Derivation of a Variable Rate Nitrogen Application Model for In-Season Fertilization of Corn

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Nitrogen Management

ABSTRACT

Nitrogen fertilizers used in crop production contribute to pollution of groundwater by nitrate and occurrence of hypoxia in the Gulf of Mexico. Economic and environmental pressures are forcing producers to improve N use efficiency. The objective of this study was to develop a production-based in-season N recommendation model for use with crop canopy sensors and remote sensing data. The approach is based on the general shape of an N fertilizer response function (sensor index vs. N rate) and the relationship between N rate and in-season crop vegetation index data. Transformation and substitution techniques were used to generate a simple function that offers an N fertilizer recommendation based on spatially variable in-season remote sensing data and established local crop production information such as the economic optimum N rate or producer defined optimum N rate. The model accommodates management zones, preplant N applications, manure mineralization, legume credits, nitrate in irrigation water, and crop growth stage. Estimates of potential yield are not needed. Instead the method relies on production information provided by the user and the generalized shape of the fertilizer N response function. Testing the model with SPAD chlorophyll meter data from irrigated corn showed that the recommended fertilizer N rate plus preplant N rate totaled 184, 164, 186, 188, and 200 kg ha^{-1} for preplant N rates of 0, 50,100, 150, and 200 kg N ha^{-1} when averaged across growth stages for 3 yr.

Fertilizer N recommendations have taken many forms since the discovery of the Haber-Bosch method for the production of anhydrous ammonia in 1909 and its commercialization in 1913. After WWII, when N fertilizer became commercially available, farmers were encouraged to apply modest amounts to their grain crops. However, once they realized that corn (*Zea mays* L.) responded favorably to supplemental N it enticed them to apply ever-higher rates. Agronomists began warning producers in the late 1960s that over-application of N fertilizer could result in groundwater contamination via nitrate leaching. By the mid-1970s, shallow groundwater used for irrigation and domestic sources of drinking water already exceeded the safe drinking water standard of 10 mg L^{-1} of nitrate-nitrogen (NO_3–N). Development of corn hybrids with ever-increasing higher yield potential prompted producers to apply ever-higher rates of N fertilizer. As a consequence, groundwater NO_3–N concentrations kept increasing until the late 1980s when N and irrigation management practices were imposed on producers in designated areas (Schepers et al., 1991, 1997). During this time, areas where rain-fed production is common began to measure elevated concentrations of NO_3–N in rivers in the spring when subsurface drainage systems (tile drains) were operational. This situation was attributed to leaching of excess residual N (NO_3) remaining in the soil after the previous crop and mineralization of manure that was applied in the fall and winter. One consequence has been the development of hypoxic conditions in the Gulf of Mexico.

The environmental consequences that resulted from the above mentioned N and manure management practices have prompted the development of a variety of improved management schemes to reduce NO_3 losses via runoff and leaching. For example, many irrigated producers have now converted from furrow irrigation to center-pivot systems in attempt to reduce the quantity and improve the uniformity of water application (Schepers et al., 1995). In addition, an ever-increasing number of producers have adopted reduced tillage and no-till practices to reduce runoff and conserve water. A further refinement in N management is associated with the recognition that the greatest potential for NO_3 leaching is in the spring when precipitation exceeds crop water use. For example, in much of the U.S. Corn Belt region, long-term average precipitation exceeds evapotranspiration before 15 June. Yet, conventional N management practices involve large doses of fertilizer N being applied much earlier and even before crop planting. The exception might be center-pivot irrigation systems that are equipped to inject liquid fertilizer into the water (fertigation). In an attempt to improve synchronization

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Abbreviations: ΔSI, delta sufficiency index; EONR, economic optimum nitrogen rate; LAI, leaf area index; MZ, management zone; N_{APP}, nitrogen application rate; N_{COMP}, nitrogen in excess of N_{OPT} to satisfy soil limited conditions; N_{CRD}, nitrogen credits from previous crop and manure; N_{OPT}, optimal nitrogen rate; $N_{PreFert}$, nitrogen applied before in-season nitrogen application; NO_3–N, nitrate-nitrogen; NUE, nitrogen use efficiency; SI, sufficiency index; VRA, variable rate application.

between crop N need and soil N supply, some producers make sidedress applications of N fertilizer with conventional tractor-drawn applicators (before V6-V7 growth stages). High-clearance applicators (sprayers) are becoming more common which allows for even greater opportunities for N synchronization. Meanwhile, <15% of the total aboveground N uptake by modern corn hybrids has occurred by the V7 growth stage (~5% total dry matter accumulation at V7)(Shanahan et al., 2007). However, by silking (VT), ~60% of the total N uptake has occurred and accumulated dry matter amounts to ~40%. Therefore, ~45% of the crop's total N uptake occurs during a 30-d period (this amounts to ~60 kg N ha^{-1} uptake for a 12 Mg ha^{-1} yield). It follows that opportunities to improve N synchronization are good by delaying in-season N applications until the V7 to VT growth stages, provided the yield potential has not been reduced by an early-season N stress that can reduce yield potential.

