UREA AND UREA ADDITIVES AS FERTILIZER SOURCES FOR CORN PRODUCTION IN MINNESOTA (2017 GROWING SEASON)

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BRIEF OVERVIEW

Urea is increasingly an important nitrogen (N) source in Minnesota. Approximately 43% of our farmers use urea as their major N source. In the southwestern, south-central and west-central areas approximately 45% of the N is applied in the fall, 50% is applied in the spring, and 5% is applied at sidedress. While most of those that use urea as the major N source apply it in the spring, approximately 4% do the major application with urea in the fall and there are others that apply some of their N as urea in the fall as this application is part of the listed Best Management Practices. However, in recent years, due in part to wet spring conditions, fall urea applications have resulted in yield reduction.

The objectives of this study were to: 1) evaluate fall and spring applications of urea to determine their feasibility and calculate the economic optimum N rate for fall and spring applications when corn follows corn (CC), corn follows wheat (CWh) and corn follows soybean (CSb), 2) Investigate the role of placement (band vs. broadcast and incorporated) and of a nitrification inhibitor and polymer coating (ESN) to improve management of urea.

MATERIALS AND METHODS

The study was conducted at the following Research and Outreach Centers during the 2017 growing season: Northwest (Crookston), West Central (Morris), Southwest (Lamberton), and Southern (Waseca). At Crookston 2 experimental sites were established under w**heat-corn (CWh) (**Wheatville very fine sandy loam, clayey till substratum, 0 to 2 percent slopes) and **corn-soybean (CSb) rotation** (Gunclub silty clay loam, 0 to 2 percent slopes). Lamberton had also 2 experimental sites under **corn-sobyean (CSb) (**Normania loam, 1 to 3 percent slopes and small section of Amiret loam, 2 to 6 percent slopes) and **corn-corn (CC)** rotation (Amiret loam, 2 to 6 percent slopes, Webster clay loam, 0 to 2 percent slopes, small portion with Normania loam, 1 to 3 percent slopes). Morris experimental site under **corn-corn (CC)** rotation was established on Forman-Aastad complex soil, 1 to 4 percent slopes and a very small portion of Aastad clay loam, 1 to 3 percent slopes. Waseca had 2 experimental sites under **corn-soybean (**Nicollet clay loam, 1 to 3 percent slopes, Canisteo-Glencoe complex, 0 to 2 percent slopes, and a small portion of Webster clay loam, 0 to 2 percent slopes) and **corn-corn (CC)** rotation (Clarion loam, 2 to 6 percent slopes, Nicollet clay loam, 1 to 3 percent slopes, and a very small portion of Webster clay loam, 0 to 2 percent slopes).

Treatments are presented in Table 1. The treatments included a full set of N rates for fall and spring pre-plant (PP) applications of broadcast and shallow incorporation of urea (BI) to allow us to determine N response and calculate the economic optimum N rate (EORN). Rates ranged from 0 to 240 lb N/acre in CC and since the yield response is expected to maximize at a lower rate for CSb and CWh the rate ranged from 0 to 200 lb N/ac. There is also a comparison of different sources, placements, and timings: the standard practice that consist of anhydrous ammonia (AA) with N-Serve in the fall and without N-Serve in the spring, ESN broadcast and incorporated by tillage (BI), and urea with or without the nitrification inhibitor Instinct II either as BI or banded application (SSB) all as spring and fall applications. The sub-surface banded fertilizer was applied below the crop row position (except for urea and urea+Instinct treatments at Waseca that were applied between the crop rows). For the comparison treatments, we used a sub-optimal rate (most responsive portion of the response curve) to be able to more easily detect differences due to treatment. Treatments 15 to 24 were applied at 120 lb N/ac in CC and at 80 lb N/ac in CSb and CWh except for AA that was always applied at 120 lb N/ac because a lower rate was not achievable with the available equipment. The treatments were organized in a randomized complete block design replicated four times.

Plant dry biomass and N uptake were measured at V6 and R6 development stages. Canopy sensing was performed with the Crop Circle and normalized difference red-edge (NDRE) index were calculated for the V6 and V12 development stages. At harvest grain yield was calculated and grain N content measured. After harvest soil samples from the 0-12, 12-24, and 24-36-inch depth increments were collected and analyzed for ammonium-N and nitrate-N and total inorganic N (TIN) was calculated. Statistical analysis was performed using the SAS software and program. Differences were established at P=0.05.

RESULTS AND DISCUSSION

In Lamberton except for June and September precipitation was above normal from April to October (Table 2). In Morris most of the growing season was wetter than normal but July was excessively drier. In Waseca April and June were near normal or slightly below but May, July and October were excessively wet, and August and September were drier than normal. At Crookston most of the growing season was drier than normal except for June that was near normal and September that was wetter than normal (Table 2).

Lamberton had similar temperature than normal mean monthly air temperature throughout growing season (Table 2). In Morris mean monthly air temperature was above normal in April and at the end of the growing season. At Waseca mean monthly temperatures were consistently above normal, except in May and August. In Crookston, the beginning of the growing season was cooler than normal air mean temperatures, with temperatures similar to the normal in July, August and September (Table 2)

Grain yield and N removal

At all sites and crop rotations, except Crookston under CSb rotation, there was a significant positive response in grain yield and grain N removal to N rate application, but the response varied with sites and time of application (Table 3, 4, Fig. 1). Spring applications produced greater yield and N removal than fall applications in all sites and crop rotations except for Lamberton CC and Crookston CSb (that had no response to N) where there were no differences due to application timing (Table 4). These data show that overall spring applications of urea are more advantageous than fall applications across Minnesota, even in sites where the potential for N loss is relatively low.

In Lamberton, the CC crop for fall application had a linear response to N (yield was not maximized) where yield was 200 bu/a for fall at the highest N rate (240 lb N/ac) (Fig. 1a). Spring application for CC crop had a quadratic response and the yield was 202 bu/ac at the highest N rate (240 lb/N/ac). Overall, similar grain yield and grain N removal were observed for the fall and spring application (Table 3,4). In Lamberton the CSb crop had a quadratic-plateau response to N for the fall application while it had a quadratic response for the spring application (Fig. 1b). For the fall application the EONR was 170 lb N/ac and the yield at the EONR was 183 bu/a. There was a significant difference between fall and spring application when averaged across all N rates (Table 3), the spring yielded 9 bu/ac more than fall.

In Waseca, the CC crop had a linear response to N for the fall application while it had a quadratic-plateau response for the spring application (Fig. 1c). This difference is highlighted by the significant N rate by time interaction (Table 3). For the spring application the EONR was 206 lb N/ac and the yield at the EONR was 224 bu/a. For the fall the yield at the highest N rate (240 lb N/ac) was 222 bu/a. Overall, the spring application yielded 22 bu/a more than the fall application (Table 3). In Waseca the CSb crop had a quadratic-plateau response to N for both fall and spring applications (Fig. 1d). For the fall application the EONR was 156 lb N/ac and the yield at the EONR was 226 bu/a. For the spring application the EONR was 132 lb N/ac and the yield at the EONR was 233 bu/a. Averaged across N rates the spring application yielded 11 bu/ac more than the fall application. These data follow a similar pattern as observed in 2016 (2016 report) and indicate that fall urea in south central Minnesota should not be used because the potential for N loss is too great. This follows current University of Minnesota BMPs.

In Crookston, the CWh crop had a quadratic-plateau response to N for both fall and spring applications (Fig. 1e). For the fall application the EONR was 182 lb N/ac and the yield at the EONR was 157 bu/a. For the spring application the EONR was 111 lb N/ac and the yield at the EONR was 155 bu/a. Averaged across N rates the spring application yielded 8 bu/ac more than the fall application. The CSb crop showed no significant response to N application both at fall and spring application (Fig. 1f). Although there was no significant difference for time of application, numerically the trend was for greater yield (10 bu/ac) with spring application than fall application (Table 3).

In Morris, the CC crop had a linear response to N (yield was not maximized) for both fall and spring applications (Fig. 1g). Grain yield was 140 bu/a for fall and 182 bu/ac for the spring at the highest N rate (240 lb N/ac) (Fig. 1g). There was a significant difference between fall and spring application when averaged across all N rates (Table 3), the spring application yielded 27 bu/ac more than the fall application (Table 3).

The source of N and method of application also showed difference in yield response at all locations except Crookston (Table 5).

Anhydrous ammonia (AA) had similar grain yield than ESN but greater than the other N sources/placements in both crops at Lamberton and in the CSb crop at Waseca. It is important to remember, however, that AA in CSb was applied at 120 lb N/ac whereas the other treatments were applied at 80 lb N/ac. This must be taken into account when interpreting the results in Fig. 2; a direct comparison of AA can be done in the CC crop only because all sources were applied at the same rate of 120 lb N/ac. At Waseca under CC greatest yield was observed in the Urea+Instinct treatment, similar to urea both subsurface applied, and greater than the other N source treatments (Table 5).

