Research Article

Received: 11 June 2019 Revised: 23 August 2019 Accepted article published: 31 August 2019 Published online in Wiley Online Library: 31 October 2019

(wileyonlinelibrary.com) DOI 10.1002/jsfa.10008

Evaluation of OptRx™ active optical sensor to monitor soybean response to nitrogen inputs

Saravanan Sivarajan,[a,b] Mohammadmehdi Maharlooei,[a,c*] Herman Kandel,[d] Ryan R Buetow,[e] John Nowatzki[a] and Sreekala G Bajwa[a,f]

Abstract

BACKGROUND: Active optical crop sensors have been gaining importance to determine in-season nitrogen (N) fertilization requirements for on-the-go variable rate applications. Although most of these active in-field crop sensors have been evaluated in maize (*Zea mays* L.) and wheat (*Triticum aestivum* L. emend. Thell.), these sensors have not been evaluated in soybean [*Glycine max* (L.) Merr.] production systems in North Dakota, USA. Recent research from both South Dakota and North Dakota, USA indicate that in-season N application in soybean can increase soybean yield under certain conditions.

RESULTS: The study revealed that OptRx™ sensor reading did not show any significant differences from early to midway through the growing season. The NDRE (normalized difference red edge) index data collected towards the end of the growing season showed significantly higher values for some of the N treatments as compared to others in both years. The NDRE values were strongly correlated to grain yield for both years under tiled ($r = 0.923$) and non-tiled ($r = 0.901$) drainage conditions. Certain soybean varieties displayed significantly higher NDRE values over both years. The three varieties tested across years, under both tiled and non-tiled conditions, showed a significant linear relationship between late August NDRE values and yield ($R^2 = 0.85$ for tiled and $R^2 = 0.81$ for non-tiled).

CONCLUSION: In this research, the study results show that the OptRx™ sensor has the potential to work for soybean as well, though later in the crop growing season. Further investigation is needed to confirm the use of OptRx™ sensor for variable rate in-season N applications in soybeans.

Keywords: OptRx™ sensor; nitrogen; soybeans; vegetation index

INTRODUCTION

Soybean [*Glycine max* (L.) Merr.] is one of the major crops grown in the United States. It has become an increasingly important crop in North Dakota, as the soybean area in the state grew by 27% from 2012 to 2016, with 2.43 million hectare harvested in 2016.[1] According to the US Department of Agriculture, the 2016 production of soybean in the nation was 117.3 million Mg with North Dakota ranking ninth in the nation with production of 6.78 million Mg.[1]

Ground based active optical crop sensors have been gaining importance for determining in-season fertilization requirements for variable rate nitrogen (N) applications[2–6] in field crops such as maize (*Zea mays* L.) and wheat (*Triticum aestivum* L. emend. Thell.). There are several in-field active optical sensors available on the market, including Trimble handheld Greenseeker™ (Trimble Navigation Limited, Sunnyvale, CA, USA), OptRx™ (Ag Leader Technology, Inc., Ames, IA, USA), Crop Circle™ ACS-210 (Holland Scientific, Lincoln, NE, USA), and SPAD™ meter (Minolta SPAD-502; Minolta Corp., Ramsey, NJ, USA). These active optical sensors calculate vegetative indices such as normalized difference vegetation index (NDVI) to direct in-season N application in various crops. Most vegetative indices can also be determined using passive sensors through aerial and satellite imageries to develop N rate recommendations. There are issues for aerial and satellite images including cloud cover and the time lapse between when the image is taken and when the image becomes available to the grower. Conversely, the active optical sensors can be integrated into a fertilizer applicator to sense the N needs of the crop and make the variable rate application in one pass of the equipment.

Ground based active optical sensors emit their own source of light and determine the vegetative index by measuring the light

* Correspondence to: M Maharlooei, Department of Biosystems Engineering, Shahid Bahonar University of Kerman, Kerman, Iran. E-mail: maharlooei@uk.ac.ir

a Department of Agricultural & Biosystems Engineering, North Dakota State University, Fargo, ND, USA

b VIT School of Agricultural Innovations and Advanced Learning (VAIAL), Vellore Institute of Technology, Vellore, India

c Department of Biosystems Engineering, Shahid Bahonar University of Kerman, Kerman, Iran

d Department of Plant Sciences, North Dakota State University, Fargo, ND, USA

e Agronomy Research Division, Dickinson Research Extension Service, North Dakota State University, Dickinson, ND, USA

f College of Agriculture & Montana Agricultural Experiment Station, Montana State University, Bozeman, MT, USA