Determining how much N fertilizer will be required by a corn crop is an imperfect science at best. Early N fertilizer recommendations were usually built around the expected yield or yield goal. The N fertilizer recommendation was back-calculated from the yield goal by assuming a typical grain protein content and harvest index (grain N/total N uptake ratio), and further assuming some level of N use efficiency, and finally giving credit for other N sources (e.g., previous legume crops, manure, N mineralization, and N in irrigation water). This approach uses a "mass balance" concept which is in contrast to the flat-rate approach used in Iowa, Illinois, and Minnesota where the recommended N rate is based on the geographical region with allowances for soil type and long-term precipitation (Nafziger et al., 2004). The justification for the later approach is that the scientific literature shows that corn yields are largely insensitive to fertilizer N rate even though residual N levels were incorporated into the recommendations. As such, fertilizer N recommendations in these states do not consider residual soil N levels or yield goals because near-maximum yields across broad geographic regions are generally achieved with the recommended N rate. Neither of these approaches account for spatial variability in soil within a field. Yield potential is variable within a field because of inherent spatial differences in fertility levels and water availability. Therefore, crop response to N fertilizer would be expected to vary in the same manner. Scharf et al. (2005) conducted a series of N-rate trials within a field and found the magnitude of crop response to applied N to shift with differences in yield potential that were probably influenced by water availability. Maximum yield was achieved with a different N rate for each location in the field as expected since other sources of available N varied spatially. Each yield response function could be roughly superimposed onto a generalized quadratic plateau response function (yield vs. fertilizer N rate).

The plateau portion of a quadratic plateau function can be used to indicate about how much excess N was applied. The most important attribute of the function is where yield becomes relatively insensitive to increases in N fertilizer additions. This portion of the function is where profitability can be assessed based on the unit price of fertilizer N and the unit value of grain produced. The general shape of fertilizer N response functions is similar for many grain crops and therefore offers an opportunity to develop a robust, science-based, approach for determining the N requirement of a crop. The combination of this relationship and in-season assessment of crop vigor has the potential to be a useful tool as producers strive to increase profitability and promote environmental sustainability.

A priori knowledge of crop response to applied amounts of a nutrient is useful for guiding fertilizer application based on the sensed biophysical properties of the crop. This concept involves measuring a crop or plant's growth attributes under programmed and documented field conditions and generating a regression model relating the sensed biophysical properties to nutrient application requirements. Typically, sensor measurements are normalized to reduce the effects of cultivar, canopy structure (i.e., growth stage and leaf architecture), and differences in the sensor/plant distance relationships, thus allowing the developed model to be applied across many different fields and types of crop. The objective of this study was to develop a generalized N application model that is customizable for region and field specific N inputs and to present preliminary results obtained from an experiment with irrigated corn in Nebraska. The goal was to develop an N application model compatible with contact and remotely sensed measurements for implementation in variable-rate applicator (VRA) systems.

MATERIALS AND METHODS

Nitrogen Application Model

Derivation of the N application model is broken down into two sections: (i) Model Background and (ii) Model Parameterization. In the Model Background section, the underlying assumptions pertaining to the model synthesis are presented. The Model Parameterization section explains how the application of boundary conditions to the general N application model can be used to generate a completely parameterized N application model using only sensor and regionally specific N recommendations.

Model Background

The N application model developed by the authors of this paper involves directly relating normalized sensor measurements to a generalized plant growth function. The sensor normalization technique used by the N application model is referred to as the sufficiency index (SI) (Peterson et al., 1993; Biggs et al., 2002). 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

$$\mathrm{SI} = \frac{\mathrm{VI}_{\text{Sensed Crop}}}{\mathrm{VI}_{\text{Reference}}} \qquad [1]$$

where SI is the sufficiency index ($0 \le \mathrm{SI} \le 1$), $\mathrm{VI}_{\text{Sensed Crop}}$ is the vegetation index (or measurement) of the sensed crop, and $\mathrm{VI}_{\text{Reference}}$ is the vegetation index (or measurement) of the non-N limited crop.

Values for the VI terms in Eq. [1] can be standard vegetation indexes (or remotely sensed reflectance measurements) calculated from proximal, aerial or satellite sensors, or contact-type leaf chlorophyll measurements from a SPAD meter for example. Two common vegetation indexes that are often used in SI calculations are the chlorophyll index (CI) and the normalized difference vegetation index (NDVI) (Hatfield et al., 2008).

The following N application model derivation assumes the generalized plant growth function can be described using a second order polynomial having downward concavity. As such, the normalized sensor measurement vs. the generalized plant growth function can be stated mathematically as

$$\mathrm{SI} = a_2 N^2 + a_1 N + a_0 \qquad [2]$$

where SI is the sufficiency index, a_2, a_1, a_0 are coefficients for the generalized plant growth function ($a_2 < 0$ and $a_1 > 0$), and N is the nitrogen rate in lbs ac^{-1} or kg ha^{-1}.

