Efficient Nitrogen Fertilization of Wheat Grown in Minnesota
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Daniel Kaiser, Albert Sims, and Jochum Wiersma

Nitrogen is the nutrient most limiting to cereal grain crops grown in Minnesota. Efficient utilization of nitrogen is important since fertilizer prices have risen greatly over the past few years. Unlike corn, nitrogen recommendations for wheat production in Minnesota are still based on yield goal times an efficiency factor (2.5 x yield goal) minus N credits for much of the major wheat growing areas. With the price of nitrogen ever increasing interest has been placed in determining the feasibility of managing N on an economic basis. Also unlike corn, wheat prices are partially determined by protein quality so economic optimum N rates must consider both yield and quality. Yield response curves to N rates are invaluable in determining economic optimum N rates and the confidence in those curves increases with response trials from increasing environments (sites and years). The purpose of this study was to evaluate the N needs for hard red spring wheat grown in Minnesota.
Objectives of this work are to:

1. Determine adequate N fertilizer needs of hard red spring and winter wheat grown in Minnesota.

2. Establish the efficacy of a split application of nitrogen for hard red winter wheat.

3. Evaluate N uptake and utilization through the growing season of two spring wheat varieties, which vary in grain yield and protein potential, from straight and polycoated urea N sources.

4. Determine the effects on spring wheat grain yield and protein of various combinations of straight and polycoated urea N sources applied in a single pre-plant application.

Spring Wheat Nitrogen Rate Studies (Objective 1)

Methods
Sites were established at six locations in 2008, five locations in 2009, and three in 2010 (Table 1). The original project was scheduled to be completed in 2009. However, some funds were left for travel and labor such that additional studies could be conducted in the Red River Valley in 2010. Eight locations were in traditional spring wheat areas in the Red River Valley while six additional locations were in areas in southern Minnesota where spring wheat has established itself in the crop rotation. Spring wheat variety varied by location (Table 1). Seven nitrogen rates (0, 30, 60, 90, 120, 150, and 180 lbs. of N/ac) were applied as urea broadcast and incorporated prior to seeding. Additional phosphorus, potassium, and sulfur fertilizer was applied as needed based on soil tests taken from each location. All treatments were replicated four times at each location. Small plots measuring 6.5 by 28 feet were used in northern locations while 10 by 25 foot plots were located in the south. Initial soil samples were taken from the 0-6, 6-12, and 12-24 inch soil depths. The 0-6 inch depth was analyzed for phosphorus, potassium, pH, and organic matter. All depths were analyzed for nitrate nitrogen. A summary of soil test information is given in Table 2. Variables studied were grain yield, moisture, test weight, and protein.

Statistical analysis was conducted using SAS. The GLM procedure was used to assess the main effect of nitrogen on yield, protein, test weight, and protein production per acre. When the analysis indicated the main effect of nitrogen was significant ($P \leq 0.05$) response curves were compared for the Linear, Quadratic, Quadratic Plateau, and Linear Plateau curve fitting procedures using PROC REG and PROC NLIN. Curve fitting parameters were used to determine which best fit the data from each location. For all models except for the Linear, critical levels defined as the nitrogen rate needed to maximize yield, protein, test weight, or protein yield. Economic analysis was done across Northern and Southern locations using the maximum return to nitrogen (MRTN) model to determine the point at which the last dollar invested returned a dollar in crop yield and the amount plus or minus $1 from the MRTN value. When analysis was conducted within locations the 2' nitrate test was not used. When compared across locations, yields were converted to a relative basis (% of maximum) and the soil test N was combined with applied fertilizer to determine total available N.

Grain Yield and Protein Responses

A summary of grain yield and protein responses for Northern Minnesota locations is given in Figure 1, and Figure 2 contains summary data from Southern Minnesota. Measured values for yield are given in Table 3. Grain yield was significantly increased by nitrogen fertilizer at nine locations, Hallock, Kilkenny, and Waseca in 2008, Foxhome, Lamberton, and Waseca in 2009, and Fergus Falls, Hallock, and Halstad in 2010. The nitrogen rate applied was large enough to maximize yields at six of the locations. The only exception were the Hallock location in 2008 and 2010 where a quadratic model was fit to the data and the yield did not appear to maximize within the fertilizer rates applied (180 lbs maximum). The lack of response at the other locations may have indicated that soil N supply, either though nitrate carryover or N mineralization from organic matter, was high enough for the achieved yields. This is especially true for the Strathcona site in 2008 where the residual soil N levels were the highest of any location (Table 2). A small amount of N was applied to the rest of the field for soybean which could explain some of the increase at this site. However, the rate was small and would not account for the large amount of N found in the soil. One major surprise was the lack of yield response at the Perley location in 2008. Yields at this site were on par with other fields in the Northwest during 2008, but the difference between the non-fertilized control and the highest rate of fertilizer was only 10 bu./ac. Lack of response to N at the southern locations was surprising, but not unexpected since yield was likely limited by environmental factors and N was likely used in the production of protein rather than starch or the ability for the soils to mineralize N was greater and supplied more of the total N. It was clear that sites in Northern Minnesota showed a higher yield response to N, especially when you compare the yield produced per pound of N at Lower N rates.

The amount of N needed to maximize yield, listed in Table 3, ranged from 74 to 180 lbs of N per acre (fertilizer N only). In general it took less N to maximize yields in Southern Minnesota ranging from 74 to 120 lbs of N per acre. For the Northern Minnesota locations it took from 114 to 180 lbs of N per acre. The amount of N needed was reflected in the yield potential between those regions. Relative yield values were calculated for each individual location and the data combined for either Northern or Southern Minnesota to determine the amount of N needed to maximize yield with the 2' soil N test (Soil test N + applied fertilizer N). Figure 3 summarizes data from Northern Minnesota and Figure 4 is for Southern Minnesota. For the Northern Minnesota sites, most data followed tightly along the same curve with yield increasing in a curve linear fashion up to 150 lbs of applied + soil N per acre. The only site that did not fit the curve well was Hallock 2010. It is likely that some of the applied N was lost due to ponded water on the site after seeding in the spring and some of the N applied volatilized. For the Southern locations, yield responded linearly increasing to maximum yield with around 135 lbs of applied plus soil N. Taking a soil test for N is not recommended at these locations, but the amount did seem to be a factor related to yield across locations. A major problem with the data collected from the Southern sites was more variability which was likely due to different varieties being seeded at each location. All Northern locations were seeded to Knudson, which is a high yielding variety with moderate protein potential. The consistency of the Northern sites likely caused most sites to fit better along the Quadratic Plateau function. In Northern Minnesota, grain yields were reduced 65% on average when no fertilizer was applied while yields were reduced only 20% in the south. This data seems to agree with the current difference in recommended N for differing areas in the state. It is important to note that maximum yield attained did not vary greatly between Southern locations. The may indicated the importance of selecting varieties better adapted to conditions in the region as well as applying the right about of N. Nitrogen application is important, but in many soils in the South mineralization can occur for a significant amount of time that can easily supply a large amount of N for the crop, and predicting the amount of N that can be mineralized is very difficult.

Nitrogen increased grain protein at all locations except for Strathcona and Perley in 2008, and Halstad in 2010 (Table 4). Again, the response at Strathcona is not surprising when focusing on residual N at this site, but the lack of response at Perley for both yield and protein is puzzling since the amount of residual N in the soil was not extremely high and conditions were not sufficient for high amounts of N mineralization. This site had some standing water early in the growing season therefore it is possible that some nitrate may have moved between plots during periods of saturation or lost due to volatilization. This is difficult to confirm, but soil samples taken after harvest (not shown) also show little difference in soil nitrate levels which may confirm this effect. Models fit to the data show that protein was not maximized by the nitrogen rates used in the study at almost all locations. At most of these locations protein increased in a linear fashion until the highest N rate in the study. At two locations in 2009, Norseland and Waseca, the percentage increase in protein diminished as N rate increased but still did not appear to maximize at the highest N rate. At the three locations where protein did plateau, Norseland 2008, Waseca 2008, and Lamberton 2009, the N rate needed to maximize protein was generally higher than the rate that maximized yield. The only exception to this was Lamberton 2009 where protein was unexpectedly maximized with a lower N rate than yield.

It was apparent from the data that protein levels were higher in the southern locations. This is likely due to more yield limiting factors at the southern location leading to more N being utilized for protein in the grain. The other major result was that protein responded to higher amounts of N than yield. This is not surprising since it has been long known that yield tends to maximize at lower nitrogen rates and that if yield potentials are high protein can be low if too little N is applied. The data from 2008 and 2009 does confirm why grain protein was low in many production fields. It is apparent that in most cases farmers fertilizing for historical averages of

60 or 65 bushels per acres likely were under fertilizing for protein during those years (150 to 162 lbs. total N recommended). This illustrates one major problem with yield goal based systems. At the beginning of the growing season high yields were not expected either year, but averaged 100 bushels or more at the end of the season. It is clear that a system needs to be created to better recommend nitrogen rates in Northern Minnesota. Data such as was gathered in this study was important in many extension meetings explaining reasons for low protein wheat in 2008 and 2009.

Comparisons between response in protein for the northern (Figure 5) and southern (Figure 6) locations showed little difference. In both areas protein increased in a linear fashion to a maximum value. The N rate that achieved the plateau was 208 lbs. in the north and 175 lbs. in the south. At both locations protein was about 80% of the maximum value when no fertilizer N was applied and increased by 0.09% of the maximum value per lb. of N applied. It is again clear that the amount of N that maximizes protein is greater than that for yield. It is important to note that the 2010 data from Northern Minnesota was not included in the data analysis across locations. There was very little protein response for the last year of this study, and overall the grain protein levels were higher on average than the past two years. It is likely that increased N mineralization played a part in the increased grain protein during 2010. When factoring in yield and protein, the protein yield per acre generally followed the same response as yield indicating a major impact of yield on this factor. At the northern sites protein yield maximized at around 220 lbs of N per acre. Factoring in a yield of 100 bu. per acre at that value it would have taken 2.2 lbs of N to maximize yield and protein at these locations which is well within the current recommendations. For southern locations the relative protein yield across sites was more consistent than yield alone, but did follow the general trend of yield. For these locations it took 162 lbs of N to maximize protein yield which equates to 2.4 lbs of N per bu. of grain. The agreement with both factors indicates that the current recommendation of 2.5 lbs of N per bushel of grain can still be used; however, the major limitation with this recommendation is the need to accurately predict the yield of the crop in a particular year. This issue came up in 2009 with most farmers applying enough N to maximize yield in the Red River Valley region, but likely undercut the amount needed for maximizing protein. A better system needs to be developed that either deemphasizes the yield goal or allows more flexibility in N applications, especially late in the season that may be used to increase protein of wheat.

Grain Test Weight and Moisture

Grain test weight was significantly affected by N rate at Kilkenny and Norseland in 2008 and Lamberton and Foxhome in 2009 (Table 5). Test weight decreased in a linear fashion with increasing nitrogen rate at Kilkenny, Norseland, and Lamberton. At Foxhome there was no significant pattern to differences in test weight. In general test weight values were greater with the higher N rates, which is different for the southern locations where test weights were lower. Differences between high and low N rates were only 1.7 lbs./bu. at either location in 2008 but were large at Lamberton in 2009 differing by nearly 6 lbs. per bu. between the check and highest N rate. Average test weight at Kilkenny was higher than all the other trials and about 4 lbs./bu. higher than average. All other locations were near average values for grain protein (60 lb./bu.). Nitrogen rate significantly affected grain moisture at Norseland and Waseca in 2008 (Table 6). At both locations grain moisture increased by nearly 1.0% at the highest N rate. There were no significant impacts on grain harvest moisture at any other location. Both effects at either location could have been due to increased biomass production from excess N application. The effect of excess N was not evident in increased lodging or greenness at harvest. However, preventing over application of N should be a high priority to limit the potential effects of lodging or delaying dry down of the grain late in the season.

Economic Optimum Nitrogen Rates

Economic optimum nitrogen rates were calculated based on the data across locations. Wheat is different than corn in that both yield and quality are important in determining the value of the crop produced. In order to calculate the optimum nitrogen rate, yield response curves were determined with the raw yield data and protein was calculated based on the total amount of protein produced per acre divided by the yield (on a mass basis). The cost of nitrogen plus the estimated discounts ($/bu. per fifth % of protein below 14%) were subtracted from the value of the crop to determine the net return per acre. Figure 9 includes graphs of the data from the northern data at a crop price ratio of 0.10 and an estimated discount of $0.10 per fifth of a percent protein and Figure 10 shows southern results. Using a price ratio can be advantageous because the crop price and price of N tend to mirror each other therefore the ratio may not fluctuate as much as the actual fertilizer cost. Data from Northern Minnesota shows that the MRTN at varied from 148 to 212 lbs of N for the 0.10 probability level and 134 to 205 lbs for the 0.15 (Table 7). The northern data shows that as the amount of the discount increased, the difference between the MRTN values became smaller indicating the importance of the protein on the general value of the crop. In general N rates that maximized yields were near 200 lbs in order to maximize return per acre. These numbers agree with new recommendations for Eastern North Dakota for discounts of $0.10 per fifth. It appears that high yielding moderate protein varieties may require more N to maximize profit when discounts are high. However, producers may be reluctant to apply high rates due to concerns over lodging from excess N availability in years with low yield potentials. An important question that could not be addressed with this study is if there are differences in how N should be recommended for varieties with differing protein potentials. For high protein varieties if there is no advantage for protein above 14% it would not pay to apply more N to increase protein. It is therefore possible that less N could be applied to maximize yield and protein at levels at or above that for the discount.

For Southern Minnesota locations economic optimum N rates were lower (Table 8). This is mainly due to lower yield levels and higher protein potentials at these locations. At the 0.10 price ratio the MRTN and high values did not change at 122 lbs of N at the MRTN and 137 lbs at the high end. The major difference at this price ratio was at the Low end, which varied based on the amount of the discount per fifth. Since protein levels were higher in the south the effect of the protein discounts were not as severe. At the high discount levels the amount of N at the low end of the range trended higher and was closer to the MRTN value. When the price of N relative to price of wheat increased it had a large impact on the MRTN values. For instance at the 0.15 price ratio, the N rate at the MRTN ranged from 93 to 120 lbs. Similar to the lower price ratio, the recommended rate on the high end of the range did not vary as much as the low end of the range. It is clear that net returns from N in much more sensitive to input prices and protein discounts in Northern Minnesota than in the South due to the responsiveness to yield and protein at those locations. What is unclear from this data is 1) if the MRTN approach should be used for wheat; 2) if the full amount of nitrate N in the soil should be used for the MRTN calculation; and 3) if the data with soil test N should be used at all in Southern Minnesota? This data does show that N rates for wheat should be increased in Northern Minnesota or that yield goals should be re-evaluated for these areas and that nitrogen rate guidelines seem to be close for the Southern locations. However, more data should be generated for both locations in order to build a larger N rate database.

