Active-Optical Reflectance Sensing Evaluated for Red and Red-Edge Waveband Sensitivity

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ABSTRACT

Uncertainty exists with corn (*Zea mays* L.) N management due to year-to-year variation in crop N need, soil N supply, and N loss from leaching, volatilization, and denitrification. Active-optical reflectance sensing (AORS) has proven effective in some fields for generating N fertilizer recommendations that improve N use efficiency. However, various sensors utilize different wavebands of light to calculate N fertilizer recommendations making it difficult to know which waveband is most sensitive to plant health. The objective of this research was to evaluate across the US Midwest Corn Belt the performance and sensitivity of the red (R) and red-edge (RE) wavebands. Forty-nine N response trials were conducted across eight states and three growing seasons. Reflectance measurements were collected and topdress N rates (40 to 240 lbs N ac^{-1} on 40 lbs ac^{-1} increments) applied at approximately V9 corn development stage. Both R and RE wavebands were compared to the at-planting N fertilizer rate, V5 soil nitrate-N, and end-of-season calculated relative yield. In every comparison the RE waveband demonstrated higher coefficient of determination values over the R waveband. These findings suggest the RE waveband is most sensitive to variations in N management and would work best for in-season AORS management over a geographically-diverse soil and weather region.

INTRODUCTION

Active-optical reflectance sensors emit visible and near infrared wavebands of modulated light onto the corn canopy and measure the intensity of light reflected back (Shanahan et al., 2003). Active-optical reflectance sensors capture plant condition information in small areas within fields and have the ability to assess spatially-variable crop N requirements (Solari et al., 2008). Such a diagnostic tool can aid in recommending the correct amount of N fertilizer applied to reach optimal N (Scharf et al., 2002; Barker and Sawyer, 2010; Kitchen et al., 2010; Scharf et al., 2011). Unlike soil- or tissue-test based in-season N fertilizer rate recommendations, AORS can be directly mounted to a fertilizer applicator making it possible to collect reflectance data and apply variable N fertilizer rates in an on-the-go one-pass operation.

Generally, the chlorophyll content or photosynthetic health of a corn plant can be determined by measuring the relative reflectance of visible light in the 440-690 nm spectral range, while the plant's structural size is primarily captured using reflectance in the near infrared wavebands (760-900 nm). Typically, reflected light in both spectral regions is measured by AORS and used to calculate a vegetative index that is an indicator of the N status of the plant (Kitchen et al., 2010). Compared to chlorotic and N deficient plants, healthy corn plants absorb more (reflect less) visible light and as the plant increases in size near infrared light reflectance increases. Thus, the application of AORS for N management often is based upon the relative reflectance readings between adequately N fertilized corn and un-fertilized or deficiently N fertilized corn (Biggs et al., 2002; Teal et al., 2006; Solari et al., 2008; Kitchen et al., 2010). Reflectance measurements are first gathered from a strip or area in the field that is not N-limited. This is referred to as an N reference or N rich strip and is usually established at planting by applying enough fertilizer to insure the corn is not N limited. These measurements are then used with AORS N rate recommendation algorithms. These algorithms are considered to be the core of successful AORS based N fertilizer management (Scharf, 2010).

Despite documented economic and environmental benefits found in some situations (Scharf et al., 2011), AORS for corn N management have shortcomings. For example, N stress must be detectable by the sensors when comparing reflectance readings between the N reference and target corn (Barker and Sawyer, 2010; Solie et al., 2012; Franzen et al., 2016). If no measured difference exists between target and reference corn, then the sufficiency or response index is unity and uncertainty exists for how much additional N should be applied, if any. Generally, a point of saturation is reached where added N no longer increases yield when either the response or sufficiency index is near unity (Gitelson and Merzlyak, 1996; Holland and Schepers, 2010). Also, previous research has shown that AORS measurements are significantly related to relative yield (Holland and Schepers, 2010; Solari et al., 2010; Tagarakis and Ketterings, 2017). As reflectance saturation is reached, relative yield approaches one indicating no measured yield response with additional N. The unique growing conditions and environments under which various sensor types and algorthims were developed may limit their utility over larger geographic areas. These circumstances create challenges when determining which sensor and the associated wavebands utilized are most sensitive to plant N response.

