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Spring Wheat Response to Fertilizer Nitrogen Following a Sugar Beet Crop Varying in Canopy Color

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Abstract. Experiments were conducted in the Red River Valley (RRV) of Minnesota to determine the responses of hard red spring wheat (*Triticum aerstivum* L.) to fertilizer N after a sugar beet (*Beta vulgaris* L.) crop that varied spatially in canopy color and N content. A color aerial photograph was acquired of the sugar beet field just prior to root harvest, and six sites were selected that varied in sugar beet canopy color, three each of green and yellow canopy sites. The three green sugar beet canopies returned 369, 265, and 266 kg N ha^{-1} to the soil while the three yellow sugar beet canopies returned 124, 71, and 73 kg N ha^{-1} to the soil. Spring wheat response to fall-applied urea-N fertilizer (0, 45, 90, 135, and 180 kg N ha^{-1}) was determined the following year at each of the above antecedent canopy sites. Soil NO_3-N in the top 0.6 m of soil varied among the locations with a range of 35 to 407 kg NO_3-N ha^{-1} at the green canopy sites and 12 to 23 kg NO_3-N ha^{-1} at the yellow canopy sites. Application of fertilizer N according to traditional recommendation methods would have resulted in fertilizer applications at all three yellow canopy sites and two of the three green canopy sites. At the antecedent green sugar beet canopy sites, fertilizer N had little or no effect on spring wheat grain yields, grain N concentration, anthesis dry matter, and anthesis N content. In contrast, fertilizer N increased all four parameters at the antecedent yellow sugar beet canopy sites. The data indicate that fertilizer N management can be improved by using remote sensing to delineate management zones according to antecedent sugar beet canopy color.

Keywords: sugar beet canopy, nitrogen, spring wheat, remote sensing

Introduction

Nitrogen (N) fertilizer recommendations for hard red spring wheat, the crop that generally follows sugar beet in the Red River Valley (RRV), are based on soil NO_3-N in the top 0.6 m of the soil profile and the yield goal (Dahnke *et al.*, 1992; Rehm *et al.*, 1998). Soil sampling for NO_3-N analysis usually occurs immediately after sugar beet harvest or early the following spring. In either case, soil NO_3-N measurements reflect only the inorganic N available to the wheat, and the fertilizer recommendation does not consider potential N availability from the sugar beet canopies. Previous research has shown that 1 kg N in green, high N concentration sugar beet canopies is equivalent to approximately 0.5 kg fertilizer N to the following wheat crop (Abshahi *et al.*, 1984; Moraghan and Smith, 1996). However, 1 kg N in yellow sugar beet canopies is equivalent to approximately 0.25 kg fertilizer N (Moraghan and Smith, 1996).

The variable contribution of N in the sugar beet canopies has not been considered in the fertilizer recommendations for a spring wheat crop following sugar beet. At harvest time sugar beet canopies in the RRV of Minnesota and North Dakota can vary from bright yellow to dark green within the same field. Green canopy color is associated with chlorophyll content, which is in turn positively correlated with N concentration (Wolfe *et al.*, 1988). Yellow sugar beet canopies indicate low N status or deficiency levels and dark green canopies indicate N sufficiency levels. If sugar beet canopies have excess N concentrations, relative to sufficient levels, there may not be a noticeable difference in the green color because chlorophyll production will have reached a plateau at a lower N concentration (Blackmer and Schepers, 1995; Blackmer *et al.*, 1996b). Remote sensing such as aerial photographs can be useful in determining relative N status of crops over an entire field (Blackmer *et al.*, 1996a). Variation of sugar beet canopy color and N status within a sugar beet field or plot area can be determined from a digitized aerial photograph (Binford *et al.*, 1995; Moraghan *et al.*, 1996). Just prior to sugar beet root harvest in the RRV, these sugar beet canopies are chopped, shredded, and returned to the soil.

The objective of this experiment was to compare hard red spring wheat response to fertilizer N when grown on areas where sugar beet canopy returned to the soil the previous year was yellow or green. We hypothesized that remote sensing, in this case aerial photography, could be used to delineate a sugar beet field into different fertilizer N management zones based on the sugar beet canopy color.

Materials and methods

An 18 ha commercial sugar beet field at the Northwest Research and Outreach Center near Crookston, Minnesota, was selected as the test field. An aerial photograph was taken with Ektachrome 100 Professional Film (Eastman Kodak, Rochester, NY) from an elevation of 1500 m above the field surface in late September, 1995 about 4 days prior to sugar beet root harvest. Six sites within the field were selected based on visual determination of sugar beet canopy color (three green and three yellow) in the photograph (Figure 1). The classification of the soil at each of the six sites is shown in Table 1.

The color photograph was scanned and converted into a 24 bit true color digital image with a resolution of about 0.3 m^2 $pixel^{-1}$. Sugar beet canopy color was quantified by inputting the digital image into Adobe Photoshop Version 5.0 (Adobe Systems Inc., San Jose, CA) and determining the digital number for the primary colors of red, green, and blue at each of the six selected sites. Digital numbers are based on brightness of each color with values ranging from 0 to 255. Digital numbers for each primary color represent the average value from all the pixels (approximately 1350 pixels) within individual site areas. Selected sites were located within the digital image by using known field measurements and a grid overlaying the image loaded into Adobe Photoshop.