In Lamberton, although not statistically significant, the subsurface band applications of urea (with and without Instinct) showed a trend for greater yield relative to broadcast and incorporated urea in the CC and CSb rotations. In Waseca in CC the subsurface band application produced greater yields than the broadcast and incorporated application for both Urea and Urea+Instinct. However, in Waseca CSb no differences were detected among Urea treatments. At Morris Urea had greater yields when was subsurface band applied than broadcast and incorporated (Table 5), however for Urea+Instinct the differences were not significant.

Spring applications had greater yield than Fall application across N sources in Waseca CC and CSb and Crookston CWh (Table 5). In general terms, the response of grain N removal to N source and placement treatments followed a similar trend to those observed for grain yield (Table 6).

Across all locations and crop rotations the AA/I treatment had similar grain yield than U/SSB and ESN/BI but greater than the rest of the treatments (Fig. 2). Urea subsurface band treatment yielded more than the urea broadcast and incorporated treatment. Across all locations and crop rotations in 2017 growing season, Urea+Instinct applied in a subsurface band had similar grain yield relative to the Urea+Instinct broadcast and incorporated treatment (Fig. 2). As with the response to N rate, in general the fall application resulted in lower yields regardless of N source (Table 5).

Plant N uptake and canopy sensing

In general plant N uptake increased with N rate at all locations except Crookston CSb where there were no differences (Table 7 and 8). At V6 generally N uptake increased with N rate to 80 or 120 lb N/ac rate, but for total N at R6 uptake continued to increase with additional fertilizer N rates. Plant N uptake was greater under Spring application than Fall application at all stages in Morris CC, Waseca CC; and at V12 and Total N uptake at R6 at Crookston CWh and Waseca CSb (Table 7 and 8). No differences were observed between fall and spring applications across N rates in Crookston CSb (Table 8). Lamberton CC had greater plant N uptake at V12 with no differences at V6 or in Total N uptake at R6 (Table 7). Differences between time of application were only significant at the end of the growing season on Total N uptake at R6 at Lamberton CSb (Table 8).

The N source and placement treatments produced small and inconsistent differences in plant N uptake across the various locations and crop rotations and for the different development stages (Table 9 and 10). At Lamberton CC had no difference in plant N uptake at V6. At V12 Urea /SSB had similar plant N uptake than AA/I and ESN/BI and significantly greater than all other N sources and placement treatments. However, at R6 total plant uptake was greatest in the AA/I, followed by ESN/BI, and all the urea treatments had the lowest uptake (Table 9). Morris CC showed only differences in total N uptake at R6 (Table 9) with AA/I, U/SSB, Urea+Instinct/SSB and ESN/BI having similar values and greater uptake than Urea/BI. At Waseca CC, Urea/SSB and Urea+Instinct/SSB had lower plant N uptake at V6, with no differences at V12 among sources/placement treatments. However, total N uptake at R6 was greater in the Urea/SSB and Urea+Instinct/SSB than the rest of the treatments (Table 9). Lamberton CSb showed the lowest plant N uptake at V6 and V12 under U/BI treatment, total N uptake at R6 in the AA/I treatment was similar to ESN/BI but greater than the other treatments (Table 10). At Waseca CSb, Urea/BI had similar plant N uptake than Urea+Instinct/BI but greater than the rest of the treatments at V6; while at V12 AA/I had similar plant N uptake than U/SSB and U+I/SSB but greater than rest of the treatments (Table 10). No differences in plant N uptake were observed among sources/placement in Crookston CWt and CSb rotation (Table 9 and 10).

Canopy sensing measurements both at V6 and V12 development stage were linearly correlated to grain yield but the relationship was stronger at V12 (R^2=0.69) than at V6 development stage (R^2=0.46) (Fig. 3). In general, the relationship improves as the plant becomes a better integrator of growing season conditions up to the time of sensing. Regardless, the data highlight the fact that it may be difficult to use sensing technologies alone to improve N management. By the time the correlation becomes stronger it would be difficult to supply N unless high-clearance equipment is available. Insufficient N until V12 can also result in reduced yield potential that cannot be regained with a late N application.

Soil measurements

At Lamberton in CC, soil N-NH_4^+ was similar among rates, however soil N-NO_3^- increases with N rate at all depths (Table 11) at V4. At V4 Spring applications had greater soil N-NO_3^- than fall applications at the surface depth (0-12"), but soil N-NO_3^- was greater in the deeper depths for Fall than Spring application timing (Table 11). At post-harvest sampling no differences were detected among N rates or time of application at any depth (Table 11). There were not significant differences on the soil N-NH_4^+ and N-NO_3^- content at any depth among source/placement treatment at V4 and post-harvest (Table 12).

At Lamberton in CSb, similar N-NH_4^+ concentrations were detected among N rates at V4 and Post-harvest sampling at all depths (Table 13). Soil N-NO_3^- increased with increasing N rates both at V4 development stage and Post-harvest sampling at all depths (Table 13). When N source and placement treatments were evaluated, concentration of N-NH_4^+ where similar among sources on the upper depths, but significantly different at the lowest depth 24-36", ESN/BI had similar content to AA/I and U+I/BI but greater than the rest of the treatments at V4 (Table 14). Soil N-NO_3^- at V4 and all depths was significantly greater in the AA/I than the rest of the treatments in the upper depths (Table 14). It is important to point out that AA/I was applied at 120 lb N/ac whereas all other treatments were applied at 80 lb N/ac. No differences were observed at post-harvest sampling (Table 14).

At Morris in CC, concentration of soil N-NO_3^- increased with N rate (Table 15) at V4 development stage. At Post-harvest, only the 240-N had significantly greater soil N-NO_3^- than the rest of the treatments at 12-24 and 24-36", with less differences among N rates at 0-12" (Table 15). At V4 development stage, soil N-NO_3^- concentration at 0-12" was greater under the AA/I treatment, and at 12-24", AA/I soil N-NO_3^- were similar to ESN/BI, and U/SSB but significantly greater than U+I/BI, U+I/SSB and U/BI (Table 16). No differences were detected on soil N-NH_4^+ and N-NO_3^- concentrations at post-harvest except for soil N-NH_4^+ concentration at 0-12" (Table 16).

At Waseca in CC, concentration of soil N-NO_3^- increases with N rate (Table 17) at V4 development stage. At Post-harvest, no differences were found in soil N-NH_4^+ and N-NO_3^- concentrations (Table 17). The U/BI treatment had similar soil N-NO_3^- than U+I/BI and ESN/BI, but greater than the other treatments at 12-24" depth, and lower N-NO_3^- in the AA/I and U+I/SSB in the 24-36" depth at V4 (Table 18). No differences were observed due to N source and placement treatments at Post-harvest, except at 0-12" and 12-24" where soil N-NO_3^- was greater at the U/SSB treatment (Table 18).

At Waseca in CSb, concentration of soil N-NO_3^- increased with N rate at V4 development stage and post-harvest regardless of soil depth (Table 19). No differences were found among N source and placement treatments at V4 development stage and Post-harvest (Table 20).

At Crookston CWh, soil N-NO_3^- content increased significantly with N rates only at 0-12" (Table 21), and at 0-12" and 12-24" at post-harvest sampling (Table 21). No differences were found among N source and placement treatments at V4 development stage and Post-harvest (Table 22).

At Crookston CSb, at V4 soil N-NH_4^+ and N-NO_3^- content was significantly affected by N rates at 12-24" for N-NH_4^+ and at 0-12" for N-NO_3^- (Table 23). No differences on soil N-NH_4^+ and N-NO_3^- content among N rates were observed at Post-harvest sampling except for the 0-12" depth for N-NO_3^- where the highest N rate had greater soil N content than the other N rates (Table 23). Soil N-NH_4^+ and N-NO_3^- content was not affected by N source and placement treatments at both sampling times (Table 24).

In summary, N-NH_4^+ was low regardless of N rate indicating that N transforms rapidly to N-NO_3^-. Early in the growing season (V4 development stage) N-NO_3^- increased with N rate. At

Post-harvest, however, there was very little residual N regardless of N rate. The N source and placement treatments show small and inconsistent differences at the V4 development stage.

Table 1. Treatment list.

