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Research Article

Evaluation of Sensor-Based Nitrogen Rates and Sources in Wheat

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Nitrogen (N) is one of the most essential nutrients needed to reach maximum grain yield in all environments. Nitrogen fertilizers represent an important production cost, in both monetary and environmental terms. The aim of this study was to assess the effect of preplant nitrogen (N) rate and topdress N source on spring wheat (*Triticum aestivum* L.) grain yield and quality. Study was conducted in North-Central and Western Montana from 2011 to 2013 (total of 6 site-years). Six different preplant nitrogen (N) rates (0, 220, 22, 44, 67, and 90 N rate, kg ha^{-1}) followed by two topdress N sources (urea, 46-0-0, and urea ammonium nitrate (UAN), 32-0-0) were applied to spring wheat (*Triticum aestivum* L.). The results showed that there were no significant differences in grain yield, protein content, or protein yield, associated with topdress N source.

1. Introduction

Wheat is one of the most important crops which provide nutrition (proteins, energy, and minerals) to most of the world population. United States Department of Agriculture (USDA) has in its World Agricultural Supply and Demand Estimates (WASDE) forecasted global wheat production to reach 743 million metric tons (MMT), and the demand for wheat in developing countries is projected to increase 60% by 2050 (https://www.proag.com/news/world-wheat-consumption-increases-spring-wheat-in-short-supply/). Wheat ranks third among the US field crops in planted acreage, production, and gross farm receipts, behind corn and soybeans (https://www.ers.usda.gov/topics/crops/wheat/). Excellent growing conditions for much of the US, especially throughout the Great Plains states such as Kansas, Montana, North Dakota, Nebraska, and Oklahoma, contribute to excellent US wheat production levels. In 2016-17, the US farmers produced a total of 24.6 million US tons of winter, spring, and durum wheat on 50.2 million acres of cropland (https://www.ers.usda.gov/topics/crops/wheat/).

Wheat grain yield and quality depend on multiple genes interacting with environmental factors, such as nitrogen (N) availability, water, and temperature [1, 2]. Nitrogen is generally the most limiting nutrient factor for wheat production by influencing on chlorophyll production, photosynthesis process, and grain yield and quality [3]. Increasing N supply to a wheat crop can increase photosynthesis rate and consequently increase canopy biomass and grain yield. However, excessive N fertilization in cultivated land has profound environmental impacts such as nitrate leaching, soil denitrification, ammonia volatilization, and nitrous oxide emissions, which contaminate water and air and aggravate the climate change [4, 5]. While N losses cannot be avoided completely, they can be substantially reduced with sustainable agricultural practice such as adjusting N rate, timing and using the most appropriate fertilizer source, and adopting precision nutrient management technologies [6].

Crop canopy sensors have been developed to help growers to assess crop N status and make the best management decision based on actual crop condition and increase crop NUE [7]. Crop canopy sensors are designed to measure crop spectral reflectance at specific wavelength and generate vegetation indices (VIs) such as Normalized Difference Vegetation Index (NDVI) to assess specific crop characteristics of interest such as N status [8, 9]. These VIs can be used to generate field maps that show spatial variability of crop condition. These VIs have also been integrated into different algorithms to estimate crop N content, make fertilizer N recommendations, and increase economic return for producers [10]. Over 30 sensor-based algorithms have been developed since early 1990s. These algorithms are crop, region, and sensor specific and need to be calibrated for new crop in new region and new sensor used. For example, spring wheat (US, Canada, and Mexico) algorithm was developed as a collaborative effort of Oklahoma State University, Agriculture and Agri-Food Canada, and International Maize and Wheat Improvement Center (CYMMIT). This algorithm is a modified version of the spring wheat algorithm developed by the Oklahoma State University [11]. This algorithm is based on the relationship between sensor data collected early in the growing season and the yield attained across years and locations. The maximum wheat yield potential was set at 8000 kg ha^{-1} and the NUE at 35%. [12]. This algorithm is based on one single N application, immediately after sensing event, which is recommended to occur at Feekes 5-6 while the timing of applications and the source of N can affect the amount of N recovered or the nitrogen use efficiency (NUE) in a given year.

