EVALUATION OF NITROGEN FERTILIZER TECHNOLOGIES AND FERTILIZER TIMING FOR SUGAR BEET PRODUCTION

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Justification: Nitrogen is the single most researched nutrient for sugar beet as nitrogen is the nutrient most likely to limit production. Numerous trials in Minnesota and North Dakota have been conducted studying nitrogen rate and the impact of residual nitrate on sugar beet yield and quality. Most of these studies have included spring nitrogen rates usually applied as urea. Nitrogen suggestions assume the same amount of N is required for fall versus spring application on N if best management practices are followed. As nitrogen is applied in the fall in some cases, more research needs to be conducted to determine if fall application of nitrogen can continue to be an acceptable practice.

While spring application of nitrogen is generally suggested for most crops to limit the potential for spring N losses, wet springs present challenges to plant crops at optimal times amid getting fertilizer applied and fields prepared for planting. Fall application of all fertilizer is advantageous to limit the number of field operations which must be completed prior to planting. Current nitrogen best management practices for much of the sugar beet growing regions in Minnesota maintain fall nitrogen application as an acceptable practice. Anhydrous ammonia is the source of nitrogen encouraged for use in the fall due to the impacts anhydrous ammonia has on soil nitrifying bacteria. Fall application of urea has been considered acceptable in Western and Northwestern Minnesota but the practice is being increasingly questioned due to increased rainfall in areas presenting a greater risk for nitrogen loss.

Urea and anhydrous ammonia when applied to the soil both result in the accumulation of ammonia and ammonium in the soil. Urea differs in that it must be hydrolyzed by the enzyme urease before ammonium is forms. The urease enzyme is ubiquitous in soils and hydrolysis of urea can be rapid if the appropriate conditions exist in the soil. Since urea does not impact soil microorganisms the same as anhydrous ammonia the conversion of urea can be quicker presenting greater risks for nitrate loss while shallow application can present volatility issues also representing a potential loss for the product. More recent data collected from multiple locations in Western Minnesota has shown a significant yield penalty for identical rates of nitrogen applied to corn in the fall versus in the spring. The corn yield penalty is greater when corn follows corn which could be partially due to immobilization of nitrogen by the corn residue. With typical rotations of sugar beet following corn a comparison of fall versus spring nitrogen applied as urea is needed to determine the efficiency of fall versus spring application or urea to determine if changes to nitrogen best management practices are warranted, or if sugar beet differs enough where fall urea can still be an acceptable practice even if it is not suggested for corn.

Nitrification inhibitors are currently available to be used for urea which could limit the potential for nitrate accumulation in the soil profile. Research with N-serve applied with anhydrous ammonia has demonstrated that nitrapyrin is an effective nitrification inhibitor. The primary nitrification inhibitor for urea historically was dicyandiamide (DCD). Mobility of the DCD molecule has led to inconsistent results with this product. More recently Dow has released Instinct which is an encapsulated nitropyrin product for use with urea. Research has shown no overall benefit for Instinct applied with broadcast urea for corn, but the product is still sold to growers with a promise of reducing nitrogen loss from fall urea applications. Inhibitor research is needed in sugar beet production to determine if the additional cost of the products justifies their use for fall application.

Polymer coated urea is available in Minnesota as the product ESN. Polymer coated urea differs from inhibitors as the polymer coating provides a barrier which slows the release of nitrogen to the soil. Water moves into the polymer coating dissolving urea which then diffuses through the coating into the soil. The rate of release of urea through the polymer coating is related to soil moisture and temperature. Cool or dry soils can limit release subsequently resulting in a deficiency of nitrogen for the plant even through there may be adequate nitrogen in the soil for the crop. The lack of predictability of release and higher cost of the product has resulted in polymer coated urea suggested for application as a blend rather than 100% of the nitrogen required applied as ESN. However, ESN has been demonstrated as being effective at limiting nitrogen loss in high loss environments and thus may be better suited for fall application than urea treated with an inhibitor. Data reporting fall application of polymer coated products on sugar beet is scare and is needed to determine if this practice is better and what the optimal blend rate may be.

Objectives:

1. Evaluate nitrogen fertilizer requirement for sugar beet.
2. Compare the efficiency of fall versus spring application of urea for the southern and northern growing region through impacts on root yield and sugar content.
3. Determine if polymer coated urea (ESN) blends with urea results in greater root yield and recoverable sugar per acre when applied in the fall.
4. Determine if root yield and recoverable sugar are greater when commercially available nitrification and/or urease inhibitors marketed for use with urea when applied in the fall.

Materials and Methods: Two field locations were established in at new locations in Fall 2020, 2021, and 2022 (Table 1). Each year, one of the field trials was located in the northern growing region at the Northwest Research and Outreach Center at Crookston following wheat in 2021 and 2022 and soybean in 2023. The second second located on an on-farm trial location in the southern growing region following corn near Hector in 2021 and near Renville in 2022 and 2023. There are two separate studies at each location.

Study 1 consists of six N rates at Crookston (0 to 200 lbs) and eight in the southern region (0 to 210 lbs). All N is applied as urea in the fall and in the spring. Trials consist of a split plot design where main plots consist of N rate and sub-plots within each main plot will be N timing such that the same rate can be applied side by side for comparison. Fall application are targeted to the end of October or when the soil has stabilized below 50°F and incorporated as soon as possible after application. Spring fertilizer application was made just prior to- and incorporated before planting (Table 2).

Study 2 consists of multiple fertilizer sources applied at a sub-optimal N rate applied in fall and spring. The target rate was 45 lbs of N only which, including the four-foot nitrate test, the total N should account for roughly two-thirds to three quarters of the suggested N needed for sugar beet production. The 45 lb rate was not meant to represent an optimal rate of N applied to sugarbeet. Rather, the 45 lb N rate should be on the more responsive part of the N response curve allowing for easier detection of smaller differences related to N availability from the sources used. A split plot design is used for the source trial where main plots will consist of N source and sub-plots will be time of application.

N sources consist of:

1. 0 N control
2. Urea only
3. 33% ESN/66% urea
4. 66% ESN/33%urea
5. 100% ESN
6. Super U [NBPT (urease inhibitor) +DCD (nitrification inhibitor)]
7. Agrotain (urease inhibitor) – 0.45 qt/ton (low rate similar to the NBPT rate in Super U)
8. Anvol (urease inhibitor) – 1.5 qt/ton
9. Instinct (nitrification inhibitor) – 24 oz/ac
10. Ammonium sulfate

Initial site-composite soil samples were collected from each study at each location to a depth of four feet. A summary of soil test information is given in Table 2. Stand counts were taken early in the growing season to assess phytotoxicity of the urea rates and sources. In season plant tissue samples are collected towards the end of June to early July depending on planting date. Leaf blade and petiole samples are collected, and extractable nitrate-N is determined in Dr. Kaiser's lab following extraction with water or 2% acetic acid. Petiole and leaf blade samples are additionally sent out to a private lab for total N analysis by dry combustion. The uppermost fully developed leaf blade and petiole were sampled which is consistent with what is suggested for petiole nitrate analysis. Plots were harvested at the end of the growing season and root samples will be analyzed for quality parameters.

A single variety is planted at each location and differed by location. All practices, weed and disease control, planting, and tillage will be consistent with common practices for the growing regions. Additional P, K, and S is applied as needed based on current fertilizer guidelines.

Results

A summary of the main effect significance is given in Table 3a, 3b, and 3c for the urea rate trial and Table 4a and 4b for the urea source trial for the 2021 and 2022 growing seasons, respectively. Figures 1 through 5 summarize sugar beet response to N for the rate trials only. Data are summarized across all rate or treatments when the statistical analysis indicated no N rate or source by time interaction for a given locations. The summary of the main effect of time for the rate and source trials is given in Table 5a, 5b, and 5c for 2021, 2022, and 2023, respectively.

An application error resulted in the loss of all fall treatments for the urea source trial at Crookston 2021. The spring treatments were applied as planned and the source main effect at Crookston only summarizes the spring treatments. There was also a misapplication of treatments at the Renville 2022 site. I am still sorting through the treatments to know what can be used so none of the Renville 2022 data are reported other than the petiole nitrate data will be summarized in the graph comparing petiole nitrate-N to relative root yield. All 2023 data were collected as planned.

Sugar beet emergence was significantly impacted by N rate at nearly all locations (Tables 3a to 3c and Figure 1a to 1c). Sugar beet emergence was less as the rate of N applied as spring urea increased. Fall urea had a slight impact on sugarbeet emergence in some cases but the impact was mostly seen in the fall with the highest rates of urea application. When decreased, sugarbeet emergence decreased linearly as fertilizer rate increased. Emergence was poor at Crookston in 2022 (Tables 3b and Figure 1b) but nitrogen rate and timing did not impact emergence at this location.

Urea source impacted emergence at both locations (Table 6a) in 2021, but seldom affected emergence in future years. In 2021, all sources reduced emergence at Crookston while emergence was greater for most urea sources compared to the control at Hector. Due to the differences in response between the two locations, the ranking of sources generally differed except for urea treated with instinct which resulted in the lowest emergence of all treatments. Urea sources did not impact emergence at Crookston in 2022 (Table 6b). The lack of impact of sources on sugar beet emergence is not unexpected as only 45 lbs of N were applied which may have not been enough N to impact emergence.

Sugar beet root yield as impacted by N application rate at Hector but not at Crookston and time was not significant at either site (Table 4a). Root yield responded to 130 lbs of total N (applied N plus nitrate-N in a four-foot soil sample) at Hector (Figure 2a). Dry soils at Crookston resulted in less and more variable root yield. If root yield did vary by N rate the likely would not have been any additional yield produced passed around 120 lbs of total N at Crookston. The fact that timing of application did not impact root yield likely resulted from the dry soils and a lack of potential for leaching of nitrate.

Root yield was not impacted by nitrogen rate and timing at Crookston in 2022 (Table 4b). Residual nitrate in the soil in Fall of 2021 was extremely high (Table 2). No- or very little nitrogen would be suggested based on the fall four-foot soil nitrate test at Crookston.

Root yield was highly affected by N rate in 2023 at both locations (Table 4c and Figure (2c). Residual nitrate in the soil profile was relatively low at both locations (Table 2). Time of application was significant at Crookston. However, the fall urea application tended to outyield the spring application. It is not clear why fall application of urea produced greater root yield but it could be due to shallow incorporation of urea in dry soils. It also took less N to maximize root yield when urea was applied in the fall at Crookston, but the total N required was still within current suggestions for sugar beet in the Northern growing region. Root yield exceeded expectations at Renville and the response to N was slightly greater than suggested.

Root yield varied by urea source only at Hector (Table 6a) in 2021. Almost all urea sources increased root yield over the non-fertilized control. The greatest yield was produced with the 33% ESN, urea plus Anvol, and urea plus Agrotain treatments. Anvol and Agrotain are urease inhibitors which slow volatility of ammonia by reducing the rate of hydrolysis of the urea. Super-U also contains NBPT, the active ingredient in Agrotain, but at a lower rate that what is applied with the suggested application rate of Agrotain. Issues with coating of the fertilizer resulted in a NBPT rate applied that was roughly 2x that of the amount of NBPT in Super-U (Agrotain rate was targeted to supply the same NBPT rate as in Super-U). It should be noted that this dataset is limited in that it is one site-year total. The addition of more site-years of data is needed to make a conclusion of the optimal urea source. Urea sources did not impact root yield in 2022 at Crookston (Table 6b). In 2023, sources impacted sugar beet root yield at both locations (Table 6c). Similar to the rate trial, fall application outyielded spring at Crookston.

The decrease in plant population did not impact sugar beet root yield. The loss of population was compensated for by the sugar beet plants which increased the mass of roots per plant (not shown). While higher rates of N as spring urea could reduce yield the effect on root yield should be minimal if the variety planted can compensate by growing larger roots. A reduction in emergence without a resulting decrease in yield was also seen in 2020.

Recoverable sucrose per ton was affected by urea rate and timing at both 2021 locations, but the time by rate interaction was not significant. Fall urea application resulted in 3% more recoverable sucrose at both locations. Urea rate resulted in a general decrease in recoverable sucrose at both locations (Figure 3a). In both cases increasing urea rate decreased recoverable sucrose per ton. The decrease was relatively minor at the rate where root yield was maximized at Hector. There was no impact of urea rate and timing on recoverable sucrose at Crookston in 2022 (Figure 3b) or both locations in 2023 (Figure 3c).

Urea sources had a relatively minor impact on recoverable sucrose (Table 6a to 6c). Most sources did not differ from the non-fertilized control except for Super-U which resulted in the lowest recoverable sucrose per ton at both locations.

Recoverable sucrose per acre is summarized for the rate study in Figure 4a, 4b, and 4c. Recoverable sucrose was not impacted by urea rate at Crookston in 2021 while recoverable sucrose was maximized by 80 lbs of total N at Hector and did not increase or decrease beyond that point. Time of urea application did not impact recoverable sucrose per acre at most locations (Table 5a to 5c). For the source trial there was no impact of urea source on recoverable sucrose per acre at Crookston 2021, but recoverable sucrose was increased by urea sources at Hector (Table 6). Most sources were similar, but 100% ESN produced slightly less recoverable sucrose than the other urea sources.