reflected back at the sensor. Active sensors are less expensive, relatively small in size, readily available to be used throughout the growing season, not affected by ambient lighting conditions, and can work both during day and night. Active sensors have been used in the past to manage N application to various crops, primarily maize and wheat.[5,7,8] Crop Circle ACS-210 active optical canopy sensor was used to determine side dress N rates in maize at the V6–V7 growth stages and shown that the relative green normalized difference vegetation index (GNDVI) was strongly related to the calculated economic optimum nitrogen rate (EONR).[9] A study on in-season N stress in maize showed that the N stress could be detected using a SPAD meter and N rate algorithms could be developed to make variable rate N applications between the V8–V12 growth stages of maize.[10] It was reported that sensor guided N rate applications based on algorithms could out-yield the uniform N rates chosen by producers.[5] One of the passive optical sensing methods that were successfully developed for detecting N status of maize was the GreenIndex™ using a cell phone camera that was developed into an app by Spectrum Technology (Spectrum Technologies, Inc., Aurora, IL, USA). A digital imaging technique was developed to assess leaf N concentration in maize leaves from color images produced by GreenIndex™ called dark green color index (DGCI). The DGCI calculated from GreenIndex™ images were strongly correlated to SPAD meter readings with an r^2 of 0.91.[11] Although numerous studies on optical sensors have evaluated NDVI for assessing crop N status,[6,12,13] NDVI tends to become saturated at high chlorophyll content or abundant biomass conditions, and is very sensitive to canopy background brightness.[14] A new normalized index called red edge NDVI has been reported to be accurate in estimating crop N status at high chlorophyll content and high biomass conditions.[2,7,15,16] The red edge NDVI is influenced by leaf structure, canopy coverage and chlorophyll content but less affected by leaf orientation, sun elevation angle and soil background.[17]

Although N application is not typical in soybean as it is a N fixing plant, there has been considerable interest in recent years in using N fertilization to maximize yield. Research in the Upper Midwestern United States showed that N fertilization inconsistently increased yield. Yield varied due to soybean variety, trial location, and weather during the growing season. Applications of N seldom increased the net revenue for soybean.[18–20] A research study conducted in Kansas showed that late season N fertilization at the R3 growth stage (beginning pod) increased yield in irrigated soybeans.[21–23] Applying N in soybean with tile drainage also showed a yield increase of 2.8% as compared to no tile drainage.[24] Many of the commercially available crop sensors are being evaluated and tested in maize and wheat crops to determine N needs mid-season. These crop sensors have not yet been evaluated in soybean production systems in North Dakota and there are hardly any studies conducted on N application using these sensors in soybeans nationwide. The use of optical crop sensors may be able to identify the need for N in soybean on a real-time basis, and make appropriate in-season applications of N to avoid plant stress, and reduce potential yield losses. The objective of this research study was to evaluate the effectiveness of the OptRx™ active optical sensor in soybean over different growth stages and N application rates under tiled and non-tiled drainage systems for their ability to detect crop N status and estimate grain yield.

MATERIALS AND METHODS

Description of study area

The research experiments were conducted at North Dakota State University's research site NW22 (latitude 46° 55′ 57.10″ N, longitude 96° 51′ 32.49″ W) located in Fargo, North Dakota, USA, during the 2013 and 2014 crop seasons. The soil type at NW22 was silty clay up to 1.5 m with an average growing season rainfall of 406 mm. The North Dakota annual growing season is from April 1 to September 30 with an average maximum and minimum temperature of 23 °C and 10 °C, respectively. The average air temperature for the study area during the growing season is 16 °C and the frost-free period averages 130 days.

Table 1. Analysis of variance (ANOVA) results for different drainage, nitrogen (N) and variety treatments, main and interaction effects on normalized difference red edge (NDRE) values for 2013 and 2014 seasons

Days After Planting (DAP)	Drainage (main plot)	N-Treatments (sub-plot)	Variety (sub-plot)	Drainage × N-treat	Drainage × variety	Variety × N-treat	Drainage × variety × N-treat
	P > *F*						
2013							
48 (July, 3)	<0.001***	0.415	0.479	0.765	0.724	0.937	0.434
53 (July, 8)	0.092*	0.198	0.632	0.819	0.879	0.204	0.767
60 (July, 15)	<0.001***	0.027**	0.506	0.401	0.529	0.052*	0.220
79 (August, 5)	0.857	0.588	0.066*	0.910	0.308	0.995	0.192
87 (August, 13)	0.765	0.075b	0.029**	0.815	0.703	0.002***	0.460
2014							
55 (July, 9)	<0.0042***	0.849	0.405	0.161	0.999	0.478	0.847
67(July, 21)	0.051*	0.569	0.434	0.122	0.983	0.091*	0.328
81 (August, 4)	0.839	0.761	0.035**	0.288	0.577	0.599	0.189
95 (August, 15)	0.260	0.085*	0.971	0.659	0.311	0.214	0.784
102 (August, 22)	0.352	0.078*	0.700	0.595	0.820	0.391	0.798

*Means are significant at 0.1 confidence level.
**Means are significant at 0.05 confidence level.
***Means are significant at 0.01 confidence level.

Design of experiment

The experimental design for the study area was similar for the 2013 and 2014 growing seasons. A split plot with a randomized block design was used with drainage as the main factor, and N rate and variety as the sub-plot factors in a factorial arrangement. There were two drainage treatments (tiled and non-tiled), six N treatments, four varieties, and four replications, resulting in a total of 192 plots. The six N rates included 0, 56, 84 kg N ha^{-1} at emergence, 56 kg ha^{-1} at the R2–R3 growth stage, 28 kg ha^{-1} at emergence with 28 kg N ha^{-1} at the R2–R3 growth stage [N source used was urea (46-0-0)], and 56 kg N ha^{-1} as ESN (Agrium Inc, Canada) at emergence. The ESN refers to a polymer coated N fertilizer that improves N use efficiency and reduces loss of N to the environment.