Tables and Figures

Table 1. Trial location and planting information for spring wheat N rate studies.

Year	Location	County	Soil Type	Soil Texture	Variety
2008	Hallock	Kittson	Northcote	Clay	Knudson
	Kilkenny	Le Sueur	Kilkenny	Clay Loam	Glenn
	Norseland	Nicollet	Le Seuer	Clay Loam	Traverse
	Perley	Norman	Whapeton	Clay Loam	Knudson
	Strathcona	Roseau	Percey	Loam	Knudson
	Waseca	Waseca	Webster	Clay Loam	MN03119-4
2009	Foxhome	Wilkin	Elmville	F. Sandy Loam	Knudson
	Lamberton	Redwood	Ves	Loam	Faller
	Norseland	Nicollet	Le Seuer	Clay Loam	Traverse
	Perley	Norman	Fargo	Silty Clay	Knudson
	Waseca	Waseca	Webster	Clay Loam	na
2010	Fergus Falls	Otter Tail	Formdale-Buse	Clay Loam	Knudson
	Hallock	Kittson	Northcote	Clay	Knudson
	Halstad	Norman	Fargo	Silty Clay	Knudson

Table 2. Spring soil test averages across replications for Spring wheat N trials.

		Soil Test (0-6")†				
Year	Location	P	K	SOM	pH	Nitrate N‡
		-------ppm-------		---%---		
2008	Hallock	54	472	6.6	7.9	22
	Kilkenny	67	242	3.3	6.4	62
	Norseland	23	270	5.1	5.4	80
	Perley	10	278	6.4	7.8	36
	Strathcona	13	121	2.7	8.2	164
	Waseca	7	156	5.6	5.7	39
2009	Foxhome	22	161	3.1	7.2	29
	Lamberton	8	134	3.7	5.4	38
	Norseland	5	186	8.1	7.9	52
	Perley	32	355	5.4	7.5	40
	Waseca	7	118	6.2	5.6	27
2010	Fergus Falls	15	293	4.2	7.1	37
	Hallock	22	455	6.3	7.9	44
	Halstad	17	393	4.3	8.0	26

† P, Olsen phosphorus; K, ammonium acetate potassium; SOM, soil organic matter; pH, soil pH.

‡ 0 to 2 foot soil nitrate level.

Table 3. 2008 to 2010 Yield averages for nitrogen rate treatments for the spring wheat N rate study.

		Nitrogen Applied (lbs N/acre)								Statistics†		
Year	Location	0	30	60	90	120	150	180	avg.	Sig.	Model	MaxN
		bushels/acre								---*P>F*---		--lbN/ac--
2008	Hallock	31.4	58.8	71.9	85.0	86.7	92.0	94.3	74.3	<0.01	Quad	180
	Kilkenny	40.9	50.2	55.7	63.8	55.4	52.5	57.8	53.8	0.01	QP	88
	Norseland	83.2	88.0	89.9	94.0	89.2	85.3	87.9	88.2	0.28	--	--
	Perley	73.1	76.5	81.4	85.2	86.4	88.2	89.1	82.8	0.62	--	--
	Strathcona	93.8	96.3	97.7	99.2	99.3	99.6	97.0	97.6	0.98	--	--
	Waseca	42.0	50.9	56.4	59.4	59.5	58.1	58.1	55.4	0.01	LP	74
2009	Foxhome	47.3	73.3	89.8	97.2	105.0	106.1	107.0	89.4	<0.01	QP	133
	Lamberton	54.6	52.9	57.2	63.8	67.7	62.1	66.8	60.7	0.04	LP	120
	Norseland	69.1	68.4	71.6	72.6	71.0	71.4	74.3	71.2	0.60	--	--
	Perley	85.4	98.7	107.8	113.9	115.6	116.6	118.6	108.1	<0.01	QP	133
	Waseca	44.6	46.6	44.4	50.9	50.3	50.8	52.3	48.5	0.35	--	--
2010	Fergus Falls	64.0	80.8	91.2	97.3	102.1	101.3	102.9	91.4	<0.01	QP	130
	Hallock	22.3	33.5	48.4	59.9	69.6	68.6	76.7	54.1	<0.01	QP	207
	Halstad	53.3	61.2	75.8	81.5	92.2	90.6	90.0	77.8	<0.01	LP	114

† Sig., significant for main treatment effects (nitrogen rate) according to ANOVA; Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied).

Table 4. 2008 to 2010 grain protein averages for nitrogen rate treatments from the spring wheat N study.

		Nitrogen Applied (lbs N/acre)								Statistics†		
Year	Location	0	30	60	90	120	150	180	avg.	Sig.	Model	MaxN
		%								---*P>F*---		--lbN/ac--
2008	Hallock	11.5	11.2	11.1	12.0	12.4	13.0	12.8	12.0	<0.01	Lin	180
	Kilkenny	11.5	11.7	12.7	14.0	14.9	15.3	15.5	13.7	<0.01	Lin	180
	Norseland	11.0	11.8	12.6	13.2	14.2	14.8	14.8	13.2	<0.01	LP	144
	Perley	12.6	12.5	13.0	12.7	12.9	13.4	13.6	12.9	0.66	--	--
	Strathcona	13.4	13.3	13.3	13.3	13.1	13.5	13.3	13.3	0.63	--	--
	Waseca	13.2	13.6	14.5	15.0	15.9	16.0	16.4	14.9	<0.01	QP	168
2009	Foxhome	11.7	11.2	10.9	11.6	12.9	12.5	13.8	12.1	<0.01	Lin	180
	Lamberton	14.8	15.4	15.8	16.4	16.3	16.5	16.4	15.9	<0.01	LP	95
	Norseland	13.3	13.3	13.9	14.0	14.6	14.3	14.6	14.0	<0.01	Quad	180
	Perley	10.8	11.1	11.4	12.2	12.4	12.6	13.0	11.9	<0.01	Lin	180
	Waseca	15.4	16.2	16.7	16.4	17.1	17.4	17.3	16.6	<0.01	Quad	180
2010	Fergus Falls	13.5	13.1	13.4	13.7	14.1	14.3	14.3	13.7	<0.01	Lin	180
	Hallock	13.5	12.9	12.4	13.1	13.3	14.0	14.2	13.3	<0.01	Lin	180
	Halstad	13.1	13.1	12.8	12.9	12.9	12.7	12.8	12.9	0.27	--	--

† Sig., significant for main treatment effects (nitrogen rate) according to ANOVA; Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied).

Table 5. 2008 to 2010 average grain test weights for the spring wheat N rate study.

		Nitrogen Applied (lbs N/acre)								Statistics†		
Year	Location	0	30	60	90	120	150	180	avg.	Sig.	Model	MaxN
		---lbs/bushel---								---*P>F*---		--lbN/ac--
2008	Hallock	60.1	60.2	59.4	60.4	61.2	60.5	60.3	60.3	0.39	--	--
	Kilkenny	64.8	64.9	64.9	64.1	63.8	63.5	63.2	64.2	<0.01	Lin	180
	Norseland	60.0	59.9	59.7	59.9	59.0	58.4	58.3	59.3	<0.01	Lin	180
	Perley	59.9	59.6	59.4	60.1	59.1	58.9	58.7	59.4	0.39	--	--
	Strathcona	58.3	58.0	57.6	58.8	58.1	57.4	58.3	58.1	0.87	--	--
	Waseca	59.4	60.5	59.0	59.9	59.5	58.9	59.4	59.5	0.54	--	--
2009	Foxhome	58.2	58.9	58.6	58.5	59.2	58.7	59.2	58.8	0.01	NM	--
	Lamberton	61.3	60.5	59.8	58.4	58.2	58.6	55.6	58.9	<0.01	Lin	180
	Norseland	57.5	57.5	57.2	57.5	56.9	56.9	56.7	57.2	0.08	--	--
	Perley	59.8	59.7	59.5	60.1	59.7	58.9	59.3	59.6	0.33	--	--
	Waseca				na					--	--	--
2010	Fergus Falls	62.0	62.7	62.5	62.4	62.6	62.5	62.6	62.4	0.95	--	--
	Hallock	56.0	53.2	58.9	58.6	59.3	59.0	59.3	57.7	0.38	--	--
	Halstad	59.9	60.1	60.7	61.0	60.7	60.3	61.0	60.5	0.58	--	--

† Sig., significant for main treatment effects (nitrogen rate) according to ANOVA; Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied).

Table 6. 2008 to 2010 treatment average grain harvest moisture for the spring wheat N rate trials.

		Nitrogen Applied (lbs N/acre)								Statistics†		
Year	Location	0	30	60	90	120	150	180	avg.	Sig.	Model	MaxN
		---%---								---*P>F*---		--lbN/ac--
2008	Hallock	14.7	14.5	14.6	14.5	14.3	14.2	14.4	14.5	0.10	--	--
	Kilkenny	12.9	12.3	12.4	12.3	12.5	12.5	12.3	12.5	0.78	--	--
	Norseland	12.6	12.6	12.9	12.9	12.7	13.4	13.2	12.9	0.00	Lin	180
	Perley	13.5	13.8	13.8	13.3	13.5	13.9	13.9	13.7	0.28	--	--
	Strathcona	15.3	15.9	16.2	15.6	15.0	16.1	15.5	15.7	0.58	--	--
	Waseca	13.5	13.4	13.1	12.9	12.9	12.7	12.8	13.0	0.00	Quad	180
2009	Foxhome	12.8	12.4	12.5	13.0	12.9	12.8	13.1	12.8	0.90	--	--
	Lamberton	15.1	15.9	16.1	17.0	16.5	16.3	18.6	16.5	0.25	--	--
	Norseland	13.8	14.2	13.7	13.8	14.6	13.9	14.3	14.0	0.20	--	--
	Perley	11.6	11.5	11.4	11.7	11.3	11.9	12.3	11.7	0.51	--	--
	Waseca	13.3	13.3	13.4	13.3	13.2	13.3	13.3	13.3	0.58	--	--
2010	Fergus Falls	11.1	11.1	11.3	11.3	11.4	11.2	11.2	11.2	0.96	--	--
	Hallock	13.1	13.3	13.2	13.3	13.6	13.5	13.3	13.3	0.98	--	--
	Halstad	13.1	13.1	12.8	12.9	12.9	12.7	12.8	12.9	0.27	--	--

† Sig., significant for main treatment effects (nitrogen rate) according to ANOVA; Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied).

Table 7. Economic evaluation of N rate response of spring wheat from spring applied urea in Northern Minnesota at two N price ratios at various discount levels. The maximum return to N (MRTN) value indicates the point in which a dollar invested in N returns a dollar in crop value and the low and high values indicate the range in N rates plus or minus one dollar from the MRTN. The MRTN value includes both applied N plus the amount of N in a 2’ soil N test taken in the Spring.

	EONR (0.10)†			EONR (0.15)†		
Discount $/fifth	low	MRTN	high	low	MRTN	high
	---------------lbs total N/ac---------------			---------------lbs total N/ac---------------		
0.00	135	148	156	124	134	144
0.05	155	168	183	139	151	163
0.10	187	197	208	171	183	193
0.15	198	207	216	189	197	205
0.20	204	212	220	197	205	213

†MRTN, Maximum return to N for specified nitrogen price ($/lb):crop price ($/bu); EONR, Economic optimum nitrogen rate.

Table 8. Economic evaluation of N rate response of Spring wheat from spring applied urea in Southern Minnesota at two N price ratios at various discount levels. The maximum return to N (MRTN) value indicates the point in which a dollar invested in N returns a dollar in crop value and the low and high values indicate the range in N rates plus or minus one dollar from the MRTN. The MRTN value includes both applied N plus the amount of N in a 2’ soil N test taken in the Spring.

	EONR (0.10)†			EONR (0.15)†		
Discount $/fifth	low	MRTN	high	low	MRTN	high
	---------------lbs total N/ac---------------			---------------lbs total N/ac---------------		
0.00	107	122	137	78	93	107
0.05	114	122	137	84	104	121
0.10	117	122	137	106	119	124
0.15	118	122	137	114	120	124
0.20	118	122	137	117	120	124

†MRTN, Maximum return to N for specified nitrogen price ($/lb):crop price ($/bu); EONR, Economic optimum nitrogen rate.

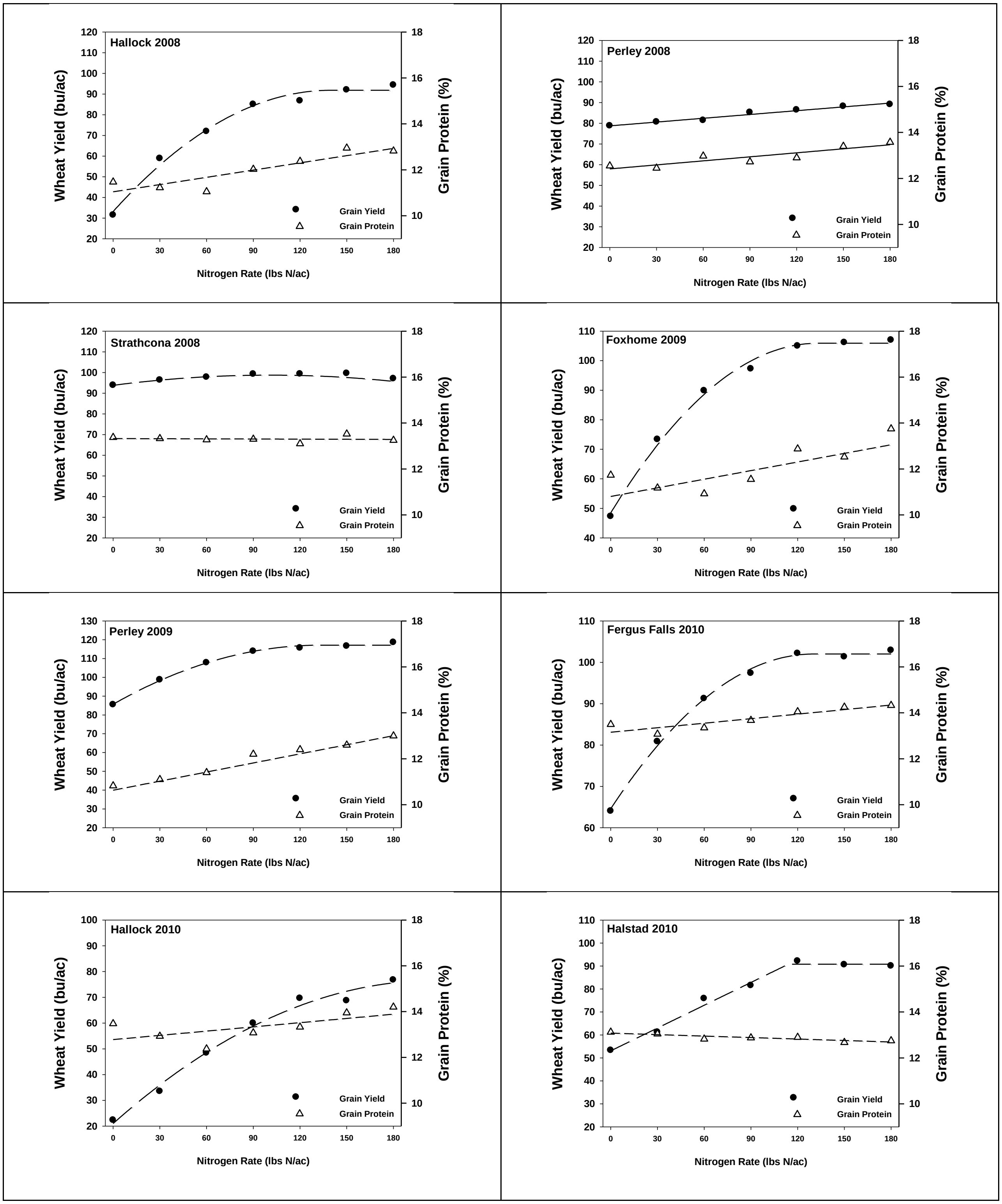

Figure 1. Nitrogen rate effects on grain yield and protein at spring wheat N rate locations in Northern MN conducted from 2008 to 2010. Closed circles represent measured grain yield data (adjusted to 13.0%) and open triangles represent grain protein.