An investigation was conducted to compare AORS waveband performance across a large geographical area, which represents a range of soil and weather scenarios. The objective of this research was to compare across the US Midwest Corn Belt the performance and sensitivity of the R and RE wavebands used with AORS algorithms for making in-season corn N fertilizer recommendations. Such waveband comparison could additionally lead to a better understanding of how AORS algorithms may be altered for making improved in-season N fertilizer recommendations.

MATERIALS AND METHODS

Research Sites and Locations

Research was conducted as part of public-industry partnership as outlined in Kitchen et al., 2017. For this investigation, N fertilizer application response field-plot studies were conducted with standardized protocols and methods across a wide range of soil and weather conditions, and have been previously documented (Kitchen et al., 2017). Forty-nine corn N response trials were conducted from 2014 to 2016 in eight Midwest Corn Belt states. In each state, two sites contrasting in soil productivity were selected for each growing season, one located on a highly productive soil and the other on a relatively less productive soil (MO had three sites for 2016; Fig. 1). Productivity was determined by historical yield and general soil productivity. Additional site descriptions, site characterization protocols, and management details can be found in Kitchen et al. (2017).

Plot and Treatments

Nitrogen fertilizer application treatments were replicated four times in a randomized complete block design. Dry-prilled NH_4NO_3 fertilizer was used for all N treatments and was broadcast by hand. Eight treatments (0 - 280 lbs N ac^{-1} in 40 lbs ac^{-1} increments) constituted the "at planting" application treatments and were applied within 48 hours of planting. Six treatments defined a "split" application with 40 lbs ac^{-1} N at planting and the remainder (40 - 240 lbs N ac^{-1} in 40 lbs ac^{-1} increments) as a side-dress targeted at V9 ± one developmental growth stage (Kitchen et al., 2017).

Active-Optical Reflectance Sensing

Active-optical reflectance sensing measurements were collected the same day or immediately preceding the split N application using the RapidSCAN CS-45 (RS) Handheld Crop Sensor (Holland Scientific, Lincoln, NE). The RS sensor provides reflectance information for three different wavebands of light: red (670 nm, R), red edge (720 nm, RE), and near-infrared (780 nm, NIR). All three wavebands were utilized in calculating the vegetative and sufficiency indices. Manufacturer recommendations were followed for calibration and operation. The sensor was held approximately 2 ft directly above the top of the corn row as the operator steadily walked approximately 2.5 mph alongside the row. Only plot rows used for yield measurements (2 – 3 rows per plot depending on plot layout) were sensed individually and then averaged to obtain plot level readings.

Reflectance Measurements Evaluated

Corn plots that received 200 and 240 lbs N ac^{-1} at planting were used as the N reference. The exception was the 2015 Missouri LoneTree (less productive) site where, because of extreme early-season N loss noted with a visual N deficiency, the plots that received 280 lbs N ac^{-1} at planting were used as the reference. The vegetative index used is the Inverse Simple Ratio (ISR), defined as:

$$ISR = \frac{R}{NIR} \qquad [1]$$

Measurements were taken to obtain ISR values from both N reference corn ($ISR_{reference}$) and target corn (ISR_{target}). The sufficiency index (SI) was then calculated as follows:

$$SI = \frac{ISR_{target}}{ISR_{reference}} \qquad [2]$$

A second SI was obtained for evaluation by substituting RE for R in Eq. [1] above.

Performance Evaluation and Statistics

Results were examined to determine if AORS measurements were sensitive to soil and crop N status. This was accomplished three different ways. First AORS SI (ISR using RE) was examined as a function of at-planting N rates (mean of 4 replications). This relationship was fit using a quadratic model.

