Active-Crop Sensor Calibration Using the Virtual-Reference Concept

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Abstract

Active crop canopy sensors open the door for making in-season fertilizer nitrogen (N) applications any time of the day. Using the crop as a bio-indicator of N status and vigor holds great promise to increase N use efficiency, protect the environment, and increase profitability. However, monitoring crops when they are rapidly growing makes it potentially difficult to calibrate sensors and interpret the data. Establishing N-rich areas within a field has been proposed as a way to maintain a group of plants that can be used as a non-N limiting reference at any growth stage. This approach is problematic for producers and commercial applicators in several ways. A virtual reference strip approach that does not require any special attention on the part of producers is proposed and demonstrated using data from an N-rate study with irrigated corn.

Keywords: active canopy sensors, algorithm, calibration, nitrogen, sufficiency index

Introduction

Calibration of laboratory and field instruments usually involves collecting data from some type of accepted standard materials or compounds. This approach works well for most physical and chemical measurements; however, such procedures become problematic when dealing with biological systems like plants that go through a number of physiological states during the growing season. In addition, genetic composition differences between cultivars can affect the architecture of plant canopies and relative color of the leaves. While laboratory procedures can be used to quantify parameters like leaf nitrogen (N) concentration, interpreting such data for the purpose of making management decisions is difficult because of cultivar and growth stage differences. Other factors such as cropping history, previous manure applications, and cultural practices can also affect crop vigor and color. For these reasons, Peterson et al (1993) utilized the findings of Schepers et al (1992) and proposed normalizing Minolta SPAD meter readings to a reference situation that was known to have received modestly excessive amounts of N fertilizer. The reference crop needs to be managed the same as the rest of the field or other treatments except for having received enough N so that the crop is not N deficient. This field situation is sometimes referred to as being “N-rich”. During the normalization process, the SPAD meter readings from the plants in question are divided by the reading from the reference plants. The resulting quotient was originally termed the “Sufficiency Index” (*SI*) and used to make decisions regarding fertigation of corn in Nebraska. Later the concept was extended to guide sensor-based in-season N fertilizer recommendations (Biggs et al, 2002). Scientists at Oklahoma State University prefer to discuss in-season crop vigor measurements in terms of the potential for a yield response so they invert the SI value and call it a “Response Index”. It should be noted that the reason the N-rich reference concept works to normalize SPAD data is because a little extra N availability is not harmful to corn plants. At some point along the scale of N adequacy, another nutrient becomes limiting and subsequent N uptake amounts to “luxury consumption”. At this point, leaf chlorophyll status is maximized as recorded by SPAD meters.

Adapting the SI concept to commercial production practices might seem to be straight forward until one realizes that the concept was developed for research plots that were intentionally positioned on the landscape to minimize spatial variability. Extending the normalization concept to whole-field situations raises questions related to determining the appropriate reference value. If one assumes that additional N fertilizer in selected areas of the field will reduce or remove the spatial variability in yield, then the task at hand would be to characterize an area with adequate N and use that SPAD value as the reference for the entire field. In practice, producers following this strategy typically install one or more N-rich strips in their fields to use as the reference. For convenience purposes and to simplify record keeping, producers would prefer to use the same area of the field as the N-rich reference year-after-year. However, using the same area of the field as the N-rich reference for a second year violates the premise that the reference should represent the nutrient status of the rest of the field in all respects except for having received additional N fertilizer. Therefore, it is imperative that the N-rich reference strips be moved to a new area each year.

Raun and colleagues (2005) observed spatial variability in plant vigor within N-rich strips in most wheat fields so they developed sprayer equipment to establish a grouping of nine N-rate plots (each 1 m^2) in a 3 x 3 configuration (referred to as postage-stamp plots) . This application device allowed them to readily place many mini-N rate plots within a field. However, they found the border effect between N-rate plots made it difficult to clearly identify the reference plot within the group of nine plots. They subsequently transformed the 3 x 3 grouping into a field strip with progressively higher or lower N rates (referred to as ramped calibration strips). Each subplot was typically ~16-m long so multiple ramps of nine N rates could be established within a field strip. They soon realized that soil properties frequently changed substantially within the distance of one complete ramp (perhaps 150-m total length). Scharf et al (2006) modified the ramp concept by establishing a series of adjacent N-rate strips that were harvested with a combine fitted with yield monitoring equipment. The yield map was broken into 16-m long segments which allowed them to construct a series of N-response functions along the length of the field strip. It should be noted that the yield values were subject to the uncertainties associated with yield maps and the series of N rates were only randomized between strips. Solari et al (2008) enlarged the postage-stamp concept so that subplots were the width of the planter by 16-m long to keep the N-rate subplots in close proximity (used either 2 x 2 or 3 x 3 groupings). This design addressed the need for randomization within a grouping and made it possible to evaluate the effect of soil properties on the shape of individual N-response functions. Hand harvesting of such studies provides excellent data, but the approach is quite laborious. Below and colleagues (personal communication, 2009) established multiple N-rate groupings in fields according to management zones throughout the Midwest and found the yield plateau and shape of the N-response function varied within a field and especially between fields.