Petiole and leaf blade nitrate concentrations were determined following sampling in early to late-July. The targeted sampling time was 40-50 days after planting at each site. Nitrogen rate and timing affected petiole and leaf blade nitrate-N concentration in 2021 (Table 3a) while only rate impacted blade and petiole nitrate-n concentration in 2022 (Table 3b). Both petiole (Tables 5a and 5b) and leaf blade (Table 6a and 6b) nitrate-N concentration increased with increasing N application rate. In general, petiole and leaf blade nitrate-N concentrations did not plateau and increased beyond the highest rate of N applied even at Crookston in 2022 where the residual nitrate-N content in the soil was high and the relative amounts of nitrate-N in the leaf blade and petiole samples were extremely high compared to samples collected from the 2021 locations. While the main effect of timing was significant in 2021, there was no timing x rate interaction indicating that in general fall application of urea resulted in less nitrate-N in the plant tissue, but the effect of N and the shape of the N response curves were similar even though the maximum values achieved were different based on timing.

Nitrogen rate impacted both petiole and leaf blade nitrate-N concentration at both locations in 2023 (Figures 5c and 6c). Time of application impacted only petiole nitrate N concentration at Crookston where petiole nitrate-N concentration was greater with fall urea application. In all cases the concentration of nitrate-N increased with increasing rate of applied N and was not maximized with the greatest rate of urea applied. There was an interaction between rate and timing for petiole nitrate-N concentration at Crookston, However, the interaction was generally due to no difference in nitrate-N concentration based on time of application with the lowest rates of urea applied.

Source effects on petiole and leaf blade nitrate-N concentration are summarized in Tables 6a through 6c. The timing main effects on leaf blade nitrate-N concentration differed for all three locations in 2021 and 2022 (Tables 5a and 5b) but did not differ in 2023 (Table 5c). Petiole nitrate-N only varied based on time of application for the two 2021 locations (Table 5a) and not at any of the other locations. The relative rankings among the sources varied by site and individual site effects will not be discussed but are given in Tables 6a through 6c. A source x time interaction only occurred at Hector in 2021 for petiole nitrate-N concentration and at Crookston in 2021 for leaf blade nitrate-N concentration. Again, these individual effects will not be discussed on a site-by-site basis in lieu of an analysis across locations.

The urea source data was analyzed across the five field locations. It should be noted that only the spring application from Crookston in 2021 was utilized while both fall and spring data from the remaining locations. There was no significant impact of time or source on sugarbeet emergence (Figures 7). Root yield was impacted by source but not time (Figure 8). The root yield data are somewhat messy, but root yield tended to be greater with the urea sources where Anvol or Agrotain were applied or with AMS. This would indicate that the loss pathway of N from urea was more related to volatilization of ammonia rather than nitrate leaching. Recoverable sucrose per ton was not impacted by urea source (Figure 9).

Leaf blade and petiole nitrate-N concentration were analyzed but only petiole nitrate-N concentration is summarized in this report (Figure 10). Both main effects of time and source significantly differed but the interaction between time and source was not significant. For the time main effect, petiole nitrate-N concentration was significantly greater following spring application. For sources, the greatest increase in petiole nitrate-N concentration was produced with Anvol and Instinct. The next greatest increase was due to 33% of N as ESN and Super-U which did not differ from each other. Agrotain, AMS, 100 and 66% ESN did not differ from straight urea and were only slightly better than the 0N control. In general, there was no class of inhibitor that was better than another (urease versus nitrification inhibitors). The 33% ESN blend was slightly better than 66 or 100% but was still slightly worse than Anvol or Instinct. More data will be added as additional sites are added.

Petiole nitrate concentration was regressed with relative yield from previous studies and the data are given in Figure 11. Data indicate that 100% of maximum root yield was achieved with a petiole nitrate concentration near 850 ppm. However, relative root yield for plots ranged from 50-110% for petiole nitrate concentration less than 850 ppm. The high range in relative yield levels for petiole nitrate concentration does present some issues for using petiole nitrate concentration to assess nitrate sufficiency to direct supplemental application of N for sugar beet. The range in relative yield values is like what is seen with other tests such as the corn basal stalk N test. While we could say that 850 ppm would be a sufficient petiole nitrate concentration for sugar beet what to do if you concentration is below that level is more difficult to determine. As we continue the nitrogen work, we will add more data to the dataset. One item of note is that root yield at Lake Lillian did not respond to nitrogen and yield levels were 40+ tons like Wood Lake, yet many of the petiole nitrate concentration were less than 850 ppm. Past research has also not been able to calibrate the petiole nitrate test. The petiole nitrate test may work to help manage nitrogen at specific locations, but it may not be possible to determine which locations it may work until yield data is available at a given location.

The petiole nitrate-N data was also compared to the difference in the amount of nitrogen applied relative to the rate that maximized root yield at each location (Figure 12). The petiole nitrate-N concentration at the optimal N rate was 750 to 800 ppm slightly lower than the optimal value shown in Figure 11. Nitrate-N concentration continued to increase beyond the optimal N rate indicating luxury uptake of nitrogen by the beet plant. Below the 750 ppm, the relationship between petiole nitrate-N concentration and root yield was relatively linear but also relatively vertical making it difficult to determine potential suggested application rates of N when the petiole nitrate-N concentration was below 750 ppm. Optimal application rate could be as much as 100 lbs N or as little as 50. It should be noted that petiole nitrate concentration can be highly affected by plant stress, including moisture stress, around the time of sampling. In addition, concentrations are diurnal meaning they can fluctuate from daytime to nighttime. Sampling should be collected at oar near the same time of the day. Most samples in this study were collected between 10 am and 2 pm the day of sampling.

Petiole nitrate-N concentration was also related to recoverable sucrose per ton (Figure 13). There was no clear relationship between the two variables but that may be due to differences in recoverable sucrose based on site or variety. Recoverable sucrose per ton tended to be lower at the southern locations and appeared to decrease with increasing petiole nitrate-N concentration. However, the decrease in petiole nitrate-N seemed to occur at concentrations near concentrations that resulted in maximum root yield.

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Table 1. Location, planting and sampling information and dominant soil series for each location.

		Date of					Soil		
Year	Location	Urea Application		Planting	Tissue Sampling	Harvest	Series	Texture†	Classification‡
2021	Crookston	29-Oct	4-May	4-May	8-Jul	14-Sept	Wheatville	FSL	Ae. Calciaquoll
	Hector	6-Nov	30-Apr	30-Apr	12-Jul	29-Sept	Canisteo-Glencoe	CL	T. Endoaquoll
2022	Crookston	1-Nov	27-May	27-May	22-Jul	20-Sept	Wheatville	FSL	Ae. Calciaquoll
	Renville	3-Nov	21-May	24-May	19-Jul	19-Sept	Normania	L	Aq. Hapludoll
2023	Crookston	4-Nov	10-May	10-May		14-Sept	Wheatville	FSL	Ae. Calciaquoll
	Renville	1-Nov	3-May	3-May	12-Jul	9-Oct	Leen-Okaboji	SiCL	T. Calciaquoll

† CL, clay loam; FSL, fine sandy loam; SiCl, silty clay loam.

‡Ae, aeric; Aq, aquic; T, typic

Table 2. Summary of soil test results for 2021 locations.

		0-6” Soil Test				Soil Test Nitrate-N	
Year	Location	Olsen P	Ammonium Acetate K	pH	SOM	0-2’	2-4’
		----------ppm----------			----%----	-------------------lb/ac-------------------	
				Urea Rate Trials			
2021	Crookston	9	159	8.2	3.0	25	43
	Hector	8	168	7.3	5.4	21	39
2022	Crookston	9	140	8.2	2.7	135	9
	Renville	11	155	7.1	3.9	22	8
2023	Crookston	6	113	8.3	2.8	15	24
	Renville	11	181	8.1	7.1	31	--
				Urea Source Trials			
2021	Crookston	12	140	8.2	2.3	39	70
	Hector	7	151	7.6	4.0	25	68
2022	Crookston	9	140	8.2	2.7	135	9
	Renville	13	222	7.3	4.0	30	14
2023	Crookston	6	113	8.3	2.8	15	24
	Renville	11	181	8.1	7.1	31	--

Table 3a. Summary of analysis of variance for main effects of nitrogen application rate (N rate) and time of application (Time) and their interaction at Crookston (CRX) and Hector (H), MN in 2021.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H
	--------------------	--------------------	--------------------	--------------------	--------------------	*P*>F	--------------------	--------------------	--------------------	
N rate	***	0.10	***	***	***	***	0.50	**	0.10	*
Time	***	***	**	***	*	*	0.66	0.88	**	**
N ratexTime.	***	***	0.13	0.16	0.88	0.45	0.13	0.90	0.25	0.46

†Asterisks represent significance at P<0.05,*; 0.01, **; and 0.001, ***.

Table 3b. Summary of analysis of variance for main effects of nitrogen application rate (N rate) and time of application (Time) and their interaction at Crookston (CRX) and Renville (R), MN in 2022.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	--------------------	--------------------	--------------------	--------------------	--------------------	*P*>F	--------------------	--------------------	--------------------	
N rate	0.50	na	0.07	na	*	na	0.69	na	0.25	na
Time	*	na	0.20	na	0.07	na	**	na	0.38	na
N ratexTime.	0.34	na	0.87	na	0.80	na	0.42	na	0.88	na

†Asterisks represent significance at P<0.05,*; 0.01, **; and 0.001, ***.

Table 3c. Summary of analysis of variance for main effects of nitrogen application rate (N rate) and time of application (Time) and their interaction at Crookston (CRX) and Renville (R), MN in 2023.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	--------------------	--------------------	--------------------	--------------------	--------------------	*P*>F	--------------------	--------------------	--------------------	
N rate	***	*	***	***	0.13	***	***	**	0.44	0.68
Time	***	***	0.08	0.25	0.92	0.70	***	0.20	0.66	0.92
N ratexTime.	***	***	*	0.61	0.08	0.17	0.08	0.38	0.60	0.83

†Asterisks represent significance at P<0.05,*; 0.01, **; and 0.001, ***.

Table 4a. Summary of analysis of variance for main effects of urea source (Source) and time of application (Time) and their interaction at Crookston (CRX) and Hector (H), MN in 2021.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H
	-----	-----	-----	-----	----- *P*>F -----	-----	-----	-----	-----	-----
Source	***	**	0.10	0.07	0.06	0.12	0.18	**	*	*
Time	na	0.58	na	***	na	**	na	0.26	na	0.63
SourcexTime.	na	0.55	na	*	na	0.40	na	0.62	na	0.95

†Asterisks represent significance at *P*<0.05,*; 0.01, **; and 0.001, ***.

Table 4b. Summary of analysis of variance for main effects of urea source (Source) and time of application (Time) and their interaction at Crookston (CRX) and Renville (R), MN in 2022.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	-----	-----	-----	-----	----- *P*>F -----	-----	-----	-----	-----	-----
Source	0.99	na	0.81	na	*	na	0.99	na	0.23	na
Time	0.08	na	0.43	na	0.35	na	*	na	*	na
SourcexTime.	0.08	na	0.44	na	*	na	0.08	na	0.42	na

†Asterisks represent significance at *P*<0.05,*; 0.01, **; and 0.001, ***.

Table 4c. Summary of analysis of variance for main effects of urea source (Source) and time of application (Time) and their interaction at Crookston (CRX) and Renville (R), MN in 2023.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Recoverable Sugar (ton)	
Effect	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	-----	-----	-----	-----	----- *P*>F -----	-----	-----	-----	-----	-----
Source	0.14	0.96	0.16	0.18	0.56	0.12	0.10	*	0.17	0.31
Time	0.18	0.86	0.56	0.41	0.71	0.08	***	0.88	0.43	0.28
SourcexTime.	0.57	0.13	0.35	0.22	0.40	0.27	0.19	0.19	0.64	0.34

†Asterisks represent significance at *P*<0.05,*; 0.01, **; and 0.001, ***.

Table 5a. Summary of the main effect of in-urea timing or source for selected variables at Crookston (CRX) and Hector (H), MN in 2021. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant. Data are given separately for the urea rate and source trials at each location. Fall treatments for the Crookston source trial were not included in this dataset.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Time	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
					Urea Rate Trial							
Fall	79a	86a	1702b	764b	478b	89b	19.4	39.5	326a	246a	6340	9690
Spring	72b	74b	2147a	1307a	622a	125a	19.1	39.6	316b	240b	6027	9479
					Urea Source Trial							
Fall	--	84	--	647b	--	47b	--	33.9	--	261	--	8587b
Spring	--	83	--	1005a	--	90a	--	34.6	--	260	--	8859a

†Numbers followed by the same letter are not significantly different at the $P \leq 0.10$ probability level.

Table 5b. Summary of the main effect of in-urea timing or source for selected variables at Crookston (CRX) and Renville (R), MN in 2022. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant. Data are given separately for the urea rate and source trials at each location. Fall treatments for the Crookston source trial were not included in this dataset.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Time	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
					Urea Rate Trial							
Fall	72a	na	5299	na	1372b	Na	23.5a	na	316	na	7409a	na
Spring	56b	na	5740	na	1593a	Na	20.5b	na	312	na	6400b	na
					Urea Source Trial							
Fall	60.3b	na	567	na	3447	Na	21.7b	na	306b	na	6664	na
Spring	68.5a	na	599	na	3322	Na	23.3a	na	312a	na	7263	na

†Numbers followed by the same letter are not significantly different at the $P \leq 0.10$ probability level.