Canopy dry matter and N content were determined from three randomly selected 3.7 m sections of row (0.56 m spacing) within each site. Above ground plant material was

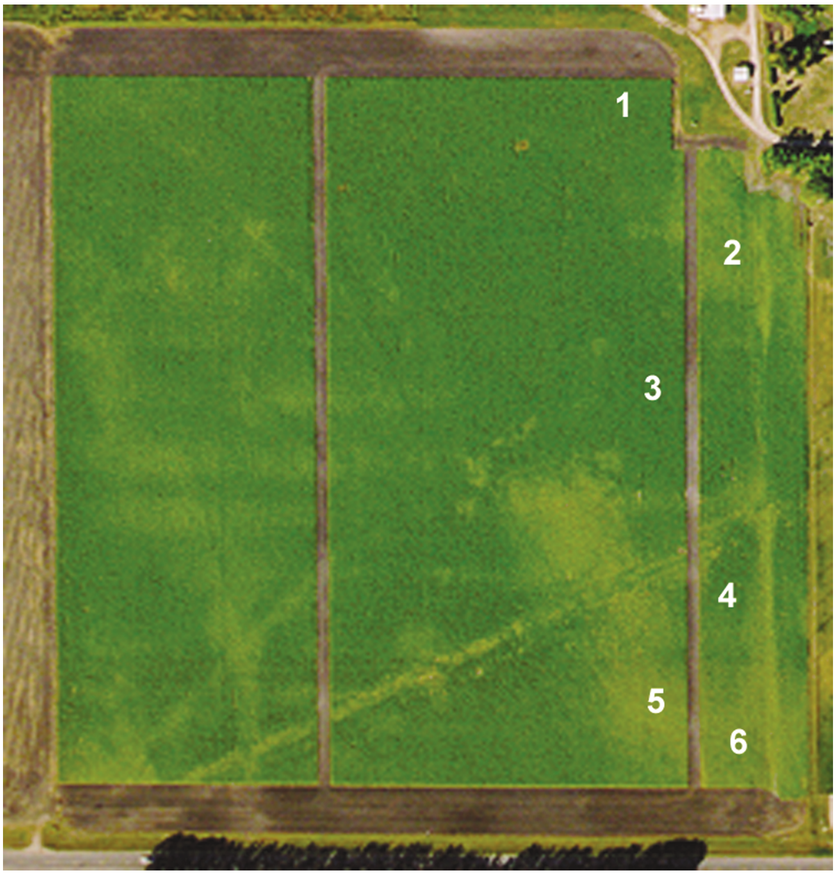

Figure 1. Color aerial photograph of sugar beet field 4 days prior to harvest with locations of the each of the six selected sites.

weighed, chopped, and mixed. Subsamples were taken, weighed, dried, and reweighed to determine total dry matter accumulation. Subsamples were then finely ground and analyzed for total N. A 0.4 m diameter metal disk was buried at each site and the actual experimental area was triangulated from the disk. Each disk was georeferenced with an OmniSTAR 7000 (OmniSTAR, Inc., Houston, TX) differential GPS unit. The entire field was tilled after sugar beet harvest. After tillage, the GPS receiver was used to relocate each buried disk and the experimental area was reestablished through triangulation measurement.

Nitrogen rate trials were established at each site with fall-applied urea-N fertilizer at rates of 0, 45, 90, 135, and 180 kg N ha^{-1}. The experimental design was a randomized complete block with four replications at each site. Individual plots were 2.1 m wide and 9.1 m long. Urea N fertilizer was broadcast and incorporated with a field cultivator. In the spring, plots were tilled with a field cultivator and hard red spring wheat (variety P2375) was then planted in 0.15 m wide rows at a seeding density of approximately 2,800,000 seeds ha^{-1}.

Table 1. Soil series and taxonomic classification names of soils located at each of the selected field sites

Site	Series	Soil classification
1	Glyndon	Coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
2	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquoll
3	Glyndon	Coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
4	Glyndon	Coarse-silty, mixed, superactive, frigid Aeric Calciaquoll
5	Bearden	Fine-silty, mixed, superactive, frigid Aeric Calciaquoll
6	Wyndmere	Coarse-silty, mixed, superactive, frigid Aeric Calciaquoll

Wheat plants were sampled at anthesis from four adjacent rows, 1.2 m in length. Plants were clipped at ground level, dried, and weighed to determine dry matter accumulation. Samples were then chopped, subsampled, finely ground, and analyzed for total N. At maturity a small plot combine was used to harvest grain from 10 rows, 4.1 m in length. Grain was dried and weighed to determine grain dry matter accumulation. A subsample was finely ground and analyzed for total N concentration.

Soil samples were collected from each control plot (0 kg N ha^{-1}) at each site in late fall after plot establishment. Three 3.75 cm cores were taken from each sampled plot, divided into 0.0–0.15, 0.15–0.30, 0.30–0.60, and 0.60–1.20 m depths, and composited. Nitrate-N was determined at all depth increments as well as bulk density to determine NO_3-N quantity.