The above observations indicate that the in-season vegetation index value (integration of chlorophyll status and the amount of biomass) of the "reference" plants probably needs to be determined by management zone rather than for an entire field. The goal of this research effort was to test and evaluate a method developed by Holland (2007) that was convenient, reliable, and dynamic to systematically determine the vegetation index value of reference plants without using an N-rich strip.

Materials and Methods

This study was conducted on a field with a single soil type (Hord silt loam; fine-silty, mixed mesic Pachic Haplustolls) with 0-1% slope. Tillage involved chopping the corn stalks from the previous year with a rotary shredder followed by two disk operations prior to planting. The field was under linear-drive sprinkler irrigation with 8-row wide strips (0.91-cm spacing) planted to Pioneer brand P33D83 on 20 May, 2009 at a population of 74,000 plants/ha. These 400-m long strips had been planted to continuous corn since 1991 with five N rates (0, 50, 100, 150, and 200 kg N/ha) applied to the same plots at planting. Other strips were in a corn/soybean rotation or in continuous corn with a base N rate of 150 kg/ha. Individual plots were each 16-m long and separated with a 1-m wide bare-soil alley. Each strip accommodated four replications of the randomized treatments. Two strips were involved in the study, thus providing eight replications.

At the V9 (14 July, 2009) and V12 (21 July, 2009) growth stages, two ACS-470 (Holland Scientific, Inc., Lincoln, NE, USA) active sensors were mounted on a John Deere high-clearance sprayer[3]. Sensors were positioned at least 60-cm above the tallest plants in rows three and six of the 8-row plots. These sensors were outfitted to record canopy reflectance in the red (670 nm), red edge (730 nm), and near infrared (NIR, >760 nm) wavebands at 5 Hz to correspond with GPS data collected at the same rate. Rate of travel through the field was ~4.5 km hr^{-1} (~1.25 m s^{-1}) which amounts to a set of recorded sensor readings about every 25 cm (average of ~2 plants).

N Application Model and Calibration Method

The N application model utilized in this research involved directly inserting normalized sensor data (*SI* values) into a generalized plant growth function. The *SI* is the ratio of a real-time sensed crop property to the same measurement from a known or standard crop (reference) and is described mathematically as

$$SI = \frac{VI_{Sensed\ Crop}}{VI_{Reference}} \qquad (1)$$

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[3] Mention of a company or trade name does not imply endorsement by the USDA-ARS or the University of Nebraksa.

where, SI is the sufficiency index ($0 \le SI \le 1$),

$VI_{Sensed\ Crop}$ is the vegetation index (or measurement) of the sensed crop, and

$VI_{Reference}$ is the vegetation index (or measurement) of the non-N limited crop.

The Chlorophyll Index (*CI*) developed by Gitelson et al (2003, 2005) in eq. 2 was incorporated for use to calculate the *VI* terms in eq. 1. The CI has the following mathematical form:

$$\mathrm{C}I_{\mathrm{Re}d\ Edge} = \left[\frac{\rho_{NIR}}{\rho_{\mathrm{Re}d\ Edge}} - \mathbf{1} \right] \quad (2)$$

where ρ_{NIR} is the near infrared (NIR) waveband reflectance and

$\rho_{Red\ Edge}$ is the red edge waveband reflectance.