In the Great Plains, wheat growers can choose to apply all N before planting or split N fertilizer between preplant starter and the midseason topdress. Several N fertilizer sources—dry and liquid— are available to producers. The growers often chose N source based on current price per unit of N as well as currently available application equipment. Contrasting results in comparing dry with liquid N products in wheat have been reported. Several studies demonstrated that there are no differences in NUE between dry and liquid fertilizers [13, 14]. Some studies showed that NUE might be lower with liquid N sources due to significant ammonia loss [15]. Other researchers found that liquid N products may be superior in terms of crop yield and quality, as well as being more environmentally friendly, due to greater plant availability and thus more efficient uptake [16]. For example, in a long-term winter wheat study in Oklahoma (total of 80 site-years), liquid N products resulted in an almost 20% advantage in NUE compared to dry granular N source. Knowing the relative NUE of preplant and topdress and what type of N products is more efficient, dry or liquid one, are important for calibrating the developed algorithms, estimating crop N needed with higher accuracy to reach the potential yield plateau.

The objective of this study was to determine whether dry or liquid N source would result in significantly superior results in spring wheat production. Specifically, we assess the effect of preplant N rate and topdress N source on spring wheat grain yield and quality.

2. Methods and Materials

2.1. Study Areas. This study was conducted for three consecutive growing seasons (2011–2013) at two experimental locations: one dryland site, at Western Triangle Agricultural Center (WTARC), Conrad, MT (48.309794 and −111.924684), and one irrigated site at Western Agricultural Research Center (WARC), Corvallis, MT (46.328179 and −114.089873). Initial soil test results (2011) for each location are detailed in Table 1. The experimental design was a randomized complete block design (RCBD) with four replications. The main plot treatments included six preplant N rates (0, 22, 44, 67, 90, and 220 kg N ha^{-1}) applied at planting by side-banding granular urea (46-0-0) approximately 2.5 cm below the seed. The subplot treatments were two topdress N sources (dry granular urea and liquid urea ammonium nitrate (UAN)) (28-0-0) (Table 2). Treatment 1 (0 kg N ha^{-1}) was established as an unfertilized check plot and treatment 2 (220 kg N ha^{-1}) served as a nonlimiting N-rich reference. In total, there were 40 plots at each experimental location. Hard red spring wheat (*Triticum aestivum* cv. Choteau) was planted with a small plot drill with Conserva Pak™ openers manufactured by Swift Machining (Washougal, WA) at a density of approximately 1.8 million plants per hectare.

Table 1: Initial preplant soil test results (0–60 cm), Conrad and Corvallis, 2011.

	Conrad	Corvallis
Soil series	Scobey clay loam	Burnt Fork silt loam
pH	7.7	7.8
O.M.	3.7	1.5
NO_3-N	50	57
P (ppm)	20	18
K (ppm)	272	221
EC (mmhos/cm)	0.48	0.35

Table 2: Treatment, preplant N rate, and topdress N source for each study site.

Trt	*Preplant N rate, kg ha^{-1}	**Topdress N source
1	0	-
2	220	urea
3	22	urea
4	44	urea
5	67	urea
6	90	urea
7	22	UAN
8	44	UAN
9	67	UAN
10	90	UAN

2.2. Field Data Collection and Generating Topdress N Prescriptions. Within each study plot, Normalized Difference Vegetative Index (NDVI), was measured using a GreenSeeker hand-held optical sensor (Trimble Navigation Ltd., Sunnyvale, CA) at Feekes 5 of growing stage (early jointing, beginning of stem elongation, prior to first visible node). Then, the Spring Wheat (US, Canada, Mexico) algorithm (http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php) was used to calculate topdress N rates for each treatment. The algorithm uses maximum NDVI (measured NDVI in treatment 2, non-limiting N reference), measured NDVI for each treatment, seeding date, date of sensing (NDVI measurement date), and yield goal (average yield goal for the area) as input parameters to calculate topdress N rates. In some cases, treatment 2 did