The roots of Eq. [2] are shown in Eq. [3] below.

$$N = \frac{a_1}{2a_2} \pm \sqrt{\frac{a_1}{2a_2} \div^{2} \quad \frac{a_0}{a_2} + \frac{\mathrm{SI}}{a_2}} \qquad [3]$$

Differentiating Eq. [2] with respect to the variable N yields the solution for the N rate where peak crop growth performance occurs. Computing the first derivative for Eq. [2] with SI equal to 1.0, yields Eq. [4] below.

$$0 = 2a_2 N + a_1 \qquad [4]$$

Rearranging terms in Eq. [4] to solve for N yields the optimal nitrogen rate (N_{OPT}).

$$N_{\mathrm{OPT}} = \frac{a_1}{2a_2} \qquad [5]$$

The optimal N rate determined above would be the rate that most extension specialists recommend to farmers to maximize crop yield. N_{OPT} will be a determining factor for control of the N application model as will be shown below. Maximizing profitability requires additional calculations involving the unit cost of N fertilizer and the unit value of corn grain.

Additionally, setting N equal to zero ($N = 0$) in Eq. [2] results in

$$a_0 = \mathrm{SI}(0) \qquad [6]$$

where SI(0) is the sufficiency index when the applied fertilizer rate equals zero ($N = 0$).

The SI(0) term represents the lower bound for plant growth. The usefulness of this lower boundary is that it establishes the primary range of SI values [SI(0) to SI(N_{OPT})] over which the VRA system will control N fertilizer rates. The difference between the point in Fig. 1 where SI equals 1.0 and the point where the response curve intersects the y axis is referred to as ΔSI; or mathematically, 1– SI(0). The value for ΔSI will vary in magnitude depending on sensor measurement type and growth stage which will be discussed later.

The zero N fertilizer condition [SI(0)] is sometimes referred to as a check response. Factors that affect the magnitude of the intersection point include cropping history, preplant fertilizer, organic matter, crop residue, etc. In some instances, ΔSI can approach zero. This happens when the crop has adequate amounts of soil N and hence the real-time sensed crop properties have values equal to the standard sensed crop property (reference) resulting in SIs approximately equal to 1.0.

To relate the amount of N to be applied with respect to the N that is contained in the soil and available to the crop, the solution to Eq. [2] as shown in Eq. [3] should be subtracted from the optimal N rate for the crop. This difference represents the N required by the crop to reach optimal growth. Nitrogen in Eq. [3] is assumed to be indicative of relative soil N status and thus should be subtracted from N_{OPT} which results in Eq. [7] below.

$$N_{\mathrm{APP}} = N_{\mathrm{OPT}} \quad N = \frac{a_1}{2a_2} \quad \frac{a_1}{2a_2} \pm \sqrt{\frac{a_1}{2a_2}\div^{2} \quad \frac{a_0}{a_2} + \frac{\mathrm{SI}}{a_2}} \div = \pm\sqrt{\frac{a_1}{2a_2}\div^{2} \quad \frac{a_0}{a_2} + \frac{\mathrm{SI}}{a_2}} \qquad [7]$$

The negative term in Eq. [7] is extraneous and therefore is discarded. The general form of the N application model to be used in a sensor-based VRA system is shown below in Eq. [8].

$$N_{\mathrm{APP}} = \sqrt{\frac{a_1}{2a_2}\div^{2} \quad \frac{a_0}{a_2} + \frac{\mathrm{SI}}{a_2}} \qquad [8]$$

Model Parameterization

Synthesis of the model that will be used for sensor-based N application involves simplifying Eq. [8] by placing it into a parameterized form that can use many years of agronomic and regionally developed science. This involves applying the known boundary conditions developed above to Eq. [2] such that when SI = 1.0, $N = N_{\mathrm{OPT}}$ and $a_0 = \mathrm{SI}(0)$ are substituted into Eq. [2] we obtain the following.

$$1 = a_2 N_{\mathrm{OPT}}^2 + a_1 N_{\mathrm{OPT}} + \mathrm{SI}(0) \qquad [9]$$

Solving Eq. [9] for a_2, knowing that $a_1 = -2a_2 N_{\mathrm{OPT}}$ from Eq. [5], results in Eq. [10] below.

$$a_2 = \frac{[\mathrm{SI}(0) \quad 1]}{N_{\mathrm{OPT}}^2} \qquad [10]$$

Substituting the right side of Eq. [10] into Eq. [8] for a_2 with a_0 equal to SI(0) and simplifying yields Eq. [11].