Trt#	Product	Method	Time	Rate (lb N/ac)
1	check	check	Fall	0
2	Urea	Broadcast	Fall	40
3	Urea	Broadcast	Fall	80
4	Urea	Broadcast	Fall	120
5	Urea	Broadcast	Fall	160
6	Urea	Broadcast	Fall	200
7	Urea	Broadcast	Fall	240
8	check	check	Spring PP	0
9	Urea	Broadcast	Spring PP	40
10	Urea	Broadcast	Spring PP	80
11	Urea	Broadcast	Spring PP	120
12	Urea	Broadcast	Spring PP	160
13	Urea	Broadcast	Spring PP	200
14	Urea	Broadcast	Spring PP	240
15	AA+Nserve	Injected	Fall	120
16	Urea	Subsurface-band	Fall	120(80)*
17	Urea+Instinct	Broadcast	Fall	120(80)*
18	Urea+Instinct	Subsurface-band	Fall	120(80)*
19	ESN	Broadcast	Fall	120 (80)*
20	AA	Injected	Spring PP	120
21	Urea	Subsurface-band	Spring PP	120(80)*
22	Urea+Instinct	Broadcast	Spring PP	120(80)*
23	Urea+Instinct	Subsurface-band	Spring PP	120(80)*
24	ESN	Broadcast	Spring PP	120 (80)*

*Source/application comparison for the corn-soybean and corn-wheat rotation were compared at N rate of 80 lb N/ac, and for corn-corn rotation at N rate of 120 lb N/ac. All broadcast treatments were incorporated by tillage.

Table 2. Mean monthly air temperature and mean monthly cumulative precipitation for the 30-yr normal and the 2017 growing season and each experimental site.

		Precipitation (mm)							
Location	**Year**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Apr.-Oct. cumm.**
Waseca	**30-yr avg.**	82	100	119	113	121	93	68	695
	2017	72	130	106	167	99	51	105	729
Morris	**30-yr avg.**	59	72	102	99	85	74	64	555
	2017	57	97	96	23	252	110	73	709
Crookston	**30-yr avg.**	30	74	97	76	84	62	53	476
	2017	22	22	92	14	26	102	10	286
Lamberton	**30-yr avg.**	76	87	105	99	102	77	51	597
	2017	77	152	69	102	125	54	150	728

		Mean air Temperature (˚C)							
		April	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Apr.-Oct. avg.**
Waseca	**30-yr avg.**	7.8	14.6	20.1	22.0	20.8	16.1	8.8	15.7
	2017	9.5	14.3	21.2	23.1	19.1	17.7	9.8	16.4
Morris	**30-yr avg.**	6.6	13.8	19.1	21.3	20.1	15.0	7.5	14.8
	2017	7.4	13.1	19.7	21.8	18.3	16.3	8.8	15.1
Crookston	**30-yr avg.**	5.6	12.9	18.2	20.6	19.7	14.0	6.3	13.9
	2017	5.1	10.7	17.7	20.5	18.9	15.0	8.0	13.7
Lamberton	**30-yr avg.**	7.5	14.4	20.3	22.5	20.6	16.1	9.2	15.8
	2017	8.6	13.6	20.3	22.5	18.9	17.5	9.4	15.8

Table 3. Grain yield response to N application rates at different sites and crop rotations.

	Grain Yield (bu/ac)						
	Lamberton - CC	Lamberton - CSb	Waseca - CC	Waseca - CSb	Crookston - CWh	Crookston - CSb	Morris - CC
N rate (N)							
0-N	91 f	119 d	75 f	146 d	94 d	163	51e
40-N	109 e	138 c	108 e	186 c	123 c	165	69 d
80-N	130 d	152 b	147 d	210 b	141 b	168	106 c
120-N	168 c	190 a	173 c	223 a	151 ab	170	108 c
160-N	181 bc	189 a	198 b	229 a	151 ab	171	129 b
200-N	188 ab	192 a	209 b	232 a	159 a	159	149 a
240-N	201 a	-	225 a	-	-	-	161 a
Time (T)							
Fall	154	159 b	151 b	199 b	133 b	161	98 b
Spring	151	168 a	173 a	210 a	141 a	171	123 a
N rate (N)	<.0001	<.0001	<.0001	<.0001	<.0001	0.9531	<.0001
Time (T)	0.3473	0.0137	<.0001	0.0040	0.0311	0.2523	<.0001
N x T	0.0102	0.0846	0.0442	0.7111	0.4824	0.4818	0.0092

Table 4. Grain N removal response to N application rates at different sites and crop rotations.

	Grain N removal (lb N/ac)						
	Lamberton - CC	Lamberton - CSb	Waseca - CC	Waseca - CSb	Crookston - CWh	Crookston - CSb	Morris - CC
N rate (N)							
0-N	42 e	50 e	33 f	69 e	37 e	107	26 d
40-N	48 de	60 d	47 e	89 d	53 d	110	32 d
80-N	57 d	71 c	67 d	111 c	75 c	112	54 c
120-N	82 c	91 b	84 c	125 b	89 b	122	55 c
160-N	91 bc	95 ab	105 b	133 ab	93 ab	120	72 b
200-N	101 ab	101 a	108 b	146 a	100 a	110	86 a
240-N	109 a	-	138 a	-	-	-	96 a
Time (T)							
Fall	76	73 b	75 b	108 b	69 b	111	54 b
Spring	75	82 a	92 a	117 a	81 a	115	67 a
N rate (N)	<.0001	<.0001	<.0001	<.0001	<.0001	0.6935	<.0001
Time (T)	0.8290	0.0013	<.0001	0.0187	0.0006	0.4691	<.0001
N x T	0.1761	0.0069	0.0008	0.3283	0.5837	0.1681	0.0121

Table 5. Grain yield response to management (N sources and placement) for the experimental sites.

	Grain Yield (bu ac^{-1})						
	Lamberton - CC	Lamberton - CSb	Morris - CC	Waseca - CC	Waseca - CSb	Crookston - CSb	Crookston - CWh
Management[†]							
AA/Inj	201 a	201 a	141 a	176 c	225 a	-	-
U/Bdcst	168 cd	152 d	108 b	173 c	210 b	168	141
U/SSB	180 bc	184 bc	139 a	197 ab	211 b	-	-
U+I/Bdcst	158 d	174 c	112 b	183 bc	208 b	153	141
U+I/SSB	170 cd	179 c	127 ab	202 a	210 b	-	-
ESN/Bdcst	196 ab	194 ab	130 ab	187 bc	215 ab	169	147
Time (T)							
Fall	181	178	127	163 b	203 b	160	137 b
Spring	177	184	125	208 a	224 a	167	149 a
Management (M)	<.0001	<.0001	0.0445	0.0184	0.0386	0.2081	0.4810
Time (T)	0.4881	0.0744	0.8197	<.0001	<.0001	0.3951	0.0073
M x T	0.3528	0.3096	0.0328	0.0057	0.1169	0.8847	0.5148

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 6. Grain N removal response to N sources and placement at different sites and crop rotations.

	Grain N removal (lb N ac^{-1})						
	Lamberton - CC	Lamberton - CSb	Morris - CC	Waseca - CC	Waseca - CSb	Crookston - CSb	Crookston - CWh
Management[†](M)							
AA/Inj	117 a	103 a	85 a	84 c	123	-	-
U/Bdcst	82 c	71 d	55 c	85 c	111	112	75
U/SSB	90 bc	90 bc	79 ab	100 ab	119	-	-
U+I/Bdcst	79 c	83 c	56 c	86 bc	120	105	68
U+I/SSB	82 c	88 bc	69 bc	103 a	118	-	-
ESN/Bdcst	102 b	94 ab	71 ab	90 abc	119	112	75
Time (T)							
Fall	93	87	68	75 b	108 b	107	66
Spring	91	89	70	108 a	129 a	13	80
Management (M)	<.0001	<.0001	0.0009	0.0258	0.6341	0.6789	0.1625
Time (T)	0.5178	0.3524	0.6505	<.0001	<.0001	0.4186	0.0006
M x T	0.5693	0.4168	0.0882	0.0021	0.0540	0.9179	0.5057

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 7. Plant N uptake at V6, V12, and R6 (TotalN) development stages in response to N application rates at different sites and crop rotations.