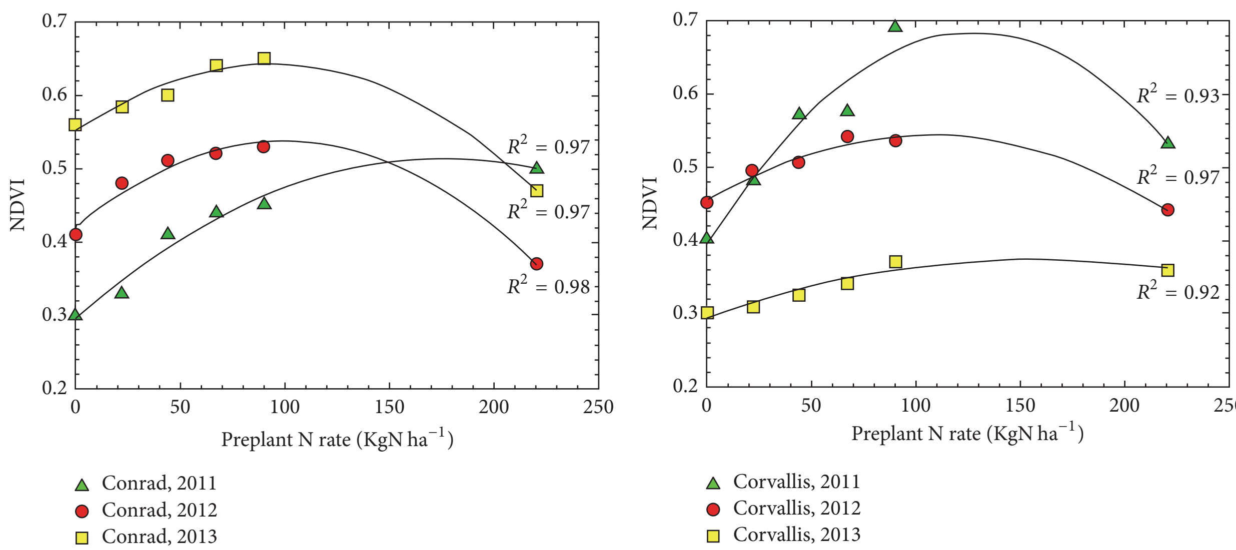

Figure 1: Relationships between Normalized Difference Vegetation Index (NDVI) and preplant N application rate for 2011, 2012, and 2013 at (a) Conrad and (b) Corvallis. Each data point represents the mean of four replications and was regressed against preplant N application rate.

not result in the highest NDVI for the location, possibly, due to the negative impact of a high N rate applied at planting affecting the seed. Then, a treatment with the highest NDVI values was chosen and used as a reference. The topdress N fertilizer was applied as urea (as dry prill, broadcasted manually) or as UAN (as a foliar spray, using a battery-operated backpack sprayer with a fan nozzle).

At maturity, wheat was harvested with a self-propelled Wintersteiger Classic Combine (Wintersteiger Inc., Salt Lake City, USA). At harvest, plot grain yield was recorded for each experimental plot using a Harvest Master GrainGage, by Wintersteiger. The harvested wheat grain was dried in the drying room for 14 days at the temperature of 35°C; then, the dried samples were weighed to determine the accurate by-plot grain yield, which was adjusted to 12% moisture. The by-plot subsamples were analyzed for total N content using near infrared reflectance spectroscopy (NIR) with a Perten DA 7250 NIR analyzer (Perten Instruments, Inc., Springfield, IL) at Agvise Laboratories (Northwood, ND).

2.3. Statistical Analysis. Grain N uptake for each plot was calculated by multiplying grain yield by total N concentration. The analysis of variance was conducted using the PROC GLM procedure in SAS v9.4 (SAS Institute, Inc., Cary, NC) and the mean separation was performed using the Orthogonal Contrasts method at a significance level of 0.05.

3. Results and Discussions

3.1. Relationship between Preplant N Rate and NDVI. Responses of NDVI to preplant N application rate for 2011, 2012 and 2013 at each study site are presented in Figure 1. Generally, there was a significant positive correlation between NDVI and preplant N application rate for all site-years.

The relationships between NDVI and preplant N application rate were linear or quadratic in nature (Figure 1). Positive quadratic relationships were more frequently observed between preplant N application rate and NDVI when wheat NDVI values were relatively high.

At Conrad site, the average NDVI values were 0.40, 0.47, and 0.58 in 2011, 2012, and 2013, respectively. Conrad was a dryland site, so differences in NDVI values for same preplant N application rate in different years could be related to varied precipitations and, consequently, differences in soil moisture content. In 2011 season, the amount and the distribution of rainfall from May to July, from planting time to the time the NDVI was measured, were higher than in 2012 and 2013. Moreover, the daily rainfall distribution was erratic; at times, heavy rain has caused significant runoff and leaching in 2011 compared to 2012 and 2013. This may explain lower average NDVI value at Conrad in 2011 compared to other two growing seasons. In 2013 Conrad study site received almost 20 cm of snowfall in April, before wheat planting, which increased the soil moisture content considerably. The higher soil moisture amounts available at wheat planting has likely resulted in higher NDVI values in 2013 compared to 2011 and 2012.

