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Research Article

Relative Efficacy of Liquid Nitrogen Fertilizers in Dryland Spring Wheat

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The study was conducted in 2012 and 2013 at three locations in North Central and Western Montana (total of 6 site-years) to evaluate the relative efficacy of three liquid nitrogen (N) fertilizer sources, urea ammonium nitrate (UAN, 32-0-0), liquid urea (LU, 21-0-0), and High NRGN (HNRGN, 27-0-0-1S), in spring wheat (*Triticum aestivum* L.). In addition to at-seeding urea application at 90 kg N ha^{-1} to all treatments (except for the unfertilized check plot), the liquid fertilizers were applied utilizing an all-terrain vehicle- (ATV-) mounted stream-bar equipped sprayer at a rate of 45 kg N ha^{-1} at Feekes 5 growth stage (early tillering). Three dilution ratios of fertilizer to water were accessed: 100/0 (undiluted), 66/33, and 33/66. The effects of N source and the dilution ratio (fertilizer/water) on N uptake (NUp), N use efficiency (NUE), spring wheat grain yield (GY), grain protein (GP) content, and protein yield (PY) were assessed. The dilution ratios had no effect on GY, GP, PY, NUp, and NUE at any of the site-years in this study. Taking into account agronomic and economic factors, LU can be recommended as the most suitable liquid N fertilizer source for spring wheat cropping systems of the Northern Great Plains.

1. Introduction

Wheat is the main food grain produced in the United States [1]. Wheat accounts for approximately 20% of the total food calories consumed worldwide. Overall, approximately 35% of the world's population regularly depends on wheat for their nourishment. In the US, the consumption of wheat per capita exceeds that of any other food staple. Besides supplying carbohydrates, wheat also contains valuable proteins, minerals, and vitamins and essential amino acids like lysine [2]. Currently, the United States exports an average of 26.0 million metric tons of all wheat classes annually and leads in hard red winter and soft red winter wheat exports [3]. While N is considered the most common nutrient limiting yield of wheat and other cereal crops [4], N use efficiency (NUE) is currently between 40 and 50% for most cereal crop production systems [5]. A notable increase from the late 1990s estimates for NUE being 33% [6] is largely due to continuous advances in fertilizer management strategies and novel fertilizer technologies.

For many years, fertilization was driven by maximizing and sustaining crop yields as the main goal [7]. With the harmful effects of inefficient nutrient management practices resulting in soil, water, and air environments becoming a major concern, increasing fertilizer use efficiency has surfaced as a newly defined goal for crop producers. The most sensible and ethical solution to meet crops' nutrient demand is developing of more efficient crop fertilizer practices [8]. Establishing effective N management systems, updating N application guidelines, and improving NUE are the key challenges that must be addressed to sustain and enhance the sustainability of wheat production. Sustaining global food security and minimizing the negative impact of agriculture intensification on environmental quality are the most challenging issues the researchers and crop growers are facing today [9]. One of the key ways the producer can conserve fertilizer energy is utilizing fertilizer more efficiently, which entails optimizing crop yield with a minimum amount of fertilizer [10]. At least 50% of food produced in the world today is only possible due to commercial N, phosphorus (P), and potassium (K) fertilizer application to crops [11]. Commercial fertilizers are available in different forms, grades, and formulations; they can be solid (dry granular), liquids (fluid products), or gaseous (usually stored in a liquid form and transforming to gas when applied). In 2014 alone, the US crop farms expenditures related to fertilizers (including lime and soil conditioners) were $23.2 billion, surpassed only by land rent and labor costs [12].

According to the Ohio State University's Extension [13], "are liquid fertilizers equal to or better than dry fertilizers?" and "are liquid fertilizers more available than granular fertilizers?" are among the top 20 most asked agronomic questions. Inconsistent results in comparing liquid and dry N sources in wheat have been reported in literature. Many studies support the conclusion that there are no differences in the efficiency between the liquid and dry fertilizers [13, 14]. Some researchers concluded that significant ammonia loss occurs from liquid N fertilizers, which in fact decreases NUE [15]. Other research results suggest that liquid products may be superior in regard to crop yield and quality as well as being more environmentally friendly, due to superior plant availability and more efficient uptake [16]. Fluid fertilizers have been shown to have increased fertilizer use efficiently in several studies [17, 18].