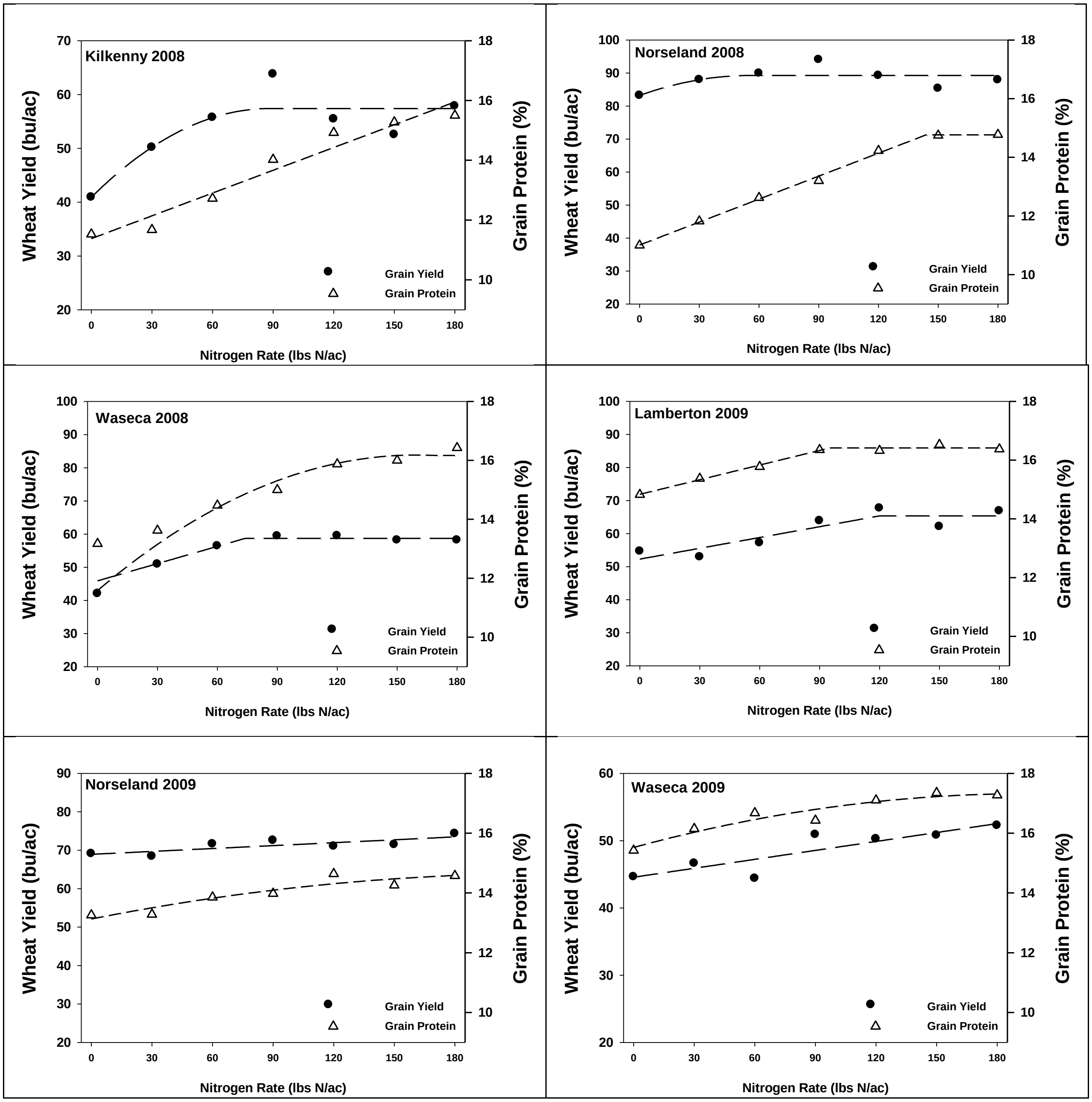

Figure 2. Nitrogen rate effects on grain yield and protein at spring wheat N rate locations in Southern MN conducted from 2008 to 2009. Closed circles represent measured grain yield data (adjusted to 13.0%) and open triangles represent grain protein.

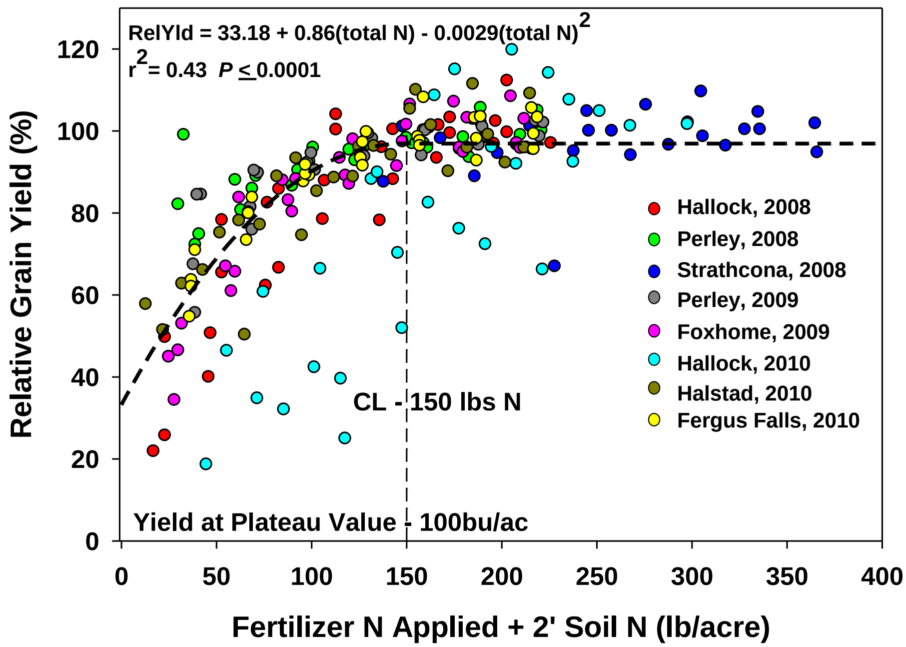

Figure 3. Relative yield response to total N in soil + applied in fertilizer across northern Minnesota locations. Maximum yield across locations was 100 bu/ac.

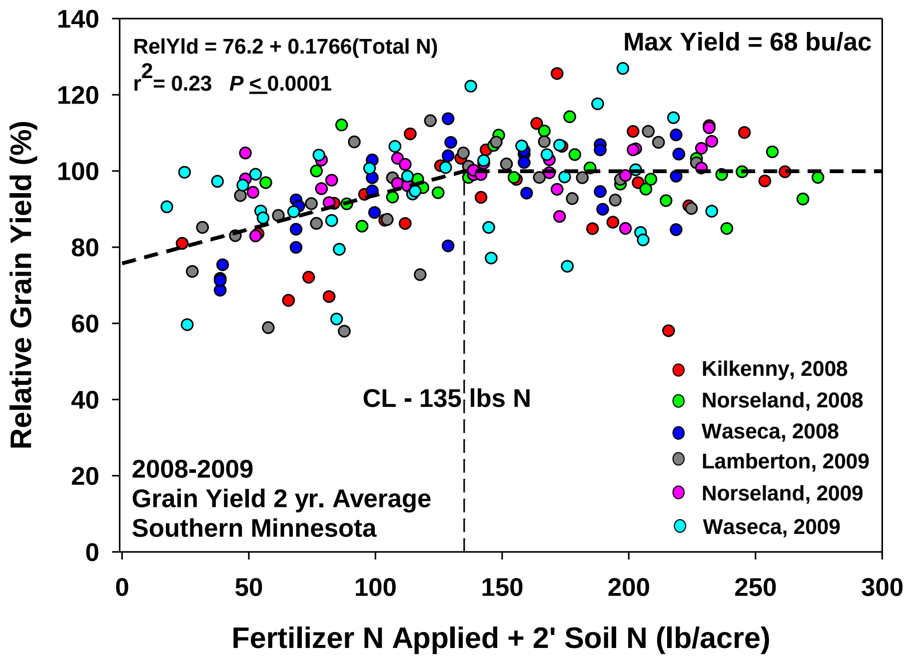

Figure 4. Relative yield response to total N in soil + applied in fertilizer across southern Minnesota locations. Maximum yield across locations was 68 bu/ac.

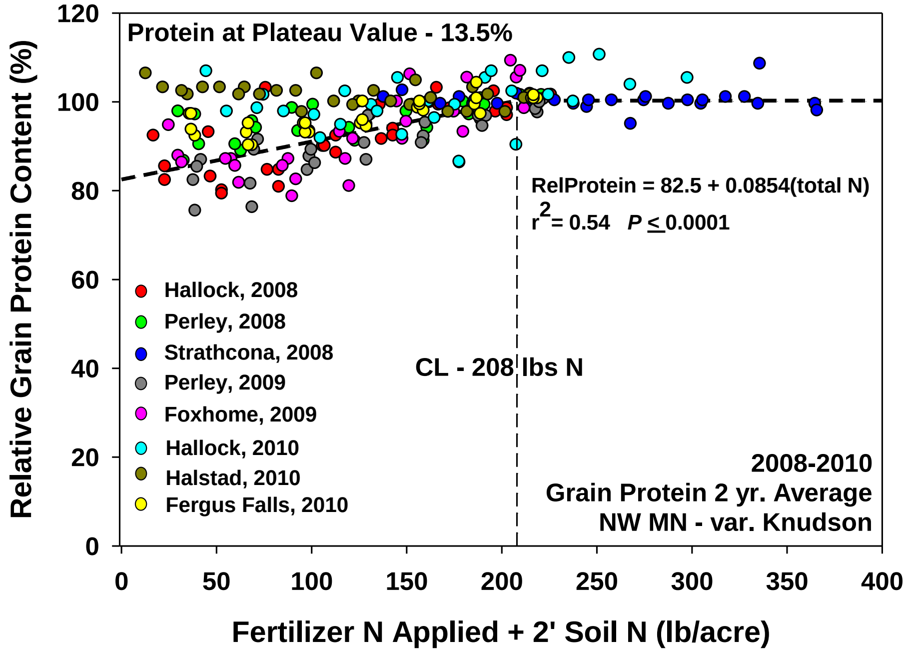

Figure 5. Relative protein response to total N in soil + applied in fertilizer across northern Minnesota locations. Maximum protein across locations was 13.5%.

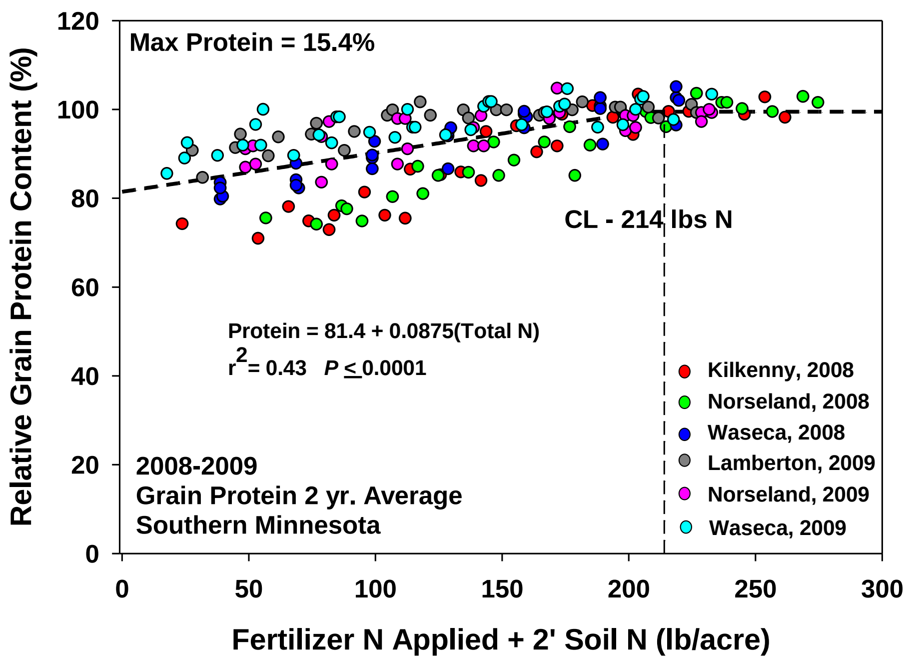

Figure 6. Relative protein response to total N in soil + applied in fertilizer across southern Minnesota locations. Maximum protein across locations was 15.4%.