At Corvallis study site, the average NDVI values were 0.54, 0.49, and 0.33 in 2011, 2012, and 2013, respectively. At Corvallis, plots received 15.24 cm of irrigation water in three equally space periods between planting and soft dough stage, annually. Precipitation data can explain the differences in average NDVI values in different years. This field received 11.25 cm, 8.08 cm, and 7.76 cm of precipitations in 2011, 2012, and 2013, respectively, from planting to the date of the NDVI measurement. The higher rainfall in 2011 apparently may have resulted in higher NDVI compare to other years.

For Conrad in 2012 and 2013 and for Corvallis in 2011 and 2012, treatment 2, 220 kg N ha^{-1}, did not reach the highest NDVI value. This was possibly because the 220 kg N ha^{-1} preplant application rate might have been damaging to seeds and/or seedlings and produced relatively poor stand. The

Table 3: Preplant N rate, topdress N rate, topdress N source, total N rate applied, and spring wheat grain yield, Conrad and Corvallis, MT, 2011.

Trt	Conrad			Corvallis		
	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}
1	-	-	942 f	-	-	2018 f
2	22	242	2690 a	24	244	3699 abc
3	22	44	1547 e	32	54	2757 d
4	22	66	1547 e	8	52	3430 bc
5	22	89	1883 cd	17	84	3833 abc
6	11	101	2152 b	24	114	3968 a
7	33	55	1480 e	32	54	3228 cd
8	22	66	1614 de	8	52	3497 abc
9	11	78	1950 bc	8	75	3363 bc
10	11	101	2152 b	17	107	3564 abc

*Preplant fertilizer N will be applied as urea. **Topdress fertilizer N rates were determined based on the NDVI values obtained using GreenSeeker, as prescribed by USA, Canada, Mexico Algorithm. Means within each column followed by the same letter are not significantly different at $p < 0.05$, as determined by Duncan's multiple range test.

Table 4: Preplant N rate, topdress N rate, topdress N source, total N rate applied, and spring wheat grain yield, Conrad and Corvallis, MT, 2012.

Trt	Conrad			Corvallis		
	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}
1	-	-	5851 d	-	-	3901 f
2	78	298	6187 d	110	330	6456 d
3	16	38	6658 c	124	146	6725 cd
4	16	60	6994 abc	124	168	6927 bcd
5	16	83	7061 abc	124	191	7465 ab
6	30	120	7263 a	124	214	6860 bcd
7	25	47	6658 c	124	146	7196 abcd
8	16	60	6725 bc	110	154	7398 abcd
9	21	88	6927 abc	124	191	7599 a
10	21	111	7129 ab	110	200	7667 a

*Preplant fertilizer N will be applied as urea. **Topdress fertilizer N rates were determined based on the NDVI values obtained using GreenSeeker, as prescribed by USA, Canada, Mexico Algorithm. Means within each column followed by the same letter are not significantly different at $p < 0.05$, as determined by Duncan's multiple range test.

decision was made to use a treatment with the highest NDVI value as an N-rich reference for those particular site-years.

3.2. Relationship between NDVI and Prescribed Topdress N Rates. The algorithm has prescribed topdress N rates ranging from 0 to 137 kg N ha^{-1} depending on the yield goal for the location and the obtained NDVI values (Tables 3–5). As it mentioned in previous section, in several instances that treatment 2 did not reach to the highest NDVI value the decision was made to use a treatment with the highest NDVI value as an N-rich reference for that particular site-year.

In some cases, the algorithm prescribed higher topdress N rate for treatment with lower NDVI values in order to boost yield potential. For example, at Conrad, in 2012, measured NDVI showed higher value in treatment 6 compared to treatment 2 (Table 6). Prescribed 30 kg N ha^{-1} topdress N for treatment 6 resulted in a total of 120 kg N ha^{-1} applied, while 78 kg N ha^{-1} topdress N prescribed for treatment 2 resulted in a total of 298 kg N ha^{-1} applied. However, treatment 6 yielded over 1000 kg ha^{-1} more compared to treatment 2. This suggests that prescribed topdress N rate for treatment 2 was excessive and did not help to optimize yield.