Second, relative yield by plot was examined as a function of the AORS SI (ISR using both R and RE), and fit using linear models by year. Relative yield was calculated as follows:

$$RY = Yield_{Plot}/Yield_{Opt} \quad [3]$$

where RY = relative yield, $Yield_{Plot}$ = the yield of each individual plot and $Yield_{Opt}$ = the site-level optimal yield (i.e., plateau of Q-P model), which is the point at which added N no longer increased yield (Kitchen et al., 2017).

Lastly, AORS SI (ISR using both R and RE) was examined by plot as a function of V5 development stage soil nitrate-N, and fitted using linear-plateau models by year. For treatments receiving N at planting, six 0 to 12 inch depth soil cores were combined and analyzed for soil nitrate-N as described in Kitchen et al. (2017).

RESULTS AND DISCUSSION

Relating Reflectance Sensing to Soil N and Yield

With no N fertilizer applied at planting, AORS SI (inverse simple ratio using RE; ISR RE) was less than 0.95 for most sites (Fig. 2; Table 1). With the majority of sites, a visual N deficiency at the time of sensing was observed with no N applied at planting. With increasing N at planting, plant N stress, as indicated by the SI, diminished. However, a few sites showed N stress even with > 80 lbs N ac^{-1} applied at planting. These sites generally experienced excessive early season rainfall on either sandy or fine-textured soils.

The SI was related to variation in relative yield, with R^2 values ranging from 0.29 to 0.58 for different years and wavebands (Fig. 3; Table 1). The relationship was better with RE than with the R reflectance. As relative yield approached one, SI also approached unity. This comparison additionaly verifies the sensitivity of the AORS data used to determine corn N status for these sites.

The SI of sensor measurements taken at V9 development stage were related to V5 corn growth development stage soil nitrate-N in the upper 12-inch (from plots that received 0 to 280 lbs N ac^{-1} at planting in 40 lbs N ac^{-1} increments) and found to best fit a linear plateau relationship (Fig. 4; Table 1). As with relative yield, the relationship using RE reflectance was better than the R reflectance. Sufficiency index values increased as soil nitrate-N increased up to approximately 15 to 19 ppm, where SI values plateaued. Thus target corn at the V5 development stage with over 20 ppm of soil nitrate-N will likely have similar V9 AORS measurements as reference corn. Interestingly, 20 ppm of soil nitrate-N present in the soil at sidedress is normally accepted as N sufficiency (Blackmer et al., 1989).

SUMMARY

The goal of this research was to apply AORS data gathered at a regional scale (US Midwest Corn Belt) and evaluate sensitivity and performance of the R and RE wavebands over a larger region. Across the three years of this investigation, similar to previous research (Gitelson et al., 2003), the RE waveband performed best over this broad region. This reinforces the principle that for AORS to work well as a tool for determining how much in-season N fertilizer to apply, crop N deficiency needs to be detected using the most sensitive waveband(s) in order to best estimate season-long plant N requirements. However, it should be noted that if N stress becomes too extreme, yield may not be recoverable. If plant N need is not detected when comparing reference and target corn (either as differences in color, biomass, or both) then using AORS alone would be insufficient to determine adequacy or N fertilization need. Even so, expressed deficiency may or may not be found over a whole field. Others have shown that crop N status at the time of sensing and side dressing is often spatially-variable within the same field, ranging from insufficient to sufficient (Scharf et al., 2005; Kitchen et al., 2010). Use of AORS within fields showing spatially-variable N need has proven effective (Scharf et al., 2011).