The N application model developed by Holland and Schepers (2010) was utilized for this research. The N application model, incorporating a back-off function, has the mathematical form:

$$N_{APP} = \left(N_{OPT} \text{-} N_{PreFert} \text{-} N_{\overline{OM}} \right) \cdot \sqrt{\frac{(1 - SI)}{\Delta SI \cdot \left(1 + 0.1 \cdot e^{m \cdot (SI_{Threshold} - SI)} \right)}} \qquad (3)$$

where, N_{OPT} is the EONR or the maximum N rate prescribed by producers,

$N_{PreFert}$ is the sum of fertilizer N applied prior to crop sensing and/or in-season N application,

$N_{\overline{OM}}$ is the N credit for the field's average organic matter content,

SI is the sufficiency index,

ΔSI is the sufficiency index difference parameter,

m is the back-off rate variable ($0 < m < 100$) and

$SI_{Threshold}$ is the back-off cut-on point.

The back-off function in eq. 3 was incorporated to conserve N for *SI* values below 0.65. The rate parameter *m* determines the rate at which the N application model decreases N supply and the $SI_{Threshold}$ determines when the back-off function starts to limit N supply. For this work, *m* was set to 40, $SI_{Threshold}$ was set to 0.65 and ΔSI was set to 0.30. The organic matter credit $N_{\overline{OM}}$ was set to 40 kg/ha for this research. This value was based on the test site's average soil organic matter of 2%.

Sensor calibration was performed by statistically analyzing previously collected real-time data. Data were post processed by manually discarding values from the bare-soil alleys and associated plot borders with mixed vegetation/soil reflectance (usually 2 to 3 sets of readings at the end of each plot). A histogram of the red-edge *CI* values ($CI_{red\text{-}edge}$) was constructed to examine the shape of the distribution function. The 95-percentile cumulative value from the histogram was selected as the reference for each replication from which to make *SI* calculations and simulate fertilizer N applications (Figure 1). Accumulation was performed from the lowest *CI* bin to the highest *CI* bin. The 95-percentile point was determined from the histogram data via linear interpolation and used to calculate *SI* values. Fertilizer N recommendations were calculated using the algorithm of Holland and Schepers (2010).

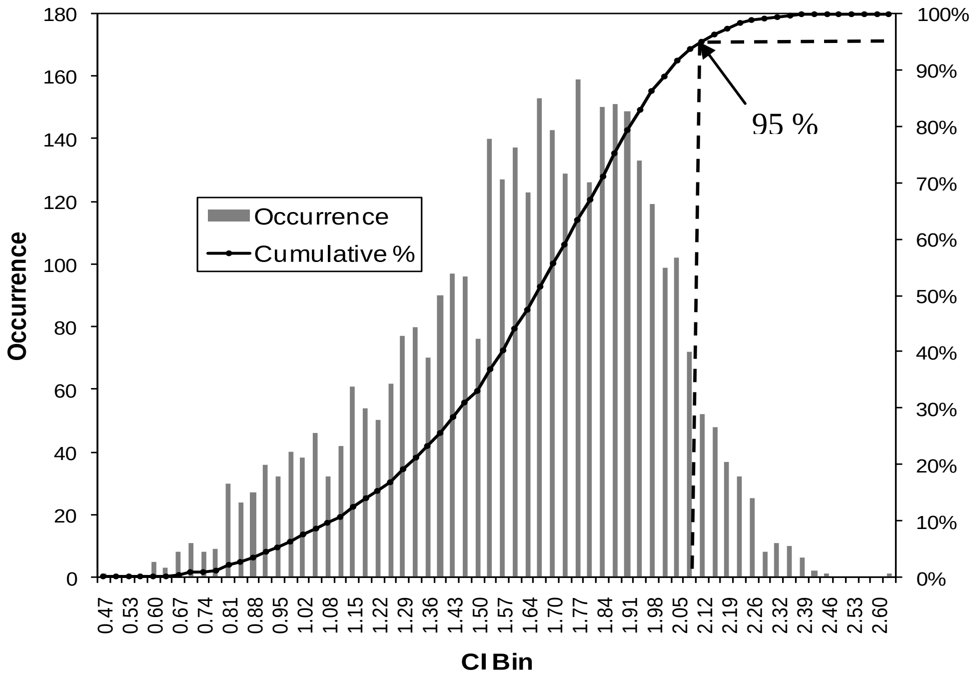

Figure 1. Sampled data distribution with cumulated percentile overlay. The 95-percentile value was utilized as the calibration point for the N application model.