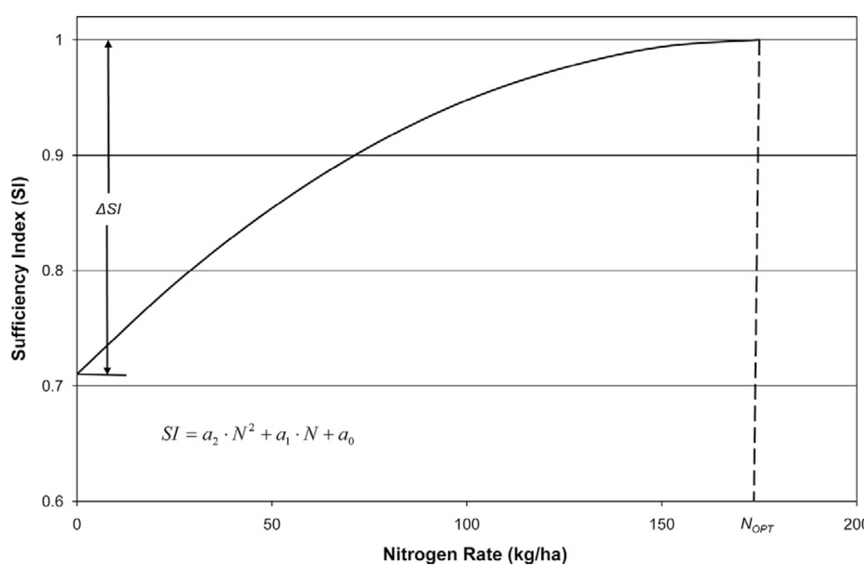

Fig. 1. Nitrogen response curve: sufficiency index (SI) vs. N rate.

$$N_{\mathrm{APP}} = \sqrt{\frac{N_{\mathrm{OPT}}^2}{1 \quad \mathrm{SI}(0)} \times (1 \quad \mathrm{SI})} = N_{\mathrm{OPT}} \times \sqrt{\frac{(1 \quad \mathrm{SI})}{\mathrm{SI}}} \qquad [11]$$

Equation [11] is the parameterized form of the N application model developed for sensor-based VRA systems. Since N_{OPT} in Eq. [5] is derived using the coefficients of a quadratic function (see Eq. [2]–[4]) and normalized sensor parameters, it provides considerable versatility to users because they can use local or regional agronomic information that describes how their crops respond to N fertilizer additions to determine N_{OPT}. It should be noted the Economic Optimum N Rate (EONR) can be substituted for N_{OPT} in Eq. [11], thereby building economics into the N recommendation (where $\mathrm{SI}_{\mathrm{EONR}} \cong \mathrm{SI}_{\mathrm{NOPT}}$). In practice, farming systems frequently involve split or even multiple applications of N fertilizer. Those N applications made before the time of crop sensing should be subtracted from N_{OPT}, as well as N credits from a previous cropping season. It follows then that N'_{OPT} is calculated for insertion into Eq. [11] using the prescribed N rate and other sources of N as follows:

$$N'_{\mathrm{OPT}} = N_{\mathrm{OPT}} - N_{\mathrm{PreFert}} - N_{\mathrm{CRD}} + N_{\mathrm{COMP}} \qquad [12]$$

where N_{OPT} is the EONR or the maximum N rate prescribed by producers, N_{PreFert} is the sum of fertilizer N applied before crop sensing and/or in-season N application, N_{CRD} is the N credit for the previous season's crop, nitrate in water, or manure application and N_{COMP} is the N in excess of N_{OPT} required by the crop under soil-limiting conditions at a given growth stage.

N_{OPT} represents the season-long N requirement for the crop grown under local conditions. Embedded within N_{OPT} are modifications (additions and losses) to the soil N pool from processes that are difficult to quantify like mineralization, immobilization, denitrification, and leaching. These processes have both spatial and temporal implications within fields as affected by the interactions between weather, soil properties, and topography. Other contributions to the soil N pool like fertilizer additions, N from manures, nitrate in irrigation water, and legume credits are under producer control and can be readily quantified. These known and quantified N sources need to be subtracted from N_{OPT} to determine the in-season N application rate.

It should be noted that a portion of the total crop N uptake, depending on the growth stage and SI of the crop, will have occurred at the time of the in-season N application. Crop N uptake (N_{UPT}) can be reliably estimated based on phenologic information and adjusted downward as crop stresses reduce SI. However, the crop is only one component within a complex soil/plant/biological system. Nitrogen deficiency symptoms (i.e., typically expressed as reduced SI values) in plants are also going to be experienced by soil fauna and flora. Therefore, in addition to applying enough N fertilizer to help the plant catch up with the reference plants to the extent possible, extra N needs to be applied to satisfy the N-deprived soil microbial community. These N-limiting soil environments are frequently associated with N immobilization which deprives the crop of much needed N. While this phenomenon is likely to be temporary, the duration of the impact on the crop is variable and the resulting crop N deficiency can have a direct effect on yield and profitability. Therefore, N_{OPT} needs to be progressively increased as the SI value decreases. As such, a compensation term (N_{COMP}) is used by the model to boost the applied N at low SI values near the SI(0) boundary. $\mathrm{N}_{\mathrm{COMP}}$ is based on the nitrogen use efficiency (NUE), SI difference from the reference SI value (1 – SI) and the theoretical N uptake by the plant at a given growth stage. An NUE value of 50% is proposed for this adjustment because it represents a reasonable allocation of the added N between the crop and soil microbial community. The NUE for the other N sources is embedded within the N_{OPT} value provided by the producer or consultant so as to capture the net effect of the local growing conditions.