Table 5c. Summary of the main effect of in-urea timing or source for selected variables at Crookston (CRX) and Renville (R), MN in 2023. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant. Data are given separately for the urea rate and source trials at each location. Fall treatments for the Crookston source trial were not included in this dataset.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Time	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
						Urea Rate Trial						
Fall	78a	87a	908a	1017	119	390	18.1a	43.1	344	276	6217a	11885
Spring	69b	79b	779b	1154	122	372	15.0b	44.2	342	276	5087b	12196
						Urea Source Trial						
Fall	81.8	84.8	501	81	77	43b	18.8a	23.5	341	279	6337a	6570
Spring	80.1	84.6	554	109	71	55a	16.5b	23.4	339	278	5506b	6512

†Numbers followed by the same letter are not significantly different at the $P \leq 0.10$ probability level.

Table 6a. Summary of the main effect of urea source for selected variables at Crookston (CRX) and Hector (H), MN in 2021. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Source	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H	CRX	H
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
None	86.4a	78.6cd	100c	471d	317c	33	18.1	29.9f	345.6a	261.5ab	6259	7092d
Urea	69.7ef	88.1a	227bc	625bcd	725bc	35	16.7	31.6def	336.2ab	261.9ab	5612	8639abcd
AMS	78.9bc	86.6a	154bc	888abc	674c	53	19.5	36.7abc	325.1bc	270.1a	6339	9768ab
33% ESN	73.7de	85.6ab	214bc	950ab	589c	79	15.7	39.0a	329.0b	263.5ab	5163	9839a
66% ESN	77.1bcd	80.1bcd	174bc	524cd	681c	53	18.5	30.7ef	329.9b	260.1b	6104	8094bcd
100% ESN	80.8b	88.5a	214bc	1064a	545c	92	19.6	34.2bcde	332.1b	262.0ab	6510	7596cd
Instinct	68.4f	75.2d	196bc	1162a	466c	104	17.9	34.0bcde	329.2b	257.1b	5909	8412abcd
Super-U	74.1cde	84.8ab	310ab	924abc	1332a	82	19.0	33.1cdef	314.8c	246.0c	5965	8922abc
Agrotain	77.3bcd	84.6abc	262bc	786abcd	744bc	48	18.7	37.6ab	327.7b	259.8b	6145	8909abc
Anvol	72.5def	80.4bcd	463a	867abcd	1214ab	109	18.9	35.5abcd	333.4b	259.4b	6282	9955a

†Numbers followed by the same letter are not significantly different at the P<0.10 probability level.
Na, data are not available

Table 6b. Summary of the main effect of urea source for selected variables at Crookston (CRX) and Renville (R), MN in 2022. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Source	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
None	67	na	467	na	2502c	na	22.4	na	323	na	7252	na
Urea	68	na	608	na	3715ab	na	22.7	na	309	na	7017	na
AMS	64	na	536	na	2845c	na	23.0	na	304	na	6992	na
33% ESN	64	na	614	na	3700ab	na	22.9	na	308	na	7050	na
66% ESN	66	na	578	na	3652ab	na	22.4	na	310	na	6953	na
100% ESN	64	na	537	na	3086bc	na	23.3	na	301	na	7022	na
Instinct	65	na	586	na	3212abc	na	22.2	na	313	na	6951	na
Super-U	69	na	641	na	3829a	na	22.5	na	305	na	6893	na
Agrotain	61	na	626	na	3635ab	na	21.5	na	307	na	6664	na
Anvol	61	na	636	na	3670ab	na	22.1	na	310	na	6845	na

†Numbers followed by the same letter are not significantly different at the $P<0.10$ probability level.
Na, data are not available

Table 6c. Summary of the main effect of urea source for selected variables at Crookston (CRX) and Renville (R), MN in 2023. Letters indicating least significant difference are only listed in the table when the main effect of timing was significant.

	Emergence		Petiole NO_3-N		Blade NO_3-N		Yield		Rec. Sugar (ton)		Rec Sugar (acre)	
Source	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R	CRX	R
	------%------		----ppm----				--tons/ac--		---lb/ton---		----lb/ac----	
None	84	85	224	12	34	18b	13.8c	19.7c	328	275	4448	5411
Urea	81	87	452	307	65	121a	16.0bc	22.8bc	351	276	5563	6302
AMS	83	86	495	28	80	27b	17.8ab	25.2ab	329	281	5732	7105
33% ESN	84	85	798	53	102	33b	18.0ab	23.2abc	342	280	6035	6503
66% ESN	77	85	555	129	86	36b	18.3ab	20.6c	334	275	6036	5683
100% ESN	80	83	325	71	75	36b	17.4ab	25.9ab	351	279	6032	7235
Instinct	81	82	555	124	59	81ab	19.0ab	21.7c	343	276	6432	6037
Super-U	81	85	824	119	115	72ab	16.8bc	23.1abc	348	279	5757	6458
Agrotain	83	84	593	87	89	26b	20.3a	26.5a	334	279	6687	7405
Anvol	75	85	453	19	35	20b	19.2ab	25.7ab	344	283	6493	7272

†Numbers followed by the same letter are not significantly different at the $P<0.10$ probability level.
Na, data are not available

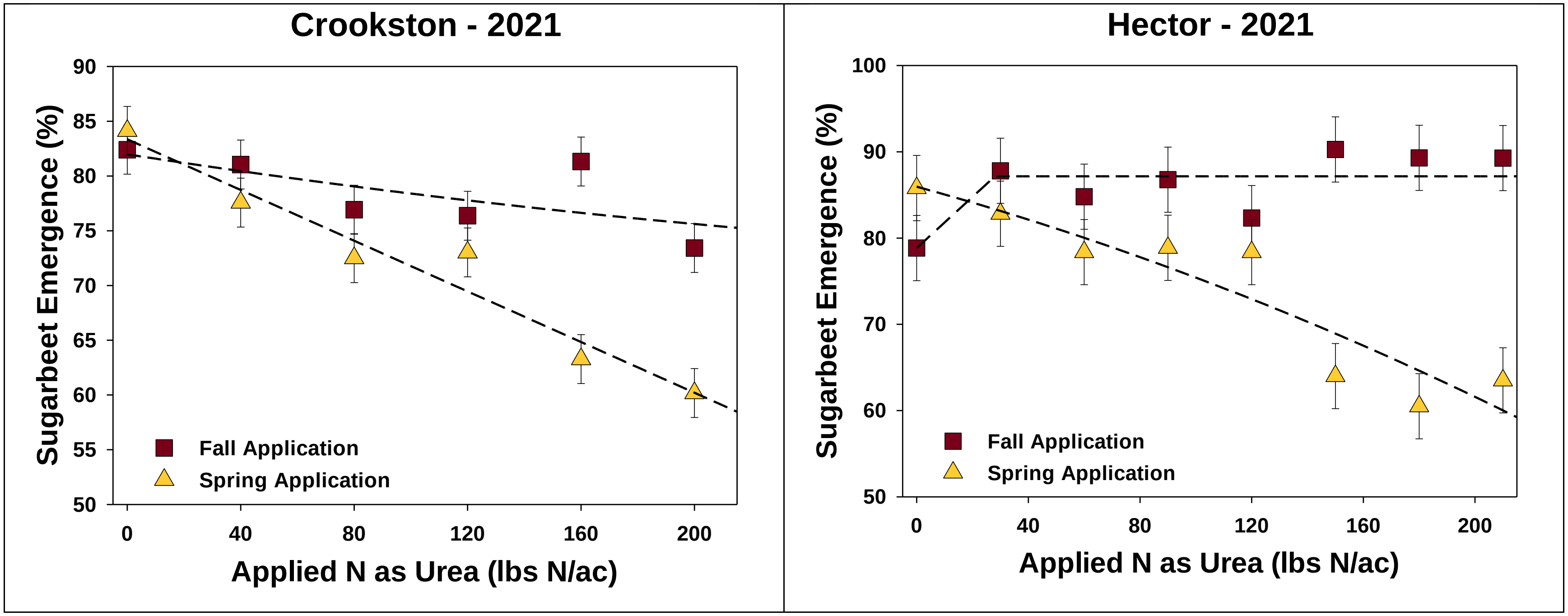

Figure 1a. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet emergence at two Minnesota locations during the 2021 growing season.

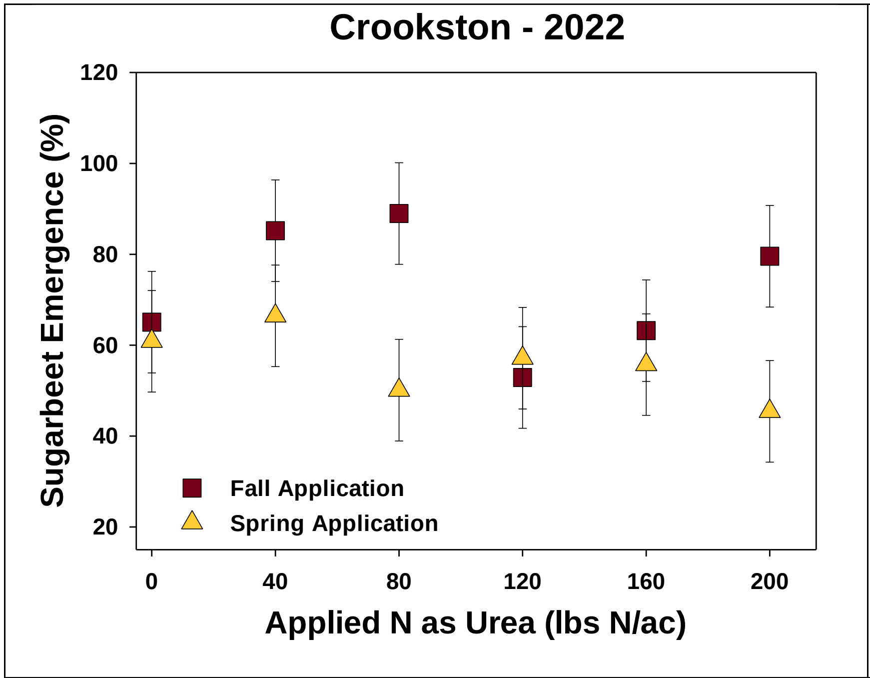

Figure 1b. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet emergence at two Minnesota locations during the 2022 growing season.

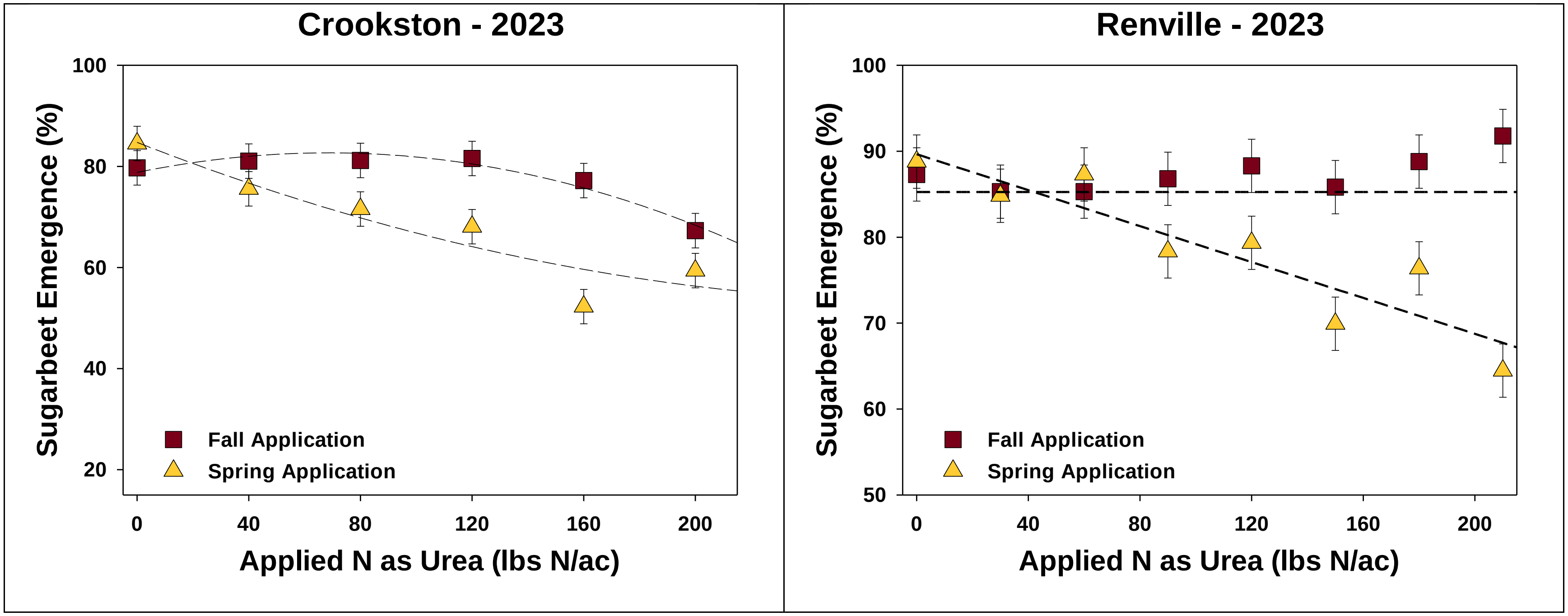

Figure 1c. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet emergence at two Minnesota locations during the 2023 growing season.