Results and Discussion

Sensor data collected while driving through the N-rate plots were used to represent the extremes in plant variability that producers might experience in commercial fields. The average 95-percentile $CI_{red\text{-}edge}$ reference values were quite uniform between replications while the averages were statistically (P = 0.05) different for the two growth stages (Table 1).

Table 1. Reference values for sufficiency index calculations at V9 and V12 corn growth stages. Reference values were obtained utilizing the 95-percentile cumulative values from a histogram generated for each replication.

Sampled Reference Values		
Rep	CI(Ref) at 95% Threshold	
	V-9	V-12
1	2.046	1.936
2	2.051	1.910
3	1.981	1.865
4	2.064	1.891
5	2.159	2.021
6	2.213	1.982
7	2.164	1.990
8	2.162	1.980
Mean	2.105	1.947
Stdev	0.080	0.055
CV	3.8%	2.8%

The lower $CI_{red\text{-}edge}$ at the V12 growth stage is attributed to development of additional N stress during this period of rapid N uptake. While the time-lapse between these two growth stages was only 7 days that was long enough for the N stress to further develop in some plants and start to change the shape of the histograms.

Sufficiency index calculations showed a significant increase in *SI* values as preplant N rates increased (Tables 2 and 3). The average *SI* values were not statistically different (P = 0.05) for V9 and V12 sensor readings. It is worth noting that the SI values for the highest preplant N rate (200 kg N/ha) was less than 1.0. Traditionally, the highest N rate would be used as the reference value to calculate the *SI* in plot studies (Peterson et al, 1993; Varvel et al, 2007). In the case of SPAD meter readings, only “representative plants” were selected for measurement. These meters have the capability to log and average up to 30 readings, but unless they are specially equipped to log the individual readings, it is not possible to post-evaluate the SPAD values and perform statistical analyses. It is possible to view and discard individual plant readings in the field before clearing the memory and proceeding to make more measurements. In the case of this study, all plants in the selected rows were monitored to generate and record over 70 readings per plot (average of 35 across both sensors). Each reading at 5 Hz intervals is the average of ~8000 readings per sensor. These readings included missing, diseased, and injured plants (double plants were very rare). It is postulated that some plants in plots with “adequate” N expressed reduced vigor that was probably associated with early-season immobilization by the incorporated crop residues from the previous year. The chlorophyll index used in this study is so named because it is especially sensitive to leaf chlorophyll content. This is in contrast to the normalized difference vegetation index (NDVI) that is primarily sensitive to living biomass that would be expected to increase as the crop grows. In contrast, the $CI_{red\text{-}edge}$ values might be expected to decline as the N deficiency becomes more pronounced.

Table 2. Comparison of average sufficiency index (*SI*) values at five N rates for irrigated corn at the V9 growth stage. Sufficiency index reference values for each replication are listed in Table 1.

V-9	Sufficiency Index Values				
Rep	N Rates (kg/ha)				
	0	50	100	150	200
1	0.582	0.754	0.813	0.901	0.904
2	0.575	0.713	0.831	0.839	0.929
3	0.514	0.715	0.787	0.858	0.872
4	0.507	0.723	0.899	0.813	0.885
5	0.533	0.641	0.901	0.824	0.898
6	0.512	0.683	0.722	0.802	0.809
7	0.540	0.726	0.813	0.757	0.854
8	0.626	0.721	0.778	0.814	0.854
Mean	0.549	0.709	0.818	0.826	0.876
Stdev	0.042	0.034	0.060	0.042	0.037
CV (%)	7.7%	4.8%	7.4%	5.1%	4.2%

Table 3. Comparison of average sufficiency index (*SI*) values at five N rates for irrigated corn at the V12 growth stage. Sufficiency index reference values for each replication are listed in Table 1.

V-12	Sufficiency Index Values				
Rep	N Rates (kg/ha)				
	0	50	100	150	200
1	0.514	0.695	0.827	0.887	0.872
2	0.524	0.657	0.829	0.844	0.910
3	0.462	0.686	0.779	0.830	0.869
4	0.487	0.679	0.845	0.840	0.904
5	0.479	0.628	0.828	0.843	0.925
6	0.510	0.686	0.800	0.845	0.858
7	0.486	0.734	0.859	0.793	0.881
8	0.610	0.709	0.804	0.860	0.898
Mean	0.509	0.684	0.822	0.843	0.890
Stdev	0.046	0.032	0.026	0.027	0.023
CV (%)	9.0%	4.7%	3.1%	3.1%	2.6%

It stands to reason that establishing an N-rich strip(s) in a field near planting time is probably over-kill in terms of meeting the N needs of the crop between the V6 and V15 growth stages. For example, at the V9 growth stage of corn, plants have accumulated ~20% of the total N that will be in the crop at harvest, which only amounts to ~35 kg/ha for a 14 Mg/ha yield. Therefore, a planting time application of ~80 kg N/ha should be adequate to avoid N stress until the V7-V10 growth stages.