In some instances, the prescribed N rates did not allow to reach optimum yield (Conrad, 2011 (Table 6)). Although higher topdress N rate of 33 kg N ha^{-1} was prescribed to treatment 7 compared to 11 kg N ha^{-1} recommended for treatment 6, it was not adequate to optimize yield. In fact, significantly lower yield was obtained with treatment 7 (1480 kg ha^{-1}), which received only 22 kg N ha^{-1} at seeding, compared to treatment 6 (2152 kg N ha^{-1}) to which 90 kg N ha^{-1} was applied at seeding. Moreover, the highest grain yield for

Table 5: Preplant N rate, topdress N rate, topdress N source, total N rate applied, and spring wheat grain yield, Conrad and Corvallis, MT, 2013.

Trt	Conrad			Corvallis		
	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}	Topdress N rate, kg ha^{-1}	Total N rate applied, kg ha^{-1}	Grain yield, kg ha^{-1}
1	-	-	4304 ab	-	-	3430 a
2	91	311	4102 b	90	310	3968 a
3	54	76	4237 ab	90	112	3968 a
4	54	98	4304 ab	90	134	4035 a
5	54	121	4573 ab	137	204	3968 a
6	54	144	4708 ab	90	180	4035 a
7	54	76	4439 ab	137	159	3430 a
8	54	98	4506 ab	90	134	3430 a
9	54	121	4842 a	90	157	3430 a
10	104	194	4573 ab	137	227	3430 a

*Preplant fertilizer N will be applied as urea. **Topdress fertilizer N rates were determined based on the NDVI values obtained using GreenSeeker, as prescribed by USA, Canada, Mexico Algorithm. Means within each column followed by the same letter are not significantly different at $p < 0.05$, as determined by Duncan's multiple range test.

Table 6: Three cases illustrating topdress N rate recommendations prescribed by US-Canada-Mexico Algorithm and grain yield results obtained following the application of prescribed N rates.

Case	Site-year	Trt	Preplant N rate, kg ha^{-1}	Topdress N rate, kg ha^{-1}	Total N rate, kg ha^{-1}	N rate difference, kg ha^{-1}	*Grain yield, kg ha^{-1}	Yield gain, kg ha^{-1}
1	Conrad, 2012	2	220	78	298	−178	6187 d	+1076
		6	90	30	120		7263 a	
2	Conrad, 2011	6	90	11	101	−46	2152 b	+672
		7	22	33	55		1480 e	
3	Conrad, 2012	3	22	16	38	+98	6658 c	+605
		6	90	30	120		7263 a	

*Means followed by the same letter are not significantly different at $p < 0.05$, as determined by Duncan's multiple range test.

that site-year was 2690 kg N ha^{-1} (treatment 2, 220 kg N ha^{-1} applied at seeding), which suggests that topdress N rates should have been higher for both treatment 6 and treatment 7.

In some cases, the topdress N rates seemed appropriate. For instance, at Conrad, in 2012, higher preplant N rate for treatment 6 (90 kg N ha^{-1}) resulted in better plant stand, reflected by the greater NDVI value compared to treatment 3 (22 kg N ha^{-1} preplant). This prompted higher N rate recommendation of 25 kg N ha^{-1} for treatment 6 compared to only 15 kg N ha^{-1} for treatment 3. A difference of 98 kg N ha^{-1} total N applied has resulted in a surplus of 605 kg ha^{-1} of wheat grain yield.

These results show that, at all site-years, N fertilizer rates recommended by the USA/Canada/Mexico Algorithm were not appropriate for grain yield optimization. For example, much higher topdress N rates were prescribed for Corvallis (the irrigated site) compared to the Conrad (dryland sites). This makes sense since the expected yield potential (YP) at the irrigated site was much greater. On the other hand, grain yields obtained at Conrad were just as high as at Corvallis, indicating that the YP was either overestimated at Corvallis or underestimated at Conrad. This puts forward a question of whether there is a need for two separate algorithms, one developed for dryland spring wheat and the other for irrigated spring wheat production systems.