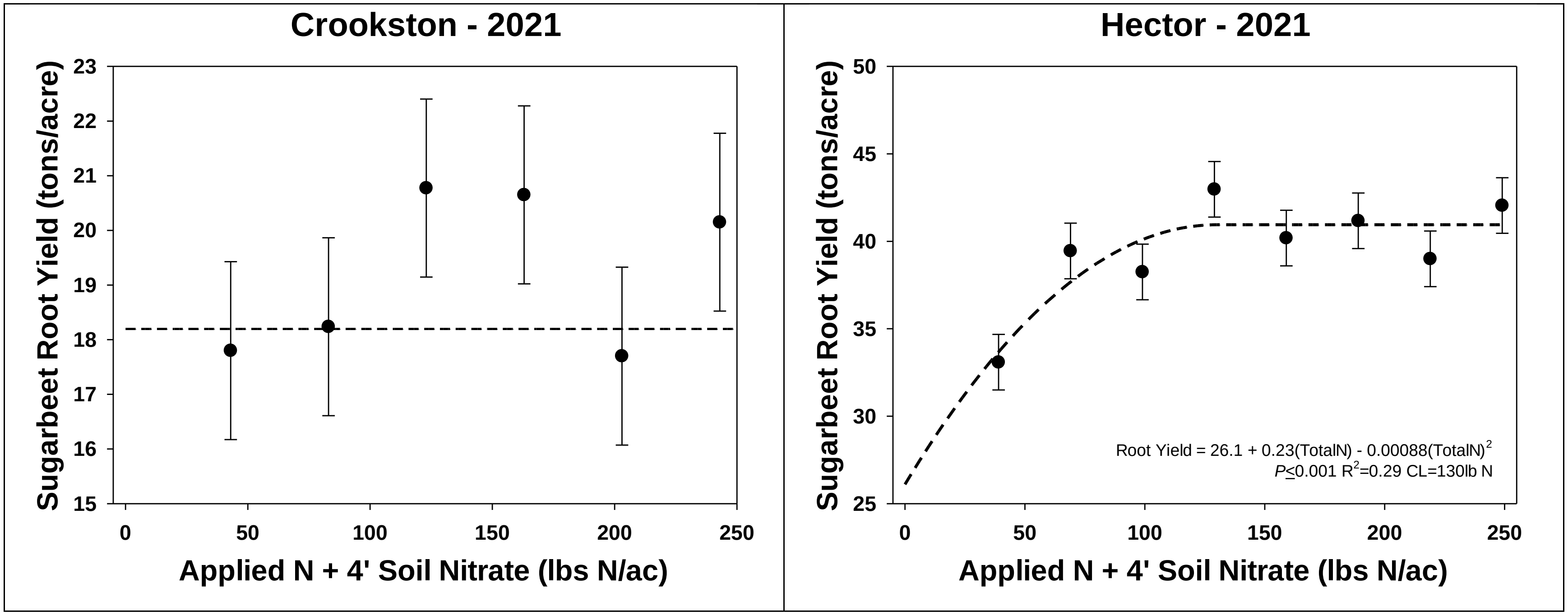

Figure 2a. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet root yield at two Minnesota locations during the 2021 growing season.

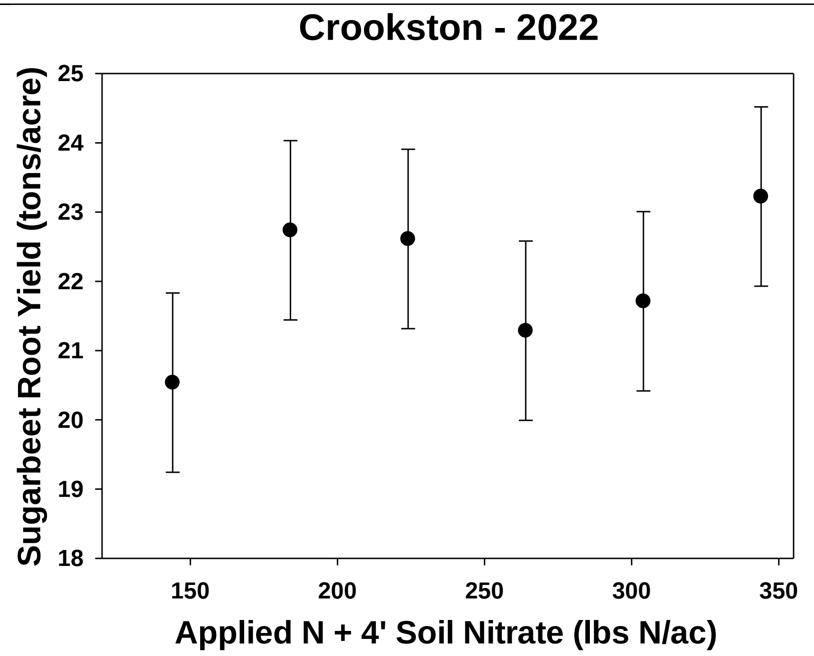

Figure 2b. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet root yield at two Minnesota locations during the 2022 growing season.

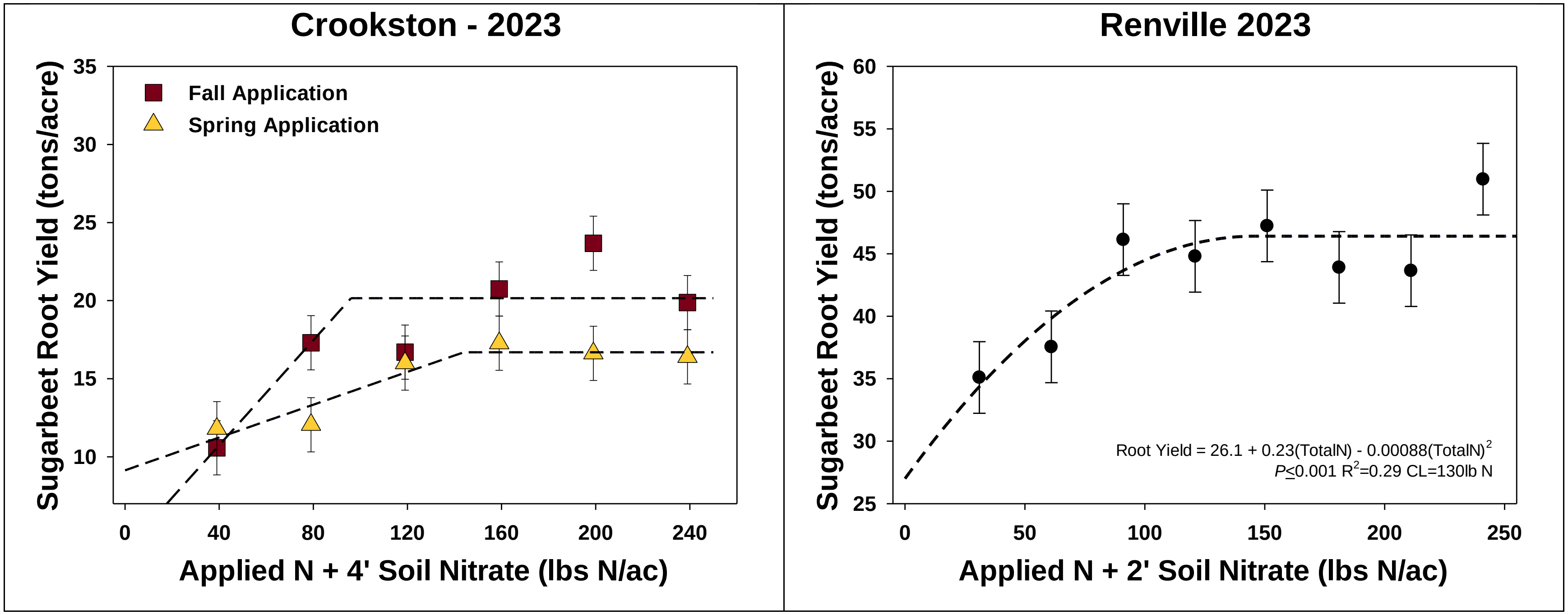

Figure 2c. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet root yield at two Minnesota locations during the 2023 growing season.

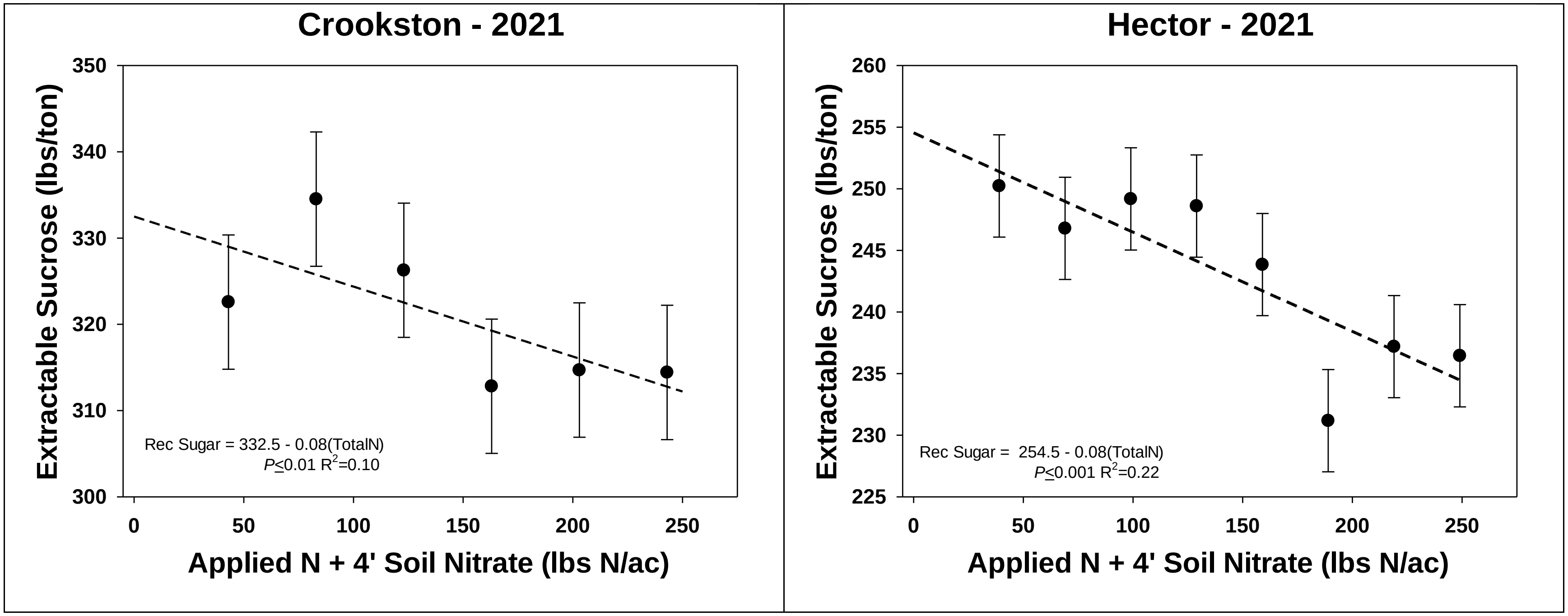

Figure 3a. Effect of nitrogen applied as spring urea plus the nitrate in a four-foot on sugar beet extractable sucrose per ton at two Minnesota locations during the 2021 growing season.

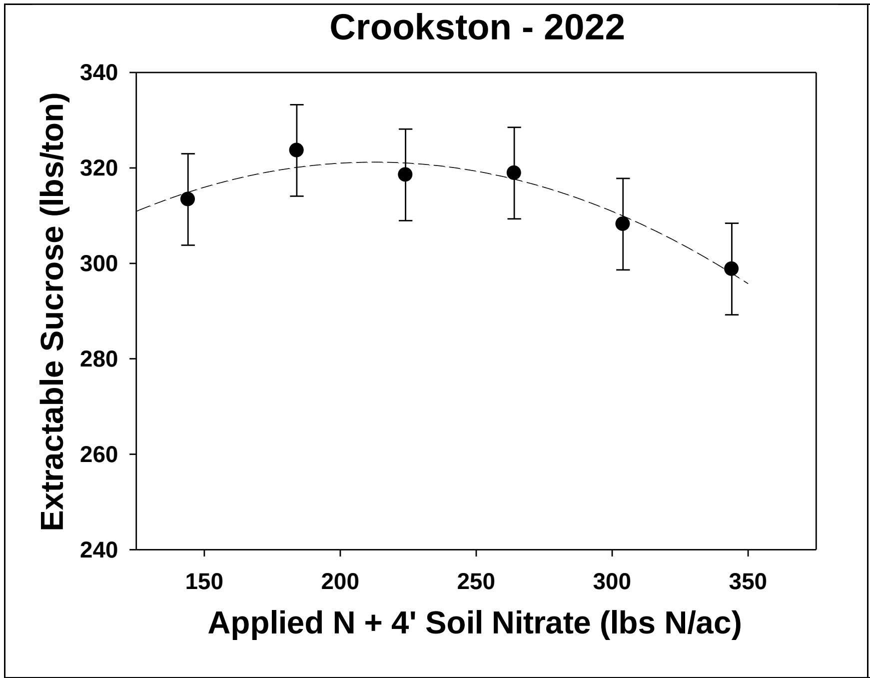

Figure 3b. Effect of nitrogen applied as spring urea plus the nitrate in a four-foot on sugar beet extractable sucrose per ton at two Minnesota locations during the 2022 growing season.