Total N was determined in plant, grain, and soil samples using a salicylic acid modified Kjeldahl procedure (Nelson and Sommers, 1973). Nitrate-N was extracted with 1 M KCl from dried soil samples and measured by automated Cd-reduction procedures (USEPA, 1979).

Statistical analysis was done using Proc GLM procedures in the Statistical Analysis System Package (SAS, 1996) across sites (Gomez and Gomez, 1984) using single degree of freedom orthogonal contrasts (Steel and Torrie, 1980) to determine interactions of wheat fertilizer N response at sites that varied in sugar beet canopy characteristics. Regression analysis was used in the Proc GLM procedure (SAS, 1996) to analyze response of spring wheat to N rates at each site.

Results

Site characteristics

Site selection was based on visual determination of green and yellow sugar beet canopy color in an aerial photograph (Figure 1). The average digital numbers for the red, green, and blue colors of all the pixels within each site are shown in Table 2. Both red and green primary color digital numbers were greater at yellow canopy sites than green canopy sites. The lower digital number observed for the green color at the designated green canopy sites (Figure 2) indicate a darker green color at these sites as compared to the higher digital number and lighter green color observed for the yellow designated sites.

Table 2. Digital numbers for red, green, and blue colors extracted from a digital image of the sugar beet field and relevant data from the sugar beet canopy at the six selected sites with a field

					Sugar beet canopy		
		Image primary colors				Nitrogen	
Site	Canopy color	Red	Green	Blue	Dry matter	Conc	Content
		Digital number*			Mg ha^{-1}	g kg^{-1}	kg ha^{-1}
1	Green	58.5	102.1	14.6	11.6	32.0	369
2	Yellow	93.8	120.1	16.6	7.0	17.8	124
3	Green	49.6	99.8	9.7	7.8	33.8	265
4	Green	66.7	105.8	3.5	9.9	26.7	266
5	Yellow	108.7	119.7	7.0	4.9	14.3	71
6	Yellow	99.0	113.9	6.0	4.7	15.6	73

* Digital numbers represent the average brightness of each of the primary colors in the pixels representing each experimental site.

Sugar beet canopy dry matter and N content at each site are shown in Table 2. Nitrogen concentration in the green canopies was greater than 26 g N kg^{-1} and less than 18 g N kg^{-1} in yellow canopies. Total canopy N content ranged from 265 to 369 kg N ha^{-1} in green canopies and 71 to 124 kg N ha^{-1} in yellow canopies. Greater N contents in green canopies, compared to those in yellow canopies, resulted from both greater canopy dry matter yields and greater N concentrations in the green canopies.

The selected sites varied in the amount of NO_3-N in the soil profile (Table 3). Yellow canopy sites had less NO_3-N in the 0.0 to 0.6 m and 0.0 to 1.20 m soil depths than green canopy sites. Soil NO_3-N was similar among yellow canopy sites with approximately 10

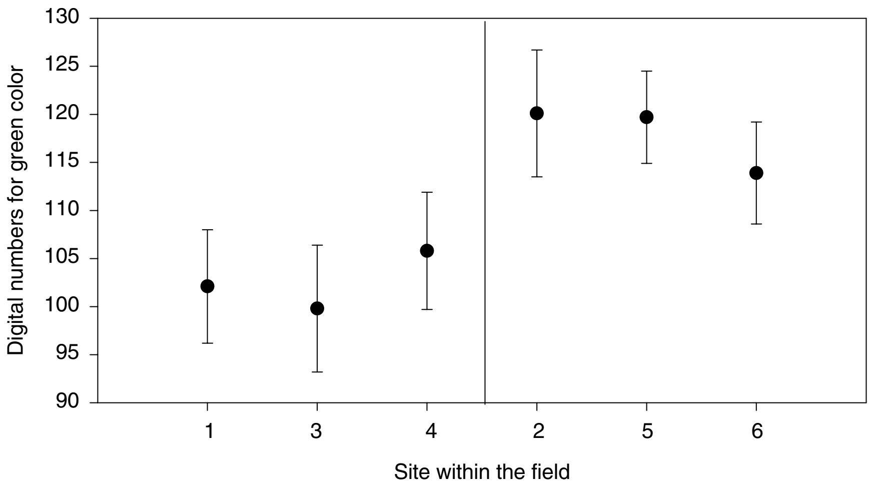

Figure 2. Average digital numbers and standard deviations for the green color of all the pixels within each of the six experimental sites within the field.