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Table 1. Quadratic, linear, or linear-plateau regression models associated with Fig. 2-4 are presented with coefficients of determination. All models were significant ($P < 0.001$). The sufficiency index (SI) used for each figure was the inverse simple ratio (ISR) of either red (R) or red edge (RE) reflectance for V9 growth stage corn. For Fig. 2, N fertilizer applied at planting in lbs N ac^{-1} units. For Fig. 3, relative yield (RY) was calculated by dividing each plot yield by the modeled site-level optimal yield. For Fig. 4, soil nitrate-N was analyzed from samples obtained by combining six 0 to 12 inch depth soil cores taken at the V5 growth stage.

Figure	**Dependent Variable**	**Independent Variable**	**Model Type**	**Waveband**	**Year**	**Equation**	r^2/R^2
2	SI	N at planting	Quadratic	R	All	$y = 0.808 + 0.0022x – 5.5E006x^2$	
				RE	All	$y = 0.883 + 0.0011x – 2.9E006x^2$	0.50
3	RY	SI	Linear	R	2014	$y = 0.832x + 0.076$	0.41
					2015	$y = 0.763x + 0.128$	0.29
					2016	$y = 0.700x + 0.208$	0.31
				RE	2014	$y = 2.186x + 1.246$	0.58
					2015	$y = 2.271x + 1.333$	0.53
					2016	$y = 1.721x + 0.796$	0.42
4	SI	Soil nitrate-N	Linear-plateau	R	2014	$y = 0.0311x + 0.5454$; $y = 1.0049$ ($x \geq 14.8$)	0.42
					2015	$y = 0.0211x + 0.6537$; $y = 1.0072$ ($x \geq 16.7$)	0.30
					2016	$y = 0.0178x + 0.6965$; $y = 1.0157$ ($x \geq 17.9$)	0.26
				RE	2014	$y = 0.0171x + 0.7458$; $y = 0.9952$ ($x \geq 14.6$)	0.60
					2015	$y = 0.0109x + 0.7982$; $y = 0.9950$ ($x \geq 18.0$)	0.49
					2016	$y = 0.0099x + 0.8154$; $y = 1.0072$ ($x \geq 19.3$)	0.48