	Plant N uptake (lb N/ac)											
	Lamberton - CC			Morris - CC			Waseca - CC			Crookston – CWh		
	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN
N rate (N)												
0-N	7 c	48 d	62 d	3 d	16 c	41 d	4 d	17 e	51 f	6	40 d	57 d
40-N	11 c	61 c	73 cd	7 c	26 d	49 d	9 c	24 e	71 e	7	62 c	71 c
80-N	16 b	68 c	84 c	10 b	15 c	5 c	11 bc	35 d	99 d	7	77 b	103 b
120-N	20 ab	93 b	113 b	10 ab	53 bc	83 c	13 ab	41 cd	123 c	7	90 a	122 a
160-N	20 ab	102 ab	124 b	11 ab	57 b	104 b	14 a	45 bc	148 b	7	99 a	128 a
200-N	20 ab	104 ab	143 a	13 a	62 ab	122 a	15 a	49 ab	154 b	7	100 a	133 a
240-N	23 a	107 a	149 a	13 a	78 a	137 a	13 ab	54 a	192 a	-	-	-
Time (T)												
Fall	16	87 a	108	7 b	40 b	80 b	10 b	35 b	108 b	7	70 b	95 b
Spring	17	79 b	107	12 a	54 a	97 a	13 a	41 a	131 a	7	85 a	11 a
N rate (N)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.1049	<.0001	<.0001
Time (T)	0.4512	0.0149	0.7068	<.0001	<.0001	0.0006	0.0020	0.0074	<.0001	0.8931	<.0001	<.0001
N x T	0.0626	0.1145	0.0451	0.0613	0.1732	0.1264	0.4780	0.0418	0.0012	0.4677	0.2742	0.8208

Table 8. Plant N uptake at V6, V12, and R6 (TotalN) development stages in response to N application rates at different sites and crop rotations.

	Plant N uptake (lb N/ac)								
	Lamberton - CSb			Waseca - CSb			Crookston – CSb		
	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN
N rate (N)									
0-N	14 d	51 d	72 e	10d	26 d	99 e	8	105	146
40-N	20 c	71 c	86 d	15 c	40 bc	124 d	8	115	150
80-N	21 bc	82 c	101 c	21 ab	38 c	155 c	9	102	154
120-N	27 a	103 ab	129 b	18 bc	43 abc	173 b	8	97	161
160-N	27 a	98 b	136 b	19 ab	48 ab	183 ab	9	104	165
200-N	25 ab	112 a	151 a	22 a	51 a	196 a	7	104	151
240-N	-	-	-	-	-	-			
Time (T)									
Fall	22	83	104 b	17	36 b	149 b	8	107	155
Spring	23	89	120 a	18	46 a	161 a	9	102	159
N rate (N)	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.1287	0.7120	0.5343
Time (T)	0.6025	0.1219	<.0001	0.0805	0.0001	0.0060	0.0883	0.4645	0.4785
N x T	0.9148	0.6236	0.0005	0.3820	0.8220	0.1512	0.3964	0.4217	0.2454

Table 9. Plant N uptake at V6 and R6 development stages in response to management practices at different sites and crop rotations.

	Plant N uptake (lb N/ac)											
	Lamberton - CC			Morris - CC			Waseca - CC			Crookston – CWh		
	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN
Management[†](M)												
AA/Inj	23	101 abc	157 a	11	65	120 a	11 a	42	120 b	-	-	-
U/Bdcst	20	93 d	113 c	10	53	83 c	13 a	41	123 b	7	77	103
U/SSB	23	113 a	120 c	11	57	115 a	7 b	48	142 a	-	-	-
U+I/Bdcst	20	94 cd	111 c	11	46	85 bc	11 a	40	121 b	7	84	97
U+I/SSB	23	96 bcd	115 c	11	52	106 a	9 b	41	142 a	-	-	-
ESN/Bdcst	24	111 ab	136 b	10	52	103 ab	12 a	43	129 ab	8	89	108
Time (T)												
Fall	23	100	127	11	52	101	11	38 b	108 b	7	75 b	94 b
Spring	22	105	124	11	56	103	11	47 a	151 a	8	92 a	14 a
Management (M)	0.5104	0.0276	<.0001	0.2857	0.2571	0.0030	0.0005	0.6238	0.0559	0.1590	0.1007	0.1736
Time (T)	0.5823	0.2691	0.4969	0.8587	0.3332	0.6485	0.8660	0.0034	<.0001	0.0584	0.0018	0.0024
M x T	0.1753	0.6879	0.5520	0.0574	0.5302	0.1801	0.0326	0.5292	0.0011	0.7674	0.0984	0.7673

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 10. Plant N uptake at V6 and R6 development stages in response to management practices at different sites and crop rotations.

	Plant N uptake (lb N/ac)								
	Lamberton - CSb			Waseca - CSb			Crookston – CSb		
	V6	V12	TotalN	V6	V12	TotalN	V6	V12	TotalN
Management[†](M)									
AA/Inj	28 a	112 a	146 a	16 b	49 a	173	-	-	-
U/Bdcst	21 b	82 c	101 d	21 a	38 bc	155	9	102	154
U/SSB	26 a	107 ab	126 bc	15 b	47 ab	163	-	-	-
U+I/Bdcst	26 a	95 bc	118 c	18 ab	37 c	161	8	108	138
U+I/SSB	24 ab	106 ab	125 bc	14 b	47 abc	159	-	-	-
ESN/Bdcst	25 a	110 ab	137 ab	16 b	38 bc	157	9	120	150
Time (T)									
Fall	26	101	123	16	38 b	147	8	110	148
Spring	24	103	128	17	47 a	175	9	110	151
Management (M)	0.0268	0.0060	<.0001	0.0193	0.0426	0.1206	0.4965	0.1536	0.3019
Time (T)	0.1204	0.7495	0.1358	0.6544	0.0044	<.0001	0.3323	0.9447	0.4405
M x T	0.0128	0.3927	0.7006	0.8414	0.9187	0.0023	0.7075	0.2975	0.9787

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 11. Soil extractable N for different N rates, time of application, and soil depth for Lamberton CC.

	Soil Extractable N (ppm) at Lamberton-CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	6.3	2.4 c	2.0	2.0 d	1.4	2.0 d	6.6	0.9	3.4	0.5	3.1	0.6
40-N	6.1	4.7 bc	1.5	3.9 bcd	1.3	4.5 bcd	6.2	1.0	3.2	0.5	3.2	0.5
80-N	6.8	4.4 bc	1.7	3.5 cd	1.6	3.7 cd	7.7	1.0	3.2	0.5	2.6	0.5
120-N	7.6	7.9 b	2.2	6.0 ab	2.3	6.5 ab	7.3	1.1	3.1	0.6	2.9	0.8
160-N	7.3	8.4 b	2.2	6.2 abc	1.8	5.8 abc	7.7	1.1	3.5	0.5	2.9	0.6
200-N	7.7	8.6 b	2.3	4.9 abc	1.8	5.1 abc	7.2	1.1	3.7	0.5	3.3	0.6
240-N	8.9	14.3 a	2.5	8.1 a	2.1	7.8 a	7.1	1.1	2.9	0.5	3.1	0.9
Time (T)												
Fall	7.2	5.5 b	2.1	5.8 a	1.8	5.8 a	7.1	1.1	3.2	0.5	2.9	0.6
Spring	7.3	9.0 a	1.9	4.1 b	1.7	4.3 b	7.1	1.1	3.3	0.5	3.1	0.6
	………………………………………………*P* values …………………………………………………											
N rate (N)	0.1354	0.0006	0.3182	0.0001	0.2657	0.0043	0.0829	0.1858	0.4868	0.4381	0.5940	0.0553
Time (T)	0.9208	0.0126	0.3725	0.0125	0.8243	0.0519	0.8147	1.0000	0.5482	0.3230	0.6237	0.4545
N x T	0.7282	0.9575	0.0520	0.4207	0.4161	0.4858	0.8369	0.1382	0.5232	0.4381	0.8088	0.9923

Table 12. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Lamberton under CC rotation

	Soil Extractable N (ppm) at Lamberton CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management[†](M)												
AA/Inj	11.9	15.3	2.5	6.7	2.0	5.2	6.8	1.3	3.4	0.6	3.3	0.9
ESN/Bdcst	9.7	9.7	1.8	5.9	1.9	7.2	7.9	12	3.5	0.6	3.3	0.9
U+I/Bdcst	6.5	5.9	1.7	4.4	1.5	4.4	6.6	1.4	3.1	0.5	2.7	0.5
U+I/SSB	12.7	8.3	1.9	3.9	1.7	3.4	7.2	1.6	3.4	0.6	3.2	0.8
U/Bdcst	7.6	7.9	2.2	6.0	2.3	6.5	7.3	1.1	3.1	0.6	2.9	0.8
U/SSB	14.1	11.1	1.8	7.8	1.8	6.6	7.7	1.3	3.8	0.6	3.7	0.9
Time (T)												
Fall	9.0	7.9	1.9	7.4 a	1.6	6.4 a	7.2	12	3.4	0.50 b	3.0	0.6 b
Spring	11.8	11.4	2.0	4.2 b	2.2	4.7 b	7.3	1.4	3.4	0.67 a	3.3	0.9 a
	………………………………………….……….*P* values ……………………………………………………….											
Management(M)	0.4389	0.2217	0.5868	0.1706	0.7437	0.1201	0.2142	0.5745	0.5660	0.8366	0.0820	0.5865
Time (T)	0.2518	0.1126	0.7201	0.0014	0.0708	0.0599	0.6626	0.3564	0.9330	0.0149	0.1893	0.0206
M x T	0.2392	0.7798	0.3838	0.0442	0.9256	0.1926	0.1890	0.6205	0.4511	0.8366	0.6209	0.7064

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 13. Soil extractable N for different N rates, time of application, and soil depth for Lamberton CSb.