Table 3. Soil nitrate-N measured in the control plots (mean of 0 kg N ha-1 plots) at each site after sugar beet harvest in fall 1996

Site	Canopy color	Specific depth increments (cm)				Cumulative depths (cm)		
		0–15	15–30	30–60	60–120	0–30	0–60	0–120
		kg NO_3-N ha^{-1}						
1	Green	107	158	142	113	265	407	520
2	Yellow	10	5	8	9	15	23	32
3	Green	51	22	37	122	73	110	232
4	Green	21	7	7	20	28	35	55
5	Yellow	6	3	3	6	9	12	18
6	Yellow	9	4	5	8	13	18	26

to 20 and 20 to 30 kg NO_3-N ha^{-1} in the 0.0 to 0.6 m and 0.0 to 1.2 m soil depths, respectively. However, green canopy sites varied in the soil NO_3-N with 35 to 407 and 55 to 520 kg NO_3-N ha^{-1} at the same respective soil depths. Site 1 had the greatest soil NO_3-N and Site 4 the least soil NO_3-N of the green canopy sites. Low soil NO_3-N levels in the yellow canopy sites is not surprising since the sugar beet canopies were showing visual signs of N deficiency. Soil variability as well as past management probably caused the large variation among the six sites in the field. Historical records indicate that Site 1, and possibly Site 3, were located in an area that received large amounts of manure up to 30 years prior. The overall data indicate that soil NO_3-N can be presumed to be low in yellow sugar beet canopy areas, but large variation in soil NO_3-N can occur in green sugar beet canopy areas.

Spring wheat growth characteristics

The spring and early summer period weather was dry in 1997. Consequently, the spring wheat crop showed visual signs of drought stress early in the growing season at Site 3 and, especially, Site 4. Early developed tillers died at these two sites, but new tillers developed later in the season. Main culms at Sites 3 and 4 were flowering at the time of the anthesis plant sampling, but tillers were small. At all other sites, tillers were headed and entering the anthesis growth stage at the time of plant sampling. Final grain harvest was delayed until tiller heads at Sites 3 and 4 were mature.

Lodging after anthesis probably limited grain yield at Sites 1, 2, 5, and 6. Lodging was not quantified, but lodging at Site 1 was uniform over the entire plot area with no differentiation among N rate treatments. At sites 2, 5, and 6 lodging primarily occurred at N rates of 90 kg N ha^{-1} and greater. Lodging tended to become more severe as N rates increased. Site 6 had the most severe lodging among the yellow sugar beet canopy sites.

Spring wheat dry matter and N accumulation at anthesis

The response of total dry matter (TDM) and total nitrogen (TN) accumulation to N rates varied with the anticedent sugar beet canopy colors (Table 4). At green canopy sites

Table 4. Single degree freedom orthogonal contrasts of selected variables over the all six sites selected on sugarbeet canopy color at harvest

	Statistical significance[b]			
	Whole plant at anthesis		Grain	
Source of variation[a]	Total DM	Total N	Yield	N Conc
G1 vs G3 & G4	N/A	N/A	**	***
G3 vs G4	**	***	ns	**
G vs Y by N Lin	***	***	***	***
G vs Y by N Quad	***	*	***	ns
G1 vs G3 & G4 by N Lin	*	*	ns	ns
Y2 vs Y5 & Y6 by N Lin	***	**	***	***
Y2 vs Y5 & Y6 by N Quad	*	ns	ns	*
Y5 vs Y6 by N Lin	ns	ns	***	*

[a] G and Y represent green sugar beet canopy and yellow sugar beet canopy, respectively. G and Y associated with a number represent the individual sites with that canopy color. N Lin and N Quad represent contrasts to test linear and quadratic response of individual measured variables to applied N rates.
[b] Nonsignificant, 0.05, 0.01, 0.001, and not applicable due to significant interactions represented by ns, *,** , ***, and N/A, respectively.

there was no response to increasing applied N for either TDM or TN (Figures 3 and 4). Conversely, at the yellow canopy sites TDM exhibited a quadratic response (Figure 3) and TN a linear increase (Figure 4) to increasing N application.

Spring wheat grain yield and N concentration at maturity

The response of grain yield and grain N concentration to fertilizer N varied with the sugar beet canopy colors (Table 4). At the green sugar beet canopy sites there was no response to fertilizer N for grain yield (Figure 5). Whereas, at the yellow canopy sites grain yield tended to display a quadratic increase in response to increasing fertilizer N application, especially for Sites 2 and 5 (Figure 5). Similarly, for grain N concentration, the greatest response to fertilizer N occurred at the yellow canopy sites, especially Sites 5 and 6 (Figure 6).

Discussion

The response of hard red spring wheat to applied fertilizer N on land previously cropped to sugar beet varied within the studied field with two primary factors contributing to this variability. First, soil NO_3-N was not uniformly distributed within the field (Table 3). Second, soil N mineralization, which was dependent on the antecedent sugar beet canopy (Table 2), varied across the six field sites.

A composite soil sample from cores taken within each of the six sites used in this study resulted in an average of 101 kg NO_3-N ha^{-1} in the upper 0.6 m of soil (average of values in Table 5). The average grain yield goal was 3.37 Mg ha^{-1} (average of grain