A model that boosts N application for corn (N_{COMP}) based on NUE, and N uptake (N_{UPT}) is shown in Eq. [13].

$$N_{\mathrm{COMP}} = \frac{(1 \quad \mathrm{SI})}{\mathrm{NUE}} \times N_{\mathrm{UPT}} = \frac{(1 \quad \mathrm{SI})}{\mathrm{NUE}} \times \frac{\times N_{\mathrm{OPT}}}{1 + e^{\left(G_{\mathrm{i}} \quad G\right)}} \div \qquad [13]$$

where N_{OPT} is the EONR or the maximum N rate prescribed by producers, α and β are scalars for the N uptake function, NUE is the nitrogen use efficiency of the plant (0 < NUE < 1), G_{i} is the growth stage inflection point of the N uptake function, and G is the vegetative growth stage of the crop, for corn $G \in \{1, 2, 3,.., 15\}$.

Comparison of the N_{UPT} model in Eq. [13] to actual N uptake by corn is shown in Fig. 2. The model was formulated from averaged data collected from six different corn hybrids grown under adequately fertilized irrigated conditions. Based

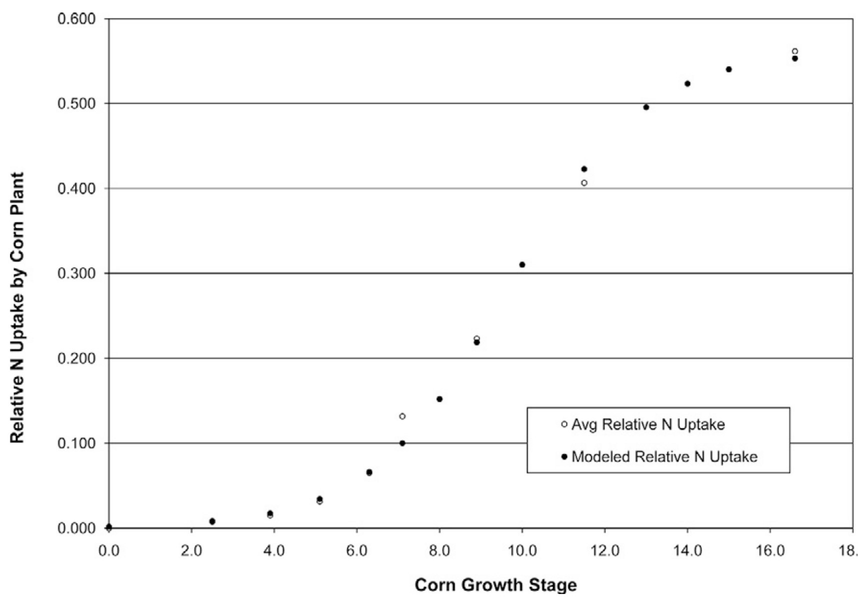

Fig. 2. Relative N uptake by corn plants as a function of growth stage. Data are averaged over 2 yr (1993 and 1994) for five modern hybrids plus B73×MO17 from the 1970s. Nitrogen uptake rates were not statistically different between hybrids until just before silking. The effect of year was not significant after adjusting for growing degree days at sampling. The parameters for the N_{UPT} model (Eq. [13]) are as follows: α = 0.562, β = 0.600 and G_i = 9.65.

on the corn growth stage, the model will reasonably predict the relative amount of N the plant has taken from the soil. The parameters α and β set the maximum uptake of N, based on N_{OPT}, and the rate of N uptake, respectively. Equation [13] uses SI and NUE factors to increase the amount of N applied to stressed plants, that is, when the SI approaches SI(0) boundary. This adjustment is necessary to acknowledge that N deficient plants are expected to contain less chlorophyll (i.e., less N) and less biomass, and thus have lower SI values. The effect of the compensation term is most pronounced at later growth stages where the plant would normally have assimilated greater amounts of N from the soil.

The N sources in Eq. [12] can be expanded to accommodate management zones by modifying the N_{OPT} term in Eq. [13] so that it can be scaled by spatially determined information. The N_{OPT} term is scaled by MZ_i which is the geospatial management zone scalar where $i \in \{1, 2, 3,.., \mathrm{n}\}$ zones and $0 \le \mathrm{MZ}_i \le 2$.

Values for MZ_{i} can typically be determined and set via analysis of historical yield maps or soil sample information. The function of the management zone scalar is to modify the normal N_{OPT} rate due to underlying soil conditions that would affect the typical growth performance of the crop. In situations where poor field conditions might result in poor yields, the management zone scalar would be set to a value <1.0 to reduce the normal sensor-based application rate.