	Soil Extractable N (ppm) at Lamberton-CSb											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	6.1 b	3.6 c	2.0	2.8 c	2.3	2.9 d	6.6	1.4 c	3.0	0.6 c	2.8	0.5 c
40-N	7.0 b	5.5 c	2.1	3.6 c	2.1	3.7 cd	6.6	1.4 bc	2.5	0.5 c	2.8	0.5 c
80-N	6.6 b	6.5 c	1.6	4.0 bc	2.5	3.7 cd	6.2	1.8 bc	2.7	0.8 bc	2.5	0.5 c
120-N	7.1 b	10.8 b	2.4	6.3 a	2.0	5.5 ab	6.2	1.6 bc	2.5	0.6 c	2.4	0.7 bc
160-N	7.8 ab	11.3 ab	1.8	5.7 ab	2.8	4.8 bc	7.1	2.1 ab	3.2	1.1 ab	3.0	0.9 b
200-N	9.2 a	14.1 a	2.6	6.9 a		6.5 a	7.2	2.5 a	2.6	1.4 a	2.8	1.3 a
240-N	-	-	-	-	-	-	-	-	-	-	-	-
Time (T)												
Fall	6.9	6.6 b	2.2	5.4	2.3	4.6	6.3 b	1.5 b	2.8	0.7	2.7	0.6 b
Spring	7.7	10.6 a	2.0	4.3	2.2	4.4	7.0 a	2.1 a	2.7	0.9	2.7	0.9 a
	………………………………………………*P* values ………………………………………………………											
N rate (N)	0.0442	<.0001	0.1840	0.0004	0.3524	0.0002	0.1259	0.0233	0.2325	0.0001	0.2197	<.0001
Time (T)	0.1552	<.0001	0.6373	0.0558	0.9035	0.6275	0.0152	0.0028	0.7739	0.0520	0.6641	0.0003
N x T	0.4102	0.1203	0.4318	0.4954	0.6918	0.9074	0.8346	0.2629	0.9614	0.0576	0.3146	0.0087

Table 14. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Lamberton under CSb rotation

	Soil Extractable N (ppm) at Lamberton CSb											
	V4						Post-Harvest					
	0-12"		12-24"		24-36"		0-12"		12-24"		24-36"	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management[†](M)												
AA/Inj	11.5	18.0 a	2.1	8.2 a	2.0 abc	5.0 ab	6.7	1.9	3.0	1.5	3.3	1.1
ESN/Bdcst	7.0	11.0 b	2.4	5.8 ab	2.9 a	6.1 a	7.1	1.7	2.9	0.7	2.7	0.7
U+I/Bdcst	8.3	8.5 b	2.1	5.3 b	2.8 ab	4.7 ab	6.9	1.5	2.9	0.8	3.1	0.6
U+I/SSB	9.6	9.4 b	2.0	3.8 b	1.9 bc	3.7 b	6.8	1.8	2.7	0.7	2.5	0.8
U/Bdcst	6.6	6.5 b	1.6	4.0 b	1.8 c	3.7 b	6.2	1.8	2.7	0.8	2.5	0.5
U/SSB	8.6	9.6 b	2.3	4.8 b	1.5 c	4.7 ab	6.7	1.8	3.3	0.7	3.0	0.6
Time (T)												
Fall	7.5	8.6 b	2.0	5.6	2.0	5.2 a	6.6	1.7	2.9	0.8	2.7	0.7
Spring	9.7	12.3 a	2.1	5.0	2.3	4.1 b	6.9	1.8	3.0	0.9	2.6	0.8
……………………………………….……………*P* values ……………………………………………………….												
Management(M)	0.4257	0.0017	0.6991	0.0165	0.0164	0.0371	0.3564	0.8113	0.4164	0.1213	0.1075	0.1231
Time (T)	0.1558	0.0169	0.6361	0.3799	0.1770	0.0277	0.1432	0.4328	0.4382	0.3344	0.1345	0.5327
M x T	0.9393	0.0804	0.0951	0.0388	0.3481	0.4536	0.5490	0.2175	0.2150	0.6657	0.6137	0.8050

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 15. Soil extractable N for different N rates, time of application, and soil depth for Morris CC.

	Soil Extractable N (ppm) at Morris-CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	2.8	17 c	1.8	2.1 e	1.9	2.6 d	5.4	1.3	3.5	0.6 b	3.7	0.5 b
40-N	2.9	2.9 c	1.6	2.8 de	2.0	2.6 d	5.7	1.6	3.3	0.6 b	3.8	0.5 b
80-N	3.9	4.01 c	1.9	5.06 cd	2.3	3.6 cd	5.8	1.5	3.8	0.6 b	3.5	0.6 b
120-N	3.0	5.9 c	1.9	4.8 d	1.8	3.9 cd	5.8	1.6	3.7	0.7 b	4.3	0.6 b
160-N	3.6	6.7 c	1.7	7.3 bc	2.0	5.5 bc	5.6	1.4	3.4	0.6 b	3.6	0.6 b
200-N	3.3	12.2 b	1.9	8.9 ab	2.1	6.1 ab	6.3	2.0	3.7	0.8 b	3.9	0.8 b
240-N	5.0	21.5 a	1.4	9.8 a	1.6	7.8 a	6.3	1.9	3.7	1.4 a	3.8	1.5 a
Time (T)												
Fall	3.1	5.6 b	1.8	6.5 a	1.9	4.1 b	5.4 b	1.5	3.5	0.6 b	3.6	0.7
Spring	3.9	10.1 a	1.7	5.1 b	2.1	5.1 a	6.3 a	1.7	3.7	0.9 a	4.0	0.8
	………………………………………………*P* values ………………………………………………………											
N rate (N)	0.1573	<.0001	0.8250	<.0001	0.3641	<.0001	0.5319	0.0744	0.8397	<.0001	0.7244	0.0004
Time (T)	0.0781	0.0024	0.7436	0.0389	0.2561	0.0612	0.0015	0.1451	0.2806	0.0075	0.1464	0.5443
N x T	0.1076	0.0538	0.6227	0.6934	0.2616	0.6081	0.8713	0.9931	0.5932	0.9489	0.4766	0.9958

Table 16. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Morris under CC rotation.

	Soil Extractable N (ppm) at Morris-CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management†(M)												
AA/Inj	5.0	22.9 a	3.0	9.9 a	1.9	3.9	5.0 b	1.4	3.1	0.6	3.5	0.6
ESN/Bdcst	3.4	8.4 b	1.3	7.3 ab	2.1	4.9	5.8 a	2.1	3.7	1.3	3.8	0.8
U+I/Bdcst	3.3	5.1 b	1.8	5.2 b	2.1	4.5	6.3 a	1.7	4.1	0.9	3.8	1.0
U+I/SSB	6.9	9.1 b	1.2	4.7 b	1.5	3.4	6.0 a	1.7	3.7	0.8	3.8	0.6
U/Bdcst	3.0	5.9 b	1.9	4.8 b	1.8	3.9	5.8 a	1.6	3.7	0.7	4.3	0.6
U/SSB	6.1	11.3 b	1.9	7.2 ab	1.5	4.0	5.7 ab	1.6	3.5	0.8	4.1	0.5
Time (T)												
Fall	3.5	9.6	1.7	8.7 a	1.7	4.4	5.6	1.5 b	3.8	0.7 b	3.8	0.5
Spring	5.3	11.3	2.0	4.4 b	2.0	3.8	5.9	1.9 a	3.5	1.0 a	3.9	0.8
	……………………………………..………*P* values ……………………………………………………….											
Management(M)	0.4327	0.0069	0.1303	0.0097	0.4863	0.7282	0.0326	0.2697	0.0751	0.1645	0.2901	0.5366
Time (T)	0.2894	0.5139	0.3724	<.0001	0.2318	0.2369	0.1800	00167	0.1301	0.0221	0.4639	0.0765
M x T	0.4365	0.5605	0.5459	0.0092	0.3521	0.2887	0.3786	0.5628	0.1018	0.7990	0.6393	0.7571

†AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 17. Soil extractable N for different N rates, time of application, and soil depth for Waseca CC.