In 2013 the four soybean varieties were 04403 (Mustang), 6088 (NuTech), PFS12R06 (Peterson Seed) and 90Y41 (Dupont Pioneer). In 2014 varieties were the same, except 0906R2 (Channel), which replaced 6088 because no seed was available in 2014. Soybean was planted with a four-row planter at 35.5 cm row spacing. Each experimental plot was 1.5 m wide and 7.6 m long. During the 2013 season, the crop was planted on May 16, emerged on June 11 at 26 days after planting (DAP), reached R2–R3 stage on July 17 at around 62 DAP, and was harvested on October 2 at 138 DAP. In the 2014 season, the soybean was planted on May 23, emerged on June 14 (20 DAP), reached R2–R3 stage on July 10 (56 DAP) and harvested on October 7 (138 DAP). The plots were harvested using a Wintersteiger Classic plot combine (Wintersteiger Ag, Ried, Austria). Yields are reported at 13% moisture content. The crop was managed according to the guidelines provided by the North Dakota Agriculture Experimental Station (NDAES), and monitored weekly for pests and diseases.

Data collection and analysis

The OptRx™ active optical sensor was tested and evaluated over 2 years. The sensor emits light at three wavelengths: 670 nm (red) and 730 nm (red edge) in the visible band, and 780 nm in the near infrared (NIR) band. This sensor calculates the normalized difference red edge (NDRE) vegetation index values as given in Eqn (1). The NDRE value represents the transition region between red and NIR portion that has higher sensitivity to chlorophyll absorption.[25,26]

$$\text{NDRE} = \frac{(\text{NIR} - \text{Red edge})}{(\text{NIR} + \text{Red edge})} \quad (1)$$

Two Ag Leader OptRx™ sensors mounted on a tractor were used to collect the NDRE values over the study area on five different dates throughout the growing season in 2013 (48 DAP, 53 DAP, 60 DAP, 79 DAP and 87 DAP), and 2014 (55 DAP, 67 DAP, 81 DAP, 95 DAP and 102 DAP). For the last two observation dates in the growing season, when the crop canopy was fully covered, the sensors were mounted on a hand pushed modified bicycle cart to collect the data and avoid causing damage to the soybeans. The sensor data were collected from the middle two rows to eliminate the edge effects. A polygon shape-file of each of the treatment plots was created in ArcGIS™ software (ESRI, Redlands, CA, USA) using global positioning system (GPS) measurements taken over the entire field. The NDRE data collected using OptRx™ were exported to ArcGIS™ software to calculate the mean NDRE value for the two middle rows in each experimental unit. Statistical analysis was performed for each date using the statistical software SAS (version 9.3, SAS Institute, Cary, NC, USA) to evaluate NDRE readings against different N application rates and soybean varieties. Analysis of variance (ANOVA) and treatment mean comparisons with a Fischer Protected LSD test were performed to evaluate treatment effects, at alpha level of 0.05. A regression analysis was conducted to evaluate the relationship between NDRE readings and yields of both years for the three same varieties grown each year, under tiled and non-tiled conditions. The crop yield was considered as the dependent variable and the NDRE values as the independent variable.