Modifying Eq. [13] to correct N'_{OPT} due to spatially variable soil conditions, that is, management zone information MZ_i, results in Eq. [14] below.

$$N'_{\mathrm{OPT}} = \mathrm{MZ}_i \cdot N_{\mathrm{OPT}} - N_{\mathrm{PreFert}} - N_{\mathrm{CRD}} + N_{\mathrm{COMP}} \qquad [14]$$

Substituting N'_{OPT} in 14 for N_{OPT} into Eq. [12] and simplifying results in the final form of the N application model shown below in Eq. [15].

$$N_{APP} = \left(MZ_i \times N_{OPT} - N_{PreFert} \quad N_{CRD} + N_{COMP}\right) \times \sqrt{\frac{(1 \quad SI)}{SI}} \qquad [15]$$

In order for the N application model to be valid, the following constraints need to be imposed on the parameters in Eq. [15].

$$MZ_i \cdot N_{\mathrm{OPT}} + N_{\mathrm{COMP}} \ge N_{\mathrm{PreFert}} + N_{\mathrm{CRD}},$$

$$\Delta\mathrm{SI} > 0, \text{ and}$$

$$0 \le \mathrm{SI} \le 1.0$$

Further, it is noteworthy that development of Eq. [15] does not involve any arbitrary coefficients or undefined relationships. Another significant attribute of the technique described herein is that it does not involve the estimation of yield potential and other assumptions associated with the mass balance approach. The opportunity to use local or regional data to generate N_{OPT} or EONR should be a considerable enticement for in-season N applications, especially since Eq. [15] builds crop sensory information into the N recommendation. Users that want to base the spatial N recommendation on their experiences or provide a maximum N application rate can substitute that value in Eq. [15]. The rationale that links in-season sensor data to yield is not absolute, but converting the data to relative sensor-derived vegetation indices and relative yield generates a function that is notoriously linear except when N stress is extreme (Varvel et al., 2007). The slope of this function typically becomes flatter (relative yield as a function of SI) as the growing season progresses, especially for situations with low mineralization rates. This is because N stresses develop quicker when the soil-available N pool is restricted. At some point, the N stress becomes severe enough to reduce yield potential and thus the N recommendation should be reduced accordingly. Building a back-off feature into the in-season N recommendation accomplishes two things. First it would tend to avoid over-application in areas where yield potential is reduced and second it serves to maintain profitability to the extent possible.

Field Test

Field plots used to test the performance of the N application model were located near Shelton, NE (40°45′01″ N, 98°46′01″ W; elevation 620 m above mean sea level) in the Central Platte River Valley. The soil is classified as a Hord silt loam (fine-silty, mixed, superactive, mesic Cumulic Haplustolls) with 0 to 1% slope. The field is under linear-drive sprinkler irrigation.

Two field studies were used to evaluate the model. The first was initiated in 1991 and consisted of a split-split randomized block design with crop rotation as the main plot (continuous corn, corn/soybean, or soybean/corn), hybrids (four) were the subplots, and fertilizer N rates (0, 50, 100, 150, and 200 kg N ha^{-1}) were the sub-subplots with four replications. Field strips (400-m long) represented each cropping system. Subplots representing the four hybrids were randomized within each field strip. Only data from the continuous corn strips within each block were used in the model evaluation. Plots were eight-rows wide (0.91-m row spacing) by 16-m long, and were delineated with a 1-m wide tilled alley resulting in a total of 24 plots per field strip. Chlorophyll meter (SPAD) readings collected at weekly intervals before silking and yield data for 2002, 2003, and 2004 were used to evaluate the in-season N recommendation model over years, crop growth stages, and N rates. The preplant fertilizer N rates served to represent scenarios analogous to management zones.

The second evaluation study involved a single corn hybrid (Pioneer brand P33D83) planted on 20 May 2009 at the rate of 74,000 seeds ha^{-1}. Starter fertilizer as 10–34–0 at the rate of 36 L ha^{-1} was applied at planting time (11.9 kg N ha^{-1}). This study consisted of two 8-row wide field strips (400-m long) that contained four blocks each (eight replications) of five N-rate plots (0, 50, 100, 150, and 200 kg N ha^{-1}) that were each 16-m long. A 1-m wide bare-soil alley separated the plots. Shortly after emergence, the N rate treatments were surface banded (~15 cm from the row) as urea-ammonium nitrate (UAN). Beginning at the V9 growth stage, canopy reflectance was measured with a pair of Crop Circle ACS-470 sensors (Holland Scientific, Inc., Lincoln, NE) positioned over rows three and six of the eight-row wide 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 h^{-1} (~1.25 m s^{-1}) which amounts to a set of recorded sensor readings about every 25 cm