The historic economic optimum N rate (EONR) for this field is 196 kg N/ha. It is reasonable to assume that the $CI_{red\text{-}edge}$ values for the 150 and 200 kg/ha N rate should be non-N limiting at the V9 and V12 growth stages. However, average *SI* for all plots were less than 1.0 indicating that there were areas within each plot that had reduced levels of chlorophyll or where plant density was reduced (Tables 2 and 3) even though the N supply should have been more than adequate. Lowering the reference threshold criteria below 95-percentile (i.e., lowering $CI_{red\text{-}edge}$ reference) would raise the SI for all situations, but this would reduce fertilizer N application rates which might not optimize the yield potential of the crop.

The occurrence of vigorous and high chlorophyll content plants with respect to the preplant N treatments was evaluated by grouping the data by N rate and generating histograms for each that used a common range of categories. The resulting figure illustrated that nearly all of the 95-percentile plants were growing in the 150 and 200 kg N/ha plots (Figure 2). Plants at the $CI_{red\text{-}edge}$ reference value of 2.105 (Table 1, V9) within the 100, 150, and 200 kg/ha N treatments constituted 26, 20, and 54% of the reference pool, respectively.

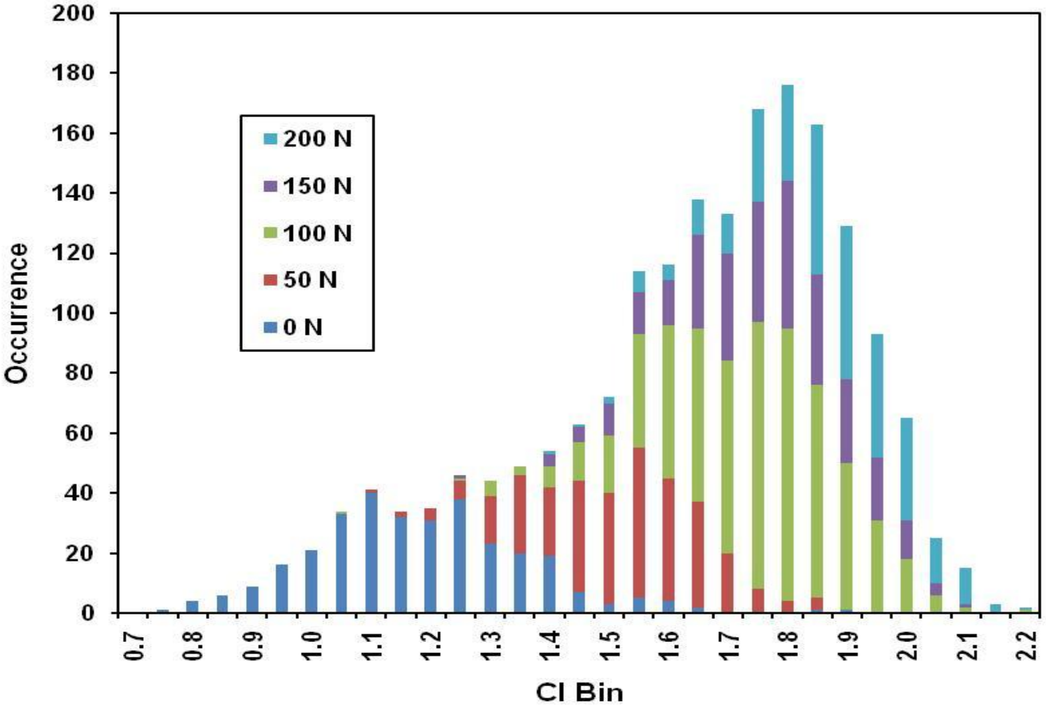

Figure 2. Occurrence of red-edge chlorophyll index values within irrigated corn plots receiving five preplant N rates (data compiled for eight replications at V9).