In a long-term experiment in Oklahoma, comprising 8 growing seasons and 10 locations, liquid N fertilizer has resulted in a 19% advantage in NUE compared to dry granular N fertilizer in winter wheat. They also found the liquid N to be more profitable, even taking into account the per-unit cost advantage of the dry product over the liquid [19]. A combined application of compatible liquid N fertilizers and chemicals, such as herbicides and pesticides, could result in substantial monetary, time, and labor savings. Liquid fertilizers are easily transported, stored, and calibrated for precise application [20]. Compared to a mix created by combining several dry fertilizers, blending of liquid products results in a much more homogeneous mixture, where each drop has the uniform analysis [21]. The higher production cost of fluid fertilizers due to higher energy requirements may be balanced by higher efficiency resulting from a more consistent and uniform application [13]. The analysis of US fertilizer market share has shown that the utilization of liquid fertilizers is on the increase compared to dry fertilizer sources [21, 22]. The success of liquid fertilizers in corn production suggests that they will be of benefit in small grain cereals as well [23].

Application of liquid fertilizers, especially to crop canopy, has been recognized as the least recommended option for N application by some researchers [24]. Application of liquid N products at high concentrations often results in leaf burn as water evaporates and the fertilizer salts remain behind. Early in the growing season, foliar application may cause leaf burn; furthermore, mid- to late-season application can cause foliar diseases and reduce grain yields due to burn injury. The documented yield reductions due to sprayed liquid N vary by application conditions and N rates; 400 to 800 kg ha^{-1} yield losses have been frequently reported. Some growers spray liquid N to wheat using flat fan or flood-jet nozzles which often can be a cause of significant leaf injury, even at early wheat growth stages, and may reduce early-season plant health critical for the grain formation [25]. Others note that leaf burn is often generally cosmetic and rarely causes yield reduction [26]. Edwards et al. [27] observed no leaf burn with application of liquid N products to wheat canopy, even at high temperatures of 25–30°C. As noted by Arnall et al. [28], liquid N fertilizers like UAN can cause leaf burning which can be considerable at higher rates, but, normally, the burning does not cause serious leaf injury and often does not impact yields, unless the product was sprayed on already significantly stressed crop. Stream nozzles and stream bars enable placement of liquid fertilizers in a concentrated band on the soil surface; this minimizes the opportunity for immobilization by soil microbial organisms. Some research has shown that streaming liquid products can lead to more efficient N use [26]. Streaming, applying the fluid fertilizers in narrow bands in either large drops or small streams, results in a concentration of the material in very small areas, which minimizes the potential for N loss. As the large drops get in contact with the plant material, there is less potential for injury, because the drops tend to roll off the plant to the soil surface. Arnall et al. [28] noted that streaming using stream bars is a preferred application method for fluid fertilizers.

Diluting fluid N fertilizers with water prior to application is one of the ways often recommended to reduce crop damage due to leaf burn. Diluting UAN 50%-50% with water reduced leaf burn in 2 of 3 years of the study; wheat recovered within 3 weeks and grain yields were not reduced [29]. The South Dakota State University's Extension Service recommends diluting liquid N to be diluted 1 : 1 with water to reduce leaf burn [30]. Similarly, the North Dakota State University's Extension Service advises growers to dilute UAN with water (1 : 1) to minimize the potential for leaf burn [31]. Furthermore, it is suggested not to apply liquid fertilizers to wheat at the rate exceeding 68 kg N ha^{-1} [32] and to corn at the rate exceeding 35 kg N ha^{-1} [33]. Gregoire [34] recorded a significant loss in yield when UAN was applied at the 45 kg N ha^{-1} rate. On the other hand, many growers are reluctant to dilute N fertilizers with substantial amounts of water because of the need to refill the tanks more often, which slows down the application time and increases application cost.