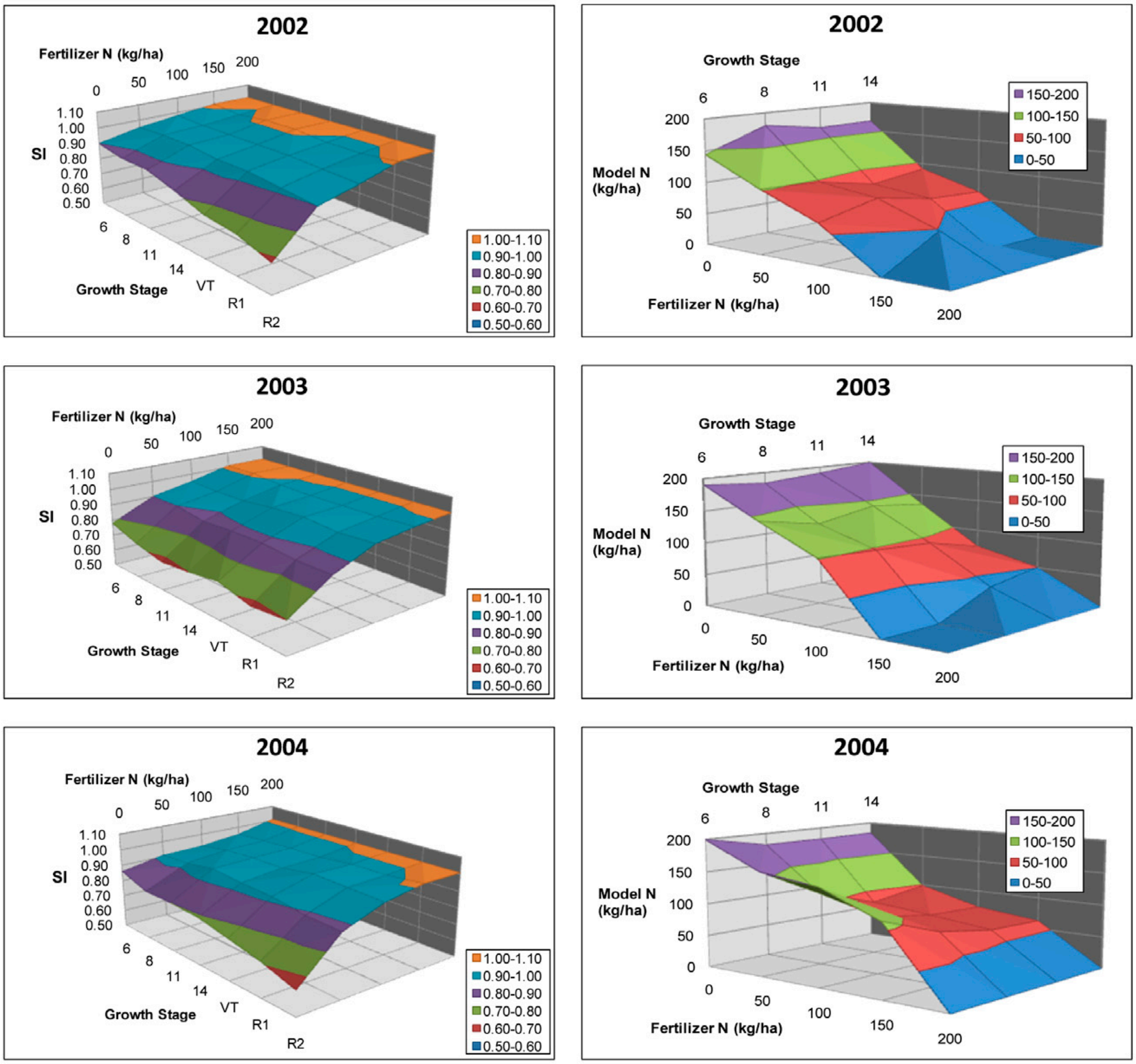

Fig. 3. SPAD meter derived sufficiency index (SI) values for 3 yr on multiple sampling dates for irrigated corn grown at five N fertilizer rates (left) and resulting in-season N fertilizer recommendations demonstrating performance of the model over years, growth stage, and crop N status (back-off function was not enabled) (right).

(average of approximately two plants). Sensors were mounted on a high clearance sprayer and oriented in the nadir position over the designated rows at a height of at least 60 cm above the upper leaves of the tallest plants. Approximately 45 data points per row remained after discarding data collected from the alley area. Sensors readings were collected on 14 July (V9), 21 July (V12), and 28 July (V15) in 2009.

Individual waveband reflectance values were used to calculate the CI ((NIR/red edge)-1) for each set of recorded sensor values (Hatfield et al., 2008). Mean CI values for each plot within a replication were then normalized to the high N-rate (200 kg ha^{-1}) plot (i.e., CI$_{\text{N-rate plot}}$/CI$_{\text{high N reference plot}}$). This produced an SI value that represents an integration of relative plant vigor and chlorophyll content. Sufficiency index values are routinely used as one of the independent variables within in-season N recommendation models to guide fertilizer applications.

RESULTS AND DISCUSSION

Field Testing

To evaluate the robustness of the algorithm across growth stages and years, SI values based on Minolta SPAD data for 2002–2004 (Table 1) from a study under continuous irrigated corn were tested (Table 1). SPAD meter readings were taken from the upper-most expanded leaf on a weekly basis before silking and at 2-wk intervals after silking (Peterson et al., 1993). The highest N rate was assumed to be non-N limiting and used as the reference when calculating SI. The calculated EONR was 168, 170, and 188 kg N ha^{-1} for 2002, 2003, and 2004, respectively, using a fertilizer N cost of \$0.88 kg^{-1} (\$0.40 lb^{-1}) and a grain price of \$138 Mg^{-1} (\$3.50 bu^{-1}).