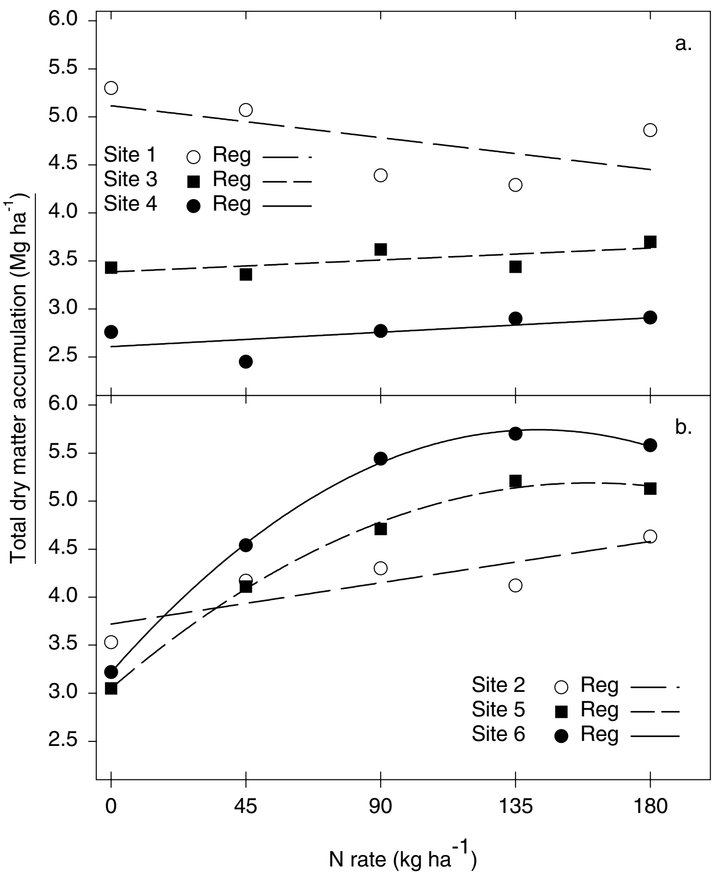

Figure 3. Spring wheat total dry matter accumulation at anthesis at each green sugar beet canopy site (a) and yellow sugar beet canopy site (b) over applied fertilizer N rates. Best fit equations for each site are below followed by significance level in parenthesis. (a) Site 1: $y = 5.11 - 3.69E - 3x$ $R^2 = 0.365$ ($P = 0.281$); Site 3: $y = 3.38 + 1.38E - 3x$ $R^2 = 0.462$ ($P = 0.207$); Site 4: $y = 2.61 + 1.63E - 3x$ $R^2 = 0.394$ ($P = 0.256$). (b) Site 2: $y = 3.72 + 4.77E - 3x$ $R^2 = 0.723$ ($P = 0.068$); Site 5: $y = 3.05 + 2.68E - 2x - 8.39E - 5x^2$ $R^2 = 0.996$ ($P = 0.004$); Site 6: $y = 3.21 + 3.54E - 2x - 1.24E - 4x^2$ $R^2 = 0.999$ ($P = 0.001$).

yield goals in Table 5). Using the average soil NO_3-N level and the average grain yield goal the traditional soil NO_3-N test equation (Dahnke *et al.*, 1992) would have resulted in a fertilizer recommendation of 39 kg N ha^{-1} over the entire field. This would have been an underestimation of recommended fertilizer N in some areas of the field and an overestimation in other areas (Table 5). If each site would have been considered one grid in a grid soil sampling strategy, field variability in soil NO_3-N would have been accounted for, but errors in fertilizer recommendations would still have occurred. Recommended fertilizer N for each site, based on soil NO_3-N and maximum grain yield observed at each site, are shown in Table 5. At sites where the antecedent sugar beet canopy was yellow and soil NO_3-N levels were relatively low, the recommended rate of fertilizer N was from 115 to 136 kg N ha^{-1}. The amount of fertilizer N required to obtain

