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Evidence for the Ability of Active-Optical Sensors to Detect Sulfur Deficiency in Corn

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ABSTRACT

Prediction of S deficiency is difficult due to poor soil test relationship to crop response. The purpose of this article is to provide evidence that the use of an N-sufficient area established for use as a standard for active-optical (AO) sensor directed in-season N application could also serve to detect S deficiency in corn (*Zea mays* L.). Nitrogen rate experiments at Oakes and Arthur, ND, exhibited corn upper-leaf yellowing in high N treatments while control treatments (0 N) were greenest. Two AO sensors were utilized to record red normalized differential vegetation index (NDVI) and red edge NDVI values. The high-N treatment had the lowest NDVI readings, and the control treatments had the highest NDVI readings. Within 24 h, an application of gypsum containing 22 kg S ha^{-1} was applied. Seven days following S application, the sites were revisited. The AO sensors were again used to record red NDVI and red edge NDVI. At both sites, the high N treatment had the highest NDVI readings and the control treatment had the lowest NDVI readings. These experiments indicate that high N treatment can increase the severity of S deficiency in corn. If a lower NDVI reading is recorded in a high N application area than in the surrounding area, S deficiency may be present.

Core Ideas

- Sulfur deficiency in corn is difficult to anticipate using soil analysis.
- When N availability is low, the affect of S deficiency in corn is minimized.
- When N availability is high, the affect of S deficiency is intensified.
- Active-optical sensors can be used along with an N-sufficient area to reveal S deficiency.

In the United States, soil S levels are decreasing and reports of S deficiency in crops is increasing in part due to decreased emissions from gaseous S-emitting industries (Schwab, 2008; Franzen, 2015a). Greater S demand from higher crop yields and continued loss of topsoil through wind and water erosion has also contributed to greater frequency and severity of S deficiency in corn and other crops. Predicting S deficiency in soils is difficult due to the poor relationship between the S soil test and crop response (Pagani and Echeverria, 2011; Franzen, 2015a, 2015b). Presence of S deficiency in corn can be better determined at physiological maturity with plant tissue analysis (Weil and Mughogho, 2000; Pagani and Echeverria, 2011), but its value to a corn grower at that growth stage is mostly academic, because there is little ability to correct the S deficiency and increase crop yield.

There is minimal literature that documents an interaction between N and S application from low plant available S soils. Some studies have attempted to determine the interaction of N with low S soil levels (Pagani et al., 2009); however, the lack of corn grain yield response with added S indicates that although the researchers tried to find sites where S deficiency was present, they were unsuccessful. The authors of this note have observed a tendency for corn fertilized with high N rates in some experiments to be more yellow in color at V5 and until maturity than lower N and control N treatments in previous years, but there was no attempt to record color differences. Malhi and Gill (2007), working on a low S availability Gray Luvisol soil in Saskatchewan documented in a S and N application study in canola (*Brassica napus* L.), that at the control S rate canola yield declined with N rate at four sites. Only when sufficient S was applied to overcome the S deficiency did N rate increase yield. In an Australian N and S rate study (Brennan and Bolland, 2008), canola grain yield decreased at the 0 kg ha^{-1} S rate when N was applied. Only when S was applied (13–34 kg ha^{-1}) did N rate increase yield.

Active-optical sensors have not been utilized in diagnosing S deficiency to date. Active-optical sensor research has mainly focused on its use to help direct N fertilizer rates in-season for various crops. The two main approaches to the use of AO

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Abbreviations: AO, active optical; CC, Crop Circle; GS, GreenSeeker; INSEY, in-season estimate of yield; NDVI, normalized differential vegetation index; NIR, near infrared.

sensors in directing in-season N application are to establish an N-sufficient area within the field to use as a standard at the time of side-dress application (Raun et al., 2001) and the use of a virtual reference within the field as the standard (Holland and Schepers, 2013). A virtual reference would be one or more visually “greener” areas that would theoretically be a field area with sufficient N.