Several liquid N fertilizers varying in analysis are currently available on the market. These products include N or a blend of N and other macro- and micronutrients. Some of N foliar fertilizers include UAN, LU, and HNRGN. Urea ammonium nitrate is the most commonly used fluid N fertilizer. Urea ammonium nitrate (28-0-0 or 32-0-0) is a nonpressurized solution that can be used in a variety of agricultural crops. The versatile liquid mix of urea and ammonium nitrate has been available to growers for a long time. It offers fast acting and long lasting plant nutrient supply in a combination of three forms of nitrogen. Nitrate-N provides quick response and ammonic-N a longer lasting response and continuous nutrition from the water soluble organic N in urea [35]. Liquid urea is a water-based urea solution (20-0-0). The noted benefits of LU include slower uptake by the plant, which helps to maintain N levels within the soil-plant system. Liquid urea is suggested for application during the warm periods in the growing season to quickly correct N deficiency [36]. The primary advantage of LU compared to UAN is that it is less corrosive and, thus, poses a lesser risk of leaf burn [37]. On the other hand, the percentage of N in LU is lower and the transportation costs are usually greater per unit of N [38]. As the manufacturer of LU indicates on the product label, the ratio of LU to water should not exceed 1 : 4 for ground application [39]. Research on LU is very limited. Generally, it has been reported that where dry urea functions effectively the fluid urea should perform equally well or better due to having advantage of greater application uniformity over dry granular urea [40].

HNRGN has been marketed since the beginning of the 1990s; it is considered as one of the most efficient direct-applied N sources. HNRGN contains several forms of N and sulfur (S) as well as trace amounts of chlorophyll building elements such as iron (Fe), magnesium (Mg), manganese (Mn), and zinc (Zn). HNRGN also contains several proprietary enhancements. The product is very low in free ammonia and has been especially developed to minimize N loss and increased plant uptake. HNRGN has a reduced salt index and, therefore, is less corrosive compared to UAN [41].

The interest of crop growers in liquid N fertilizers is sustained by the pressing need to improve the efficiency of their farming operations and the successful marketing efforts by fertilizer industry and dealers. Many wheat growers in the Northern Great Plains, including the state of Montana, are already using fluid products or considering including them in their nutrient management program. These growers are in need of up-to-date and unbiased information about currently marketed liquid N fertilizers. Overall, opinion emphasized in most scientific reports could be summarized as follows: liquid N fertilizers could be successfully utilized; however, based on the products' labels, their application is limited due to potential leaf burn, where substantial N rates must be applied to satisfy crop needs.

2. Objectives

The objectives of this study were (i) to compare the efficacy of liquid N fertilizers (UAN, liquid urea, and HNRGN) applied to spring wheat and (ii) to determine the optimum N rate and dilution ratio of liquid fertilizers and the threshold at which spring wheat grain yield is reduced due to leaf burn.

3. Materials and Methods

This field study was conducted in 2012 and 2013 at three locations: two drylands, at Western Triangle Agricultural Research Center (WTARC, near Conrad, MT (48.309794, −111.924684)) and in a cooperating producer's field (Jack Patton, Choteau County, MT (47.973032, −111.222696)), and one irrigated land, at Western Agricultural Research Center (WARC, near Corvallis, MT (46.328179, −114.089873)). Hard red spring wheat (cv. Choteau) was direct-seeded into plots measuring 1.5 by 7.6 m at the seeding rate of 1.8 million plants per hectare. Small plot drill with Conserva Pak™ openers manufactured by Swift Machining (Washougal, WA) was used to establish the research plots.

Appropriate weed and pest management control were employed when necessary. Treatment structure is reported in Table 1. At seeding, urea was applied in a band with the seed at 90 kg N ha^{-1} to all treatments except for the unfertilized check plot. At Feekes 5 growth stage (early tillering), 45 kg N ha^{-1} was applied utilizing an all-terrain vehicle- (ATV-) mounted stream-bar equipped sprayer. Three liquid N sources, UAN, LU, and HNRGN, and three dilution ratios of fertilizer%/water%, 100/0, 66/33, and 33/66, were evaluated. Because HNRGN contains Fe, Mg, Mn, and Zn, soil analysis was used to ensure that any of these nutrients were not deficient and can be corrected prior to top-dressing application. Similarly, because HNRGN contains S, plant samples were taken prior to top-dressing application to determine possible S deficiency and correct it as needed. At maturity, spring wheat was harvested with Hage 125 plot combine in 2012 and Wintersteiger Classic plot combine in 2013.