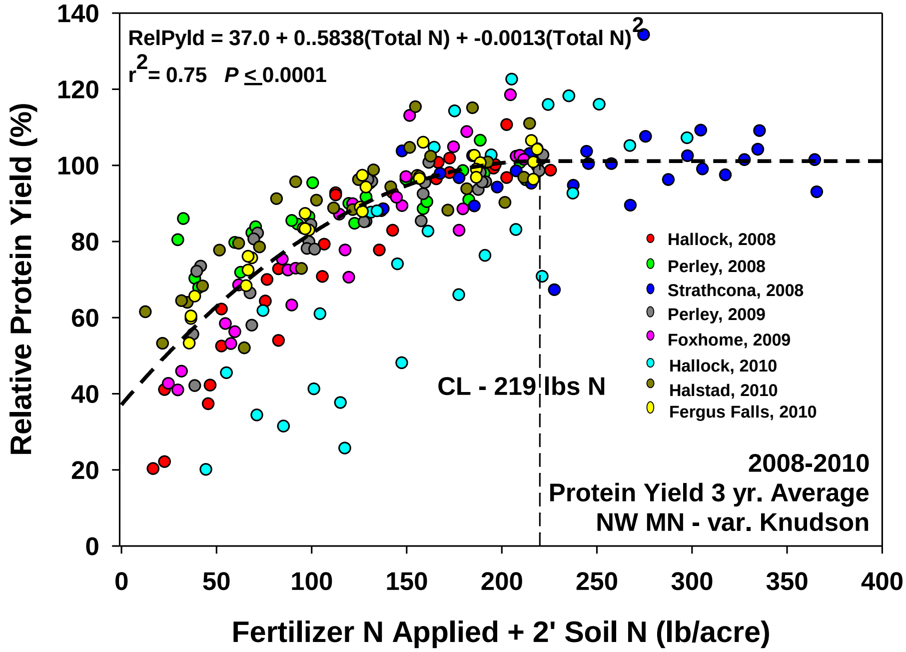

Figure 7. Relative protein yield response to total N in soil + applied in fertilizer across northern Minnesota locations. Maximum protein yield across locations was 796 lb/ac.

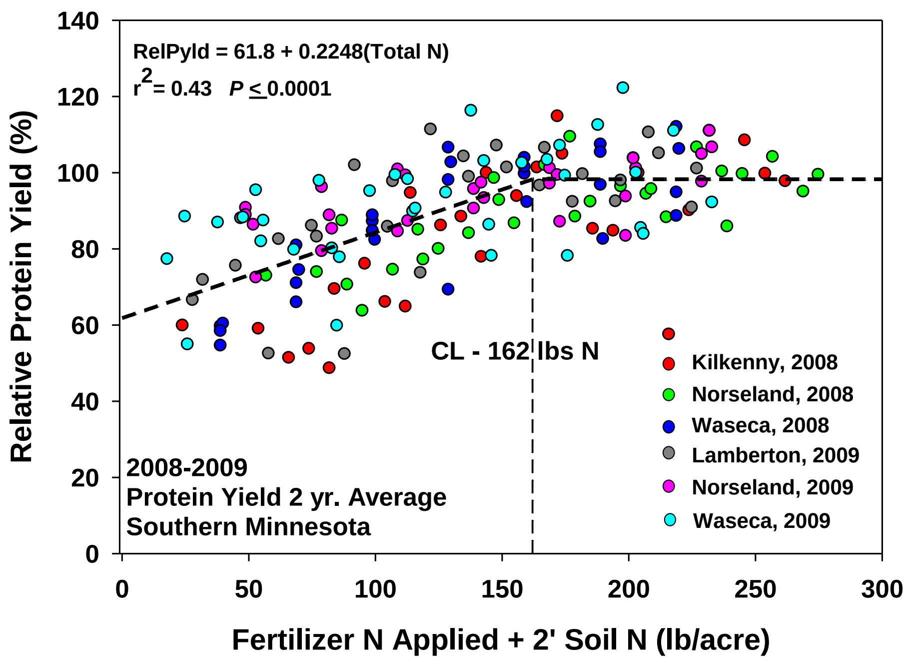

Figure 8. Relative protein yield response to total N in soil + applied in fertilizer across southern Minnesota locations. Maximum protein yield across locations was 658 lb/ac.

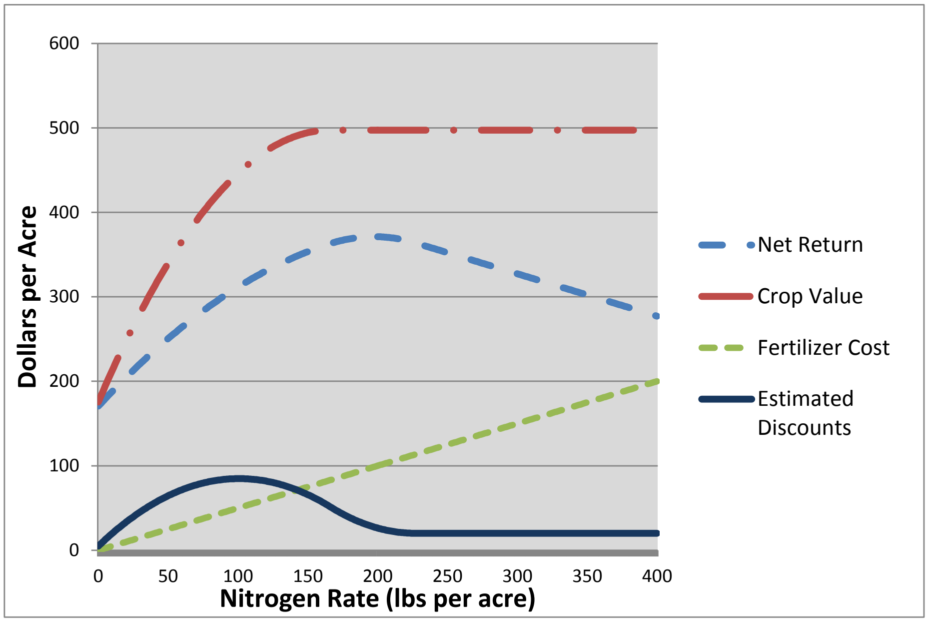

Figure 9. Economic assessment for optimum nitrogen rate for 2008-2010 wheat N rate data from Northern Minnesota at the 0.10 price ratio and discount of $0.10 per bushel per fifth of a percent protein below 14%. Plots are for net return per acre, the value of the crop produced per acre, fertilizer N cost, and estimated discounts.

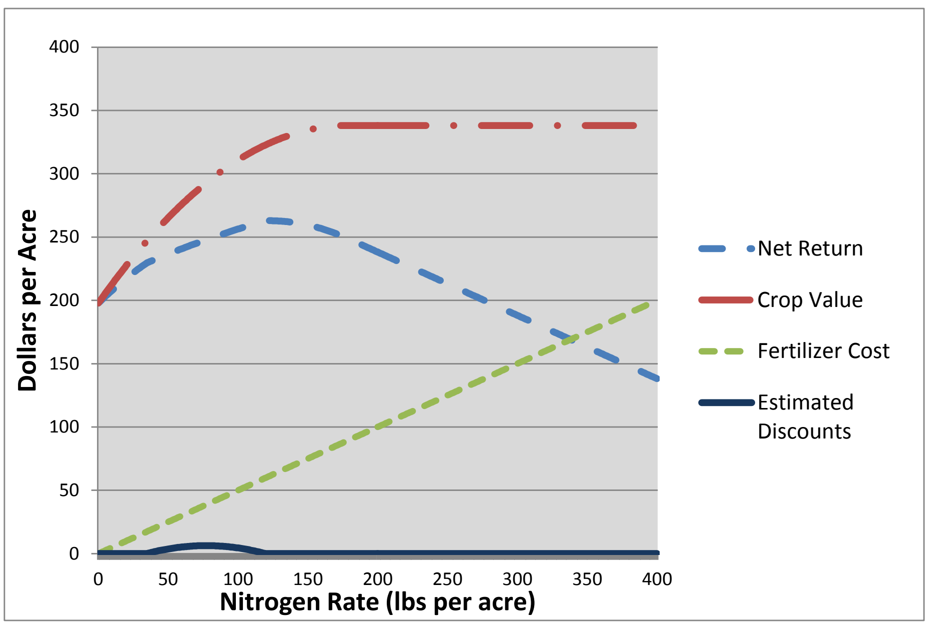

Figure 10. Economic assessment for optimum nitrogen rate for 2008-2009 wheat N rate data from Southern Minnesota at the 0.10 price ratio and discount of $0.10 per bushel per fifth of a percent protein below 14%. Plots are for net return per acre, the value of the crop produced per acre, fertilizer N cost, and estimated discounts.

Winter Wheat Nitrogen Rate Studies (Objective 2)

Methods

Two sites were established in the Fall of 2008 and two in the Fall of 2009 (Table 9). At all locations rates of 0, 30, 60, 90, 120, 150, and 180 lbs. of N per acre were applied as ammonium nitrate (34-0-0) prior to seeding. The variety 'Jerry' was seeded at both northern trials while 'Expedition' was used in the south. In 2008, all nitrogen rates except for the two highest rates were applied in large blocks measuring approximately 30 feet wide and 50 feet long at Waseca and 19.5 feet wide by 50 feet long at Underwood. In spring each large block was split into six subplots were rates of 0, 30, 60, 90, and 120 lbs. of N per acre were top-dressed as ammonium nitrate. For the 2009 locations, the highest two fall rates, 150 and 180 lbs., were established so that three N rates could be applied in the spring (0, 30, and 60 lbs. per acre). Main blocks measured 30 feet wide by 50 feet long at Lamberton and 15 feet wide by 50 feet long at Crookston. Initial soil samples were taken from each of the 4 replications at both locations at depths of 0-6, 6-12, and 12-24 inches. Additional P, K, and S fertilizer was applied to limit response to these nutrients. Previous crop was small grains at all locations except Waseca which was soybean. In the spring before fertilizer was applied, additional 2' soil samples were collected from each main plot and analyzed for nitrate nitrogen. Also at this time, 3' of row of spring regrowth were sampled and analyzed for total N in the biomass. A summary of initial soil test information is given in Table 9. Grain yields and protein content was measured from each subplot area. Spring field conditions caused significant winter kill at the Waseca location in 2009. Some data will be left out of the analysis of that location for the replications that were greatly affected.

Statistical analysis was conducted using SAS. The GLM procedure was used to assess treatment differences for fall and spring N application and their interaction. When the analysis indicated that either was significant the REG and NLIN procedure was used to determine the best fit models for the data. Model fitting procedures were the same as those explained in the spring wheat section of the report. Treatment effects are considered significant at $P \leq 0.10$.

Spring Regrowth and Soil Test Data

Summary data of nitrogen uptake in the spring is given in Table 10. Nitrogen rate significantly ($P \leq 0.10$) influenced spring regrowth and nitrogen uptake at three locations. At Underwood and Waseca N uptake increased linearly to the 180 lb. Fall N rate. The amount of applied N that it took to increase N uptake by 1 lb. in the spring was 6 lbs. at Waseca and 8 lb. at Underwood. At Crookston the increase was curvilinear and increased to a maximum of around 120 lbs. of N. The responses at each individual location indicate a poor efficiency of uptake of N with high application rates in the Fall. Figure 9 summarizes the efficiency of N uptake for given fertilizer rate. The efficiency of uptake was calculated by subtracting the amount of N taken up in the control (0 N Fall) from that taken up with each individual N rate divided by the amount of fertilizer N applied. In most cases the relative efficiency was higher at the lower application rates. The only exception was for Underwood in which the relative efficiency was approximately similar for all N application rates. The highest efficiencies were the 30 lb. rate at Lamberton and 60-90 lb. rates at Crookston. However, the values were still only about 30-35% of the applied N. Apparent N recovery was 15% or less for rates of 150 lbs. or higher. This indicates that higher application rates are not as efficient which can put the nitrogen at a risk for loss over the winter since there was ample time for conversion to nitrate following fall application. A small application of N may be warranted in the Fall but the rate should not be too high as to pose a risk for N loss.

Soil nitrate was assessed using two foot tests taken in the spring (Figure 10). At all locations the soil test increased in a linear fashion due to fall applied N. This result indicates that there is some carryover of fall applied N to the spring. However, the locations varied in the relative potential for N carryover. Soils were heavier textured at Waseca and Crookston therefore there should be a higher potential for N carryover. By examining the slopes of the regression lines we can determine a relative efficiency of carryover of N following the fall application. The data shows that on average 71% of the N applied at Waseca and 65% at Crookston could be measured in the top two feet in the spring. It is reasonable to assume that not the entire amount of N was lost though. Crop uptake and N leaching below two foot and not lost through denitrification or leaching may account for some of the 29% or 35% difference between applied N and N measured in the 2' soil test. In contrast there was only 16% of the applied N remained in the spring at Lamberton and 12% at Underwood. Internal soil drainage was such that at these locations that these was a higher likelihood of leaching losses. Therefore, soil texture and drainage has to be considered when planning for Fall N applications. There is not enough uptake into the plant that would help alleviate potential losses of N to economically justify 100% of the N applied in the Fall.

Grain yield and Protein

Grain yield was significantly ($P \leq 0.10$) increased by spring N at all locations. Fall N only affected yields at all locations except for Waseca (Table 11). At Crookston and Underwood the amount of N needed to maximize yield in the spring varied by Fall N rate (Table 12). At Lamberton the analysis indicated differences in the effect of spring N on yield for the Fall N rates. However, the optimum Spring N rate at this location was 0 for all Fall N rates. Many of the plots at this location had significant lodging which indicates excess N was available for the crop. At Underwood, the amount of N needed to maximize yields in the Spring was about 40 lbs. per acre regardless of Fall N rates. At Crookston the Optimum spring N rate was 60 lbs. when no N was applied in the Fall and 30 lbs. when 30 was applied in the Fall. While there were some similarities between the Underwood and Crookston locations yields always were increased by nitrogen application at Underwood but the high N rates decreased yields at Crookston. Similar to the Lamberton location there was significant lodging in the high N rate plots at Crookston. Significant winterkill at Waseca made it difficult to determine optimum N rates, thus no analysis was performed on the data. The statistical analysis found significant differences in the amount of N needed in the spring but a model could not be fit to the data to determine an optimum rate. In general the data shows that little N was needed to maximize yields at most locations which is surprising since most sites did not have large amounts of residual N at the start of the season. It is likely that mineralization from organic matter supplied most of the N to the crop and no N was expected from previous crop credits. This data also shows that less N appears to be needed to maximize yields of winter wheat compared with spring wheat. While we have no direct comparisons for this study the amount of N needed per bushel of winter wheat was less than the 1.5 lbs found in the spring wheat study, but yield potentials were also lower. It is likely that N rate recommendations should be modified if a grower is raising winter instead of spring wheat. However, the data does not include a large number of locations so more data would be beneficial to add to the database.