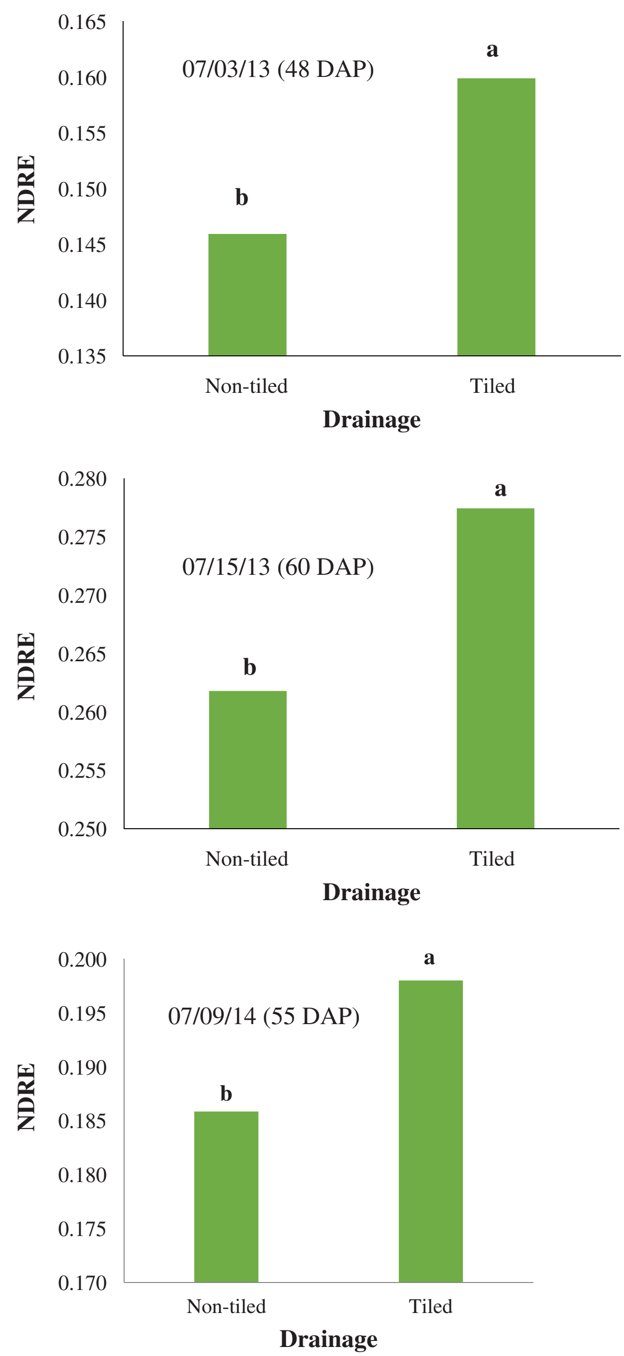

Figure 1. Normalized difference red edge (NDRE) index for tiled and non-tiled drainage treatments. Means with different letters are significantly different ($\alpha = 0.05$) between main treatments.

Table 2. Mean normalized difference red edge (NDRE) values for different nitrogen (N) treatments and plant growth stages

	2013				2014				
	Days after planting				Days after planting				
N-Treatment	48	60	79	87	55	67	81	95	102
0	0.156^{a}	0.256^{b}	0.326^{a}	0.315^{b}	0.195^{a}	0.255^{a}	0.335^{a}	0.350^{ab}	0.375^{a}
56E	0.153^{a}	0.276^{a}	0.328^{a}	0.317^{b}	0.192^{a}	0.249^{a}	0.326^{a}	0.329^{b}	0.356^{b}
84E	0.148^{a}	0.264^{ab}	0.326^{a}	0.335^{a}	0.191^{a}	0.244^{a}	0.329^{a}	0.348^{ab}	0.365^{ab}
56R2–R3	0.152^{a}	0.271^{a}	0.332^{a}	0.316^{b}	0.189^{a}	0.254^{a}	0.332^{a}	0.347^{ab}	0.361^{ab}
28E-28R2–R3	0.158^{a}	0.276^{a}	0.338^{a}	0.324^{ab}	0.188^{a}	0.250^{a}	0.341^{a}	0.360^{a}	0.373^{ab}
56E-ESN	0.150^{a}	0.270^{a}	0.338^{a}	0.335^{a}	0.196^{a}	0.260^{a}	0.338^{a}	0.349^{ab}	0.373^{ab}

Means in the column with the same letter are not significantly different at $P < 0.05$.

Table 3. Mean normalized difference red edge (NDRE) values for different varieties and plant growth stages

	2013				2014				
	Days after planting				Days after planting				
Variety	48	60	79	87	55	67	81	95	102
90Y41	0.151^{a}	0.274^{a}	0.321^{b}	0.316^{b}	0.189^{a}	0.249^{a}	0.318^{b}	0.347^{a}	0.366^{a}
4403	0.150^{a}	0.265^{a}	0.331^{ab}	0.317^{b}	0.194^{a}	0.258^{a}	0.338^{a}	0.345^{a}	0.365^{a}
12R06	0.154^{a}	0.268^{a}	0.341^{a}	0.327^{ab}	0.188^{a}	0.247^{a}	0.333^{ab}	0.350^{a}	0.366^{a}
6088	0.156^{a}	0.270^{a}	0.333^{ab}	0.336^{a}	–	–	–	–	–
0906R2	–	–	–	–	0.197^{a}	0.254^{a}	0.344^{a}	0.347^{a}	0.372^{a}

Means in the column with same letter are not significantly different at $P < 0.05$.

RESULTS

Measured NDRE

The average NDRE values for all the different treatments varied throughout the season, from 0.153 at 48 DAP to 0.324 at 87 DAP in 2013, and from 0.192 at 55 DAP to 0.367 at 102 DAP in 2014. Drainage treatments had a significant impact on the early season NDRE values in both years (Table 1). The tiled and non-tiled plots showed significant differences in NDRE values at 48 and 60 DAP in 2013, and 55 DAP in 2014. The NDRE values were significantly higher in tiled plots as compared to non-tiled plots (Table 1; Fig. 1).

There was no distinct trend observed for NDRE values for N treatments with different rates or DAP, but an increase in NDRE value was observed for different dates in both years (Table 2). The interactions of drainage × N treatment, drainage × variety, and drainage × N treatment × variety did not show any significant effect on NDRE in 2013 or 2014. However, the variety × N treatment interaction had an effect on NDRE index during the middle range of the growing season in both years (Table 1).

NDRE response to N treatments

The NDRE values and significance levels for different N treatments at different DAP for both years are shown in Table 2. The mean NDRE values ranged from 0.148 to 0.158 (48 DAP) and 0.315 to 0.335 (87 DAP) for 2013 crop season and NDRE values in 2014 year ranged from 0.188 to 0.196 (55 DAP) and 0.361 to 0.375 (102 DAP). The NDRE measured with the OptRx™ sensors did not show a response to N treatments at early or mid-season growth stages from around 48 DAP and 79 DAP, respectively in 2013, and around 55 to 81 DAP, respectively in 2014 (Table 2). However, significant differences in N treatments was found during later stages of crop growth for both years. During the 2013 season, significant differences were observed between some of the N treatments at around 60 and 87 DAP. Again, during 2014 crop season, significant differences were found for some of the N treatments at 95 and 102 DAP as the NDRE values were the lowest for the control treatment compared to other N treatments at both 60 and 87 DAP during the 2013 season, whereas in 2014, different N treatments followed a similar trend at 95 and 102 DAP, respectively (Table 2).