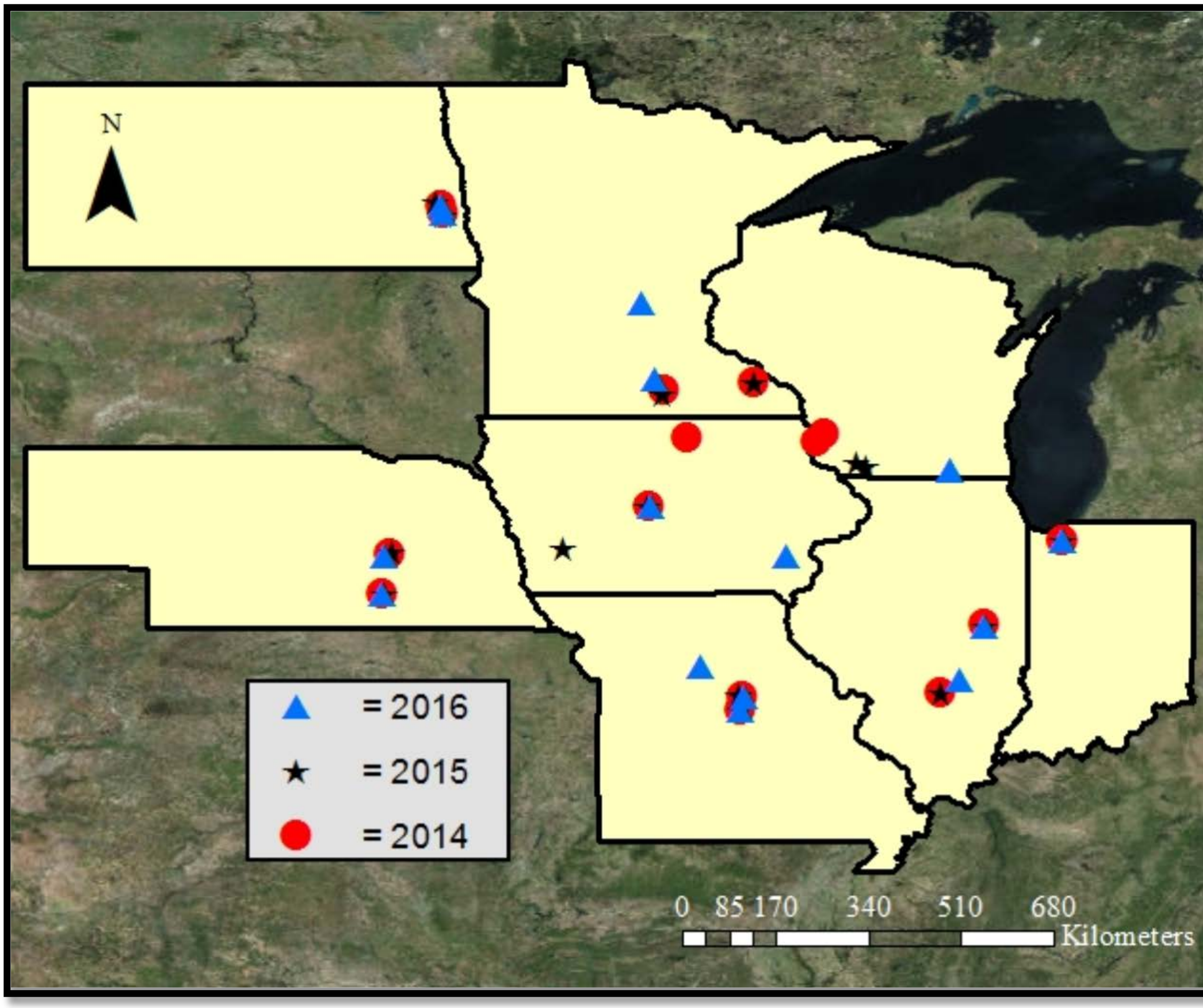

Figure 1. Field research sites were located within eight US Midwest Corn Belt states (Iowa, Illinois, Indiana, Minnesota, Missouri, Nebraska, North Dakota, and Wisconsin). Each state contained two sites for three growing seasons (2014-2016), totaling 49 sites (Missouri had three sites in 2016). The 2014, 2015, and 2016 sites are represented by red circles, black stars, and blue triangles, respectively.