Protein responded differently to Fall and Spring N than Yield. Unlike yield, protein was significantly ($P \leq 0.10$) increased at all locations by either Fall or Spring N (Table 13). Increases were generally linear indicating a potential for greater increase in protein beyond the highest spring application rate (150 lbs.) for Crookston and Lamberton. At Underwood and Waseca protein increased in a curvilinear fashion to a maximum of 129 lbs. at Underwood and 112 lbs. at Waseca. The reasons for differences in response are unclear, but may be due to the year. The magnitude of protein responses were generally about 1-2% increase between the control and highest fertilizer rates. It is important to note that winter wheat is not marketed the same as spring wheat thus there is not necessarily a set level that will be charged a discount when the protein level is below. This somewhat simplifies determining optimum N rates for the crop. Still, many growers want to maintain modest protein levels so it must be factored in when making N recommendations.

Figure 11 shows an economic analysis of three of the locations. The analysis was conducted using a price ratio (price of N/value of the crop) of 0.10. The analysis was conducted with the following assumptions: $5 per bushel wheat, $0.50 per pound N in the spring, a 20% increase in N price for spring N, and with and without a discount of $0.10 per fifth when protein was below 12%. The 12% level was used because it is around the basis where winter wheat is traded at. The economic optimum N rate varied by location. The MRTN (maximum return to N) value at Underwood was achieved with 90 pounds of total N with either 30 or 60 lbs. being applied in the Fall. Overall, the yield levels pointed to slightly higher yields with 60 lbs. of Fall N at this location. Protein was increased by only spring application at this location. The effect of adding the discount into the data had little impact on the interpretation at this location. At Crookston a total of 60 lbs. of N was needed to maximize profit and it did not matter if it was applied in Fall, Spring, or as a 50/50 split. When a protein discount was assessed then the highest return was to the 60 lbs. of N applied in the Fall. This difference was due to an increase in protein from the 60 lb. Fall N rate. At Lamberton, the rate with the highest was no N applied in the Fall or Spring. The return from 30 and 60 lbs. of Fall applied N was approximately similar to the absolute control. Therefore, a small amount could be applied in the Fall but likely was not needed. There is no clear evidence why no N was needed at Lamberton. Soil test N prior to seeding was the lowest at this location (Table 9) and there was little to no increase in soil N in the spring following fall application (Figure 10).

The differences in responses between locations necessitate further investigation of methods to assess N need. The fall soil N test is recommended for parts of Minnesota to adjust nitrogen rates. Since samples were taken in the spring for this study they could be used to determine if there is some relationship between the spring 2' N test and the amount of N needed to maximize yields. Since there was no or a negative response to N at Waseca and Lamberton these locations were not used in the analysis. At Underwood, the yields for the 0 and 30 Fall N rates produced slightly lower yield so they were also discounted from the analysis. For the spring wheat studies, protein yield was used to factor in both yield and protein to maximize both with the nitrogen recommendation and compared to that for yield. A similar analysis was conducted for the Underwood and Crookston locations. Different models were fit to the data and the model fitting parameters were similar for the Quadratic and Linear plateau models. In both cases yield increased either up to 90 lbs. of total N for the Quadratic- and 67 lbs. for the Linear Plateau model (Figure 12). In comparison protein yield increased up to 102 lbs. of total N for the Quadratic- and 80 lbs. for the Liner Plateau models (Figure 13). The fit of both models indicates that there is a potential for taking a 2' soil test in the spring in order to determine the amount of fertilizer N that should be applied. The main decision for Fall N would be how much is needed in order to maximize yield and protein potential. At sites such as Underwood with a high leaching potential at least 30 lbs. to a maximum of 60 lbs. would have benefited yield while at Crookston less could be applied. The spring test would also be better equipped to assess for carryover of Fall N which has major advantages when determining what rate to apply in the spring. When compared to average yields for the two locations it took 1.0 to 1.2 lbs. of N per bushel to maximize yield depending on which model was used and 1.2 to 1.7 lb. per bushel for protein yield. This shows that when including protein along with yield more N is needed to maximize protein yield than for grain yield alone. For spring wheat, the amount of N needed to maximize yield was about 1.5 lbs. per bushel for similar areas of the state. When protein is factored in it can take between 2.0 to 2.5 lbs. per bushel in order to maximize yield and protein at around 14%. This data has major limitations in that yield potentials were similar between most locations thus we are limited in some of the conclusions at this time. To reiterate a previous comment, more data would be beneficial to determine the optimum N rates. However, this data has provided a good start for determining optimum nitrogen rates.

Table 9. Spring soil test averages across replications for winter wheat locations.

				Soil Test (0-6")†				
Year	Location	County	Soil Series§	P	K	SOM	pH	Nitrate Nǀ
				-------ppm-------		---%---		---lb/ac---
2008	Underwood	Otter Tail	Arvilla SL	36	90	2.2	5.4	29
	Waseca	Waseca	Nicollet CL	83	274	4.7	6.0	48
2009	Crookston	Polk	Bearden CL	11	272	3.2	8.1	46
	Lamberton	Redwood	Ves L	12	162	3.9	5.4	20

† P, Olsen phosphorus; K, ammonium acetate potassium; SOM, soil organic matter; pH, soil pH.

ǀ 0 to 2 foot soil nitrate level.

§ CL, clay loam; L, loam; SL, silt loam.

Table 10. Nitrogen uptake of winter wheat spring regrowth based on nitrogen rate applied in the fall.									
	Nitrogen Rate							Statistics†		
	0	30	60	90	120	150	150	Sig.	Model	MaxN
	--------------------------------lbs N/ac-------------------------------							---*P>F*---		--lbN/ac--
Underwood	9	10	18	18	18	29	34	<0.01	Lin	--
Waseca	54	46	40	58	51	92	71	0.02	Lin	--
Crookston	13	20	34	46	39	35	38	0.01	Quad	118
Lamberton	24	34	34	35	40	33	35	0.66	--	--

† Sig., significant for main treatment effects (nitrogen rate) according to ANOVA; Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied).

Table 11. Results of the analysis of variance for main treatment effects and their interactions for winter wheat yield (adjusted to 13%) and protein.						
	Yield			Protein		
	Fall N	Spring N	FN x SN	Fall N	Spring N	FN x SN
	---*P>F*---					
Underwood	0.09	<0.01	0.17	0.77	<0.01	0.62
Waseca	0.71	0.08	0.88	0.57	<0.01	0.44
Crookston	0.09	<0.01	<0.01	<0.01	<0.01	0.88
Lamberton	<0.01	<0.01	<0.01	<0.01	<0.01	0.23

† Resuts for the analysis of variance for main treatment effects (Fall N and Spring N) and their interaction (FN x SN) at each locations. Effects are considered significant at *P* <0.10.

Table 12. Summary of yield averages for Fall N and Spring N rates at each location and model fitting data for spring N rates for individual fall rates up to 120 pounds.

		Spring N rate (lbs N/ac)						Statistics†	
Location	Fall N (lb/ac)	0	30	60	90	120	150	Model	MaxN
		--------------------------------bushels/acre--------------------------------							--lbN/ac--
Underwood	0	25	50	40	36	47	40	QP	28
	30	28	47	51	57	56	48	QP	63
	60	31	49	58	57	58	54	QP	40
	90	33	49	56	60	54	59	QP	40
	120	40	59	58	59	57	61	QP	40
	150	44	--	--	--	--	--	--	--
	180	48	--	--	--	--	--	--	--
Waseca	0	43	57	55	51	51	56	NE	
	30	44	61	55	59	56	55		
	60	45	55	58	53	51	56		
	90	60	58	55	57	61	52		
	120	59	61	61	56	60	61		
	150	60	--	--	--	--	--	--	--
	180	58	--	--	--	--	--	--	--
Crookston	0	31	53	65	64	62	64	QP	65
	30	42	66	64	68	66	64	QP	29
	60	64	69	58	64	61	59	Lin	0
	90	63	60	64	52	56	57	Lin	0
	120	60	63	55	55	48	49	Lin	0
	150	52	59	65	--	--	--	--	--
	180	55	53	50	--	--	--	--	--
Lamberton	0	76	77	75	70	78	63	Lin	0
	30	78	80	67	75	68	58	Lin	0
	60	83	76	69	70	66	60	Lin	0
	90	85	70	63	62	61	58	Lin	0
	120	66	65	53	62	59	52	Lin	0
	150	63	58	62	--	--	--	--	--
	180	63	69	57	--	--	--	--	--

† Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied). NE, non-estimatable.

Table 13. Summary of grain protein averages for Fall N and Spring N rates at each location and model fitting data for spring N rates for individual fall rates up to 120 pounds.

		Spring N rate (lbs N/ac)						Statistics†	
Location	Fall N (lb/ac)	0	30	60	90	120	150	Model	MaxN
		---%---							--lbN/ac--
Underwood	0	11.1	11.2	13.7	13.9	14.1	14.2	QP	129
	30	10.7	12.2	13.4	14.1	14.2	14.3	QP	129
	60	10.3	11.9	13.0	13.2	14.3	14.4	QP	129
	90	9.9	12.0	13.4	13.9	14.4	14.4	QP	129
	120	10.2	12.0	13.4	13.5	14.1	14.4	QP	129
	150	10.5	--	--	--	--	--	--	--
	180	11.0	--	--	--	--	--	--	--
Waseca	0	12.9	13.2	13.6	13.5	13.3	13.8	QP	112
	30	13.1	13.1	13.2	13.3	13.4	13.3	QP	112
	60	13.1	13.0	13.2	13.3	13.2	13.5	QP	112
	90	13.1	13.3	13.4	13.2	13.4	13.5	QP	112
	120	13.1	13.3	13.4	13.4	13.4	13.5	QP	112
	150	13.3	--	--	--	--	--	--	--
	180	13.2	--	--	--	--	--	--	--
Crookston	0	11.3	11.4	10.9	11.7	12.6	12.9	Lin	150*
	30	11.2	11.2	11.6	12.0	12.6	12.6	Lin	150*
	60	11.8	11.9	12.7	12.9	13.4	13.5	Lin	150*
	90	12.1	12.7	12.8	13.3	13.5	13.6	Lin	150*
	120	12.5	12.7	13.5	13.8	13.8	13.9	Lin	150*
	150	13.3	13.0	13.4	--	--	--	--	--
	180	13.4	13.7	13.7	--	--	--	--	--
Lamberton	0	12.1	13.1	13.3	13.8	13.6	14.1	Lin	150*
	30	12.6	12.7	13.4	13.6	13.8	14.1	Lin	150*
	60	12.9	13.6	13.8	13.5	14.0	14.4	Lin	150*
	90	13.2	13.4	13.8	13.9	14.0	14.2	Lin	150*
	120	13.7	13.4	14.1	14.2	14.2	14.5	Lin	150*
	150	13.5	14.2	14.3	--	--	--	--	--
	180	13.7	13.9	14.2	--	--	--	--	--

† Model, regression model that best fits the data (lin, linear; Quad, quadratic; QP, quadratic plateau; LP, linear plateau; NM, no model); MaxN, N rate where response was maximized (a rate of 180 indicates no maximum was achieved with N rates applied). NE, non-estimatable.

* Highest N rate did not maximize protein

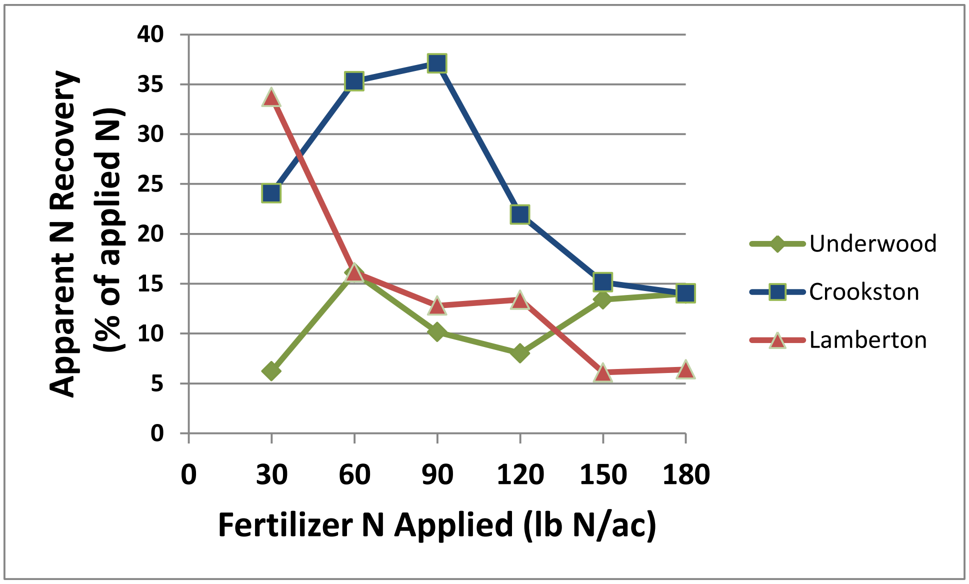

Figure 9. Apparent N recovery in spring biomass of fall applied fertilizer for winter wheat at three locations in Minnesota. Apparent N recovery is defined (N uptake with fertilizer/N uptake with no fertilizer)/N rate applied.

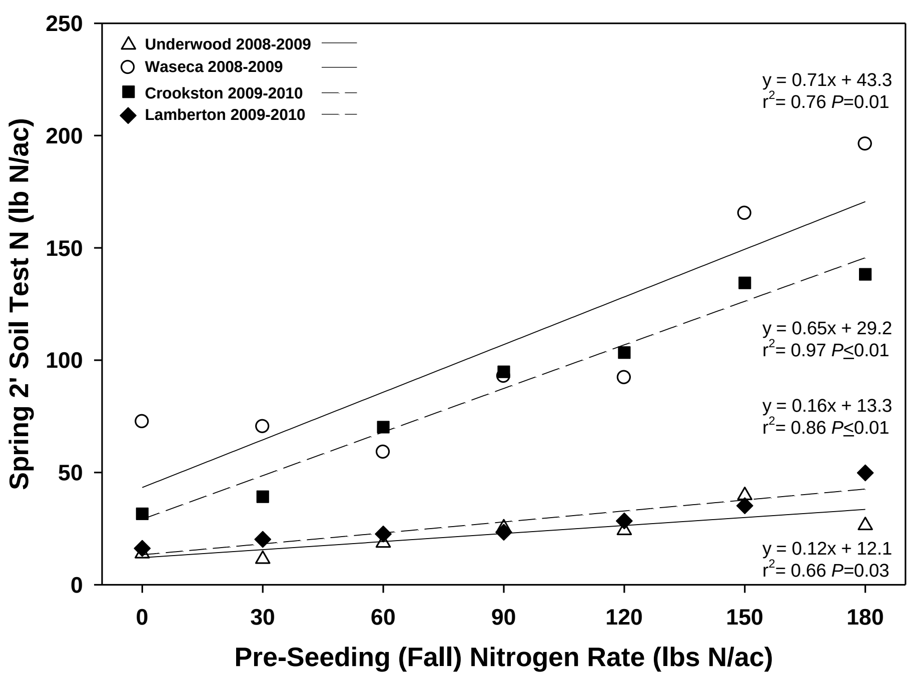

Figure 10. Average spring 2' soil test levels measured at Waseca and Underwood following nitrogen application in the spring. Initial soil N averaged 6 ppm at Waseca and 3.6 ppm at Underwood.