NDRE response to variety treatments

The NDRE values and significance levels for different varieties at different DAP for both years are shown in Table 3. There were significant differences in NDRE values observed only between some of the varieties at 79 DAP, 87 DAP in 2013, and 81 DAP in 2014. In 2013 the NDRE values, except for variety 6088 were higher

Table 4. Regression analysis of normalized difference red edge (NDRE) value *versus* yield for different varieties and drainage conditions for the late August NDRE values ($n = 12$, six nitrogen rates × 2 years). Each data point is an average of four replications

Variety	Drainage condition	Regression equations and R^2 **	Significance
90Y41	Tiled	$y = 11\,919x - 1357.6$ $R^2 = 0.79$	*
	Non-tiled	$y = 11\,329x - 1153.4$ $R^2 = 0.64$	*
4403	Tiled	$y = 18\,755x - 3324.5$ $R^2 = 0.79$	*
	Non-tiled	$y = 18\,764x - 34\,051.4$ $R^2 = 0.56$	*
12R06	Tiled	$y = 21\,470x - 4352.2$ $R^2 = 0.77$	*
	Non-tiled	$y = 17\,098x - 2998.6$ $R^2 = 0.65$	*

*Significance at 0.01.
**y = yield in kilograms per hectare, and x is NDRE value in late August.

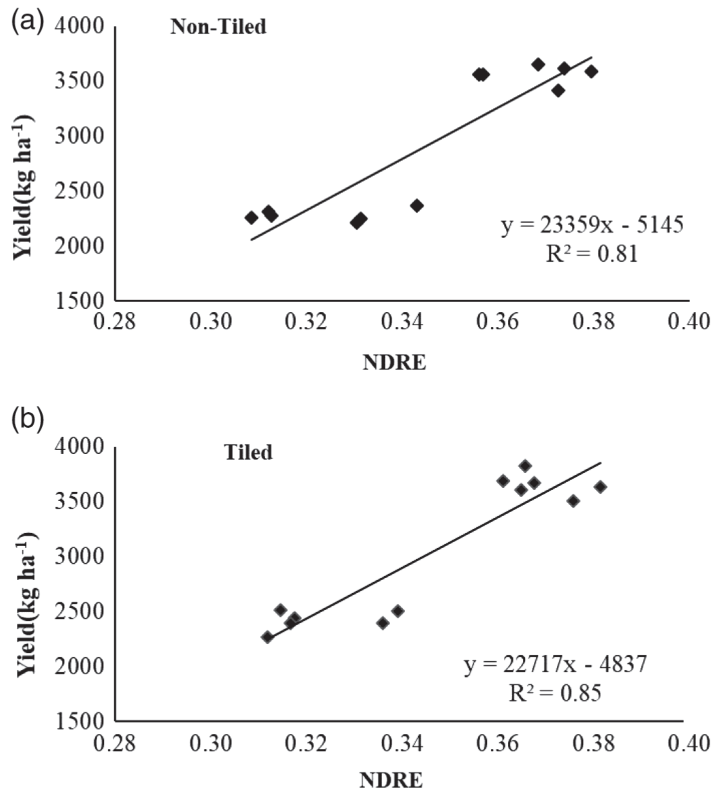

Figure 2. Relationship between yield and normalized difference red edge (NDRE) values for tiled and non-tiled. Both years for NDRE data ($n = 12$, six nitrogen rates × 2 years) recorded during late august are pooled together and correlated to yield. Each data point is an average of four replications and three varieties.

at 79 DAP as compared to 87 DAP. The variety 6088 showed the highest mean NDRE value at 87 DAP as compared to other varieties (Table 3).

Regression analysis

The linear relationship between NDRE values and yield for different soybean varieties are summarized in Table 4. The different soybean varieties under tiled and non-tiled drainage conditions were used to compare the coefficient of determination (R^2) between soybean yield and OptRx™ sensor NDRE values. The different varieties under both tiled and non-tiled conditions showed a linear NDRE relationship significantly related to soybean yield. The R^2 values were higher for tile drainage compared to non-tiled drainage conditions for 90Y41 and 12R06. Figure 2 indicates that the observed NDRE values, averaged across all three varieties used in this experiment, were more closely related to yield for the tiled plots ($R^2 = 0.85$) compared to non-tiled plots ($R^2 = 0.81$). In both cases the higher NDRE values resulted in higher soybean yield.

The relationship between NDRE values and yield for different N treatments under tiled and non-tiled drainage conditions are shown in Fig. 3. In general the late August NDRE readings were higher than the mid-August readings. However, the late August NDRE value was lower for the control and 56 kg N applied as urea or ESN for both the non-tiled and tiled conditions and for the split application (28–28 kg N at R2–R3) (Fig. 3). Soybean yields are provided for each N treatment for non-tiled and tiled conditions for 2013 and 2014. There were no significant differences in soybean yield for N treatments in non-tiled or tiled conditions for both years. In 2014 the control (no N applied) across the tiled treatments yielded less than any of the N treatments.