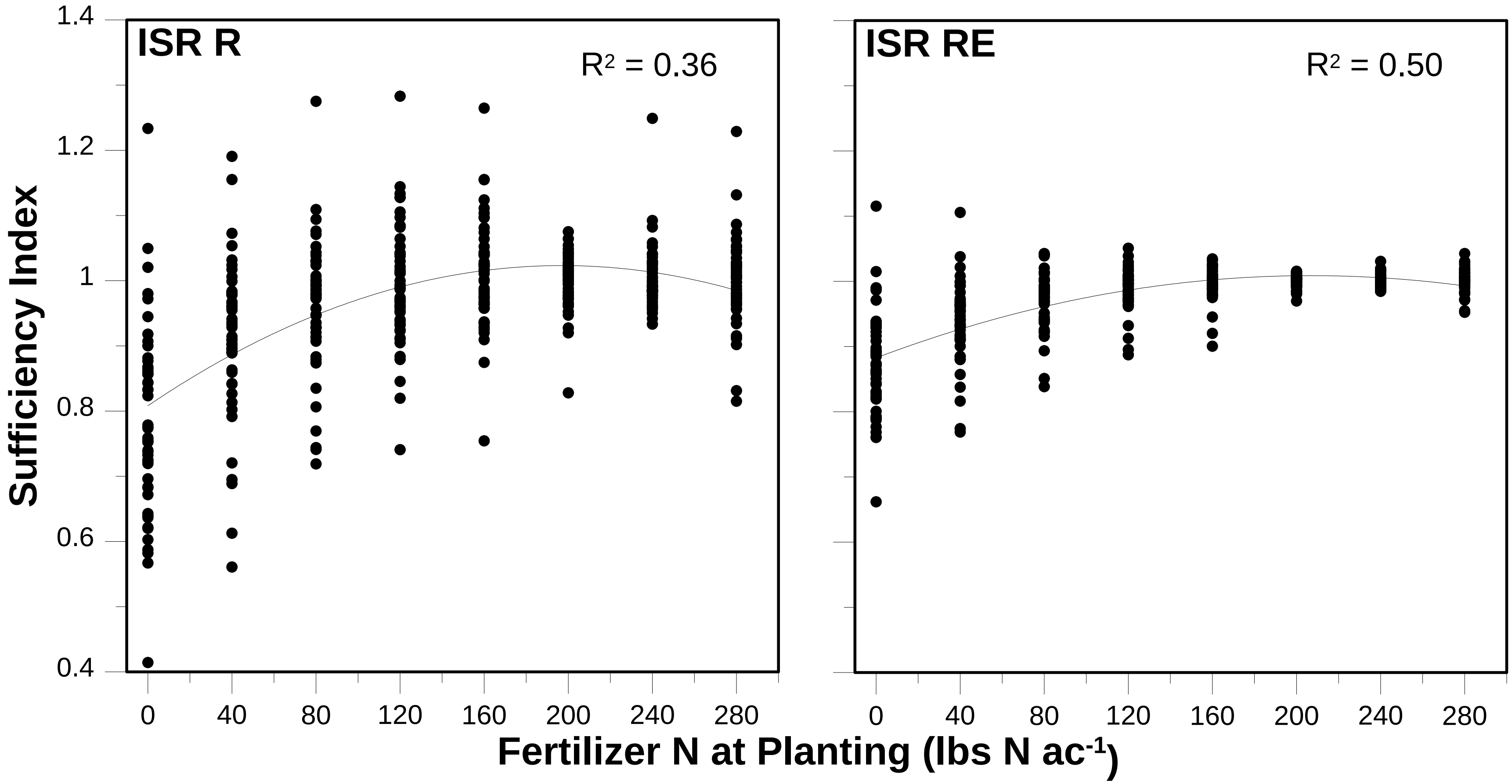

Figure 2. Active-optical reflectance sensing sufficiency index (SI) for approximately V9 corn as a function of N fertilizer rates applied at planting over 49 sites and three growing seasons (2014-2016). Reflectance SI (target by N rate and reference the mean of 200 and 240 lbs N ac^{-1} rates) were calculated with the inverse simple ratio vegetative index employing the red, red edge and near infrared wavebands (ISR RE). Data was fit using both a quadratic and quadratic-plateau model. Results were similar; the simpler quadratic model is shown here.