The field work activities are detailed in Tables 2 and 3. The harvested grain was dried in the drying room for 14 days at the temperature of 35°C. Then, the by-plot grain yield was determined utilizing scale. The subsamples (400 g) were analyzed by the Agvise Laboratories (Northwood, ND) for total N content utilizing near infrared reflectance (NIR) spectroscopy with a Perten DA 7250 NIR analyzer (Perten Instruments, Inc., Springfield, IL). The effects of N source and the dilution ratio (fertilizer/water) on N uptake (NUp), N use efficiency (NUE), spring wheat grain yield (GY), and grain protein (GP) content and protein yield (PY) were assessed. Grain N uptake was calculated by multiplying grain yield by total N concentration. N use efficiency was determined using the difference method [42] 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. The analysis of variance was conducted using the PROC GLM procedure in SAS v9.3 (SAS Institute, Inc., Cary, NC). Mean separation was performed using the Orthogonal Contrasts method at a significance level of 0.05.

4. Results

4.1. Growing Season 2012

4.1.1. Grain Yield, Grain Protein Content, and Protein Yield. In 2012, GYs were higher at Conrad (5373 to 6456 kg N ha^{-1}) and Corvallis (5406 to 6422 kg N ha^{-1}) compared to Choteau (2092 to 3033 kg N ha^{-1}). At all three locations, GYs were the highest with HNRGN. At dryland sites, the best GYs were

Table 1: Treatment structure, Choteau, Conrad, and Corvallis, 2012 and 2013.

Trt	Preplant N fertilizer (urea) rate, kg N ha^{-1}	Top-dressing N fertilizer source	Top-dressing N fertilizer rate, kg N ha^{-1}	Top-dressing N fertilizer/water ratio, %
1	0	—	—	—
2	90	UAN	45	100/0
3	90	UAN	45	66/33
4	90	UAN	45	33/66
5	90	LU	45	100/0
6	90	LU	45	66/33
7	90	LU	45	33/66
8	90	HNRGN	45	100/0
9	90	HNRGN	45	66/33
10	90	HNRGN	45	33/66

Table 2: Field activities and growing conditions, Conrad, Choteau, and Corvallis, 2012.

Field activity	Choteau	Conrad	Corvallis
Seeding date	April 24	April 18	April 15
Variety	Choteau	Choteau	Choteau
Seeding rate: seeds/ha	1.8 million	1.8 million	1.8 million
Herbicide	Bronate, Axial XL	Bronate, Axial XL	Bronate, Axial XL
Herbicide date	June 12	May 17	June 16
Sensing date	June 15	June 8	June 5
Top-dressing date	June 14	June 8	June 5
Harvest date	August 21	August 17	August 8
Average soil temperature °C	14.85	14.85	14.75
Average air temperature °C	14.25	14.25	15.75
Soil series	Scobey Clay Loam	Scobey Clay Loam	Burnt Fork Silt Loam
Soil N, kg ha^{-1}	31.7	39.5	31.7
Soil P, ppm	17	23	18
Soil K, ppm	287	423	345
Organic matter%	2.6	2.9	2.9
Soil pH	7.8	7.7	7.7

Table 3: Field activities and growing conditions, Conrad, Choteau, and Corvallis, 2013.

Field activity	Choteau	Conrad	Corvallis
Seeding date	May 1	April 26	April 20
Variety	Choteau	Choteau	Choteau
Seeding rate: seeds/ha	1.8 million	1.8 million	1.8 million
Herbicide	Supremacy, Axial XL	Supremacy, Axial XL	Supremacy, Axial XL
Herbicide date	June 7	May 29	May 20
Sensing date	June 25	June 24	June 22
Top-dressing date	June 25	June 24	June 22
Harvest date	August 23	August 19	August 12
Average soil temperature °C	15.10	15.10	15.25
Average air temperature °C	12.60	12.60	13.45
Soil series	Scobey Clay Loam	Scobey Clay Loam	Burnt Fork Silt Loam
Soil N, kg ha^{-1}	42.5	46	42.5
Soil P, ppm	21	25	21
Soil K, ppm	361	398	321
Organic matter%	2.7	2.2	2.8
Soil pH	7.8	7.7	7.8

Table 4: Treatment structure, Choteau, Conrad, and Corvallis, 2012 and 2013.