Translating the *SI* values into fertilizer N recommendations is challenging because there are several sources of N in the soil (i.e., organic matter mineralization, manures, legume credits, nitrate in irrigation water, including residual soil N and preplant N fertilizer). The above *SI* values were inserted into an algorithm developed by Holland and Schepers (2010) to simulate the N application rates based on average *SI* values for each plot (Figure 3). This algorithm allows users to account for field-specific N sources and reduce N application rates in situations where the yield potential is reduced or additional fertilizer is not likely to achieve full yield. Other in-season N recommendation algorithms (Solari et al, 2010; Varvel et al, 2007) do not offer this flexibility because they incorporate any number of local influences into a single coefficient.

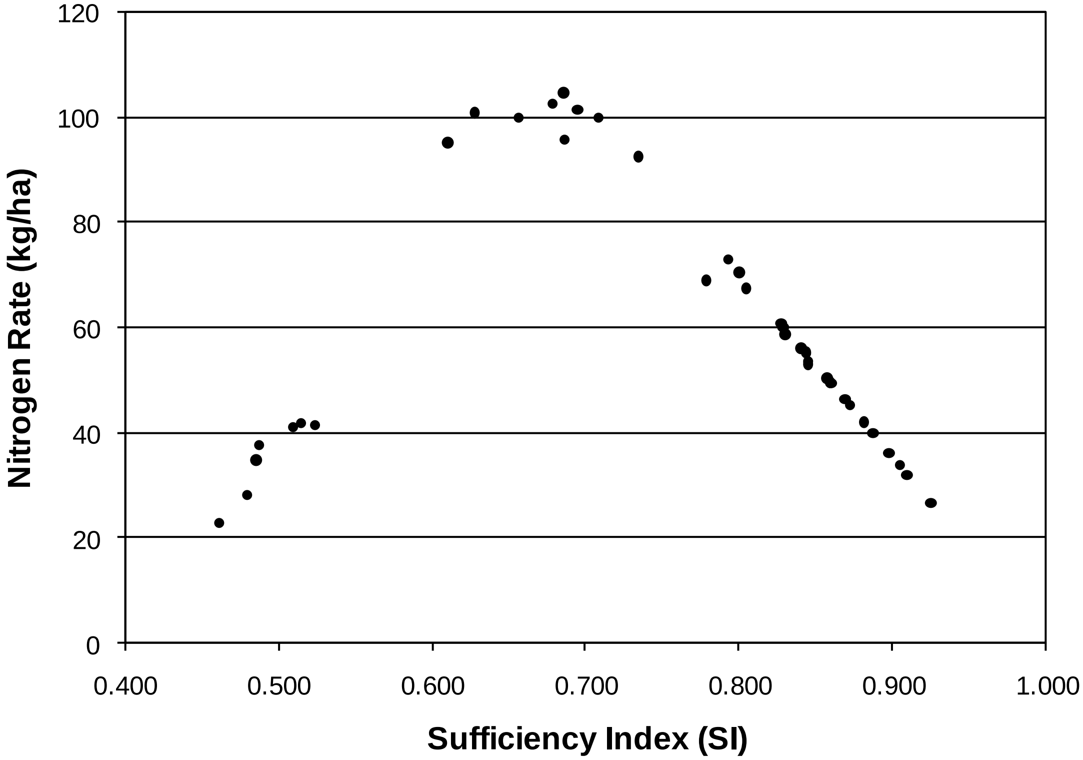

Figure 3. Recommended N application rates using the proposed calibration method for irrigated corn at the V12 growth stage. Sufficiency index values were based on the red-edge chlorophyll index and reflectance data were collected with Crop Circle 470 canopy sensors. The simulation used an economic optimal N rate (EONR) value of 196 kg N/ha, a preplant N rate ($N_{PreFert}$) of 50 kg N/ha and organic matter N credit ($N_{\overline{OM}}$) of 40 kg N/ha. The back-off function was implemented to limit N application for *SI* values less than a $SI_{Threshold}$ of 0.65.

Conclusion

The virtual reference concept to calibrate active canopy sensors offers a way for producer to move beyond the limitations and hassles of an N-rich strip. The examples presented illustrate the practicality and ease of use with the virtual reference concept. Analyzing sensor data with histograms provides new insights into factors that influence crop vigor.

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