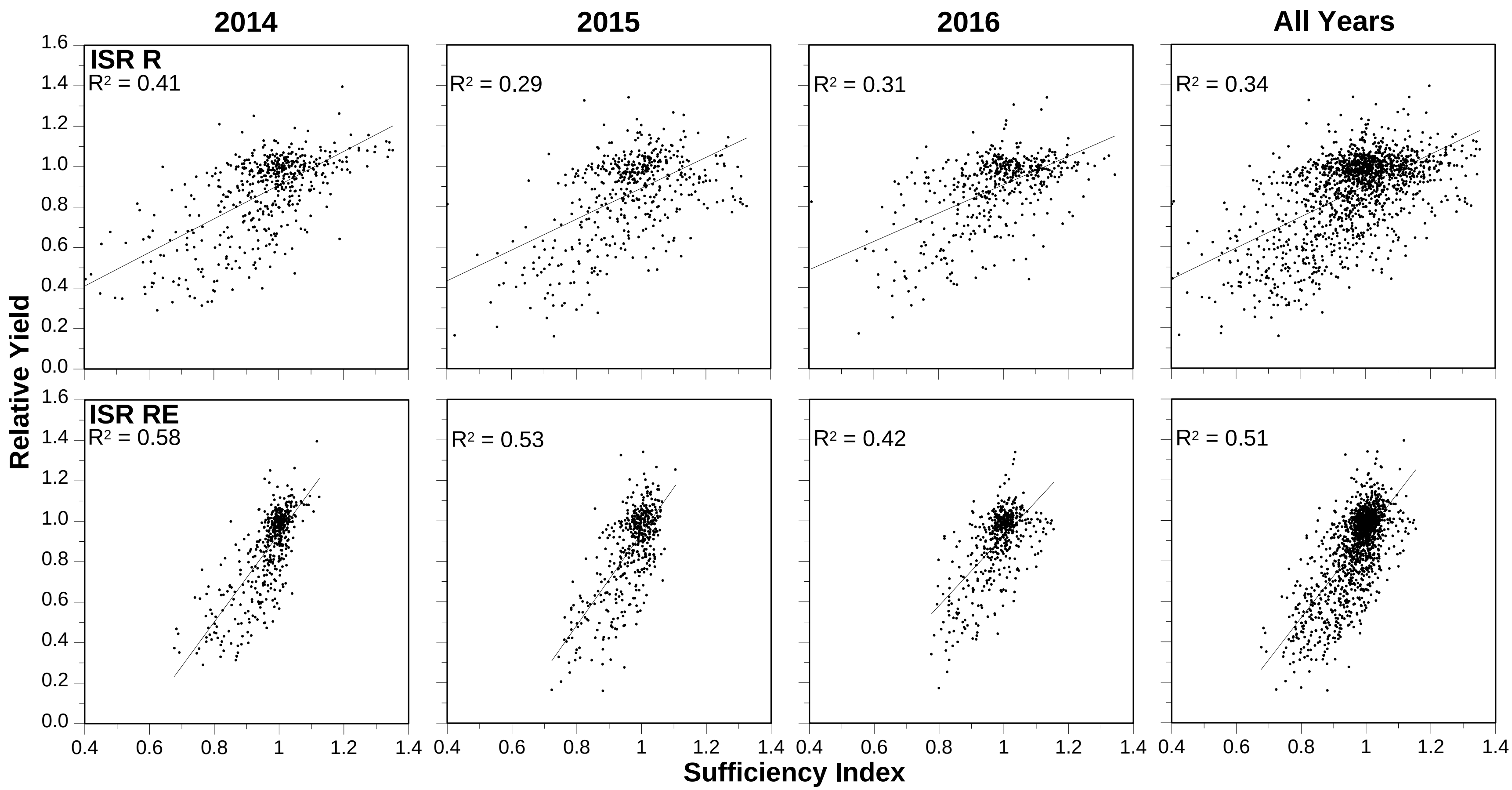

Figure 3. Sufficiency index (SI) shown in relation to the relative yield calculated by dividing each plot yield by the site-level optimal yield for plots receiving N fertilizer at planting (32 plots per site), over three growing seasons (2014-2016). Reflectance SI (target by N rate and reference the mean of 200 and 240 N ac^{-1} rates) were used with the inverse simple ratio vegetative index employing the red, red edge and near infrared wavebands (ISR RE).

