointed out that heat and moisture stress can increase grain protein content of the grain irrespective of applied N rate. Both heat and moisture stress are typical for most cropping systems in Idaho's arid growing environment. Goos et al. (1982) did not find any positive correlation between grain yield and grain protein, highlighting the complexity of poor precipitation distribution and high temperatures often experienced in the western United States. They reported that grain protein content can be effectively used as a post-harvest indicator of N nutrition adequacy for wheat grain production.

3.2 | Grain N uptake and N use efficiency

Spring wheat grain N uptake and NUE values for 2015, 2016, and 2017 are reported in Tables 6, 7, and 8, respectively. There were significant differences in NUE among locations in the different years (Tables 6–8). In this study, NUE values were significantly affected by fertilizer N rate at only 1 of 14 site-years – Rupert in 2016; other differences were not statistically significant (Tables 6–8).

In general, across all site-years, NUE was lower at very high N rates of 252 and 336 kg N ha^{-1}. This is typical of NUE trends as observed by several authors (Dobermann, 2005; Walsh & Walsh, 2020). The reason for the decrease in NUE with increased N rates is associated with increased loss due to denitrification and leaching.

Grain N uptake combines grain yield and N content into one variable, enabling the assessment of both grain production and quality, simultaneously. Grain N uptake was strongly positively correlated with grain yield at all site-years. Mean grain N uptake values varied substantially by year and location, with the lowest at Soda Springs in 2017 (43.9 kg

TABLE 6 Effect of N rate on spring wheat grain N uptake and nitrogen use efficiency (NUE) for four locations in Idaho, 2015

Fertilizer N rate	Aberdeen		Ashton		Rupert		Soda Springs	
	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	56.9	–	90.0	–	139.8	–	60.4	–
84 kg ha^{-1}	69.6	15.06	103.1	15.61	138.6	−1.40	74.9	17.29
168 kg ha^{-1}	59.1	1.30	119.6	17.62	126.7	−7.81	88.8	16.88
252 kg ha^{-1}	56.1	−0.32	149.8	23.72	139.4	−0.16	87.4	10.70
336 kg ha^{-1}	44.1	−3.80	142.1	15.51	114.4	−7.55	99.4	11.61
F test	ns[†]	ns	**	ns	ns	ns	ns	ns

**Significant at the 0.01 level.
[†]ns, not significant at $P < .05$.

TABLE 7 Effect of N rate on spring wheat grain N uptake and nitrogen use efficiency (NUE) for five locations in Idaho, 2016

Fertilizer N rate	Aberdeen		Ashton		Parma		Rupert		Soda Springs	
	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	128.1	–	93.7	–	76.5	–	112.3	–	46.5	–
84 kg ha^{-1}	144.8	19.94	89.8	−4.62	87.6	13.13	149.3	44.10	48.1	1.96
168 kg ha^{-1}	173.7	27.15	101.9	4.89	121.3	26.64	149.8	22.34	46.4	−0.04
252 kg ha^{-1}	156.9	11.44	98.0	1.72	124.7	19.12	181.7	27.55	53.9	2.93
336 kg ha^{-1}	171.8	13.01	83.8	−2.96	112.4	10.68	194.6	24.50	60.1	4.06
F test	ns[†]	ns	ns	ns	**	ns	***	**	ns	ns

**Significant at the .01 level.
***Significant at the .001 level.
[†]ns, not significant at $P < .05$.

TABLE 8 Effect of N rate on spring wheat grain N uptake and nitrogen use efficiency (NUE) for five locations in Idaho, 2017

Fertilizer N rate	Aberdeen		Ashton		Parma		Rupert		Soda Springs	
	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE	Grain N uptake	NUE
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
0 kg ha^{-1}	64.6	–	154.7	–	74.7	–	131.4	–	42.1	–
84 kg ha^{-1}	65.8	1.40	147.9	−8.17	80.0	6.35	144.2	15.25	35.4	−7.90
168 kg ha^{-1}	83.7	11.37	162.0	4.34	98.1	13.98	163.4	19.07	41.6	−0.30
252 kg ha^{-1}	71.0	2.52	147.9	−2.72	109.5	13.81	151.7	8.06	50.8	3.45
336 kg ha^{-1}	68.1	1.03	160.2	1.64	99.6	7.43	140.0	2.56	49.8	2.31
F test	ns[†]	ns	ns	ns	**	ns	ns	ns	ns	ns

**Significant at the .01 level.
[†]ns, not significant at $P < .05$.

ha^{-1}), and the highest at Rupert in 2016 (157.6 kg ha^{-1}). Mean grain N uptake values ranged from 57.2 to 131.8 kg ha^{-1} in 2015, from 51.0 to 157.6 kg ha^{-1} in 2016, and from 43.9 to 154.5 kg ha^{-1} in 2017.