The purpose of this note is to alert researchers and others that higher N rate on S deficient land may increase the severity of S deficiency symptoms in corn, and that AO sensor data might be used to evaluate S adequacy using a high-N application area as a standard, and to record crop improvement following S application.

MATERIALS AND METHODS

Two N-rate study sites, one near Oakes, ND, and another site near Arthur, ND, where S deficiency was observed, were part of a larger 2013 study with 20 locations. Of the 18 sites where S deficiency was not observed, six with the sandiest soils were fertilized with 22 kg ha^{-1} S as gypsum pre-plant and exhibited no S deficiency symptoms throughout the growing season. No pre-plant S was applied to the Oakes and Arthur sites detailed in this note. The soil series at the Arthur and Oakes site were Glyndon sandy loams (coarse-silty, mixed, superactive, frigid Aeric Calciaquoll) (Soil Survey Division Staff, 2014). The previous crop at both sites was soybean [*Glycine max* (L.) Merr]. Tillage at the Arthur site was conventional-till, with a chisel plow set to a 20-cm depth utilized in fall 2012 and a field cultivator set at 10-cm depth used spring 2013 prior to planting. The Oakes site is continuous no-till/strip-tillage, with soybean solid-seeded and corn strip-till, with the strip shank set at a 15-cm depth made in the spring. Corn in North Dakota is subject to possible mineral nutrient deficiency from N, P, K, S, and Zn. No other nutrient deficiencies to corn have been observed in our state. The relevant plant available soil nutrients at both sites are presented in Table 1. Soil pH values between 5.2 and 8.4 support maximum yields of corn in this region. Fertilizer P (Oakes and Arthur) and K (Arthur) was applied to both sites based on soil test results. The experimental design at each site was a randomized complete block with four replications and six treatments: check (no added N), 45, 90, 134, 179, and 224 kg N ha^{-1}. The N was applied as ammonium nitrate by hand within a week of planting. Each experimental unit was 6.1 m in length and 3.05 m in width. At Oakes (Table 1), soil P, K, and Zn were considered adequate for corn production. At Arthur, soil K was less than that considered adequate for corn production, therefore 67 kg ha^{-1} K_2O as fertilizer grade potassium chloride was applied to the entire experimental site at the time of N application and the farmer-cooperator applied 18 kg ha^{-1} P_2O_5 with the seed at planting as ammonium polyphosphate. The S deficiency symptoms at Oakes were observed at growth stage V6 on 18 June (497 growing degree days after planting), and those at Arthur at growth stage V6 on 20 June (516 growing degree days after planting). From 1 May to 18 June at Oakes, the area received 110 mm rainfall. At Oakes, 22 kg ha^{-1} S as gypsum was applied broadcast by hand over all treatments on 19 June. During the following 3 d Oakes received 75 mm rainfall.

The Arthur area received 137 mm rainfall from 1 May to 20 June. At Arthur, 22 kg ha^{-1} S as gypsum was applied broadcast by hand over all treatments on 20 June. Over the following 3 d, 50 mm of rainfall fell at the site. The Oakes site was revisited with sensors 7 d following S application at V7 (682 growing degree days after planting). The Arthur site was revisited with sensors 8 d following S application at V7 (704 growing degree days after planting).

The two AO sensors used in these experiments emit modulated light pulses from diodes to generate particular wavebands which are absorbed by plant tissues. In the GreenSeeker (GS) (Trimble Navigation Limited, Sunnyvale, CA) bursts of light are emitted from diodes (light emitting diodes, LED) such that red (R) (660 nm) and near infrared (NIR) (710 nm) pulses alternately for 1 ms at 40,000 Hz, with each burst composed of about 40 pulses. The illuminated area in our study was positioned perpendicular to the direction of travel, with a footprint of 61 cm wide and 1.5 cm in the row direction. According to Trimble, the GS field of view is constant for heights between 60 and 120 cm above the canopy. The operators of the GS consistently operated the sensors at 60 to 70 cm above the corn canopy. Outputs from the sensor are NDVI, defined as [(NIR – visual wavelength)/(NIR + visual wavelength)] (Sharma et al., 2015).