No Protein Discount	$0.10 / fifth discount below 12% Protein

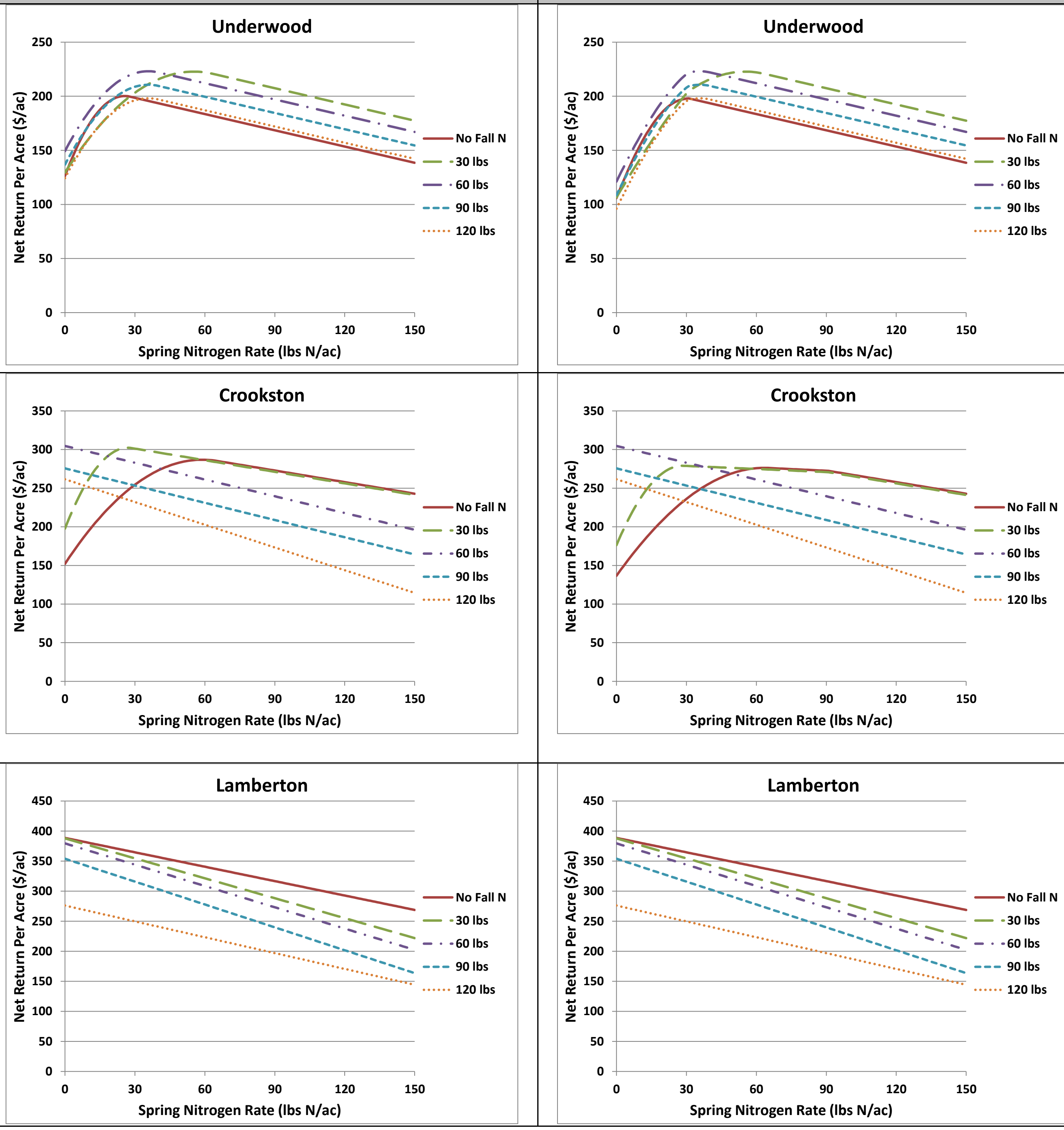

Figure 11. Net return per acre of nitrogen rate applied at three winter wheat locations for combinations of fall and spring applied nitrogen assuming a 0.10 price ratio (price of N/price of wheat) and a 20% price differential between fall and spring N. The analysis is compared with no protein discount and $0.10 per bushel per fifth of a percent below 12%.

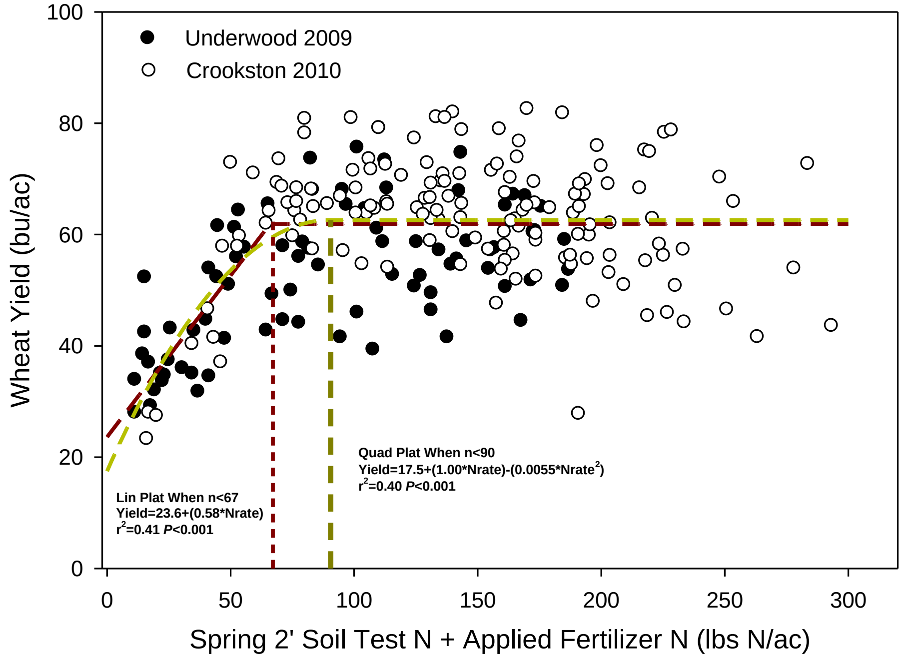

Figure 12. Winter wheat yield response to total available N (2' soil N in spring + fertilizer N) at Underwood and Crookston. Models fit to the data were the Quadratic- and Linear Plateau.

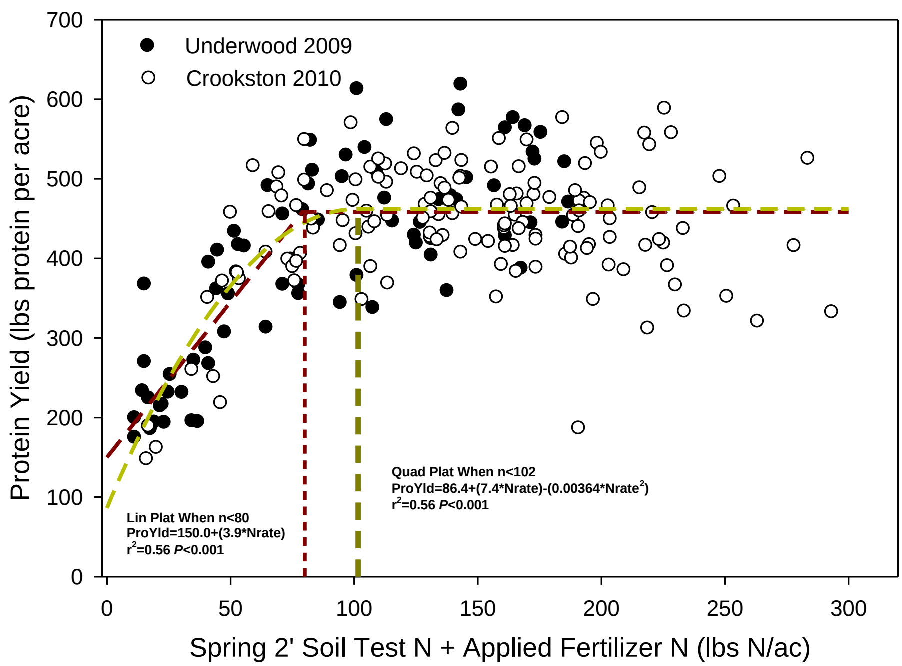

Figure 13. Relation of protein yield (lbs. per acre) of winter wheat to total available N (2' soil N in spring + fertilizer N) at Underwood and Crookston. Models fit to the data were the Quadratic- and Linear Plateau.

Nitrogen Rate Study Comparing Urea with PCU (Objective 3)

Field experiments were conducted in 2008 and 2009 to examine the response of two hard red spring wheat (HRSW) varieties to incrementally increasing rates of two nitrogen (N) fertilizer sources. The two HRSW varieties were Alsen and Knudson, which vary in their grain yield and grain protein concentration potential. Alsen generally has grain yields less than Knudson, but greater grain protein concentration. Our primary objective was to determine if these two varieties accumulated biomass and N differently throughout the growing season. An added factor to the experiment was the two N fertilizer sources, which were commercially available urea and a polycoated urea. Both N fertilizer sources were applied at rates to supply 0 to 150 lbs. N $Ac.^{-1}$ in 30 lbs. increments.

The polycoated urea consists of a urea granule that is surrounded by a polycoating that allows water and liquid N to diffuse through it. Soil water will diffuse through the polycoating then dissolves the urea granule forming liquid N. The liquid N then diffuses through the polycoating back into the soil environment. Once in the soil environment liquid N from the polycoated urea behaves similarly to the commercially available urea. The rate of N release from the polycoated urea depends on the availability of soil moisture and soil temperature, which regulates the rate of diffusion. The two years this experiment was conducted were generally cool, especially in the spring. In 2009, temperature tended to be cool throughout the growing season . Soil moisture tended to be limiting in 2008, but more favorable in 2009.

Throughout the growing season, two adjacent wheat rows 3-ft long was periodically sampled from each plot. Whole plants were hand cut at the soil surface and brought into the lab where samples were weighed and subsampled. The subsample was weighed, dried, reweighed, and ground. This process was used to determine the biomass that had accumulated at the time of sampling. The ground subsample was then analyzed for N concentration, which combined with the biomass accumulation, determined total N accumulation. In the 2008, there were five in-season samplings; 53, 63, 73, 82, and 98 days after planting (DAP). In 2008, due to the slow development of the wheat crop, caused by the cool temperatures throughout the growing season, 4 in-season samplings were conducted at 41, 53, 63, and 96 DAP. In both years, the last sampling occurred at the soft dough growth stage where total biomass and N accumulation should be at their maximum levels.

Statistical analysis was done using SAS and its PROC Mixed procedures. Contrasts were used to test meaningful comparisons. Statistical analysis results will not be shown in this report, but mention of differences in experimental factor levels indicates the effects of those factor levels was statistically significant at the 0.05 probability level. As the season of 2009 advanced it became apparent that there was plant growth gradient across the experimental site that was not accounted for with the blocking in the randomized complete block experimental design (RCBD) used. The PROC Mixed procedure allows statistical analysis using spatial variability as a co-variable instead of blocking to determine treatment differences. The Fit Statistics generated by PROC Mixed was used to determine if there was an advantage to analyzing data using spatial variability or RCBD. Based on the Fit Statistics, the appropriate analysis was conducted. Generally the later sampling dates were analyzed accounting for spatial variability. Only the first sampling in 2009 was analyzed using the RCBD. All the data in 2008 was analyzed using a RCBD.

Biomass and N accumulation increased as N rates increased at all sampling dates in both years. In some cases this response was linear, increased throughout the entire range of N rates, and in others it was quadratic, maximum levels reached at an N rate less than the maximum N rate. Response to applied N rates was expected since pre-evaluation of both experimental sites indicated the crop should respond to the application of N fertilizer. We were more interested in differences between the two HRSW varieties, the two N sources, and their interactions with N rates or each other. There was no indication that HRSW varieties responded differently to the N sources in either year.

Comparison of Urea and PCU

In 2008, urea enhanced both biomass and total N accumulation at earlier sampling dates compared to PCU. Due to the scale used in Figure 14a, this difference is difficult in biomass accumulation is difficult to see visually, but the difference was statistically significant at the 53, 63, and 73 DAP samplings. At later samplings, biomass accumulation increased at a faster rate as N rates increased with urea than PCU even though at the higher N rates, there was little difference between the two N sources. This interaction between N source and N rates was significant at the 82 and 98 DAP sampling. Total N accumulation was greater with urea than PCU at all sampling dates except 98 DAP (Figure 14b). There was also a greater response to N rates with urea than PCU at the 63 and 73 DAP samplings. This interaction between N sources and N rates was significant. However, by late in the season there was no difference in total N accumulation between the two N sources.

In 2009, urea enhanced total N accumulation at the 41 and 96 DAP samplings compared to PCU (Figure 15b). At mid-season samplings there was no difference between N sources. Biomass accumulation was enhanced with urea at all sampling dates except 96 DAP (Figure 15a).

It was apparent that N availability may have been limiting when the N source was PCU in both the 2008 and 2009 growing seasons. Early spring temperatures tended to be cold to cool in both years, which inhibits the diffusion process necessary to release PCU-N to the soil environment. In both years, plant biomass production and total N accumulation was less with PCU than urea indicating the wheat crop was probably N deficient during the early part of the growing season. Final harvest results would support this conclusion as grain yields, the potential of which is determined earlier in the growing season, was greater with urea as the N source. However, grain protein concentration was greater with PCU.