3.3. Relationship between N Rate and Source and Wheat Yield and Quality. Based on different N application rates and sources, a wide range of yields ranging from 942 kg ha^{-1} to 7667 kg ha^{-1} were obtained (Tables 3–5). In 2011 and 2012 growing seasons, grain yield response to preplant N application rate was significant at all locations (Table 7). In Conrad, the highest mean grain yield of 7263 kg ha^{-1} was obtained in 2012 when 90 kg N ha^{-1} preplan followed by 30 kg N ha^{-1} topdress was applied as urea. In Corvallis, the highest mean yield of 7667 kg N ha^{-1} was obtained in 2012 when 90 kg ha^{-1} preplant followed by 110 kg ha^{-1} topdress was applied as UAN. In contrast, the lowest grain yield, except the control, was recorded when 22 kg N ha^{-1} preplant followed by 33 kg N ha^{-1} of topdress in Conrad in 2011. These results showed that, in most cases, the higher amount of N applied resulted in higher grain yield, which in consistent with results from other studies [17, 18].

Table 7: Effect of preplant N rate and topdress N source on spring wheat grain yield (GY) and grain protein content (GP) for 6 site-years in Montana.

Effects	Growing season 2011				Growing season 2012				Growing season 2013			
	Conrad		Corvallis		Conrad		Corvallis		Conrad		Corvallis	
	GY, kg ha^{-1}	GP, %	GY, kg ha^{-1}	GP, %	GY, kg ha^{-1}	GP, %	GY, kg ha^{-1}	GP, %	GY, kg ha^{-1}	GP, %	GY, kg ha^{-1}	GP, %
Preplant N rate												
0	942	9.5	2018	14.0	5851	9.6	3901	11.0	4304	12.4	3430	14.3
22	1480	9.5	3026	15.0	6658	10.5	6994	13.0	4304	14.0	3699	17.3
44	1614	9.6	3430	13.0	6860	11.1	7129	14.0	4371	14.6	3699	16.6
67	1950	9.5	3632	15.0	6994	11.8	7532	14.0	4708	15.2	3699	17.1
90	2152	9.6	3766	15.0	7196	14.3	7263	14.0	4640	15.7	3699	17.2
220	2690	9.7	3699	16.0	6187	15.4	6456	15.0	4102	17.2	3968	17.4
F test	**	ns	* * *	**	* * *	ns	* * *	* * *	ns	* * *	ns	* * *
Topdress N source												
Urea	1749	9.6	3497	14.5	5716	11.5	5985	14.1	4439	15.2	3968	17.2
UAN	1816	9.5	3430	14.4	5582	11.6	6456	13.6	4573	14.6	3430	16.9
F test	ns	ns	ns	ns	ns	ns	* * *	* * *	ns	* * *	* * *	ns

** and * * * denote significant at 0.05 and 0.01 levels, respectively; ns denotes not significant.

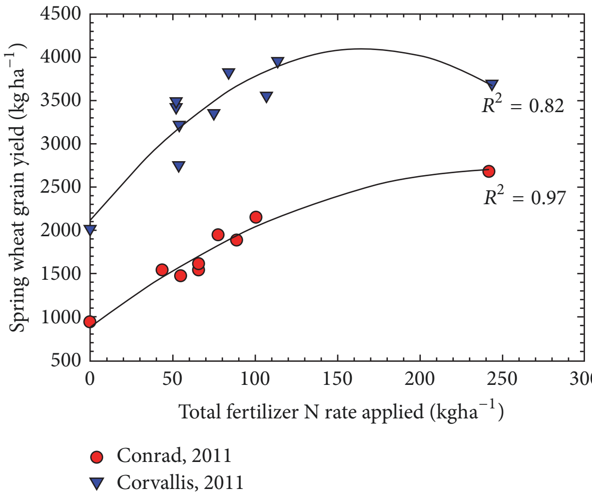

Figure 2: Spring wheat grain yield as affected by total amount of applied N fertilizer, Conrad and Corvallis, MT, 2011.

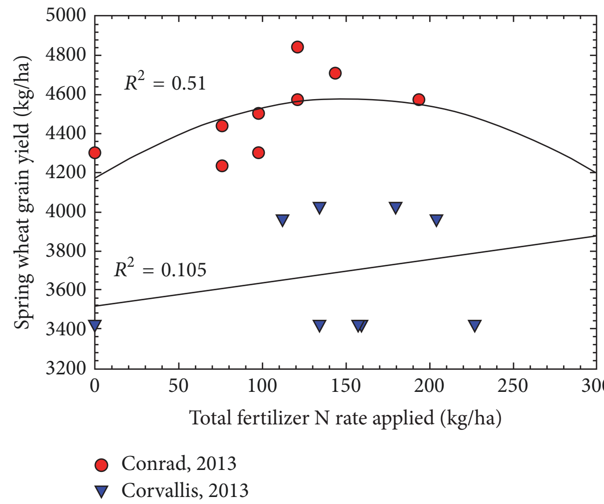

Figure 4: Spring wheat grain yield as affected by total amount of applied N fertilizer, Conrad and Corvallis, MT, 2013.