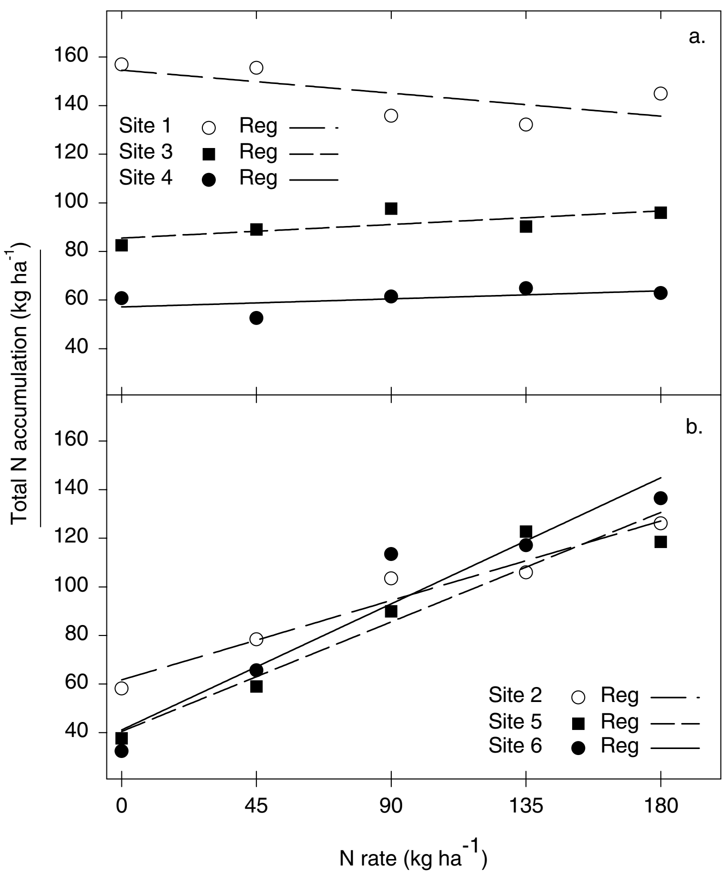

Figure 4. Spring wheat total nitrogen accumulation at anthesis at each green sugar beet canopy site (a) and yellow sugar beet canopy site (b) over applied fertilizer N rates. Best fit equations for each site are below followed by significance level in parenthesis. (a) Site 1: $y = 154 - 1.05E - 1x\,R^2 = 0.446\,(P = 0.218)$; Site 3: $y = 85.5 + 6.21E - 2x\,R^2 = 0.542\,(P = 0.156)$; Site 4: $y = 57.2 + 3.69E - 2x\,R^2 = 0.311\,(P = 0.328)$. (b) Site 2: $y = 61.7 + 3.63E - 1x\,R^2 = 0.957\,(P = 0.004)$; Site 5: $y = 40.5 + 5.00E - 1x\,R^2 = 0.926\,(P = 0.009)$; Site 6: $y = 41.1 + 5.76E - 1x\,R^2 = 0.922\,(P = 0.010)$.

the given yield goal was very similar to recommended fertilizer rates at Sites 2 and 5 (Table 5). Grain yields at Site 6 were probably much lower than would have resulted had lodging not occurred. Nevertheless, other response parameters measured also indicated a response to relatively large amounts of fertilizer N applications at all three sites with antecedent yellow sugar beet canopies. Where the antecedent sugar beet canopy was green, fertilizer N was recommended at two of the three sites, Sites 3 and 4 (Table 5). Response to applied fertilizer N from any of the measured response parameters was minimal or non-existent at both of these sites (Figures 3, 4, 5, and 6). The soil NO_3-N test does not have the ability to estimate or account for soil-N mineralization variability that may occur in the field. Nitrogen mineralization from the addition of 265 kg N ha^{-1} (Site 3) and 266 kg N ha^{-1} (Site 4) in the antecedent sugar beet canopies caused the overestimation of fertilizer N required as predicted from the soil NO_3-N test.

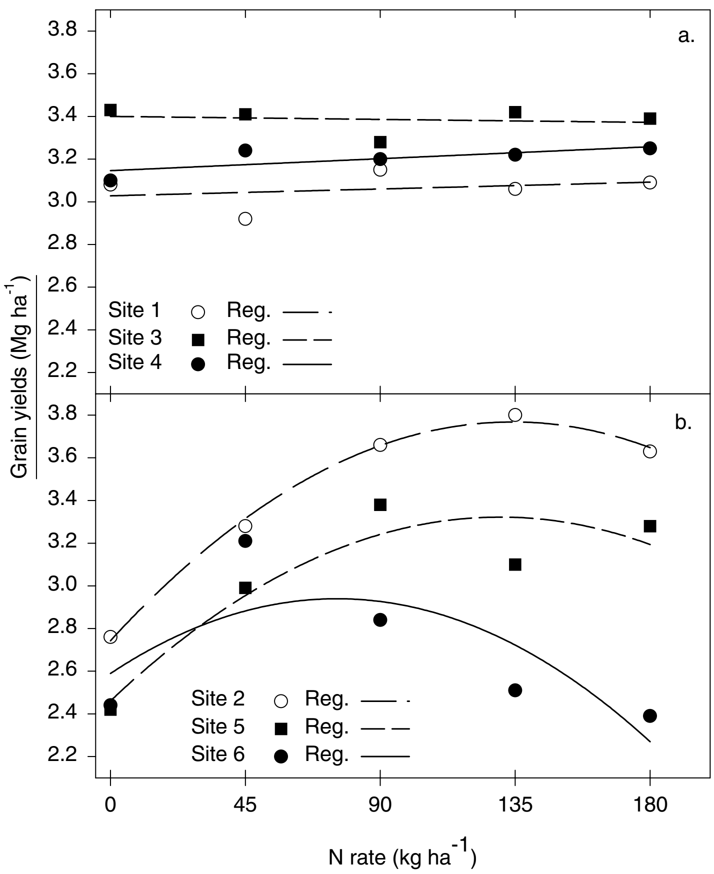

Figure 5. Spring wheat grain yield at each green sugar beet canopy site (a) and yellow sugar beet canopy site (b) over applied fertilizer N rates. Best fit equations for each site are below followed by significance level in parenthesis. (a) Site 1: $y = 3.03 - 3.33E - 4x$ $R^2 = 0.080$ ($P = 0.643$); Site 3: $y = 3.40 - 1.61E - 4x$ $R^2 = 0.034$ ($P = 0.766$); Site 4: $y = 3.14 + 6.61E - 4x$ $R^2 = 0.558$ ($P = 0.147$). (b) Site 2: $y = 2.75 + 1.53E - 2x - 5.67E - 5x^2$ $R^2 = 0.996$ ($P = 0.004$); Site 5: $y = 2.46 + 1.33E - 2x - 5.13E - 5x^2$ $R^2 = 0.865$ ($P = 0.135$); Site 6: $y = 2.59 + 9.29E - 3x - 6.16E - 5x^2$ $R^2 = 0.596$ ($P = 0.404$).