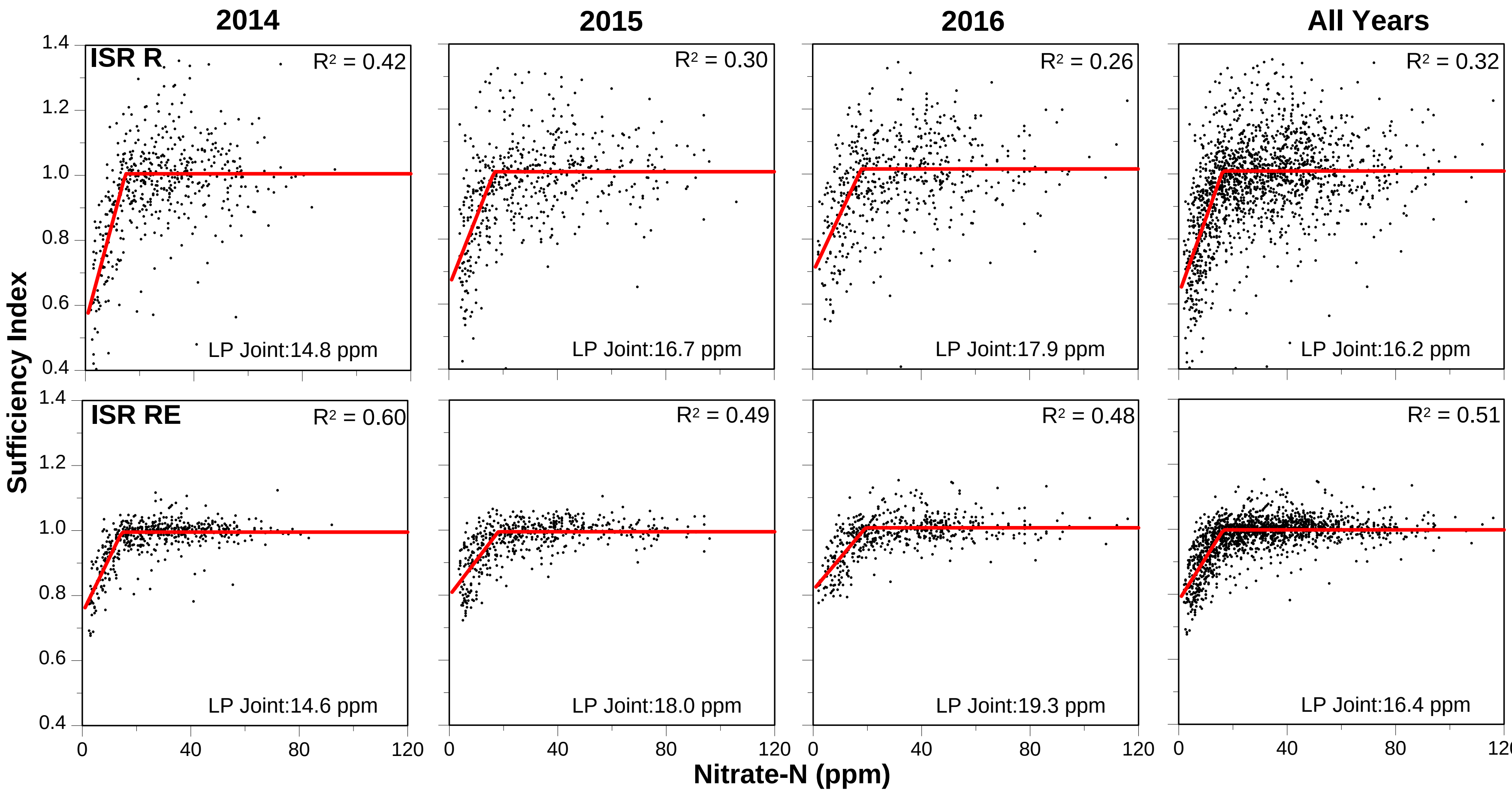

Figure 4. Sufficiency index (SI) shown in relation to V5 development stage soil nitrate-N (0-12 inch depth), fitted with a linear-plateau model. Results are for plots N fertilized at planting (32 plots per site; 0-280 lbs N ac^{-1} in 40 lbs ac^{-1} increments), over three growing seasons (2014-2016). Reflectance SI (target by N rate and reference the mean of 200 and 240 lbs N ac^{-1} rates) were used with the inverse simple ratio vegetative index employing the red, red edge and near infrared wavebands.