	Soil Extractable N (ppm) at Waseca-CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	4.6	2.8 e	2.3	2.8 f	2.3	2.8 e	6.3	2.7	3.4	1.6	3.6	1.6 b
40-N	4.6	5.3 de	1.6	5.2 ef	1.8	4.1 de	6.7	3.0	3.6	1.4	3.7	2.1 b
80-N	5.5	11.3 cd	1.8	7.4 de	1.8	5.6 cd	6.2	3.1	3.6	1.9	3.8	1.8 b
120-N	6.2	14.5 bc	1.9	10.0 cd	1.9	6.0 bcd	7.6	3.4	3.9	1.8	3.8	1.8 b
160-N	5.5	15.5 bc	1.8	11.0 bc	1.5	7.1 bc	7.5	3.8	3.4	1.9	3.9	2.1 b
200-N	5.8	18.4 b	2.0	13.4 b	2.1	7.6 ab	7.2	3.1	3.7	1.7	3.8	2.3 b
240-N	5.4	26.4 a	1.4	16.9 a	1.2	9.2 a	7.0	3.8	3.4	2.6	3.7	3.6 a
Time (T)												
Fall	5.2	8.7 b	1.8	8.5 b	1.7	5.4 b	6.8	3.2	3.6	1.6	3.7	1.8 b
Spring	5.5	18.2 a	1.8	10.6 a	1.9	6.7 a	7.0	3.4	3.5	2.0	3.8	2.6 a
	……………………………………………….*P* values ……………………………………………………											
N rate (N)	0.2820	<.0001	0.4505	<.0001	0.0053	<.0001	0.0724	0.2318	0.4666	0.1920	0.9660	0.0390
Time (T)	0.5008	<.0001	0.8392	0.0060	0.4319	0.0206	0.4389	0.4644	0.8634	0.1203	0.8362	0.0260
N x T	0.9915	0.1018	0.3842	0.8912	0.1201	0.7096	0.3700	0.3435	0.8106	0.5752	0.2302	0.4698

Table 18. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Waseca under CC rotation

	Soil Extractable N (ppm) at Waseca-CC											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management[†](M)												
AA/Inj	5.6	9.1	1.8	7.1 bc	1.8	4.8 b	6.8	2.9 b	3.6	1.4b	3.5	1.8
ESN/Bdcst	6.5	12.1	2.0	8.4 ab	3.2	7.1 a	7.1	3.4 b	3.4	1.8 b	3.8	2.7
U+I/Bdcst	81	13.9	2.3	9.3 ab	2.0	5.7 ab	6.1	3.0 b	3.6	1.6 b	4.1	2.1
U+I/SSB	8.3	9.0	1.9	5.4 c	1.5	4.1 b	6.9	3.5 b	3.8	2.3 ab	3.7	2.6
U/Bdcst	6.2	14.5	1.9	10.0 a	1.9	6.0 ab	7.6	3.4 b	3.9	1.8 b	3.8	1.8
U/SSB	7.1	8.1	1.6	7.5 bc	2.0	6.8 a	7.2	4.8 a	3.6	3.3 a	4.0	2.9
Time (T)												
Fall	6.7	8.2 b	2.0	8.1	1.9	5.8	6.9	3.3	3.6	1.7	3.9	2.1
Spring	7.2	14.0 a	1.8	7.8	2.2	5.7	7.0	3.7	3.6	2.3	3.8	2.5
	……………………………………………*P* values ……………………………………………………											
Management(M)	0.6499	0.2485	0.6039	0.0032	0.0535	0.0254	0.2518	0.0420	0.7704	0.0144	0.6154	0.1760
Time (T)	0.6468	0.0045	0.2334	0.5630	0.4174	0.7604	0.6418	0.3388	0.9670	0.0621	0.7863	0.1672
M x T	0.1854	0.2197	0.6406	0.0662	0.5022	0.0225	0.2361	0.2171	0.7622	0.1710	0.2680	0.3824

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 19. Soil extractable N for different N rates, time of application, and soil depth for Waseca CSb.

	Soil Extractable N (ppm) at Waseca-CSb											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	4.7	5.7 d	2.2	5.1 c	2.1	4.7 c	6.5	5.1 bc	3.4	3.8 b	3.4 b	4.0 b
40-N	4.8	9.4 cd	2.3	7.3 bc	2.3	5.9 bc	7.1	5.3 bc	3.2	3.6 b	3.4 b	4.3 b
80-N	4.7	11.4 c	2.0	10.5 b	2.2	7.1 b	6.8	4.6 c	3.2	4.1 b	3.5 b	4.1 b
120-N	4.5	18.2 b	2.6	15.1 a	2.2	8.9 a	6.7	6.7 ab	3.2	4.4 b	3.3 b	4.9 b
160-N	4.6	22.5 b	2.2	16.7 a	2.4	9.6 a	7.0	5.8 abc	3.4	4.5 b	4.0 a	5.4 b
200-N	5.7	29.1 a	2.1	18.5 a	2.3	10.4 a	7.6	6.9 a	3.6	8.3 a	4.0 a	10.6 a
240-N	-	-	-	-	-	-	-	-	-	-	-	-
Time (T)												
Fall	4.5	9.1 b	2.2	10.3 b	2.2	7.6	7.2 a	5.4	3.3	4.3 b	3.8 a	4.8 b
Spring	5.1	23.0 a	2.2	14.1 a	2.3	7.9	6.6 b	6.0	3.3	5.3 a	3.4 b	6.4 a
	………………*P* values………………											
N rate (N)	0.5696	<.0001	0.3791	<.0001	0.9564	<.0001	0.2312	0.0345	0.5136	<.0001	0.0034	<.0001
Time (T)	0.1050	<.0001	0.9263	0.0012	0.7240	0.6105	0.0220	0.1891	0.7616	0.0476	0.0077	0.0094
N x T	0.4810	<.0001	0.2982	0.4678	0.1336	0.3690	0.1827	0.7362	0.0703	0.0285	0.0334	<.0001

Table 20. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Waseca under CSb rotation

	Soil Extractable N (ppm) at Waseca-CSb											
	V4						Post-Harvest					
	0-12"		12-24"		24-36"		0-12"		12-24"		24-36"	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management[†](M)												
AA/Inj	5.3	13.6	2.5	11.7	2.4	8.2	6.4	5.9	3.2	4.9	3.3	4.6
ESN/Bdcst	6.2	14.6	2.3	10.4	2.6	7.3	6.8	5.5	3.6	4.1	3.8	4.4
U+I/Bdcst	4.6	13.3	2.8	10.7	2.3	8.0	7.3	6.0	3.3	4.6	3.6	4.1
U+I/SSB	5.5	8.5	2.4	8.8	2.23	6.9	7.0	5.6	3.1	3.8	3.2	3.9
U/Bdcst	4.7	11.4	2.0	10.5	2.23	7.1	6.8	4.6	3.2	4.1	3.5	4.1
U/SSB	4.9	12.7	2.0	11.6	2.5	8.7	6.7	6.1	3.3	5.3	3.4	4.1
Time (T)												
Fall	4.9	8.2 b	2.2	9.8	2.3	8.3 a	7.0	5.5	3.3	4.6	3.5	4.1
Spring	5.5	16.5 a	2.2	11.4	2.5	7.1 b	6.7	5.8	3.3	4.4	3.5	4.3
	……………………………………………*P* values …………………………………………………											
Management(M)	0.1792	0.4505	0.5869	0.5766	0.8769	0.3192	0.6500	0.3426	0.6299	0.2038	0.2115	0.8973
Time (T)	0.0912	<.0001	0.8277	0.1091	0.4860	0.0292	0.2276	0.4464	0.7726	0.5914	0.8647	0.7135
M x T	0.4310	0.4333	0.5882	0.8667	0.9869	0.8974	0.7075	0.8295	0.3284	0.9169	0.3943	0.2634

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 21. Soil extractable N for different N rates, time of application, and soil depth for Crookston CWh.