Remote sensing of the sugar beet canopy late in the growing season correctly identified those areas in the field where no fertilizer N response was observed in a subsequent spring wheat crop (green canopy sites), but the traditional NO_3-N test erroneously predicted a response. Likewise remote sensing also correctly identified those areas where a subsequent response by spring wheat to fertilizer N was observed (yellow canopy sites). Green sugar beet canopies supplied from 265 to 369 kg N ha^{-1} to the soil, and previous research indicates this would be equivalent to approximately 130 to 185 kg fertilizer N ha^{-1} (Abshahi *et al.*, 1984; Moraghan and Smith, 1996). Where the antecedent sugar beet canopy was yellow, the canopy supplied 71 to 124 kg N ha^{-1} to the soil, which should be equivalent to approximately 20 to 30 kg fertilizer N ha^{-1} (Moraghan and Smith, 1996). Previous experience with remote sensing is that yellow sugar beet canopy sites in the RRV tend to contain approximately 20 kg NO_3-N ha^{-1} or less in the soil

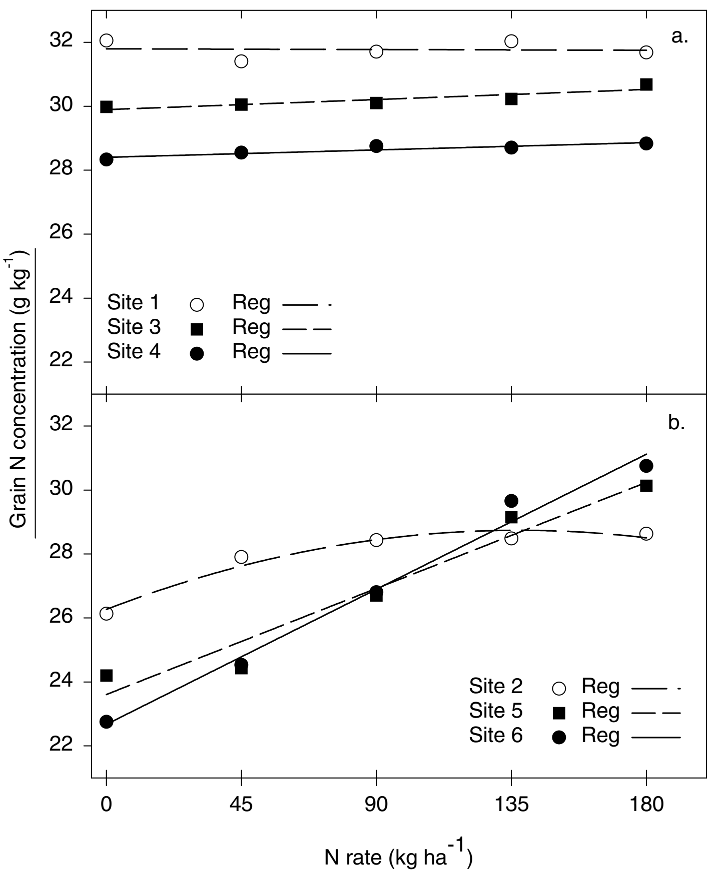

Figure 6. Spring wheat grain N concentration at each green sugar beet canopy site (a) and yellow sugar beet canopy site (b) over applied fertilizer N rates. Best fit equations for each site are below followed by significance level in parenthesis. (a) Site 1: $y = 31.8 - 2.78E - 4x\ R^2 = 0.005$ ($P = 0.907$); Site 3: $y = 29.9 - 3.50E - 3x\ R^2 = 0.802$ ($P = 0.040$); Site 4: $y = 28.4 + 2.56E - 3x\ R^2 = 0.844$ ($P = 0.028$). (b) Site 2: $y = 26.3 + 3.60E - 2x - 1.31E - 4x^2\ R^2 = 0.957$ ($P = 0.043$); Site 5: $y = 23.6 + 3.68E - 2x\ R^2 = 0.950$ ($P = 0.005$); Site 6: $y = 22.7 + 4.69E - 2x\ R^2 = 0.986$ ($P = 0.001$).

(Moraghan, 1998), which was consistent with observations in the current study (Table 5). Consequently, there may be little need to soil sample yellow sugar beet canopy sites for the soil NO_3-N test and prediction of optimal fertilizer N recommendations. Soil NO_3-N can be assumed to be 20 kg ha^{-1} and fertilizer N recommendations calculated using the same equations as with the traditional soil NO_3-N test.

Soils in the RRV of Minnesota and North Dakota are usually frozen during the winter and plant-N mineralization and denitrification losses of N are typically negligible during this period. In areas with overwinter leaching or denitrification losses, such as is found in parts of the European sugar beet growing area (Destain *et al.*, 1990; Thomsen and Christensen, 1996), remote sensing of sugar beet canopies may not be effective for making fertilizer N recommendations for the subsequent crop.