Comparison of Alsen and Knudson HRSW Varieties

There was little difference between the two HRSW varieties in biomass accumulation until the last two sampling dates in 2008 (Figure 16a) and the last three sampling dates in 2009 (Figure 17a) when Knudson accumulated more biomass than Alsen. There was no total N accumulation difference between the two HRSW varieties in 2008 except for the first sampling date where Knudson accumulated more N than Alsen (Figure 16b). However in 2009, Knudson accumulated more N than Alsen in the latter two sampling dates (Figure 17b). Both varieties responded similarly to N rates and N sources.

These two HRSW varieties differ in their grain yield and grain protein concentration potential. Knudson produced greater grain yields and lower grain protein concentration than Alsen in both years. It appears this difference began to manifest itself as greater biomass accumulation in Knudson by the last two sampling dates in both years. In 2009, the 63 DAP sampling was at the anthesis growth stage and in 2008, the 82 DAP sampling was about 10 days after anthesis. It was not consistently apparent if N accumulation differences between these two varieties could help explain why Knudson had greater grain yield and lower grain protein concentration than Alsen. There appears to be little difference in total N accumulation between the two varieties.

Urea/ESN Ratio Study (Objective 4)

Experimental Conditions

Experiments conducted at 2 sites located about 10 miles apart. Site 1 was a Beardon sicl soil with 28 lbs. soil residual nitrate-N $Ac.^{-1}$. Site 2 was a Glyndon vfsl soil with 24 lbs. soil residual nitrate-N $Ac.^{-1}$. Previous crop at both sites was soybean. Experimental design was Randomized Complete Block with 4 blocks. Both sites received broadcast application of P fertilizer prior to initial spring tillage and Knudson hard red spring wheat variety was planted at 1.6 million seed A^{-1} in 6 inch wide rows. All plots were 25ft long and 5 ft wide. The growing season at both sites was cold and moist.

Treatments consisted of various ratios of Urea/ESN fertilizer (0/100, 25/75, 50/50, 75/25, 100/0) at two N rates (60 lbs. N $Ac.^{-1}$ and 120 lbs. N $Ac.^{-1}$) plus a 0 N control. N rates represented 50% and 100% current N recommendations for a 65 bushel A^{-1} yield goal minus soil residual N minus a 20 lbs. N A^{-1} credit for a previous crop of soybean. All N fertilizer was hand broadcast prior to two passes with a field cultivator. Wheat was planted 3 days later on 14 May.

Data collected were whole plant biomass and N for total N uptake, grain yield, and grain protein. Whole plants were hand cut just above the soil surface from one interior row 3 ft. long, dried, and analyzed for N. Grain yield was determined by grain weight, adjusted to 13.5% moisture by combine harvesting the entire plot. Grain protein was determined by NIR.

Statistical analysis was done using PROC Mixed in SAS 9.12 where Rep was considered a random variable. Treatment separation was tested with single degree of freedom contrasts and difference of LSMeans. The control treatment was not included in the statistical analysis because variability across replications was substantially greater than that of the N treated plots. Therefore, statistical analysis included only those treatments where N was applied.

Results

There was substantial grain yield and total N response to applied N compared to the control at both experimental sites (Figure 18 and 19). Grain yields were quite high at both locations. Though the small plot yields were probably greater than the average yields of the fields in which the experiments resided, grain yields were generally quite high throughout much of NW

Minnesota and NE North Dakota. Yields were significantly increased with 100% recommended N rate compared to 50% N recommended N at both sites (Site 1a and Site 2a). There was no significant grain yield difference among the Urea/ESN ratios at either site. At Site 2, the middle ratio ranges tended to have lower grain yield resulting in a significantly quadratic yield response (alpha = 0.10) to the ratios. That is, 100% as ESN or Urea produced more grain than combinations of the two N sources. It is uncertain why this would occur. However, Site 2 data tended to be more variable overall than at Site 1.

Grain protein concentration significantly increased with the higher rates of N fertilizer. At both sites the higher proportion of the fertilizer mixture as ESN resulted in higher grain protein concentration (Site 1 b and Site 2 b). This was significant at both sites. Total N accumulation at soft dough was significantly increased with the higher rate of N fertilizer. Total N accumulation among the Urea/ESN ratios was variable at both sites (Site 1 c and Site 2 c). Differences among ratios were not significant at Site 1, but at Site 2 there was a significant increase in total N uptake with a greater proportion of fertilizer as urea at the 100% recommended N rate. More detailed analysis is needed. But, it appears that in 2009 greater proportions of the fertilizer mixture as ESN may have enhanced grain protein concentration without a reduction in grain yield.

Conclusions

Nitrogen rate trials indicate that current N recommendations appear to be close to those found in the spring wheat studies. Economic analysis indicates that, from 2008 to 2010, the amount of total available N needed was near 200 lbs. for Northern Minnesota and 120 lbs. for a 0.10 price ratio for locations following soybean. For winter wheat studies, the data indicate less N was needed than recommended for spring wheat. Split applications would still be recommended for winter wheat but the rate applied should vary by them amount of N that can be supplied by the soil and the leaching potential for the location. The data indicates that a spring soil N test could be used to assess the amount of N needed for winter wheat in Northern Minnesota and a range of 70-90 lbs. total available N in the Spring would maximize yield while 80-100 lbs. would have maximized protein and yield. However, application rates should be kept low in order to limit lodging. That data comparing urea and polycoated urea showed inconclusive benefits for increasing wheat yields. Nitrogen accumulation trended less for polycoated urea mainly due to the release characteristics from this product. The data showed that there was a benefit of polycoated urea for increasing protein and this effect was greater with higher percentages of PCU versus urea without sacrificing yields, but some risk of yield loss may still exist in dry or cool years. The use of this product within the optimum N rate guidelines may help to increase protein, but more data is needed to further evaluate this product due to a higher cost than standard urea.

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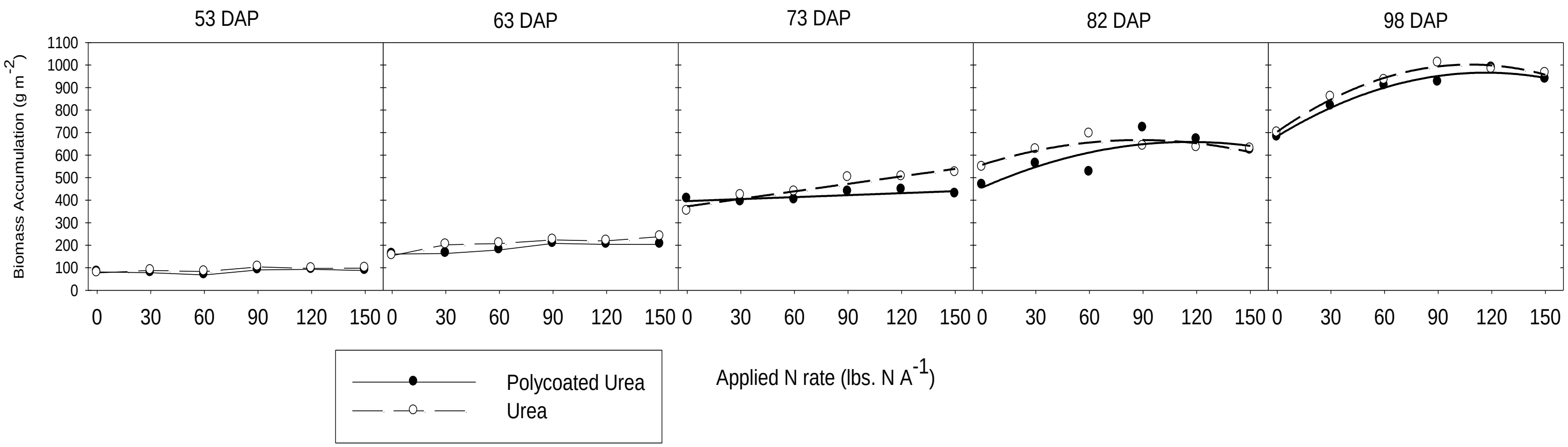
Biomass Accumulation



a. Total N Accumulation

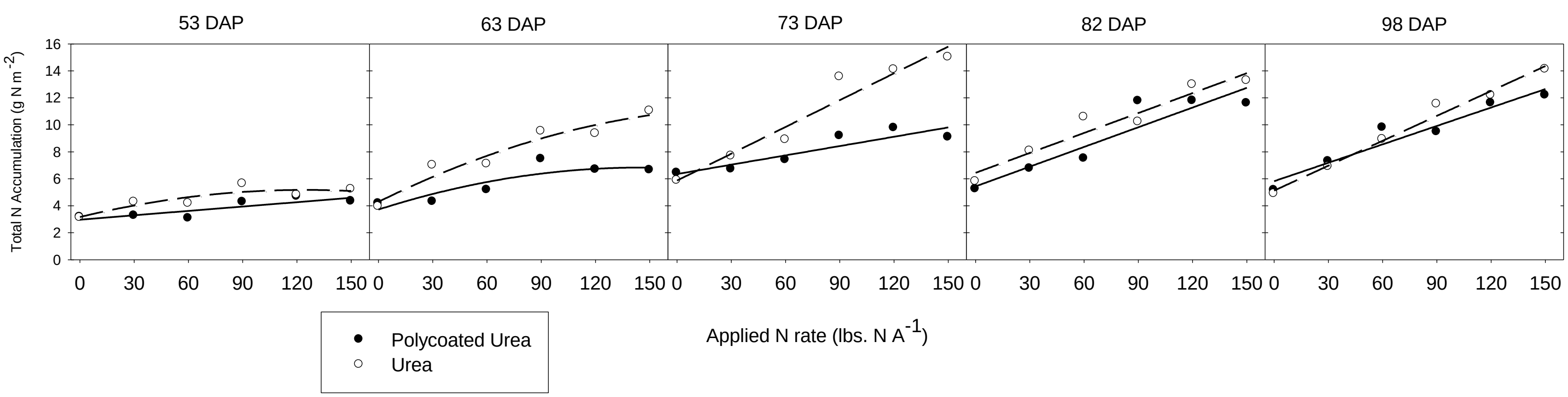
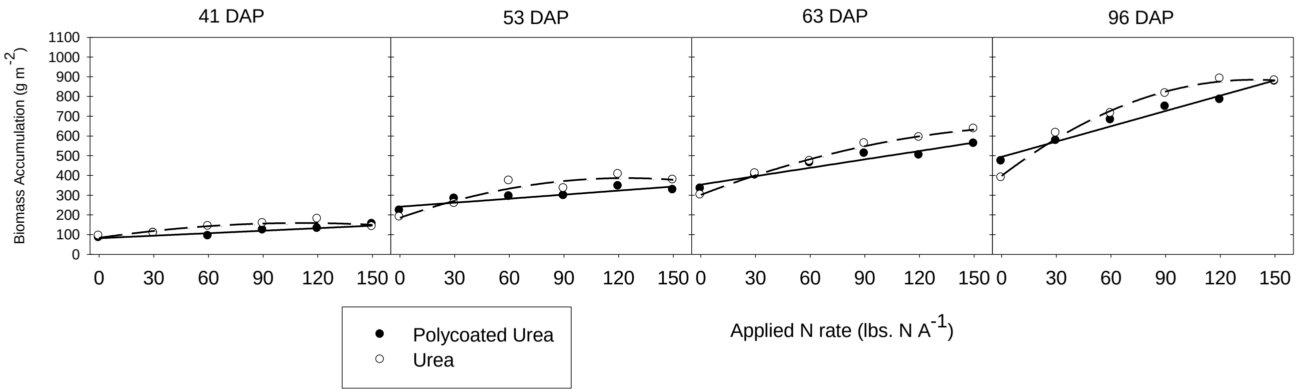


Figure 14. Biomass and total N accumulation response to applied N rates with two N sources in 2008.

a. Biomass Accumulation



b. Total N accumulation

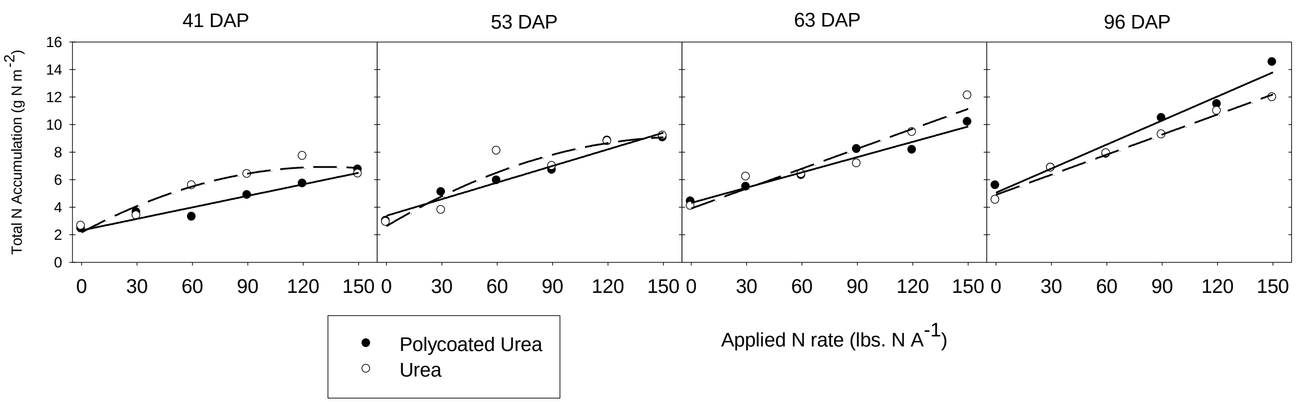
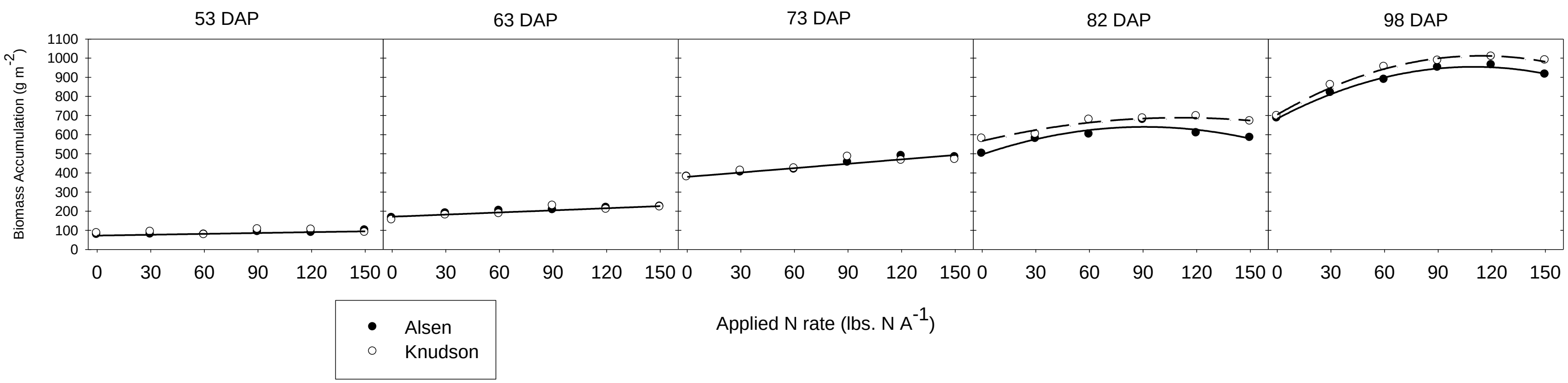