In this study, grain N uptake was significantly affected by fertilizer N rate at only 4 of 14 site-years (Tables 6–8). This disagrees with findings by Walsh and Walsh (2020a) reporting that grain N uptake was strongly positively correlated with applied N fertilizer rates at both assessed locations. Walsh and Christiaens (2016) reported that N uptake increased with an increase in pre-plant N rates at 7 of the 8 site-years, while topdress N application increased N uptake in 5 of 8 site-years.

Typically, a strong relationship between N fertilization levels and grain N uptake indicates that the N requirement per kilogram of grain yield increases at the higher yield levels (Abdel-Fattah & Merwad, 2015). This relationship provides a measure of total N uptake by the wheat crop for achieving a certain yield level and can be used for developing algorithms aiming to improve N fertilizer management. Nitrogen is the key plant nutrient for yield formation, and for determining the concentration of storage proteins in the grain. Grain protein concentration is typically enhanced with increasing N fertilizer rates (Wieser & Seilmer, 1998; Xue et al., 2016). However, higher N rates do not always improve wheat yields potentially due to high pre-plant soil residual N, emphasizing the requirement for pre-plant soil testing for N concentrations in the soil.

Optimal NUE is achieved by controlled remobilization of canopy-N to the developing grain as the crop matures (Hawkesford, 2014). Based on the University of Idaho research in wheat, it has been estimated that <50% of the N applied as fertilizer is taken up by the crop, the primary cereal grown throughout the state (Walsh & Belmont, 2015). Most measures of NUE express production as a function of N input; thus, any measurable yield increase is reflected in higher NUE. Although higher N application rates often produce higher yields, this relationship is not linear. Indeed, an economic optimum application offsets the incremental yield increases vs. the cost of additional N inputs. Hawkesford (2014) reported that with low-to-moderate N fertilizer rates of 0–200 kg N ha^{-1}, both wheat yield and grain N uptake increased simultaneously. At the highest N rate of 350 kg ha^{-1}, no further yield increase was seen, although further N uptake was evident, expressed as higher grain N content.

When NUE is calculated as a function of unit of yield achieved per unit of N input, NUE is expectedly lower with the increasing N input (Hawkesford, 2012). In this study, the general trend across all site-years was that very high fertilizer N rates resulted in very low NUE values due to disproportionate/minimal yield increases as compared to N fertilizer inputs, or even lower grain yields, in some cases. On the other hand, in this study, N application was associated with a significant boost in grain protein content in 10 of 14 site-years. This agrees with findings by Mohammed et al. (2013) that observed higher grain protein levels at lower grain yields in wheat. Thus, the N uptake and accumulation of proteins in the wheat grain were more prominent drivers for greater NUE compared with grain yield.

4 | CONCLUSION

This work aimed to determine the optimum N rate to improve grain yield and quality of spring wheat in southern Idaho. Our results indicated that optimum N rate depended on the environment and field-specific prevailing conditions. This suggests that each growing season presents its own challenges in determining crop demand for N, due to temporal variability. In terms of grain quality, grain protein was significantly affected by N rate in 10 out of 14 site-years. The results also suggest that higher N rates resulted in higher grain protein content. Nitrogen use efficiency decreased at higher N application rates. In conclusion, the issue of N rate and its effect of yield and quality of wheat should be determined based on the location, year, and environmental conditions.

Traditional N-response trials are not consistently useful in prescribing the appropriate N rate. Implementing tools like N-rich strips, in combination with crop sensors, may be beneficial for detecting and quantifying both site- and year-specific crop yield potential and the responsiveness of the crop to N fertilization. Currently, the University of Idaho researchers are actively working on updating N fertilizer guidelines for wheat with incorporation of environmental parameters such as soil moisture and crop sensors.

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AUTHOR CONTRIBUTIONS

Olga S. Walsh: Conceptualization; Data curation; Funding acquisition; Project administration; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing. Juliet Marshall: Conceptualization; Data curation; Funding acquisition; Project administration; Resources; Validation; Writing – review & editing. Eva Nambi: Writing – original draft; Writing – review & editing. Sanaz Shafian: Investigation; Writing – review & editing. Dileepa Jayawardena: Supervision; Writing – review & editing. Jackson Chad: Investigation; Methodology. Ritika Lamichhane: Investigation; Methodology; Writing – review & editing. Emmanuella Ansah Owusu: Writing – review & editing. Jordan McClintick-Chess: Investigation; Methodology; Supervision.

CONFLICT OF INTEREST

The authors declare no conflict of interests.

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