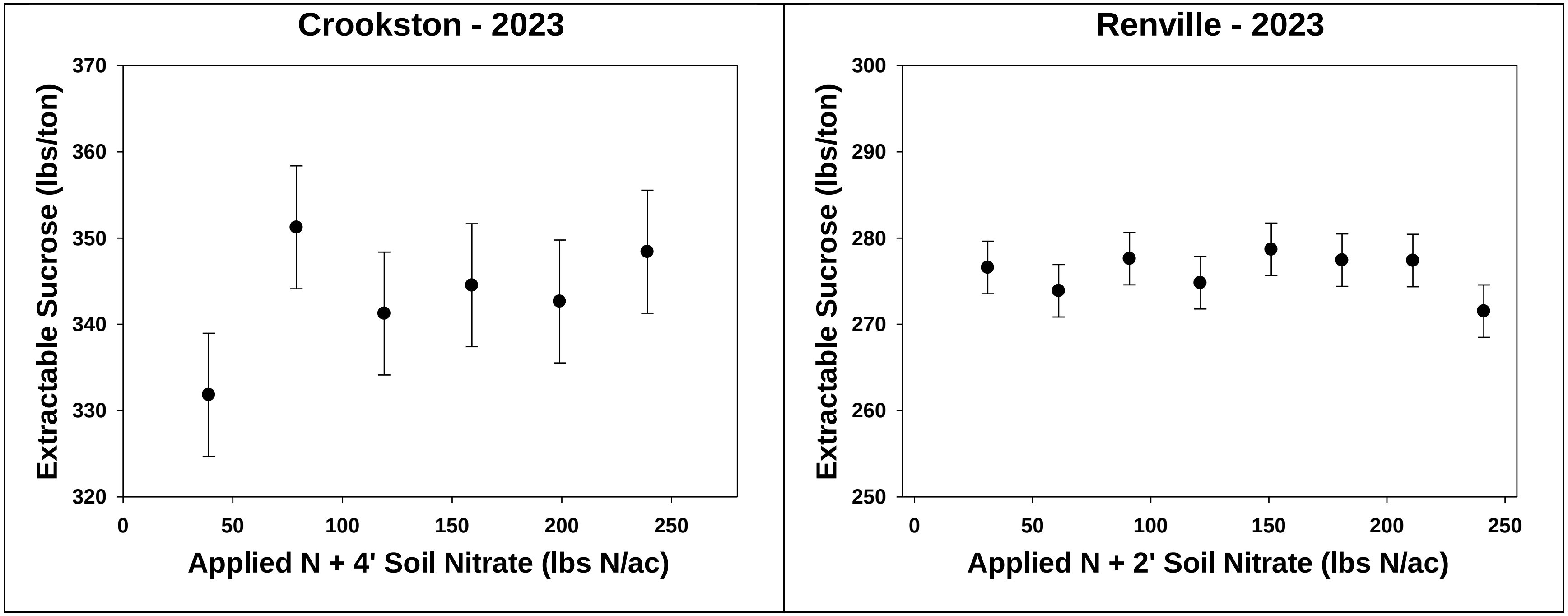

Figure 3c. Effect of nitrogen applied as spring urea plus the nitrate in a four-foot on sugar beet extractable sucrose per ton at two Minnesota locations during the 2023 growing season.

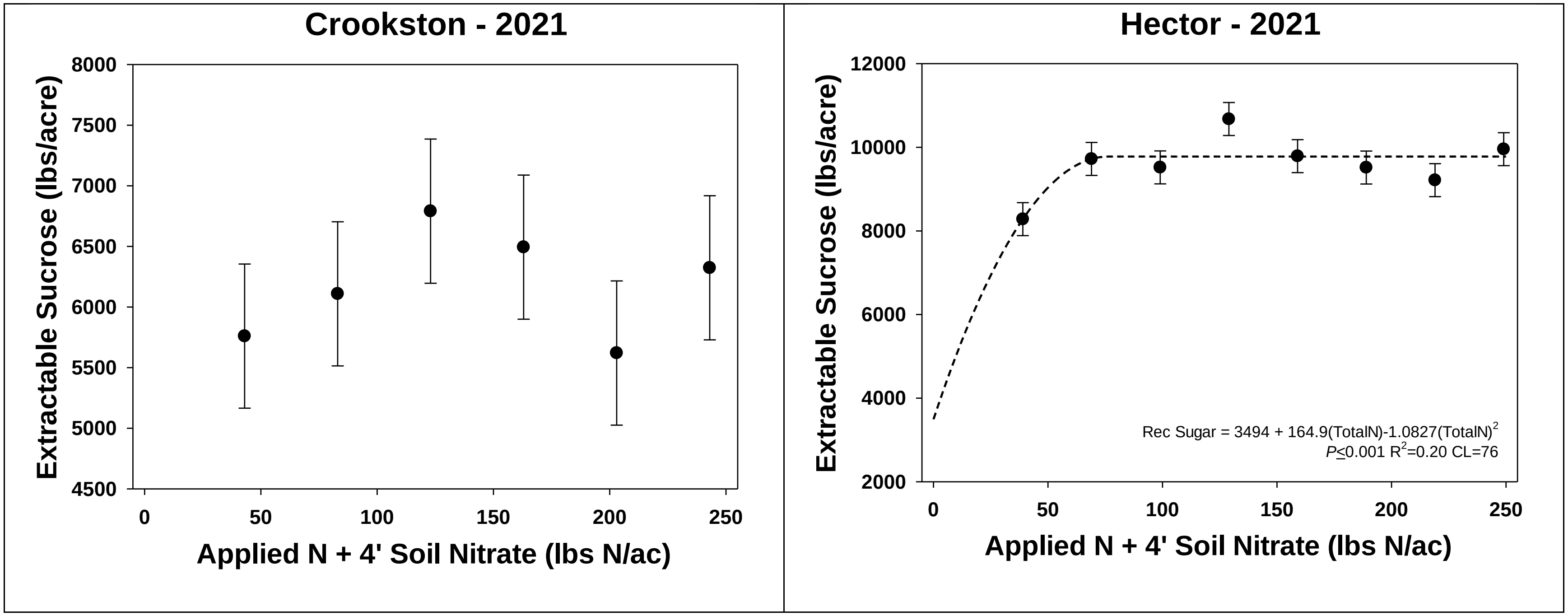

Figure 4a. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet total extractable sucrose per acre at two Minnesota locations during the 2021 growing season.

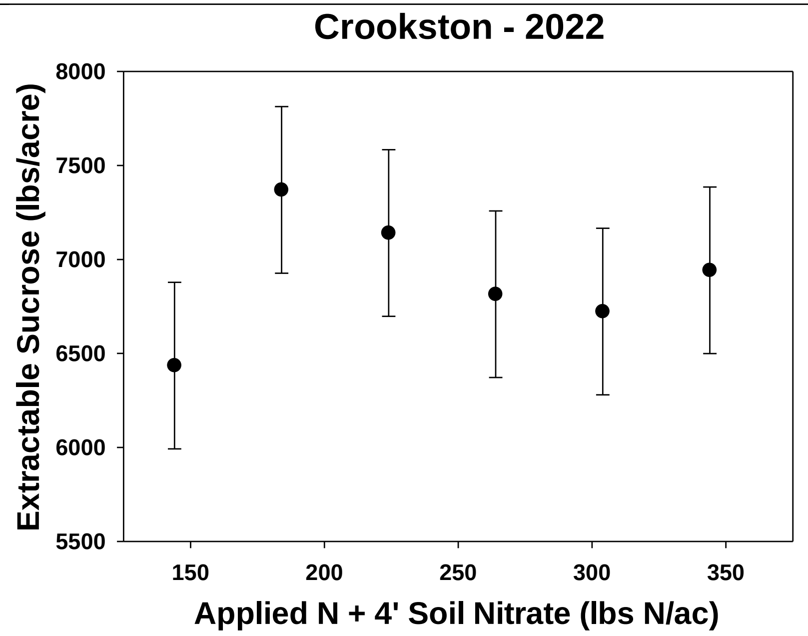

Figure 4b. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet total extractable sucrose per acre at two Minnesota locations during the 2022 growing season.

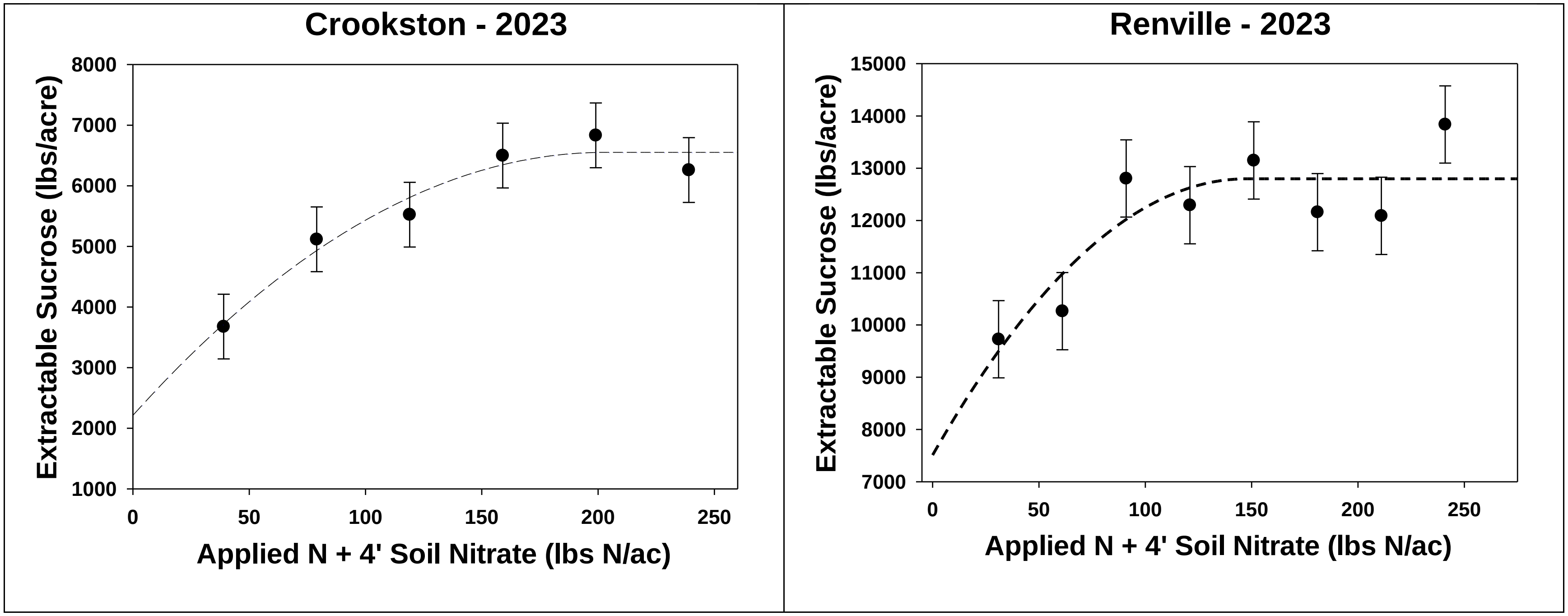

Figure 4c. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) plus the nitrate in a four-foot on sugar beet total extractable sucrose per acre at two Minnesota locations during the 2023 growing season.

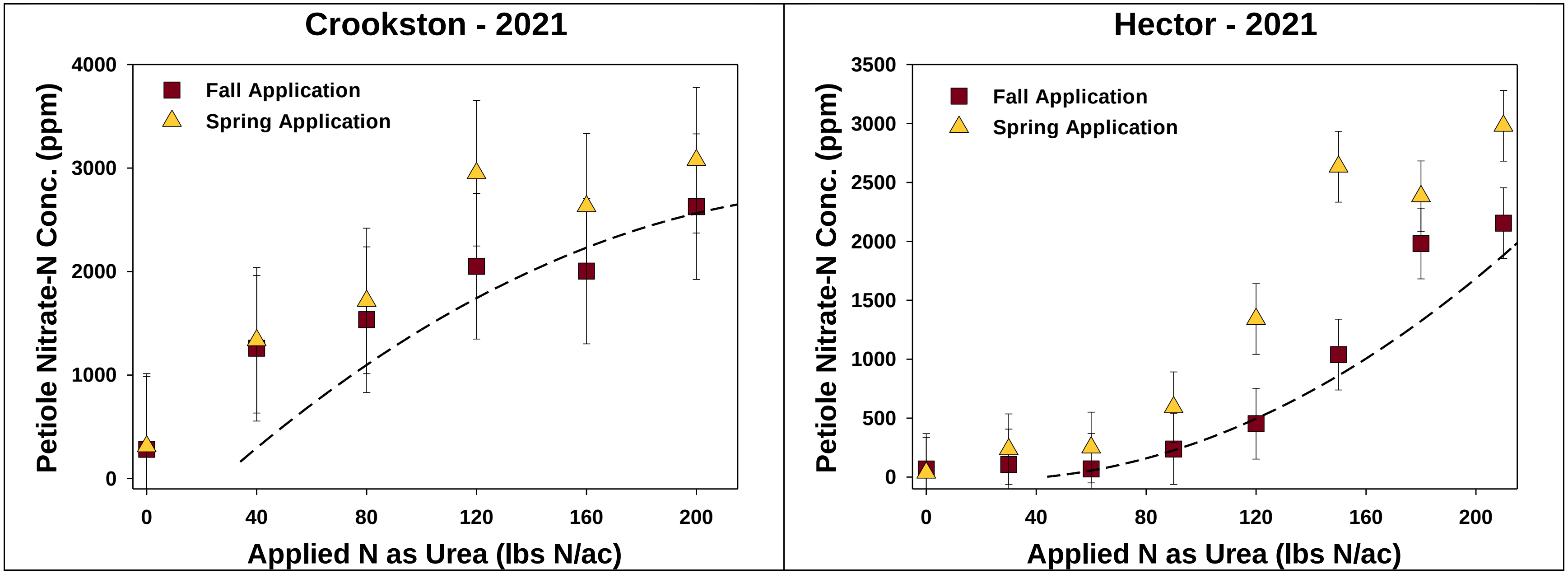

Figure 5a. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July petiole nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2021 growing season. Samples were collected but had not been analyzed at the time of this report.