Figure 15. Biomass and total N accumulation response to applied N rates with two N sources in 2009.

a. Biomass Accumulation



b. Total N Accumulation

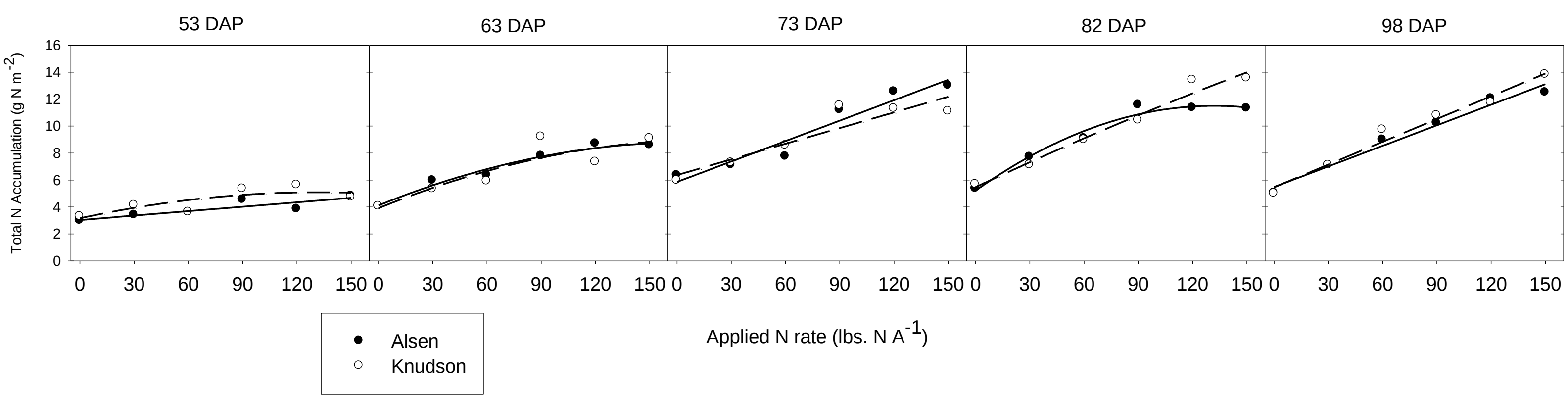
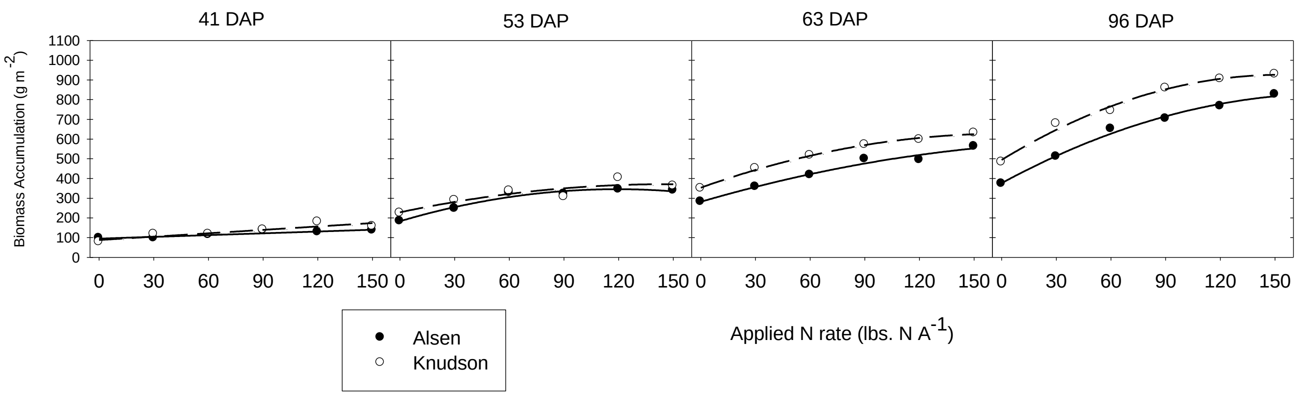


Figure 16. Biomass and total N accumulation response to applied N rates for two hard red spring wheat varieties in 2008.

a. Biomass Accumulation



b. Total N Accumulation

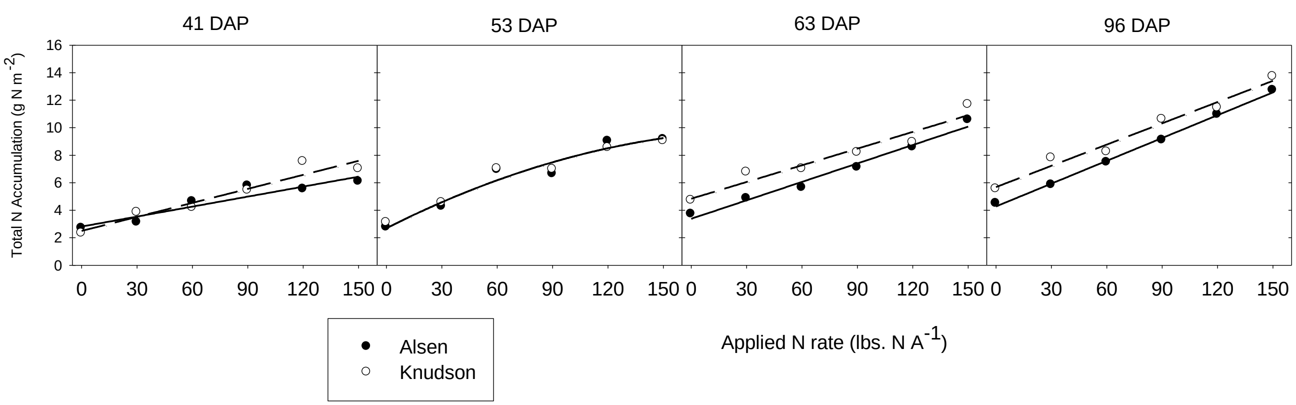


Figure 17. Biomass and total N accumulation response to applied N rates for two hard red spring wheat varieties in 2009

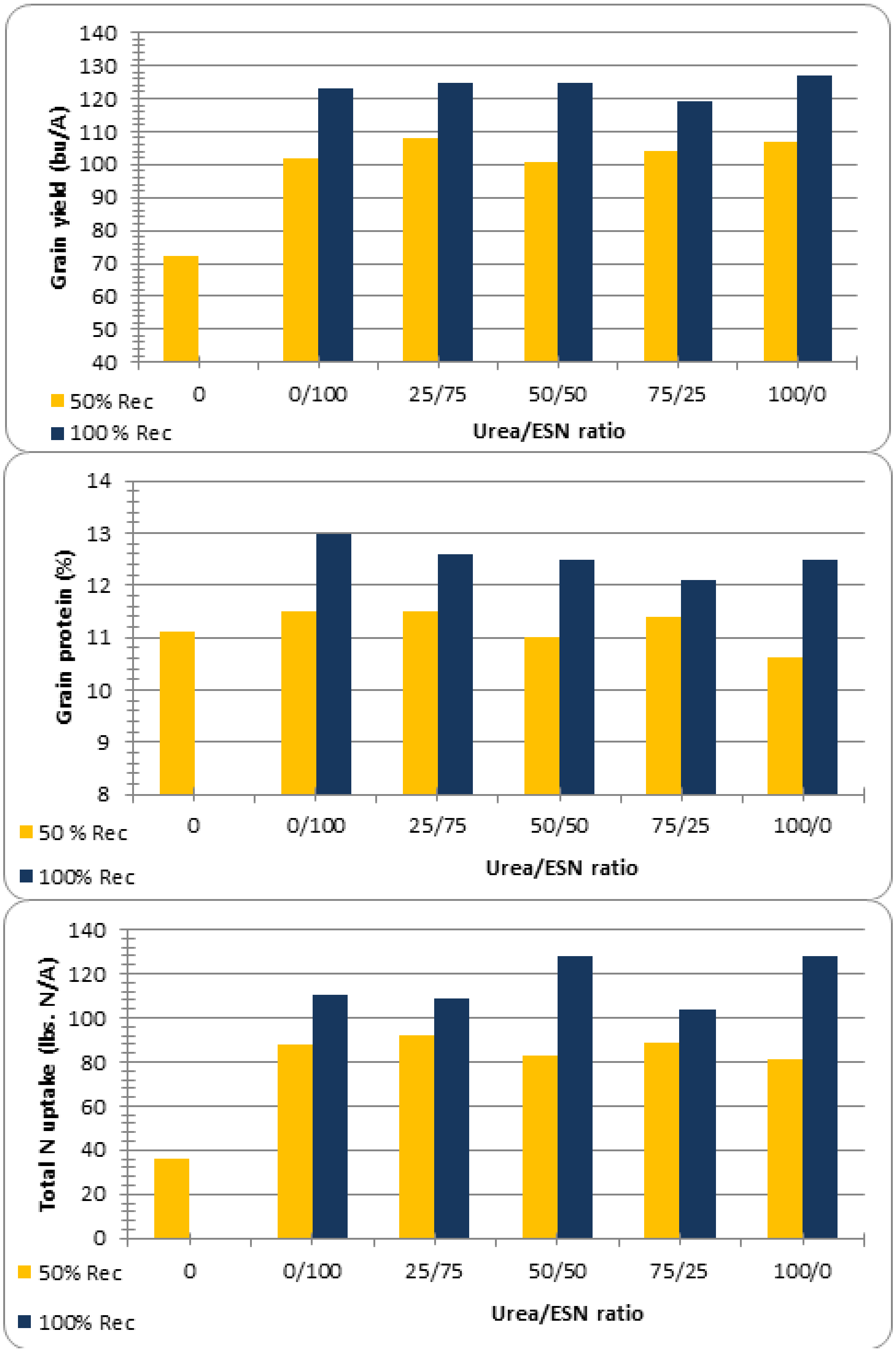


Figure 18. Grain yield (top), protein (middle), and total N uptake (bottom) for ratios of urea to ESN at Site 1 applied at 50% and 100% or recommended N rate compared to a no N control.

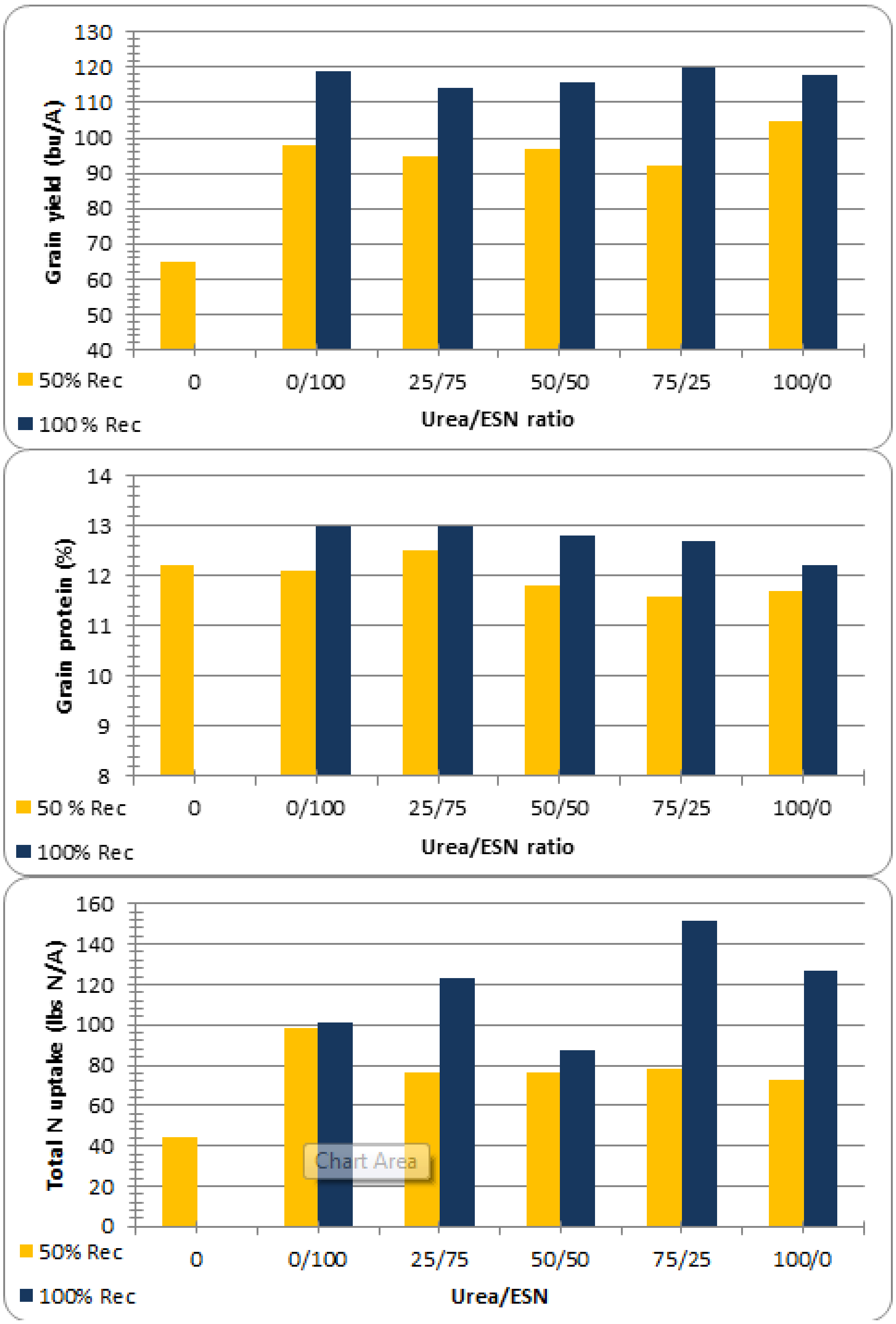


Figure 19. Grain yield (top), protein (middle), and total N uptake (bottom) for ratios of urea to ESN at Site 2 applied at 50% and 100% or recommended N rate compared to a no N control.