The source of light for the Holland Scientific Crop Circle (CC) sensor (ACS-470, Holland Scientific, Lincoln, NE) is a modulated polychromatic LED array which can emit and simultaneously measure light spectrums from 430 to 850 nm bands. For these experiments, we used two filters in the visible range (red 650 nm, red edge 730 nm) and one filter in the NIR

Table 1. Plant available soil analysis from the Oakes and Arthur locations. The sulfur soil test was not utilized, since it is non-diagnostic in this region (Franzen, 2015b).

Site	Depth	Nitrate-N†	Olsen P‡	K§	pH	OM¶	Zn#
	cm	kg ha^{-1}	g kg^{-1}			g kg^{-1}	
Oakes	0–15	10	11	210	5.4	33	1.9
	15–60	30	na††	na	na	na	na
Arthur	0–15	11	9	110	6.6	22	1.2
	15–60	23	na	na	na	na	na

† Nitrate-N determined using cadmium reduction (Gelderman and Beegle, 2015).

‡ Olsen P method detailed in Frank et al. (2015).

§ Plant available K from a dry soil sample, Warncke and Brown (2015).

¶ Organic matter using loss on ignition, Combs and Nathan (2015).

Plant available Zn using DTPA extraction, Whitney (2015).

†† na indicates analysis not conducted.

(760 nm). The sensor was calibrated using software provided by Holland Scientific. Values for CC measurements were the mean of measurements obtained within 6.1 m length of row. Outputs of the sensor are reflectance values that allow calculation of the vegetation indices red NDVI and red edge NDVI (Sharma et al., 2015). The formulas for red NDVI and red edge NDVI follow:

$$\text{Red NDVI}=\frac{\text{NIR}-\text{Red}}{\text{NIR}+\text{Red}}$$

$$\text{Red Edge NDVI}=\frac{\text{NIR}-\text{Red Edge}}{\text{NIR}+\text{Red Edge}}$$

The CC readings were taken 60 to 70 cm over the top of one interior corn row in each experimental unit and the row was noted so that subsequent sensing passes from the GS and CC would be conducted on the same row. The illuminated footprint of readings, based on the height utilized in these experiments, was approximately 30 cm wide by 14 cm in the row direction. The NDVI was calculated within the CC instrument with built-in software, whereas the GS reflectance values were stored in a text file by the sensor software and NDVI values were calculated post-process using Microsoft Excel 2013.

For each experimental unit, the GS and CC readings consisted of 30 to 50 reflectance measurements. The red NDVI or red edge NDVI were calculated on the means of the reflectance measurements. Means for each treatment area were calculated by using in-house programs for GS and CC raw data developed for Excel (Franzen, 2012). The in-season estimate of yield (INSEY) was calculated by dividing the sensor reading by the growing degree days from the date of planting to sensing.

Coefficients of determination (r^2) were calculated for relationships using the SAS procedure PROC REG for Windows V 9.2 (SAS Institute, Cary, NC). Analysis of variance was determined using PROC GLM.

RESULTS AND DISCUSSION

The qualitative symptoms of S deficiency intensified with increase in N rate at Oakes and Arthur with maximum visual light green to yellow color observed with the highest (224 kg ha^{-1}) N application at V6 growth stage (Fig. 1). The control treatment (0 kg N ha^{-1}) was observed to be the most healthy and darkest green in color. These results are consistent with what is known regarding plant S mobility. When S is taken up by plants, it is distributed to tissues where it is needed, usually newly forming growth (Mengel and Kirkby, 1987). However, when S is deficient, S is not normally translocated from older tissues to new growth (Bouma, 1967). When N is deficient, N-containing compounds are deconstructed in older plant tissues and these compounds, some containing S, are translocated to newer tissues (Cliquet and Mariotti, 1990; Malagoli et al., 2005). Therefore, if N is deficient along with S, S becomes mobile in the plant because the breakdown of protein in older plant tissues through proteolysis release amino acids, including the S-containing amino acids cystine, cysteine, and methionine, which are then translocated to younger plant tissues. However, when N is not limiting, as it was at Oakes and Arthur where N was added to the N rate treatments, S became immobile, and the intensity of the S deficiency was greater at the higher N rates. At 18 additional sites in the 2013 N rate experiments, high N treatments were the greenest compared to the control.