DISCUSSION

The NDRE values were significantly higher in tiled plots compared to non-tiled plots (Fig. 1) because of better crop growth due to better soil aeration and oxygen balance in the root zone. In 2013 the soybean grain yield was 2280 kg ha^{-1} in the non-tiled *versus* 2420 kg ha^{-1} in tiled, and in 2014, yield was 3565 kg ha^{-1} in non-tiled and 3655 kg ha^{-1} in tiled treatments. Although the statistical analysis showed that the yield increase due to tile was not significant, the increased yield trend (6.1% in 2013 and 2.5% in 2014) is consistent with previous research at the same experimental site.[27] Most likely the oxygen supply was reduced in the non-tiled area and affected the soybean yield due to waterlogged soil conditions[28] and hindered root growth and possibly nodulation in soybeans.[29] The results from the current research agreed with the findings of Board and Harville[30] who reported that the crop growth rate in a drained site increased for stress free soybean.

Significant differences in NDRE values in N treatments was found during later stages of crop growth for both years (Table 2). The potential reason that there was no difference in NDRE values during the early crop growth stages might be due to the fact that early in the season, more bare soil was visible to the sensor compared to crop canopy.

The similar trend in NDRE values at 95 and 102 DAP in 2014 might be because the data collection was performed within a 1 week interval and no change in trend occurred within different N treatments. However, the NDRE values were observed to be slightly higher at 102 DAP compared to values at 95 DAP. The N treatment pattern observed in late August for 2013 and 2014 were different, which might be due to other factors such as crop rotation, biotic and abiotic stresses (Table 2).

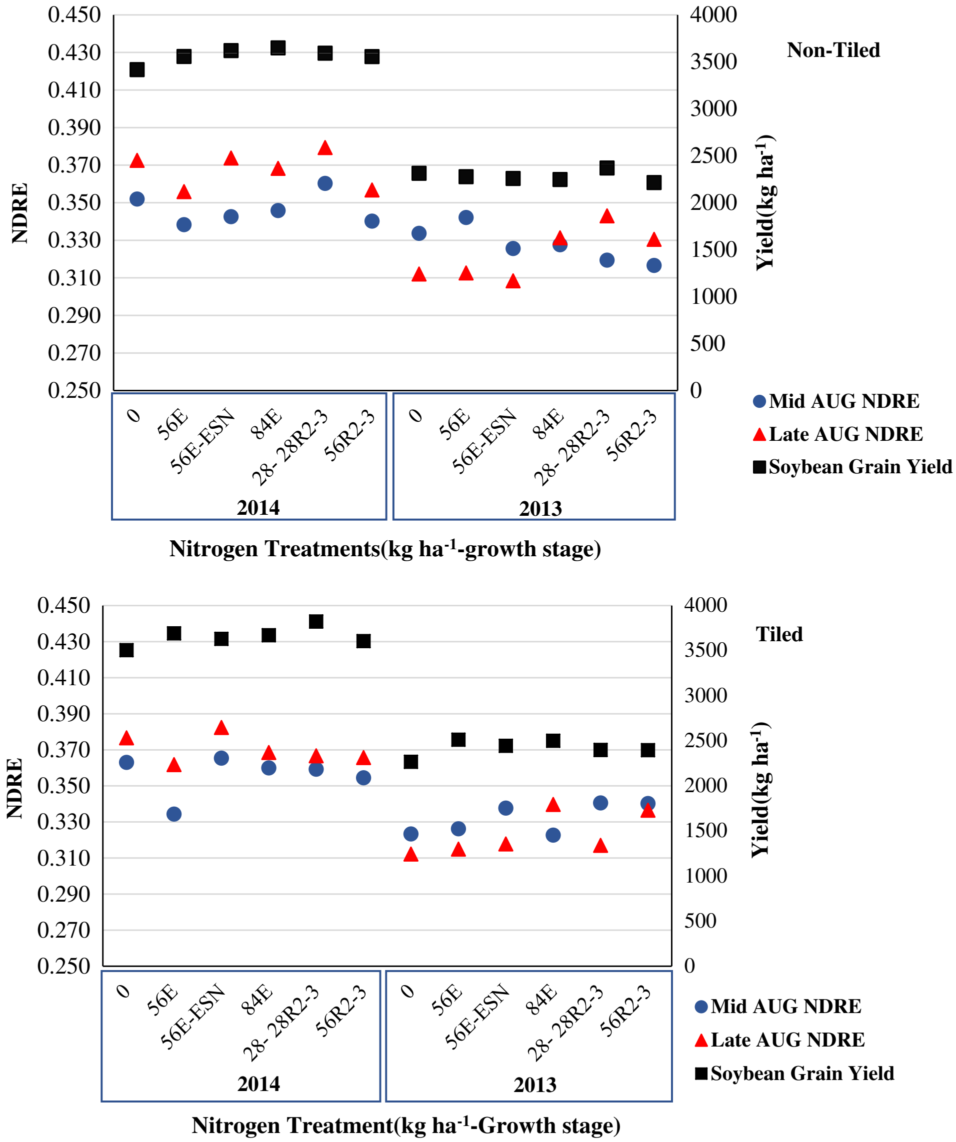

Figure 3. Relationship between yield and normalized difference red edge (NDRE) values for tiled and non-tiled with different nitrogen treatments for 2013 and 2014 crop season.