	Soil Extractable N (ppm) at Crookston CWh											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	3.2	5.2 b	2.3	1.4	2.6	0.7	5.3	1.1 b	3.7	0.5 b	4.0	0.5
40-N	4.1	8.2 b	2.7	1.6	3.0	0.9	4.9	1.3 b	3.6	0.6 b	3.9	0.6
80-N	4.5	17.9 a	3.2	2.0	3.7	0.8	4.9	1.2 b	3.3	0.5 b	4.0	0.5
120-N	4.7	19.5 a	2.6	2.4	3.1	1.1	5.3	1.5 b	3.7	0.8 b	4.3	0.8
160-N	4.4	22.6 a	2.9	2.1	3.2	0.9	4.9	1.8 b	3.3	0.9 ab	3.7	0.7
200-N	3.8	24.9 a	2.6	2.8	2.8	1.2	5.0	4.0 a	3.6	1.5 a	3.7	0.5
240-N	-	-	-	-	-	-	-	-	-	-	-	-
Time (T)												
Fall	3.9	15.0	2.6	1.9	2.9	0.9	5.0	1.4	3.5	0.5 b	3.8	0.5
Spring	4.4	17.8	2.9	2.2	3.2	0.9	5.0	2.2	3.6	1.0 a	4.1	0.7
	……………………………………………… *P* values ………………………………………………											
N rate (N)	0.1073	<.0001	0.2869	0.1661	0.2826	0.5452	0.6824	0.0136	0.6920	0.0278	0.7170	0.5661
Time (T)	0.1442	0.2094	0.1435	0.3928	0.1900	0.7988	0.8994	0.0851	0.5216	0.0133	0.2744	0.1254
N x T	0.6763	0.5251	0.4560	0.6188	0.7663	0.3054	0.7282	0.0776	0.8502	0.0664	0.9600	0.5661

Table 22. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Crookston under CWh rotation

	Soil Extractable N (ppm) at Crooskton-CWh											
	V4						Post-Harvest					
	0-12"		12-24"		24-36"		0-12"		12-24"		24-36"	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management†(M)												
ESN/Bdcst	4.2	13.8	3.1	2.2	3.0	1.2	4.9	2.1 a	3.8	0.6	4.2	0.6
U+I/Bdcst	3.7	14.2	3.3	2.8	2.6	1.1	5.1	1.1 b	3.7	0.6	3.9	0.7
U/Bdcst	4.5	17.9	3.2	2.0	3.7	0.8	4.9	1.2 b	3.3	0.5	4.0	0.5
Time (T)												
Fall	4.5	14.4	3.4	2.3	3.2	1.1	4.9	1.3	3.6	0.5	3.9	0.6
Spring	3.8	16.2	3.0	2.4	3.0	0.9	5.0	1.6	3.5	0.7	4.2	0.5
	………*P* values………											
Management(M)	0.3918	0.3041	0.9565	0.4201	0.0887	0.5223	0.6859	0.0410	0.1893	0.4866	0.7502	0.5096
Time (T)	0.1635	0.4466	0.3835	0.8732	0.6776	0.4485	0.5956	0.2528	0.7292	0.1004	0.3783	0.5350
M x T	0.7232	0.7228	0.8668	0.9187	0.8930	0.6852	0.0449	0.2619	0.7724	0.4866	0.9777	0.2969

†AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

Table 23. Soil extractable N for different N rates, time of application, and soil depth for Crookston CSb.

	Soil Extractable N (ppm) at Crookston CSb											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
N rate (N)												
0-N	2.3	13.8 c	1.2 b	13.8	1.7	27.3	3.4	2.8 b	2.5	7.0	3.6	11.4
40-N	2.5	17.3 bc	1.5 b	14.4	2.2	26.3	2.9	1.8 b	2.3	10.3	3.5	11.6
80-N	2.2	19.1 bc	1.7 b	13.3	2.4	22.3	3.4	2.9 b	2.6	12.4	3.6	13.4
120-N	2.1	24.4 ab	1.1 b	13.9	2.1	23.5	3.5	2.8 b	2.2	7.6	3.1	9.6
160-N	2.2	23.6 ab	1.3 b	11.6	2.6	21.4	3.4	2.8 b	2.5	13.6	4.0	12.5
200-N	2.7	29.8 a	2.3 a	11.6	2.5	25.9	3.1	4.3 a	2.3	13.0	3.7	14.6
240-N	-	-	-		-	-	-	-	-	-	-	-
Time (T)												
Fall	2.3	21.6	1.6	13.0	2.4	23.9	3.2	3.1	2.5	12.0	3.6	12.1
Spring	2.4	21.0	1.5	13.3	2.1	25.0	3.4	2.7	2.2	9.3	3.5	12.2
	……………………………………….…………*P* values ……………………..…………………………….											
N rate (N)	0.7406	0.0173	0.0022	0.9779	0.1830	0.7985	0.4914	0.0563	0.8033	0.6510	0.7190	0.8088
Time (T)	0.6998	0.8812	0.7085	0.9096	0.1312	0.7089	0.3552	0.3830	0.1566	0.3354	0.8032	0.9481
N x T	0.7762	0.3752	0.4327	0.0374	0.1401	0.0005	0.0210	0.9349	0.2241	0.6438	0.4497	0.1353

Table 24. Soil extractable N (ppm) as ammonium (NH_4-N) and nitrate (NO_3-N) in response to N sources and application at Crookston under CSb rotation

	Soil Extractable N (ppm) at Crookston-CSb											
	V4						Post-Harvest					
	0-12”		12-24”		24-36”		0-12”		12-24”		24-36”	
	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N	NH_4-N	NO_3-N
Management[†](M)												
U/Bdcst	2.2	19.1	1.7	13.3	2.4	22.3	3.4	2.9	2.6	12.4	3.6	24.8
U+I/Bdcst	2.4	14.8	1.4	10.3	2.5	25.6	3.2	2.2	2.8	7.5	3.8	21.0
ESN/Bdcst	2.6	15.5	1.4	13.8	2.6	20.8	3.1	2.5	2.2	15.3	3.4	23.6
Time (T)												
Fall	2.2	13.7	1.3	12.5	2.6	25.5	2.9	2.2	2.5	12.8	3.7	24.1
Spring	2.5	19.3	1.6	12.5	2.4	20.4	3.6	2.8	2.6	10.7	3.5	22.2
	……………………………………………*P* values ……………………………………………………											
Management(M)	0.5528	0.4563	0.5931	0.4884	0.9333	0.5742	0.7198	0.5622	0.3614	0.1783	0.6565	0.7073
Time (T)	0.2310	0.0731	0.3887	0.9870	0.7250	0.1950	0.0365	0.2409	0.8082	0.5185	0.6156	0.6186
M x T	0.7936	0.3525	0.4431	0.8385	0.2085	0.3751	0.2702	0.6686	0.9758	0.8764	0.0663	0.0303

[†]AA/Inj: Anhydrous ammonium+Nserve in the Fall, and anhydrous ammonium in the Spring application both injected; U/Bdcst: Urea/broadcast; U/SSB: Urea/subsurface band; U+I/Bdcst: Urea+Instinct/broadcast; U+I/SSB: Urea+Instinct/subsurface band.