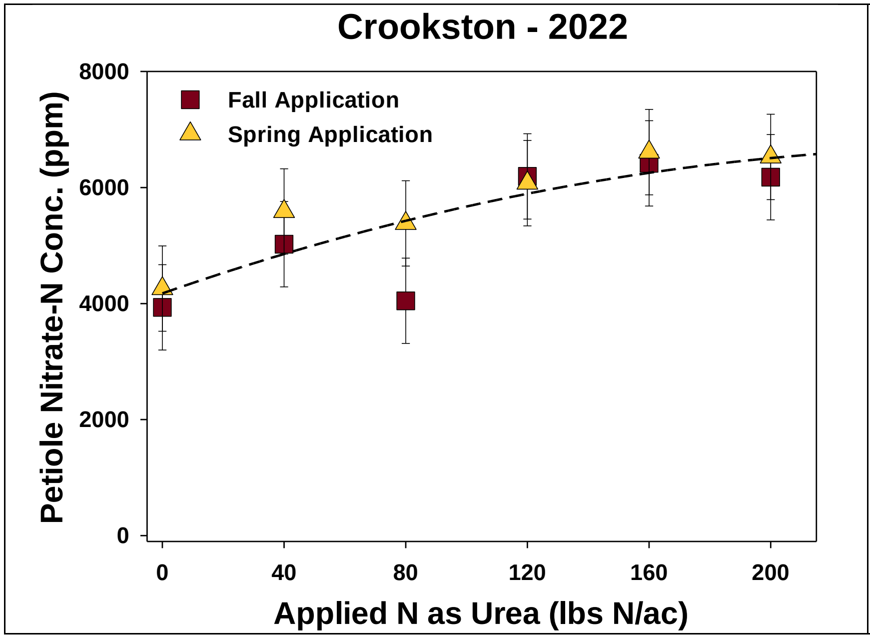

Figure 5b. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July petiole nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2022 growing season. Samples were collected but had not been analyzed at the time of this report.

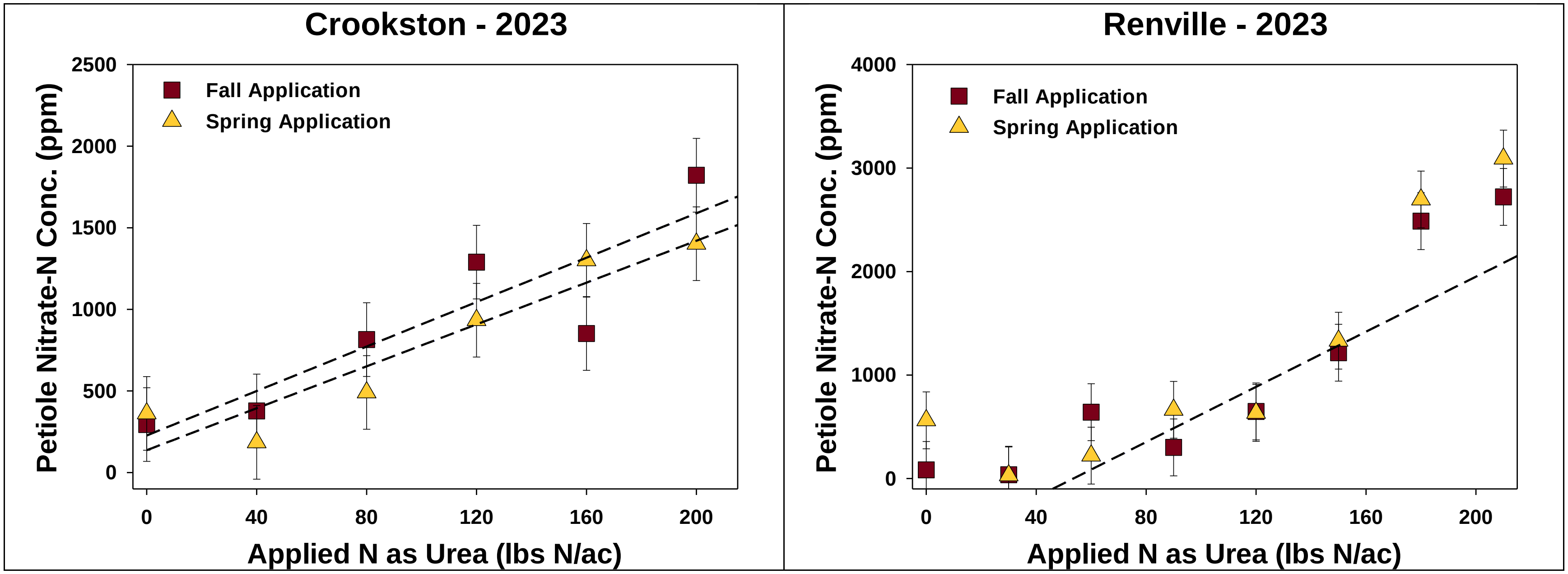

Figure 5c. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July petiole nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2023 growing season. Samples were collected but had not been analyzed at the time of this report.

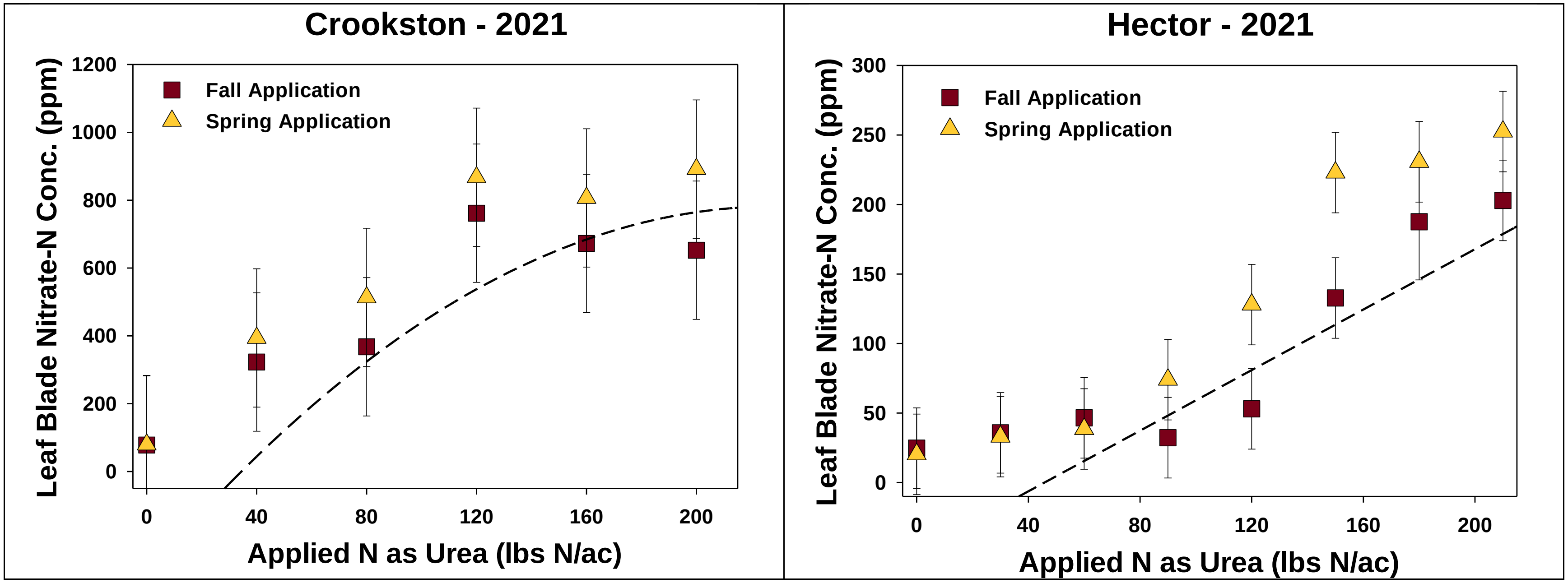

Figure 6a. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July leaf blade nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2021 growing season. Samples were collected but had not been analyzed at the time of this report.

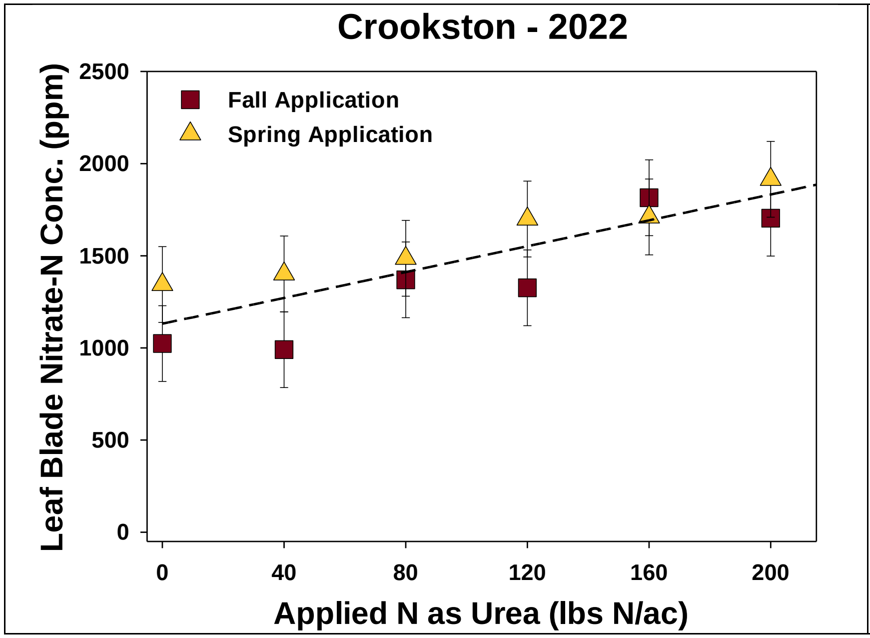

Figure 6b. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July leaf blade nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2022 growing season. Samples were collected but had not been analyzed at the time of this report.

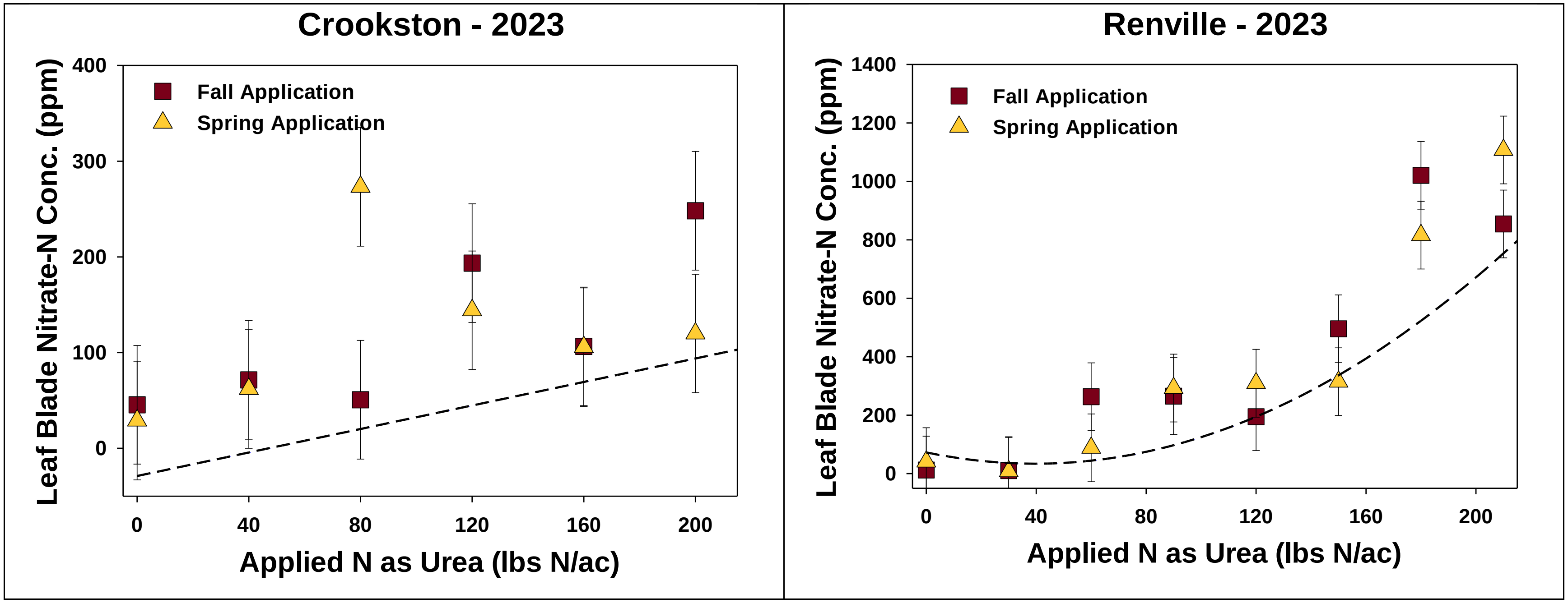

Figure 6c. Effect of nitrogen applied as fall or spring urea (data averaged for both timings) on sugar beet early to mid-July leaf blade nitrate measured from the newest fully developed leaf at two Minnesota locations during the 2023 growing season. Samples were collected but had not been analyzed at the time of this report.