There were differences in NDRE values between some of the varieties at 79 DAP, 87 DAP in 2013, and 81 DAP in 2014 (Table 3), which might be due to the difference in canopy development and genetic differences in leaf color among the varieties. The crop growth rate is influenced by soybean varieties at different growth stages.[31,32] The NDRE values were higher at 79 DAP compared to at 87 DAP in 2013, which might be due to precipitation that occurred periodically during the month of July in 2013. It was evident that the NDRE values did show differences between the N treatments (Table 2) and varieties (Table 3) late in the growing season when the plants were close to complete canopy closure. The OptRx™ sensor uses red edge light wave technology which works better later in the growing season with an increasing canopy cover. It has been reported that the red edge wavebands are more sensitive to higher chlorophyll content, N status, and biomass.[33,34] These wavebands are influenced by plant chlorophyll content, leaf structure and leaf area index (LAI).[18] The red edge based sensors consider the differences in leaf color which is directly related to greenness and chlorophyll content.[33]

The NDRE values were higher in 2014 compared to 2013 season for all the N treatments (Fig. 3). This could be potentially due to the differences in greenness of the crop between years due to growing conditions and translated in a generally lower soybean yield for 2013 with 2350 kg ha^{-1}, which had lower NDRE readings, compared with an average yield of 3610 kg ha^{-1} in 2014. This might be due to the rainfall in July 2013, which may have led to N leaching and denitrification. In 2013 the leaching and denitrification of N may have caused lower NDRE values for late August NDRE readings for the control and 56 kg N ha^{-1} (urea and ESN) treatments that were applied early in the season compared with the mid-August reading. In 2014, there was probably little to no leaching due to lower total precipitation compared with the 2013 season. The NDRE values for N treatments followed a similar pattern in both tiled and non-tiled conditions, with higher NDRE values in late August. For both years, the yield followed a similar trend with higher yields in tiled compared to non-tiled drainage with tile yields averaged for both years yielding 3.9% more than the non-tiled soybean. Past studies showed that soybean and maize crop yield performance improved in controlled tiled drainage compared to uncontrolled tiled drainage.[35]

CONCLUSIONS

This research investigated the potential use of Ag Leader OptRx™ active optical sensors in soybean production systems in North Dakota to detect the greenness status of the plants and its influence on grain yield. Early to mid-season, the N treatments and varieties did not result in different NDRE values for both years. The NDRE values were significantly different between tiled and non-tiled plots in early and mid-season for both years. At later soybean growth stages and sensor reading dates, the NDRE values showed significant differences between the N treatments and varieties during 2013 and 2014 crop seasons. In both years, significant relationships existed between NDRE and the final yield averaged across all the varieties and N treatments. This study showed that the OptRx™ sensor has the potential to detect N treatment differences later in the season indicating that it might be a potential tool in developing late season N application algorithms. Further research is needed to confirm the use of OptRx™ sensor for variable rate in-season N applications in soybeans. Collecting subsequent years of data will be necessary to evaluate the OptRx™ sensor response to N application in different varieties of soybeans.

ACKNOWLEDGEMENTS

The authors would like to thank North Dakota Soybean Council for funding this project through the grant 46000-7620-2223-FAR0022206. Thanks, are also due to the graduate students, Mr Rohit, Mr Oveis and Ms Meghan for helping the authors with the field data collection.

REFERENCES

1 USDA [home page on the Internet] National Agricultural Statistics Service (NASS), North Dakota Field Office Crop Reports. (2017). Available: https://www.nass.usda.gov/Statistics_by_State/North_Dakota/[20 April 2017].

2 Gitelson AA and Merzlyak MN, Remote estimation of chlorophyll content in higher plant leaves. *Int J Remote Sens* **18**:2691–2697 (1997).

3 Carter GA and Knapp AK, Leaf optical properties in higher plants: linking spectral characteristics to stress and chlorophyll concentration. *Am J Bot* **88**:677–684 (2001).

4 Zhao D, Reddy KR, Kakani VG, Read JJ and Carter GA, Corn (*Zea mays L.*) growth, leaf pigment concentration, photosynthesis and leaf hyperspectral reflectance properties as affected by nitrogen supply. *Plant Soil* **257**:205–218 (2003).

5 Scharf PC, Shannon DK, Palm HL, Sudduth KA, Drummond ST, Kitchen NR *et al.*, Sensor-based nitrogen applications out-performed producer-chosen rates for corn in on-farm demonstrations. *Agron J* **103**:1683–1691 (2011).

6 Franzen DW, Sharma LK and Bu H, *Active Optical Sensor Algorithms for Corn Yield Prediction and a Corn Side-Dress Nitrogen Rate Aid*. NDSU Extension Service, North Dakota State University, (2014).

7 Sharma LK, Bu H, Denton A and Franzen DW, Active-optical sensors using red NDVI compared to red edge NDVI for prediction of corn grain yield in North Dakota, USA. *Sensors* **15**:27832–27853 (2015).

8 Osborne SL, Utilization of existing technology to evaluate spring wheat growth and nitrogen nutrition in South Dakota. *Commun Soil Sci Plant Anal* **38**:949–958 (2007).

9 Dellinger AE, Schmidt JP and Beegle DB, Developing nitrogen fertilizer recommendations for corn using an active sensor. *Agron J* **100**:1546–1552 (2008).