Trt	Mean spring wheat grain yield, kg ha^{-1}					
	2012			2013		
	Choteau	Conrad	Corvallis	Choteau	Conrad	Corvallis
1	2529 (bcd)	5373 (c)	5629 (abc)	3564 (ab)	3698 (c)	1856 (b)
2	2118 (ed)	5979 (ab)	6012 (abc)	3477 (ab)	4001 (bc)	2125 (ab)
3	2233 (cde)	5810 (bc)	5710 (abc)	3403 (b)	4062 (bc)	2186 (ab)
4	2092 (e)	5837 (bc)	6348 (ab)	3490 (ab)	3954 (c)	2132 (ab)
5	2576 (bc)	6046 (ab)	5406 (c)	3537 (ab)	4593 (ab)	2361 (a)
6	2582 (bc)	6194 (ab)	5420 (bc)	3544 (ab)	4842 (a)	2139 (ab)
7	2690 (ab)	6207 (ab)	5548 (abc)	3880 (a)	4728 (a)	1957 (ab)
8	2811 (ab)	6382 (ab)	6422 (a)	3746 (ab)	4768 (a)	1957 (ab)
9	2616 (bc)	6369 (ab)	6288 (abc)	3356 (b)	5104 (a)	2246 (ab)
10	3033 (a)	6456 (a)	6147 (abc)	3867 (a)	5057 (a)	2334 (ab)

Means in the same column followed by the same letter are not significantly different at $p < 0.05$.

Table 5: Mean spring wheat grain protein content and protein yield, Choteau, Conrad, and Corvallis, 2012.

Trt	Mean spring wheat grain protein content, %			Mean spring wheat protein yield, kg ha^{-1}		
	Choteau	Conrad	Corvallis	Choteau	Conrad	Corvallis
1	13.8 (c)	10.8 (c)	13.4 (f)	391 (d)	649 (b)	845 (b)
2	17.2 (a)	12.8 (b)	14.4 (bcde)	409 (d)	856 (a)	966 (ab)
3	16.8 (ab)	13.2 (ab)	13.9 (def)	422 (cd)	862 (a)	888 (ab)
4	17.0 (ab)	13.1 (ab)	14.2 (cde)	398 (d)	858 (a)	1010 (ab)
5	16.7 (ab)	13.2 (ab)	15.1 (a)	482 (bc)	897 (a)	916 (ab)
6	16.8 (ab)	13.7 (a)	15.0 (ab)	485 (bc)	947 (a)	907 (ab)
7	16.5 (b)	13.1 (ab)	14.9 (abc)	496 (b)	908 (a)	923 (ab)
8	16.9 (ab)	13.1 (ab)	13.8 (ef)	533 (ab)	934 (a)	989 (ab)
9	17.1 (a)	13.2 (ab)	14.6 (abcd)	501 (b)	943 (a)	1027 (a)
10	16.8 (ab)	12.9 (b)	14.0 (def)	572 (a)	929 (a)	963 (ab)

Means in the same column followed by the same letter are not significantly different at $p < 0.05$.

achieved with HNRGN at 33/66 dilution ratio (treatment 10), while at Corvallis (irrigated) the highest GY was obtained with undiluted HNRGN (treatment 8) (Table 4).

The GPs ranged from 13.8 to 17.2% at Choteau (highest among the three locations). The GP values ranged from 10.8 to 13.7% at Conrad and from 13.4 to 15.1% at Corvallis. At Choteau, application of HNRGN at 66/33 dilution ratio has produced the highest GPs (treatment 9), as well as application of undiluted UAN (treatment 2). Application of LU at 66/33 dilution ratio (treatment 6) has produced the best GP at Conrad. Similar results were noted for Corvallis, where comparable GPs were achieved with the application of undiluted LU (treatment 5) and LU at 66/33 dilution ratio (Tables 5 and 6).