Table 5. Fertilizer N recommendation based on soil NO_3-N levels after sugar beet harvest and wheat grain yield goal based on maximum (averaged over 4 replications) observed yield

Sites[a]	Canopy color	Soil NO_3-N 0–60 cm	Grain yield goal	Recommended fertilizer N	Observed fertilizer N[b]
		kg ha^{-1}	Mg ha^{-1}	kg ha^{-1}	kg ha^{-1}
1	Green	407	3.15	0	0
2	Yellow	23	3.80	136	135
3	Green	110	3.43	33	0
4	Green	35	3.25	101	0
5	Yellow	12	3.38	128	130
6	Yellow	18	3.21	115	75
Avg		101	3.37	86	57

[a] Lodging at Sites 5 and, especially, at Site 6 probably reduced grain yield potential.
[b] Fertilizer N rate at which grain yields were maximized were determined by the first derivative of the quadratic equations that best fit the data (Figure 5).

The data presented in this experiment indicate that delineation of sugar beet fields into green and yellow canopy zones through remote sensing is a useful tool to direct soil NO_3-N testing and making site-specific fertilizer N recommendations. Our data indicate that no fertilizer N is required in green canopy zones regardless of the level of soil NO_3-N. In yellow canopy zones the soil NO_3-N test used to make fertilizer N recommendations was very close to that observed. However, the data also indicate that it may be possible to make fertilizer recommendations in these yellow canopy zones without a soil test by assuming 20 kg NO_3-N. Yellow canopy zones can be fertilized with GPS-equipped, variable-rate N fertilizer applicators. Remote sensing should provide a useable tool to manage fertilizer N such that excessive N applications and N leaching from the root zone are reduced. However, future work in this area is required involving more detailed image analysis and ground truthing to determine if there are critical levels of green color in the sugar beet canopy that can be used to identify transition areas between yellow and green zones.

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References

Abshahi, A., Hills, F. J. and Broadbent, F. E. 1984. Nitrogen utilization by wheat from residual sugar beet fertilizer and soil incorporated sugar beet crops. Agron. J. **76**, 954–958.

Binford, G. D., Blackmer, T. M. and Schepers, J. S. 1995. Remote sensing techniques for characterizing nitrogen status in sugar beets. Journal of Sugar Beet Research **32**, 129.

Blackmer, T. M. and Schepers, J. S. 1995. Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. J. Prod. Agric. **8**, 56–60.

Blackmer, T. M., Schepers, J. S., Varvel, G. E. and Meyer, G. E. 1996a. Analysis of aerial photography for nitrogen stress within corn fields. Agron. J. **88**, 729–733.

Blackmer, T. M., Schepers, J. S., Varvel, G. E. and Walter-Shea, E. A. 1996b. Nitrogen deficiency detection using reflected shortwave radiation from irrigated corn canopies. Agron. J. **88**, 1–5.

Dahnke, W. C., Fanning, C. and Swenson, L. J. 1992. Fertilizing wheat and rye. N. Dak. State Univ. Circ. SF-712.

Distain, J. P., Francois, E. and Guiot, J. 1990. Fertilizer nitrogen budgets of ^{15}N-labelled sugarbeet (*Beta vulgaris*) tops and $Na^{15}NO_3$ dressings split-applied to winter wheat (*Triticum aestivum*) in microplots on a loam soil. In: *Plant Nutrition—Physiology and Application*, edited by M. L. van Beusichem (Kluwer Academic Publishers, Amsterdam), p. 557–559.

Gomez, K. A. and Gomez, A. A. 1984. *Statistical Procedures for Agricultural Research*. (John Wiley and Sons, New York, NY), p. 316.

Moraghan, J. T. 1998. Sugar beet canopy type and accumulation of plant nitrogen as delineated by aerial photography and global positioning systems. Commun. Soil Sci. Plant Anal. **29**, 2953–2959.

Moraghan, J. T., Horsagar, K., Ellingson, R., Halland, J., Kieffer, K. and Richards, M. 1996. Yield variability in sugar beet fields. N. Dak. Extension Service Sugar Beet Research and Extension Reports **26**, 138–146.

Moraghan, J. T. and Smith, L. J. 1996. Nitrogen in sugar beet tops and the growth of a subsequent wheat crop. Agron. J. **88**, 521–526.

Nelson, D. W. and Sommers, L. E. 1973. Determination of total nitrogen in plant material. Agron. J. **65**, 109–112.

Rehm, G., Schmitt, M. and Eliason, R. 1998. Fertilizing wheat in Minnesota. Univ. of Minnesota Extension Service FO-3772-C.

SAS Institute, 1996. *SAS/STAT User's Guide, Version 6.11 ed.* (SAS Institute, Cary NC, USA).

Steel, R. G. D. and Torrie, J. H. 1980. *Principles and Procedures of Statistics, 2nd ed.* (McGraw-Hill Publishing Co., New York, NY), p. 363.

Thomsen, I. K. and Christensen, B. T. 1996. Availability to subsequent crops and leaching of nitrogen in ^{15}N-labelled sugar beet tops and oilseed rape residues. J. Agric. Sci. **126**, 191–199.

USEPA. 1979. Methods for chemical analysis of water and wastes, EPA-6004-79-020 (United States Environmental Protection Agency, Cincinnati, OH).

Wolfe, D. W., Henderson, D. W., Hsiao, T. C. and Alvino, A. 1988. Interactive water and nitrogen effects on senescence of maize: II. Photosynthetic decline and longevity of individual leaves. Agron. J. **80**, 865–870.