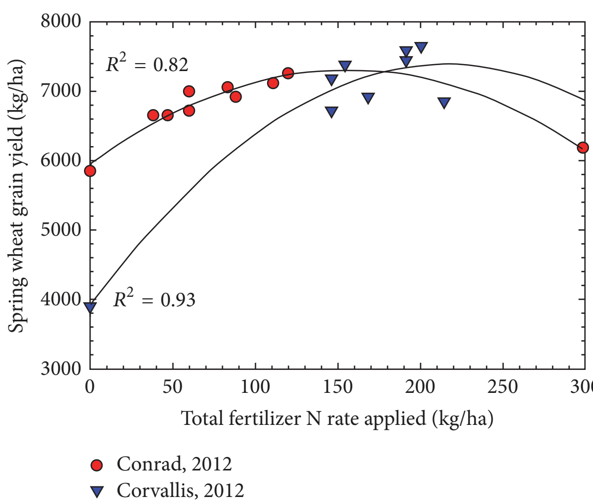

Figure 3: Spring wheat grain yield as affected by total amount of applied N fertilizer, Conrad and Corvallis, MT, 2012.

Although the application of urea resulted in slightly higher yields compared to UAN, with 1 site-year being virtually equal in yield for both N sources, the differences were no statistically significant. In addition, the results showed there were no significant differences in grain protein content values associated with topdress fertilizer N source (urea versus UAN), although slightly higher (but not statistically significant) grain protein content values were noted with urea topdress application compared to UAN (Table 7).

The relationship between total amount of N applied and spring wheat grain yield for each site-year is shown in Figures 2–4. In all cases, there was a positive correlation between total amount of applied N fertilizer and grain yield. In 2011 and 2012 for both fields, this correlation was strong with R^2 ranging from 0.82 to 0.95. In 2013, R^2 decreased for both locations. These results may indicate that the model should be calibrated for each location frequently. In 2011, at Conrad, wheat yield increased to 242 kg N ha^{-1} and at Corvallis to 114 kg N ha^{-1} (Figure 2). In 2012, at Conrad, yield was maximized at 120 kg N ha^{-1} and at Corvallis at 200 kg N ha^{-1} (Figure 3). In 2013, at Conrad, grain yield was maximized at 121 kg N ha^{-1} and at Corvallis at 134 kg N ha^{-1} (Figure 4).

4. Conclusions

Crop canopy sensors are convenient tools for assessment of crop N status and provide assistance to growers when making the best management decision based on actual crop condition. In this study, NDVI from a GreenSeeker sensor was integrated with spring wheat (US, Canada, and Mexico) algorithm to estimate crop N content and make fertilizer N recommendations.

Overall, no significant differences in wheat grain yield or grain protein content associated with topdress N fertilizer source were observed at any of the site-years. This suggests that topdress N fertilizer rates do not need to be adjusted based of fertilizer sources used, that is, the same N rates should be prescribed whether urea or UAN is applied. At the time of this writing, the cost of N sources per unit of N are volatile, with urea currently costing \$0.45 more per kg of N. Thus, growers are strongly advised to pay attention to fertilizer prices per unit of N when making decisions on what N source to use in any particular growing season, especially when there is no clear consistent advantage from using one source versus the other.

Results indicated that the three assessed algorithms developed in other regions did not provide the appropriate topdress N rate recommendations for spring wheat. Our case study emphasizes the importance of (1) calibrating the crop sensors for the local crop varieties and growing conditions and (2) developing N fertilization algorithms based on locally established YP prediction studies.

Conflicts of Interest

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

Acknowledgments

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References

[1] C. L. Da Silva, G. Benin, E. Bornhofen, E. Beche, M. H. Todeschini, and A. S. Milioli, "Nitrogen use efficiency is associated with chlorophyll content in Brazilian spring wheat," *Australian Journal of Crop Science*, vol. 8, no. 6, pp. 957–964, 2014.

[2] X. Xu, Z. Wu, Y. Dong, Z. Zhou, and Z. Xiong, "Effects of nitrogen and biochar amendment on soil methane concentration profiles and diffusion in a rice-wheat annual rotation system," *Scientific reports*, vol. 6, Article ID 38688, 2016.