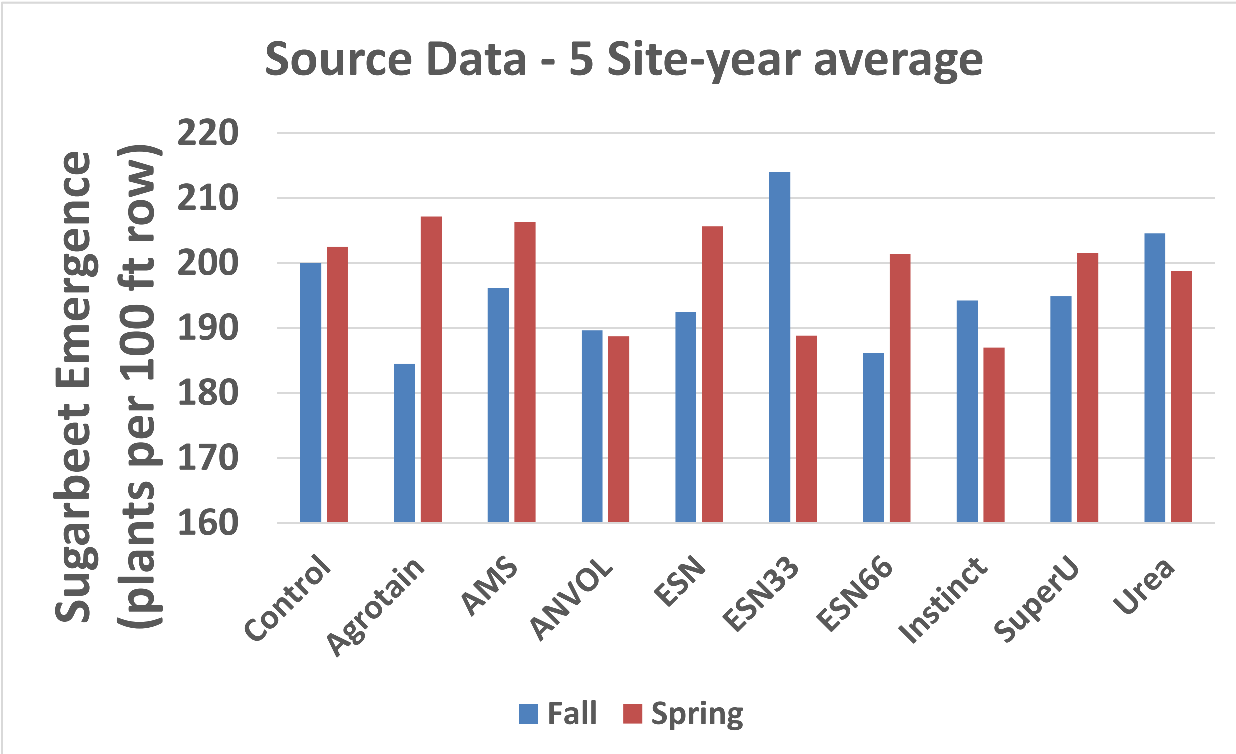

Figure 7. Summary of the impact of urea timing and source impacts on sugarbeet emergence following application of multiple urea sources and ammonium sulfate applied at 45 lbs. of N per acre summarized across 5 site-years for northern and southern Minnesota locations.

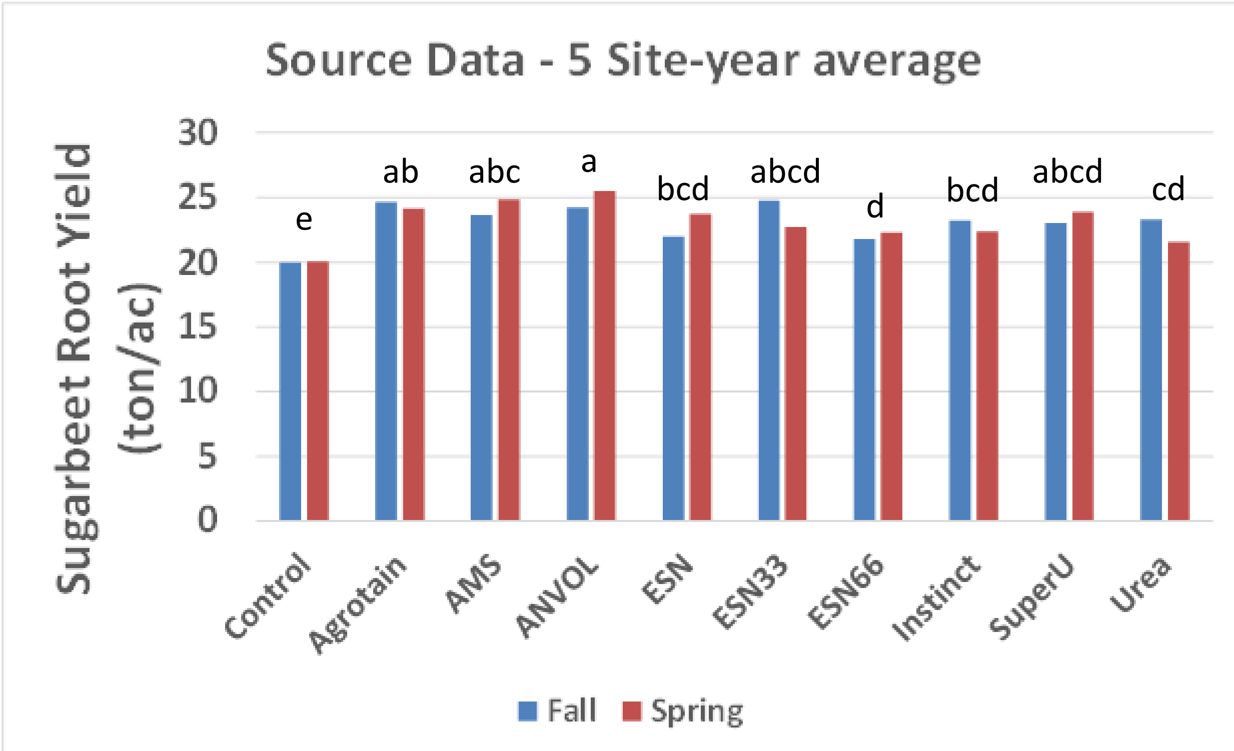

Figure 8. Summary of the impact of urea timing and source impacts on sugarbeet root yield following application of multiple urea sources and ammonium sulfate applied at 45 lbs. of N per acre summarized across 5 site-years for northern and southern Minnesota locations.

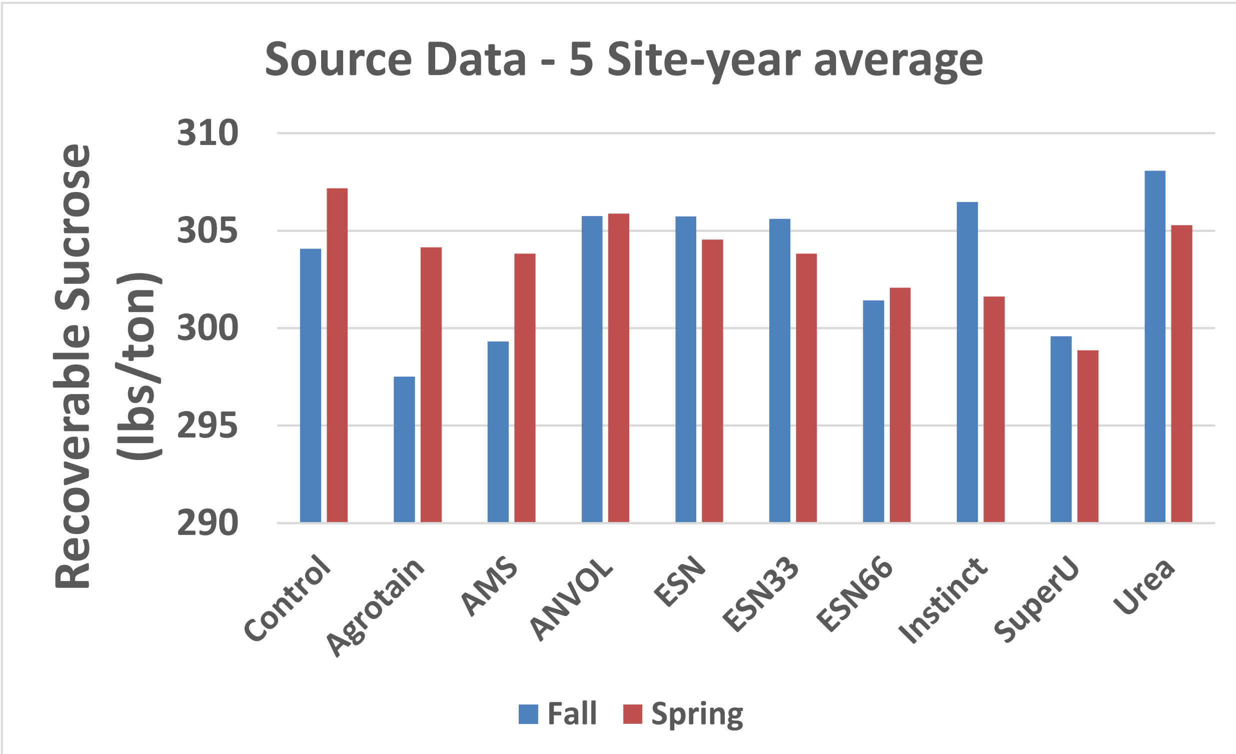

Figure 9. Summary of the impact of urea timing and source impacts on sugarbeet extractable sucrose per ton following application of multiple urea sources and ammonium sulfate applied at 45 lbs. of N per acre summarized across 5 site-years for northern and southern Minnesota locations.

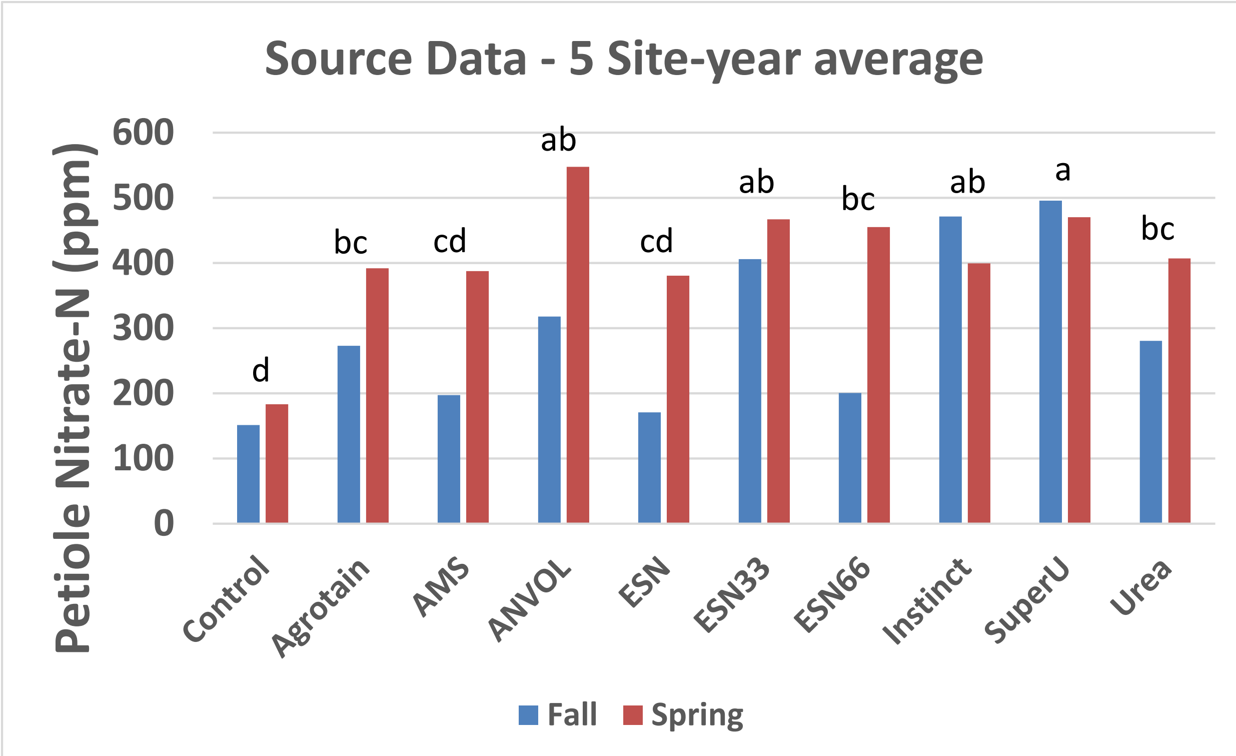

Figure 10. Summary of the impact of urea timing and source impacts on sugarbeet petiole nitrate-N concentration from the uppermost fully developed leaf 40-50 days after planting following application of multiple urea sources and ammonium sulfate applied at 45 lbs. of N per acre summarized across 5 site-years for northern and southern Minnesota locations.