In 2012, at Choteau, the best PY value of 572 kg N ha^{-1} was associated with HNRGN application at 33/66 ratio (treatment 10). The lowest PY values were obtained with UAN. At Conrad and Corvallis, the differences among the treatments were not as pronounced as at Choteau. Although at Conrad the differences were not statistically significant, the general trend was that HNRGN and LU resulted in higher PY values compared to UAN. At Corvallis, the highest PY value of 1027 kg ha^{-1} was noted for treatment 9 (HNRGN at 66/33 ratio), closely followed by treatment 4 (UAN at 33/66 ratio) (Tables 5 and 6).

4.1.2. N Uptake and Nitrogen Use Efficiency. In 2012, more pronounced differences between treatments in terms of NUp were observed at Choteau. The highest NUp values of 99 and 91 kg N ha^{-1} were observed for HNRGN applied at 33/66 ratio and undiluted, respectively. At Conrad, the differences between the treatments were not significant; treatments 6 (LU at 66/33 ratio) and 9 (HNRGN at 66/33 ratio) resulted in higher NUp values of 163 and 161 kg N ha^{-1}, respectively. Treatment 9 also produced the highest NUp at the irrigated site (Corvallis), followed by treatment 4 (UAN applied at 33/66 dilution ratio) (Tables 7 and 8).

At WTARC and Corvallis, no significant differences in NUEs associated with N source were observed in 2012. At Choteau, significantly greater NUE values were observed for HNRGN (treatments 10 and 8, followed by treatment 9), compared to LU and UAN. In general, similar trend was observed at Conrad, but the differences were not statistically

Table 6: Mean spring wheat grain protein content and protein yield, Choteau, Conrad, and Corvallis, 2013.

Trt	Mean spring wheat grain protein content, %			Mean spring wheat protein yield, kg ha^{-1}		
	Choteau	Conrad	Corvallis	Choteau	Conrad	Corvallis
1	12.5 (c)	10.6 (d)	16.0 (a)	446 (c)	394 (e)	296 (a)
2	14.9 (ab)	13.4 (ab)	15.2 (ab)	518 (b)	538 (d)	322 (a)
3	15.0 (ab)	13.5 (a)	14.5 (bc)	510 (b)	548 (cd)	317 (a)
4	15.3 (a)	13.3 (abc)	14.8 (bc)	535 (ab)	527 (d)	315 (a)
5	15.2 (ab)	13.1 (bc)	13.3 (c)	536 (ab)	603 (bcd)	314 (a)
6	14.7 (b)	13.3 (abc)	14.7 (bc)	521 (b)	641 (ab)	314 (a)
7	15.0 (ab)	13.1 (c)	14.4 (c)	584 (a)	617 (abc)	281 (a)
8	15.0 (ab)	13.4 (ab)	14.4 (bc)	564 (ab)	640 (ab)	281 (a)
9	15.4 (a)	13.4 (ab)	14.1 (bc)	517 (b)	684 (a)	316 (a)
10	15.2 (ab)	13.5 (ab)	14.8 (bc)	587 (a)	680 (a)	345 (a)

Means in the same column followed by the same letter are not significantly different at $p < 0.05$.

Table 7: Mean spring wheat N uptake and NUE, Choteau, Conrad, and Corvallis, 2012.