Fig. 1. Oakes site at V6. Yellowest areas are the 220 kg N ha^{-1} treatments and greener areas are the control treatments. Greenest area in the foreground received 12 kg S ha^{-1} as ammonium thiosulfate at planting in a grower-applied side-band.

At Arthur, all V6 INSEY values of the 224 kg ha^{-1} rate were less than the control (Table 2). At Oakes, the V6 CC red edge INSEY value was less than that of the control and GS red and CC red INSEY values of the control were not less than the 224 kg ha^{-1}. In an N rate experiment, this is opposite what is expected, since N rate would normally increase leaf area index and subsequent red NDVI readings and red edge NDVI would

Table 2. GreenSeeker (GS) and Crop Circle (CC) INSEY values before (V6) and after (V7–V8 and V12) S applications in the control and 220 kg N ha^{-1} treatments at Arthur and Oakes.

Site and sensor	Wavelength	Before S, V6		After S, V7–V8		V12	
		Control	224 kg N ha^{-1}	Control	224 kg N ha^{-1}	Control	224 kg ha^{-1}
Arthur							
GS	Red	0.000693	0.000627†	0.000823	0.000789	0.000718	0.000774*
CC	Red	0.000612	0.000534†	0.000764	0.000800	0.000728	0.000792*
	Red edge	0.000288	0.000243†	0.000382	0.000408	0.000326	0.000428*
Oakes							
GS	Red	0.000529	0.000517	0.000671	0.000736	0.000702	0.000773*
CC	Red	0.000394	0.000372	0.000743	0.000822	0.000710	0.000780*
	Red edge	0.000175	0.000157†	0.000342	0.000414*	0.000324	0.000410*

* Significant at $P < 0.05$.

† Significant at $P < 0.10$.

Fig. 2. (left) Control plot and (right) 220 kg N ha^{-1} treatment following S application at about V10.

also increase with N rate. At the V7–V8 readings at Arthur, there were no differences in GS or CC INSEY between the control and the 224 kg ha^{-1} rates, except with the CC red edge INSEY, where the INSEY value was greater than the control at the high N rate.

At V12, all AO sensor INSEY values were greater with the 224 kg ha^{-1} rates compared to the control (Table 1). Visually, high N treatments were the greenest, and the control treatment was lightest green in color (Fig. 2).

In a normal N rate experiment, INSEY readings for high N rates would be greater than the INSEY readings of the control at all growth stages. At these two sites, the high N rates at V6 had a lower INSEY value than the control. Following S application at V7–V8, there were either no significant differences in INSEY or the INSEY of the high N rate was greater, indicating that S deficiency was beginning to be relieved. At V12, the INSEY readings for the high N rate were all greater than that of the control, indicating that S nutrition was adequate and differences between AO sensor readings of the control treatment with the high-N treatment were being expressed. If in a S-deficient field situation the V6 INSEY of the visually "greenest" area had been used as a standard for in-season N application (Holland and Schepers, 2013), the wrong areas would have been fertilized, because the greenest area would have the least N availability causing the least severe S deficiency symptoms; the areas of highest N availability would have received the highest N rate and the area of the lowest N availability would have received the lowest N rate. Therefore, in areas where S deficiency is possible, the practice of using an N-sufficient area established through a high rate of N fertilizer would not only be useful as a standard for in-season N fertilization (Raun et al., 2001), but as a sentinel to indicate S deficiency.

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