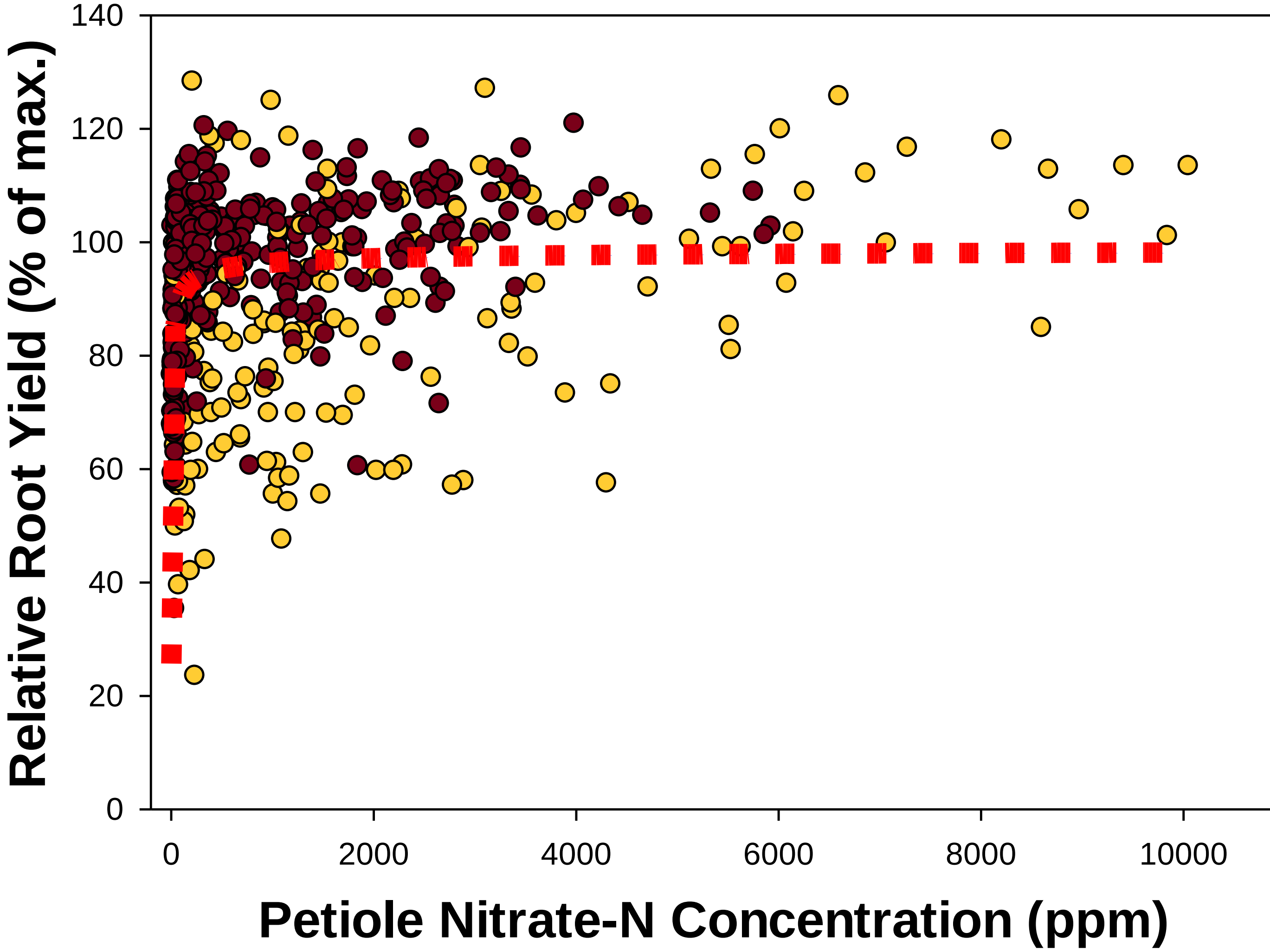

Figure 11. Relationship between relative sugar beet root yield (% of site maximum yield) and nitrate concentration in the uppermost fully developed petiole sampled in early- to mid-July roughly 40 to 50 days after planting. Maroon dots represent southern MN locations. Gold dots represent data from Crookston.

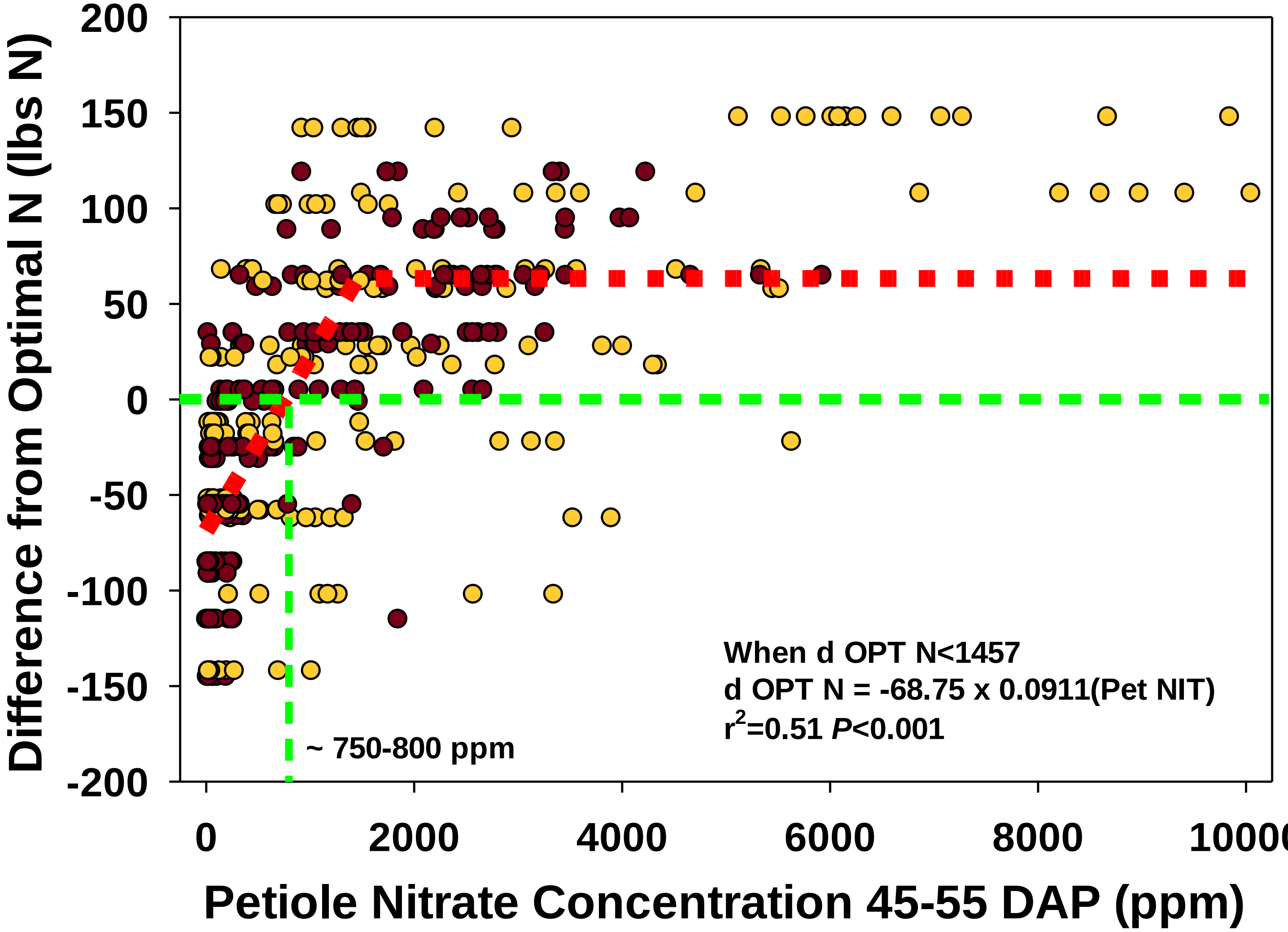

Figure 12. Relationship between the difference in the amount of N applied per plot and the amount of N required for optimum root yield and nitrate concentration in the uppermost fully developed petiole sampled in early- to mid-July roughly 40 to 50 days after planting. Maroon dots represent southern MN locations. Gold dots represent data from Crookston.

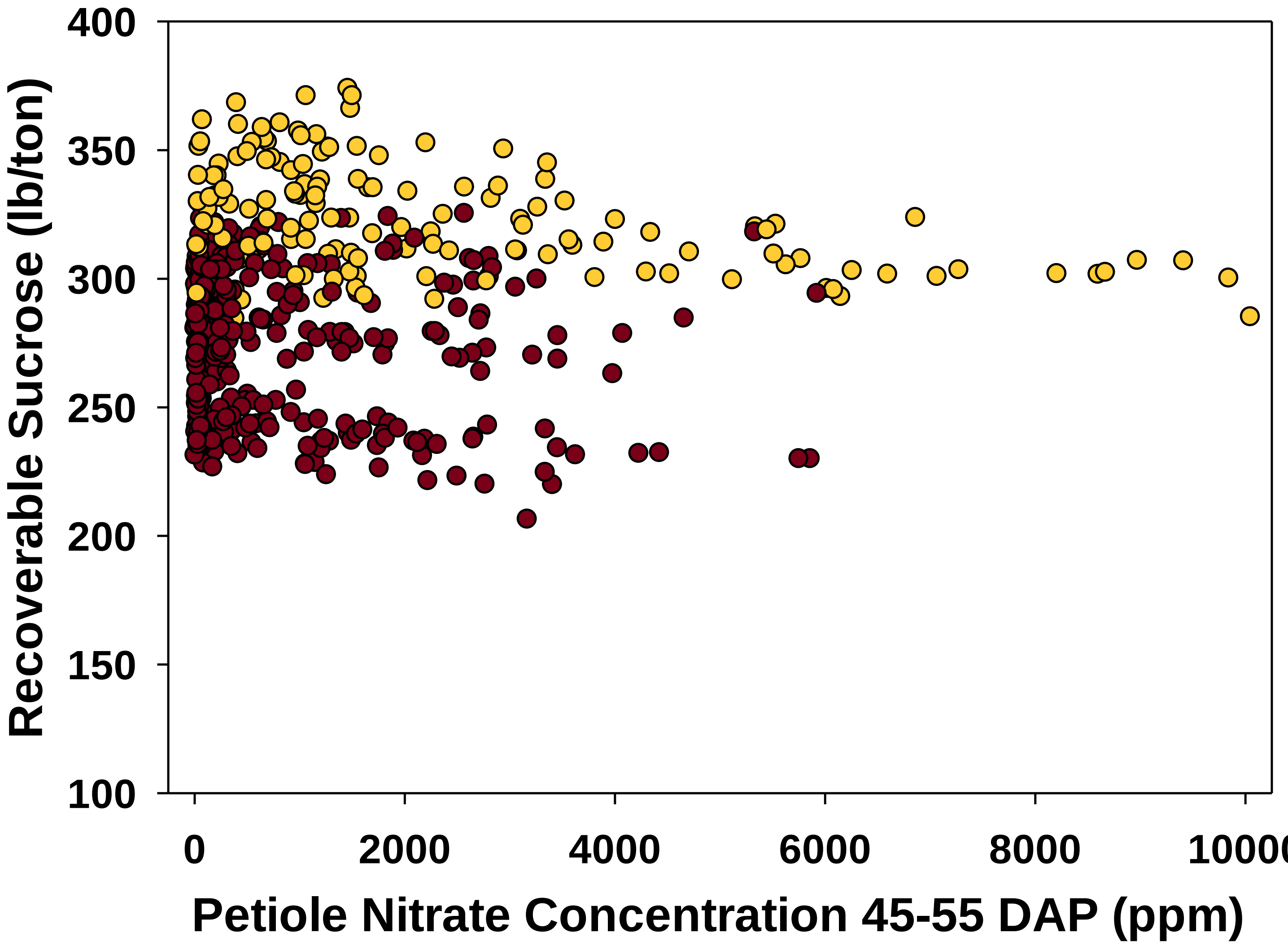

Figure 13. Relationship between recoverable sucrose per ton and nitrate concentration in the uppermost fully developed petiole sampled in early- to mid-July roughly 40 to 50 days after planting. Maroon dots represent southern MN locations. Gold dots represent data from Crookston.