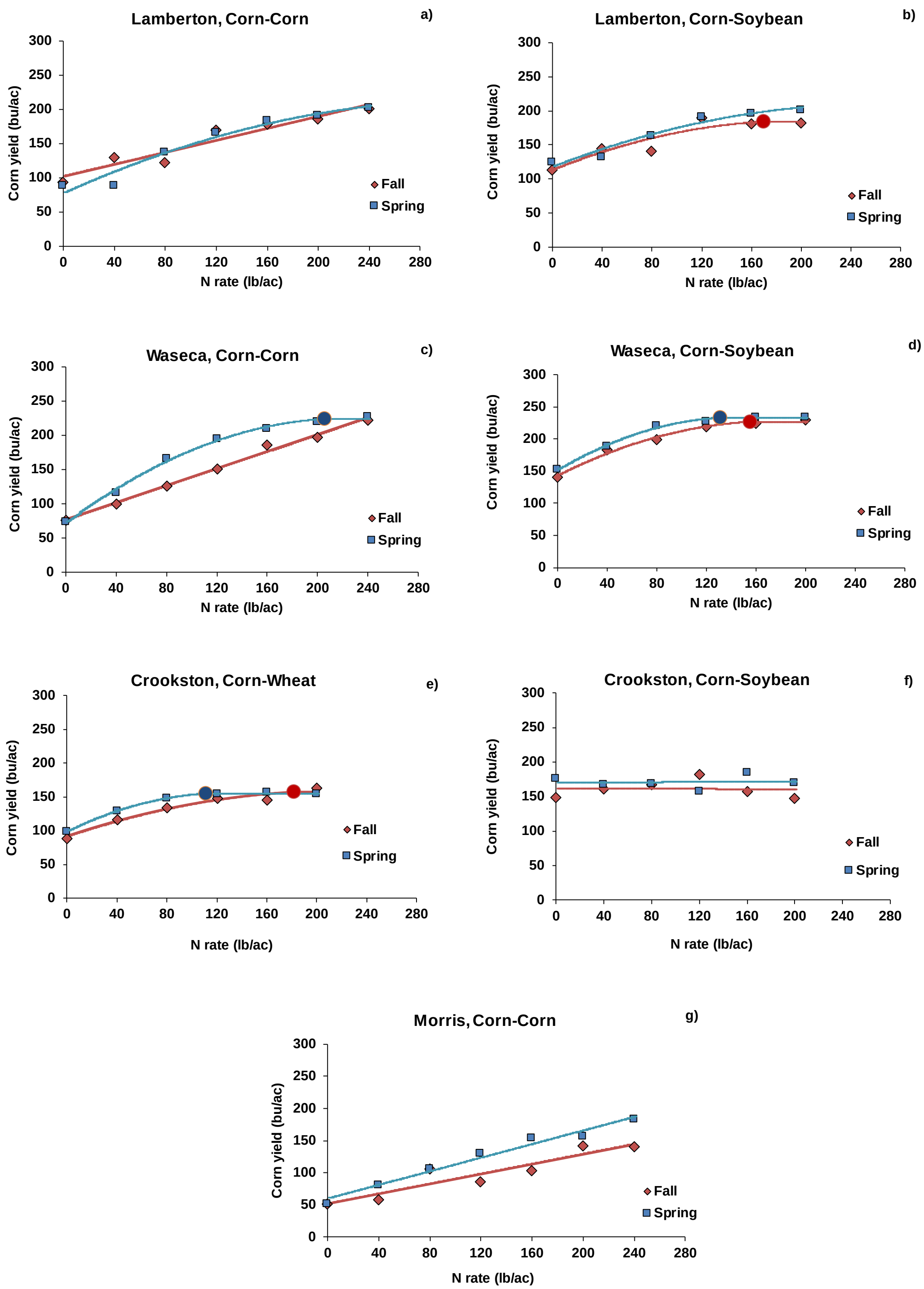

Figure 1. Yield response to N rate for different locations and crop rotations when urea was applied in the fall or the spring. The large dot symbols represent the economic optimum N rate (EONR) calculated at a 0.1 N price: corn ratio (i.e. $0.40/lb N and $4.00/bu corn).

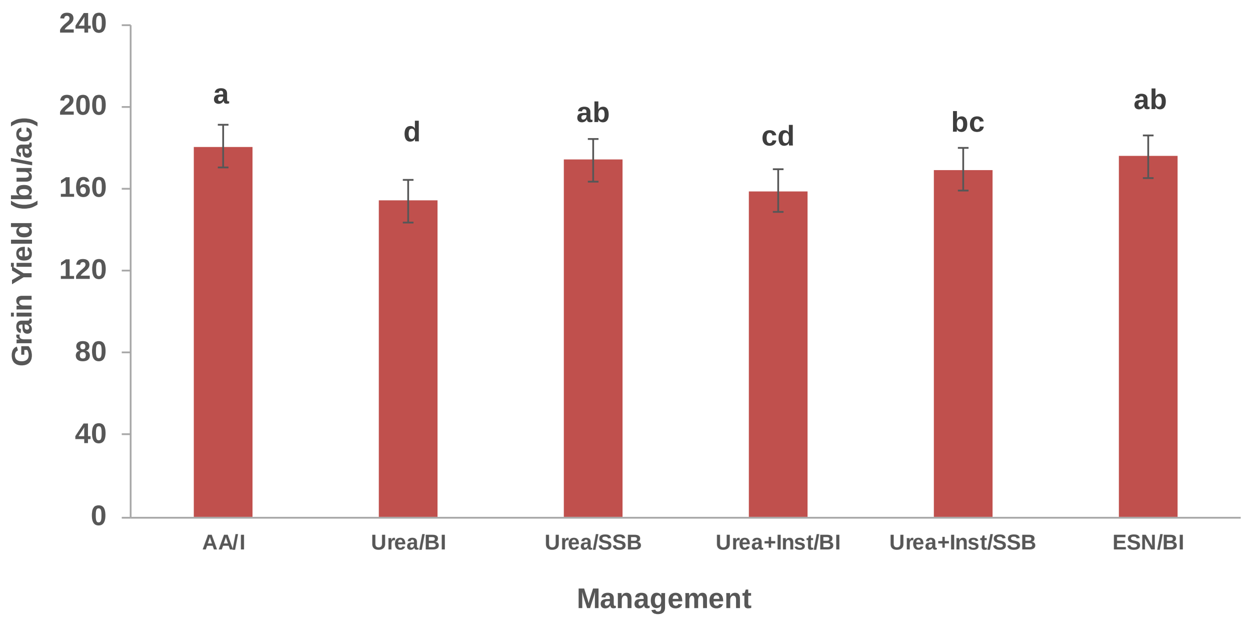

Figure 2. Corn grain yield response to N source and application method averaged across all sites (Lamberton, Waseca, Morris) and application times during the 2017 growing season. Anhydrous ammonia was applied at 120 lb N/ac in all crop rotations whereas all other treatments were applied at 120 lb N/ac in CC but at 80 lb N/ac in CSb, thus the comparison of AA with other treatments in this figure must be interpreted with caution.

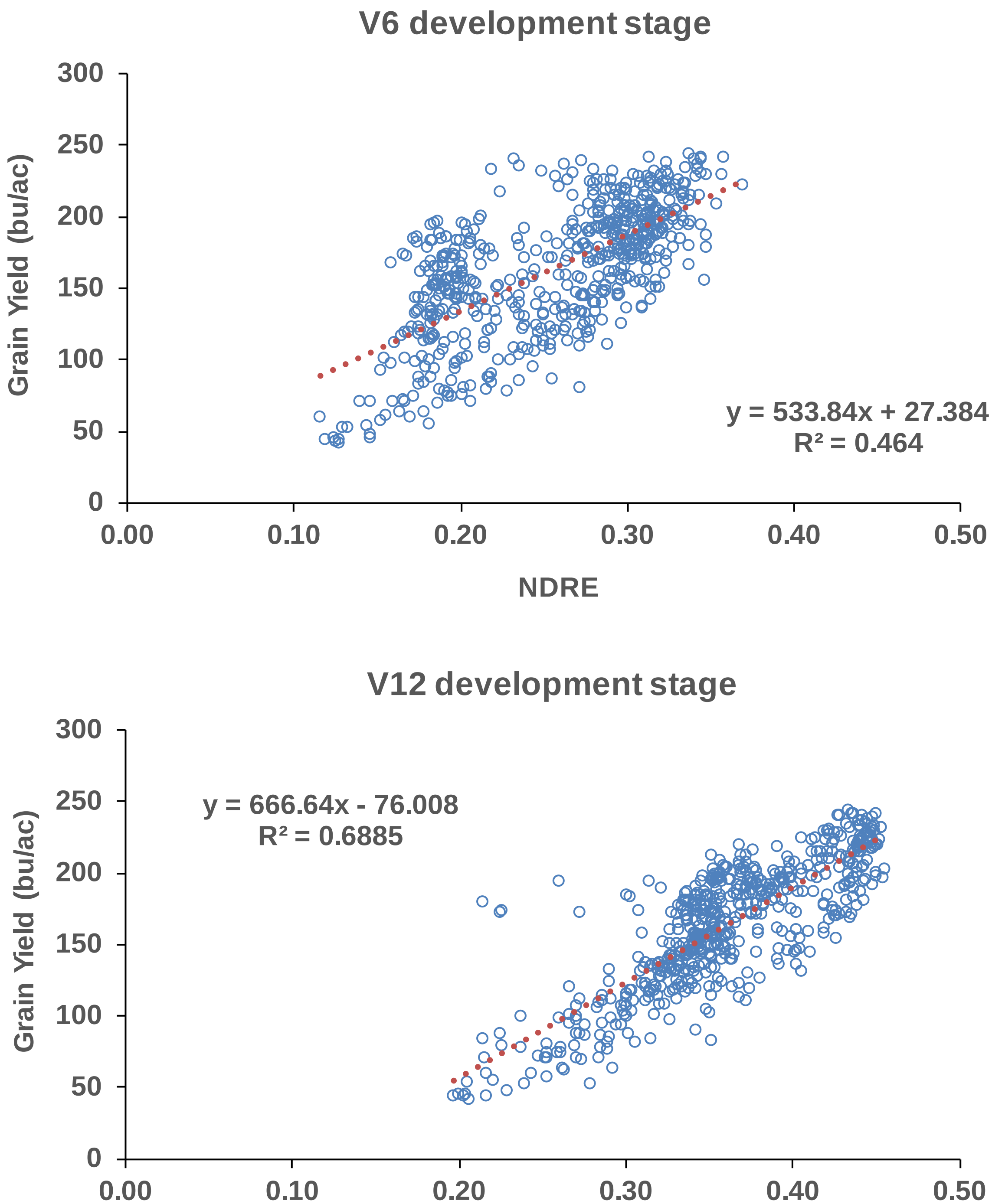

Figure 3. Relationship of grain yield and crop Circle normalized difference red-edge (NDRE) index calculated for the V6 and V12 development stages averaged across all variables in the study for 2017 growing season.