10 Hawkins JA, Sawyer JE, Barker DW and Lundvall JP, Using relative chlorophyll meter values to determine nitrogen application rates for corn. *Agron J* **99**:1034–1040 (2007).

11 Rorie RL, Purcell LC, Mozaffari M, Karcher DE, King CA, Marsh MC *et al.*, Association of "greenness" in corn with yield and leaf nitrogen concentration. *Agron J* **103**:529–535 (2011).

12 Holland KH and Schepers JS, Derivation of a variable rate nitrogen application model for in-season fertilization of corn. *Agron J* **102**:1415–1424 (2010).

13 Martin KL, Girma K, Freeman KW, Teal RK, Tubańa B, Arnall DB *et al.*, Expression of variability in corn as influenced by growth stage using optical sensor measurements. *Agron J* **99**:384–389 (2007).

14 Huete A, Didan K, Miura T, Rodriguez EP, Gao X and Ferreira LG, Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens Environ* **83**:195–213 (2002).

15 Kitchen NR, Sudduth KA, Drummond ST, Scharf PC, Palm HL, Roberts DF *et al.*, Ground-based canopy reflectance sensing for variable-rate nitrogen corn fertilization. *Agron J* **102**:71–84 (2010).

16 Maharlooei MM, Sivarajan S, Nowatzki J, Bajwa SG and Kandel H, Evaluation of in-field sensors to monitor nitrogen status in soybean crops, in *Paper Presented at 12th International Conference on Precision Agriculture*. International Society of Precision Agriculture, Sacramento, CA (2014).

17 Meer FV and De Jong SM, Imaging spectrometry: basic principle and prospective application. *Imaging Spectrom Agric Appl*:157–197 (2006).

18 Oplinger ES and Bundy LG, Nitrogen fertilization of soybean – Wisconsin results, in *Proceedings of the 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference*. University of Wisconsin, Madison, WI, pp. 19–21 (1998).

19 Randall GW and Schmitt MA, Fertilizer or manure for soybeans, in *Proceedings of the 1998 Wisconsin Fertilizer, Aglime, and Pest Management Conference*. University of Wisconsin, Madison, WI, pp. 19–21 (1998).

20 Lamb JA, Schmitt MA, Randall GW, Rehm GW and Orf JH, Evaluation of in season N application on soybean, in *Agronomy Abstracts*. ASA, Madison, WI, p. 357 (2000, 2000).

21 Lamond RE and Wesley TL, In-season fertilization for high yield soybean production. *Better Crops Plant Food* **85**:6–11 (2001).

22 Wesley TL, Lamond RE, Martin VL and Duncan SR, Effects of late-season nitrogen fertilizer on irrigated soybean yield and composition. *J Prod Agric* **11**:331–336 (1998).

23 Wesley TL, Lamond RE, Martin VL and Duncan SR, Applied N at R3 stage bumps soybean yields. *Fluid J* **25**:16–19 (1999).

24 Drury CF, Tan CS, Reynolds WD, Welacky TW, Oloya TO and Gaynor JD, Managing tile drainage, subirrigation, and nitrogen fertilization to enhance crop yields and reduce nitrate loss. *J Environ Qual* **38**:1193–1204 (2009).

25 Horler DN, Dockray M and Barber J, The red edge of plant leaf reflectance. *Int J Remote Sens* **4**:273–288 (1983).

26 Dawson TP and Curran PJ, A new technique for interpolating red edge position. *Int J Remote Sens* **19**:2133–2139 (1998).

27 Kandel HJ, Brodshaug JA, Steele DD, Ransom JK, DeSutter TM and Sands GR, Subsurface drainage effects on soil penetration resistance and water table depth on a clay soil in the Red River of the North Valley, USA. *Agric Eng Int CIGR J* **15**:1–0 (2013).

28 Russell RS, *Plant Root Systems: Their Function and Interaction with the Soil*. McGraw-Hill Book Company (UK) Limited, New York (1977).

29 Sallam A and Scott HD, effects of prolonged flooding on soybeans during early vegetative growth. *Soil Sci* **144**:61–66 (1987).

30 Board JE and Harville BG, Growth dynamics during the vegetative period affects yield of narrow-row, late-planted soybean. *Agron J* **88**:567–572 (1996).

31 Amin AK, Jahan SR, Karim MF and Hasanuzzaman M, Growth dynamics of soybean (*Glycine max* L.) as affected by varieties and timing of irrigation. *Am Eurasian J Agron* **2**:95–103 (2009).

32 Futuless KN, Toungos MD and Bake ID, Influence of varieties and planting dates on the performance of soybean (*Glycine max* L. Merr) in Mubi, Adamawa state Nigeria. *Knowl Rev* **23**:9–13 (2011).

33 Filella I and Penuelas J, The red edge position and shape as indicators of plant chlorophyll content, biomass and hydric status. *Int J Remote Sens* **15**:1459–1470 (1994).

34 Pinar A and Curran PJ, Technical note grass chlorophyll and the reflectance red edge. *Int J Remote Sens* **17**:351–357 (1996).

35 Cicek H, Sunohara M, Wilkes G, McNairn H, Pick F, Topp E *et al.*, Using vegetation indices from satellite remote sensing to assess corn and soybean response to controlled tile drainage. *Agric Water Manag* **98**:261–270 (2010).