Trt	N uptake, kg N ha^{-1}			NUE, %		
	Choteau	Conrad	Corvallis	Choteau	Conrad	Corvallis
1	67 (d)	111 (b)	145 (b)	—	—	—
2	71 (d)	147 (a)	166 (ab)	1.8 (d)	23.5 (a)	13.8 (a)
3	73 (cd)	148 (a)	153 (ab)	3.0 (cd)	24.1 (a)	4.8 (a)
4	68 (d)	147 (a)	174 (ab)	0.5 (d)	23.8 (a)	18.7 (a)
5	83 (bc)	154 (a)	157 (ab)	10.0 (bc)	28.1 (a)	8.1 (a)
6	83 (bc)	163 (a)	156 (ab)	10.3 (bc)	33.8 (a)	7.1 (a)
7	85 (b)	156 (a)	158 (ab)	11.3 (b)	29.4 (a)	8.8 (a)
8	91 (ab)	160 (a)	169 (ab)	15.8 (ab)	32.2 (a)	16.3 (a)
9	86 (b)	161 (a)	176 (a)	12.0 (b)	33.3 (a)	20.6 (a)
10	99 (a)	159 (a)	165 (ab)	20.3 (a)	31.8 (a)	13.3 (a)

Means in the same column followed by the same letter are not significantly different at $p < 0.05$.

Table 8: Mean spring wheat N uptake and NUE, Choteau, Conrad, and Corvallis, 2013.

Trt	N uptake, kg N ha^{-1}			NUE, %		
	Choteau	Conrad	Corvallis	Choteau	Conrad	Corvallis
1	76 (c)	67 (e)	50 (a)	n/a	n/a	n/a
2	89 (b)	91 (d)	55 (a)	28.6 (b)	37.7 (bc)	15.9 (a)
3	87 (b)	94 (cd)	54 (a)	27.4 (b)	38.9 (bc)	15.0 (a)
4	92 (ab)	90 (d)	54 (a)	31.2 (ab)	36.0 (c)	14.3 (a)
5	92 (ab)	103 (bcd)	54 (a)	31.3 (ab)	47.7 (abc)	22.4 (a)
6	89 (b)	110 (ab)	54 (a)	28.6 (b)	53.6 (a)	14.5 (a)
7	100 (a)	105 (abc)	48 (a)	38.6 (a)	49.8 (ab)	12.0 (a)
8	97 (ab)	110 (ab)	48 (a)	35.8 (ab)	53.5 (a)	9.9 (a)
9	89 (b)	117 (a)	54 (a)	28.7 (b)	60.0 (a)	14.6 (a)
10	101 (a)	117 (a)	59 (a)	39.4 (a)	59.5 (a)	19.1 (a)

Means in the same column followed by the same letter are not significantly different at $p < 0.05$.

significant. At Corvallis, treatment 9 produced the best NUE of 20.6% (Tables 7 and 8).

4.2. Growing Season 2013

4.2.1. Grain Yield, Grain Protein Content, and Protein Yield. In general, in 2013, the GYs were lower at Conrad (3698 to 5104 kg N ha^{-1}) and Corvallis (1856 to 2361 kg N ha^{-1}) and higher at Choteau (3356 to 3867 kg N ha^{-1}), compared to 2012. Like in the first growing season, the highest GYs at dryland sites were observed for treatments that received HNRGN: at 33/66 dilution ratio at Choteau (treatment 10) and at 66/33 dilution ratio at Conrad (treatment 9). Treatment 10 at Conrad was the second best with the GY of 5057 kg N ha^{-1}. At the irrigated Corvallis location, application of undiluted LU resulted in the yielding the highest GY, closely followed by treatments 10 and 9 (Table 4).

Like in 2012, the highest GP values were observed again at Choteau (12.5–15.4%) in 2013. The highest GPs at Choteau were achieved with the application of HNRGN at 66/33 dilution ratio followed by treatment 4, UAN applied at 33/66 dilution ratio. At Conrad, application of HNRGN at 33/66 ratio (treatment 10) and UAN at 66/33 ratio (treatment 3) resulted in the highest GP values. At Corvallis, the highest GPs were noted for the unfertilized check plot (treatment 1) and with the application of undiluted UAN (treatment 2) (Tables 5 and 6).

In 2013, at all three locations, HNRGN has performed the best compared to other N sources. At Choteau, treatment 10 (HNRGN at 33/66 ratio) resulted in the highest PY value of 587 kg ha^{-1}. Application of HNRGN at 66/33 and 33/66 ratios (treatments 9 and 10) produced the highest PY values of 684 and 680 kg ha^{-1}, respectively. At the irrigated location (Corvallis), treatment 10 has also resulted in the highest PY, although the differences among the treatments were not significant (Tables 5 and 6).