[3] D. K. Biswas and B.-L. Ma, "Effect of nitrogen rate and fertilizer nitrogen source on physiology, yield, grain quality, and nitrogen use efficiency in corn," *Canadian Journal of Plant Science*, vol. 96, no. 3, pp. 392–403, 2016.

[4] A. R. Ravishankara, J. S. Daniel, and R. W. Portmann, "Nitrous oxide (N_2O): the dominant ozone-depleting substance emitted in the 21st century," *Science*, vol. 326, no. 5949, pp. 123–125, 2009.

[5] D. S. Reay, E. A. Davidson, K. A. Smith et al., "Global agriculture and nitrous oxide emissions," *Nature Climate Change*, vol. 2, no. 6, pp. 410–416, 2012.

[6] N. Gupta, A. K. Gupta, V. S. Gaur, and A. Kumar, "Relationship of nitrogen use efficiency with the activities of enzymes involved in nitrogen uptake and assimilation of finger millet genotypes grown under different nitrogen inputs," *The Scientific World Journal*, vol. 2012, Article ID 625731, 10 pages, 2012.

[7] L. J. Thompson, R. B. Ferguson, N. Kitchen et al., "Model and sensor-based recommendation approaches for in-season nitrogen management in corn," *Agronomy Journal*, vol. 107, no. 6, pp. 2020–2030, 2015.

[8] J. Crain, I. Ortiz-Monasterio, and B. Raun, "Evaluation of a reduced cost active NDVI sensor for crop nutrient management," *Journal of Sensors*, vol. 2012, Article ID 582028, 10 pages, 2012.

[9] M. Huang, W. Zhang, L. Jiang, and Y. Zou, "Impact of temperature changes on early-rice productivity in a subtropical environment of China," *Field Crops Research*, vol. 146, pp. 10–15, 2013.

[10] J. T. Bushong, J. L. Mullock, E. C. Miller, W. R. Raun, and D. Brian Arnall, "Evaluation of mid-season sensor based nitrogen fertilizer recommendations for winter wheat using different estimates of yield potential," *Precision Agriculture*, vol. 17, no. 4, pp. 470–487, 2016.

[11] W. R. Raun, J. B. Solie, M. L. Stone et al., "Optical sensor-based algorithm for crop nitrogen fertilization," *Communications in Soil Science and Plant Analysis*, vol. 36, no. 19-20, pp. 2759–2781, 2005.

[12] J. I. Ortiz-Monasterio and W. Raun, "Reduced nitrogen and improved farm income for irrigated spring wheat in the Yaqui Valley, Mexico, using sensor based nitrogen management," *Journal of Agricultural Science*, vol. 145, no. 3, pp. 215–222, 2007.

[13] G. Silva, *All Fertilizers are not Created Equal*, 2016, http://msue.anr.msu.edu/news/all_fertilizers_are_not_created_equal.

[14] The Mosaic Company, *Fluid and Dry Fertilizers, Fluids and Solids are Equal Agronomically*, 2013, http://www.cropnutrition.com/efu-fluid-dry-fertilizers#overview.

[15] C. J. Watson, R. J. Stevens, R. J. Laughlin, and P. Poland, "Volatilization of ammonia from solid and liquid urea surface-applied to perennial ryegrass," *The Journal of Agricultural Science*, vol. 119, no. 2, pp. 223–226, 1992.

[16] E. Lombi, M. J. McLaughlin, C. Johnston, R. D. Armstrong, and R. E. Holloway, "Mobility and lability of phosphorus from granular and fluid monoammonium phosphate differs in a calcareous soil," *Soil Science Society of America Journal*, vol. 68, no. 2, pp. 682–689, 2004.

[17] Z. Abebe and H. Feyisa, "Effects of nitrogen rates and time of application on yield of maize: rainfall variability influenced time of N application," *International Journal of Agronomy*, 2017.

[18] O. S. Walsh, A. Pandey, and R. Christiaens, "Sensor-based technologies for nitrogen management in spring wheat," in *Proceedings of the Western Nutrient Management Conference*, vol. 11, Reno, NV, USA, 2015, http://www.ipni.net/ipniweb/conference/wnmc.nsf/e0f085ed5f091b1b852579000057902e/4be3031d1d87927a85257e37004fa7a8/$FILE/WNMC2015%20Walsh%20pg163.pdf.