4.2.2. N Uptake and Nitrogen Use Efficiency. In 2013, although no statistically significant differences in NUp values associated with N application source were observed at the irrigated Corvallis location, the highest NUp was noted for treatment 10 (HNRGN at 33/66 ratio). The same trend was observed at both dryland sites (Choteau and Conrad), where treatment

10 resulted in the highest NUp values of 101 and 117 kg N ha^{-1}, respectively (Tables 7 and 8).

In the second year of the study, the NUE values were higher compared to 2012 at all locations. Like in 2012, the differences between the treatments at Corvallis were not significant; higher NUEs were noted for treatments 5 (undiluted LU) and 10 (HNRGN at 33/66 ratio). Similarly, at the other two sites, the highest NUEs of 39.4 and 60% were observed for HNRGN treated plots at Choteau and Conrad, respectively (Tables 7 and 8).

4.2.3. Effect of Liquid N Fertilizer Dilution on GY, GP, PY, NUp, and NUE. The dilution ratios had no effect on GY, GP, PY, NUp, and NUE at any of the site-years in this study (data not shown).

5. Discussion

Although the effect of N source on GY was more pronounced in 2012, compared to 2013, in both growing seasons, HNRGN resulted in higher yields compared to UAN. At dryland locations, LU performed as well as HNRGN. At the irrigated location, there was little difference in yield associated with N product. In 2012, at Corvallis, lower GY but higher GP was observed with LU, compared to other N sources. The GP contents obtained in this study were excellent and ranged from 10.6% to 17.2%. Evaluation of product effect on PY and NUE allowed us to assess how efficiently N products were taken up, assimilated, and utilized to produce both yield and quality (protein). Protein yield is a valuable characteristic, especially for spring wheat in Montana. Protein yield was clearly higher with HNRGN at both dryland sites in 2012 and in 2013. Even where the differences were not statistically significant, over 35 kg ha^{-1} advantage in PY accumulation was observed with HNRGN compared to UAN. The effect of N source on NUE was very pronounced in favor of HNRGN at dryland locations in both growing seasons. The lowest NUE values were observed with UAN; LU produced intermediate results. The irrigated location had similar NUEs for all products, except for 2012, when LU resulted in lower (not statistically significant) NUE values.

Although various degrees of leaf burn were obvious during postapplication in the majority of the experimental plots, the wheat plants have recovered within next 2-3 weeks. The physical damage caused to the plants did not result in any significant yield or quality penalties. The dilution ratios had no effect on GY, GP, PY, NUp, and NUE at any of the site-years in this study (data not shown). Our results suggest that it is feasible to apply undiluted liquid N products to spring wheat when a stream bar sprayer is used without negatively impacting crop yield or quality. This statement is especially true for noncorrosive products like LU and HNRGN [43]. However, growers should be advised not to exceed the application rate of 45 kg N ha^{-1} (rate evaluated in this study) when applying undiluted liquid N fertilizers.

Over the 2008–2016 period, urea (and, thus, LU) and UAN averaged \$.24 and \$0.28 per kg of N [44]. On the other hand, HNRGN is typically about 20% more expensive, compared to UAN [45]. For this study, at the time of N fertilizer application, the costs were virtually the same for LU and UAN per unit of N, whereas HNRGN costed almost 25% more compared to both LU and UAN [46].

Many personal communications with Montana wheat growers have shown that they see LU as a very good N source choice. Popularity of LU is growing due to noncorrosive qualities. Several growers indicated that they produce their own LU on-site by dissolving dry granular urea in water. Results of our study suggested that choice of liquid N fertilizer might be more important in dryland cropping systems, compared to irrigated ones, with positive results obtained with LU at Choteau and Conrad experimental sites located in the heart of Golden Triangle: Montana's key dryland wheat producing region. In conclusion, taking into account agronomic and economic factors, LU can be recommended as the most suitable liquid N fertilizer source for spring wheat cropping systems of the Northern Great Plains.

Competing Interests

The authors declare that they have no competing interests.

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