Sufficiency index values generally declined with advancing growth stages for the lower fertilizer N rates (Table 1 and Fig. 3). Each of the 3 yr showed different trends in terms of early-season SI values. For example, 2002 showed the least check plot stress at the V6 growth stage while 2003 exhibited the greatest stress (i.e., lowest SI values). At harvest, the check-plot yields were 4.92, 3.71 and 5.23 Mg ha^{-1} for 2002–2004, respectively (Table 1). Growing conditions were exceptionally favorable in 2004 with reference plot yields of 11.53, 12.11, and 13.66 Mg ha^{-1} for 2002–2004, respectively.

Fertilizer N recommendations generated when the SPAD meter SI values were inserted into the algorithm (Fig. 3) generally declined as the planting time N rates increased. Average ΔSI values were calculated for growth stages V6, V8, V11, and V14 for years 2002, 2003, and 2004. The ΔSI values over all years were 0.15 for V6, 0.20 for V8, 0.22 for V11, and 0.23 for V14. The shape of the response surface (in-season N recommendation) was similar across years with minor fluctuations with changing growth stages (Fig. 3). An N_{OPT} value of 175 kg N ha^{-1} was used for all simulations. Output is only provided through the V14 growth stage because the crop N uptake submodel only covers pretassel in-season applications. The amount of in-season N recommended for the check plots was nearly 200 kg ha^{-1} in 2003 and 2004, but slightly less in 2002. Average in-season N recommendations across growth stages and years plus the corresponding preplant N rates (0, 50, 100, 150, and 200 kg ha^{-1}) resulted in average total N fertilizer applications of 184, 164, 186, 188, and 200 kg ha^{-1}, respectively. The average EONR for these 3 yr was 175 kg ha^{-1} which compared well with the total fertilizer N that would have been applied based on in-season SI values using the described model. In practice, the preplant N rates used in this evaluation might well represent situations in different management zones of a field.

Model performance was evaluated both over time (different growth stages) and across a range of soil N availability values for a given growth stage. Sufficiency index values generated at both the V9 and V12 growth stages (V15 not shown) showed a typical quadratic response to the range in soil N supply that was generated by applying different N rates to the plots at planting time (Fig. 4). Calculation of SI values for each sampling date makes it possible to evaluate relative changes over time. During the 1-wk period between V9 and V12, the SI values for the check plots decreased significantly from 0.672 to 0.575 at $P < 0.05$, respectively. Sufficiency index values for these two dates at the 50 kg N ha^{-1} rate decreased from 0.811 to 0.780, respectively, which were statistically different at $P < 0.1$. Sufficiency index values at the 100 and 150 kg ha^{-1} N rates were not different from each other or between sampling dates, but the SI values for both dates at the 100 kg N ha^{-1} rate were significantly lower, $P < 0.05$, than for the reference plot (i.e., 200 kg N ha^{-1}). Within sampling dates, SI values were statistically different between the 0, 50, and 100 kg ha^{-1} N rates (0.672, 0.811, and 0.919 at V9 and 0.575, 0.780, and 0.924 at V12, respectively, $P < 0.05$) (Fig. 4).

Data from the V12 sampling date were used to illustrate how the model changes the amount of fertilizer N that is recommended based on average SI calculated for each plot. In practice, an SI value would be calculated for each recorded sensor reading (i.e., 5 per second), but to illustrate the features of the model, plot values are used. Reference N vegetation index values would normally be determined by driving through one or more high N reference strips before beginning to make variable-rate N applications. Other approaches to characterize the reflectance from plants receiving adequate N have been proposed and are being evaluated, but are not appropriate to include in this discussion. The example shown illustrates that the recommended N application rate increases as the SI decreases until the ΔSI threshold is reached, at which time the back-off function begins to reduce the N application rate (Fig. 5). Differences in accumulated crop

Table 1. Chlorophyll meter data for 3 yr: 2002, 2003, and 2004. Sufficiency index data was normalized to 200 kg ha^{-1} N rate for four growth stages.

N rate	Relative SPAD V6	V8	V11	V14	Relative yield	Yield
kg ha^{-1}						Mg ha^{-1}
			2002			
0	0.90	0.87	0.87	0.82	0.42	4.92
50	0.95	0.96	0.96	0.94	0.70	8.09
100	0.98	0.97	0.97	0.97	0.88	10.20
150	1.00	0.99	1.00	1.00	0.96	11.06
200	1.00	1.00	1.00	1.00	1.00	11.53
			2003			
0	0.78	0.72	0.68	0.70	0.31	3.71
50	0.90	0.90	0.87	0.88	0.62	7.44
100	0.95	0.94	0.94	0.96	0.87	10.57
150	1.00	1.00	0.99	0.98	1.00	12.08
200	1.00	1.00	1.00	1.00	1.00	12.11
			2004			
0	0.86	0.80	0.80	0.79	0.38	5.23
50	0.91	0.92	0.95	0.93	0.67	9.05
100	0.92	0.95	0.96	0.96	0.84	11.51
150	0.95	0.96	0.97	0.97	0.92	12.59
200	1.00	1.00	1.00	1.00	1.00	13.66

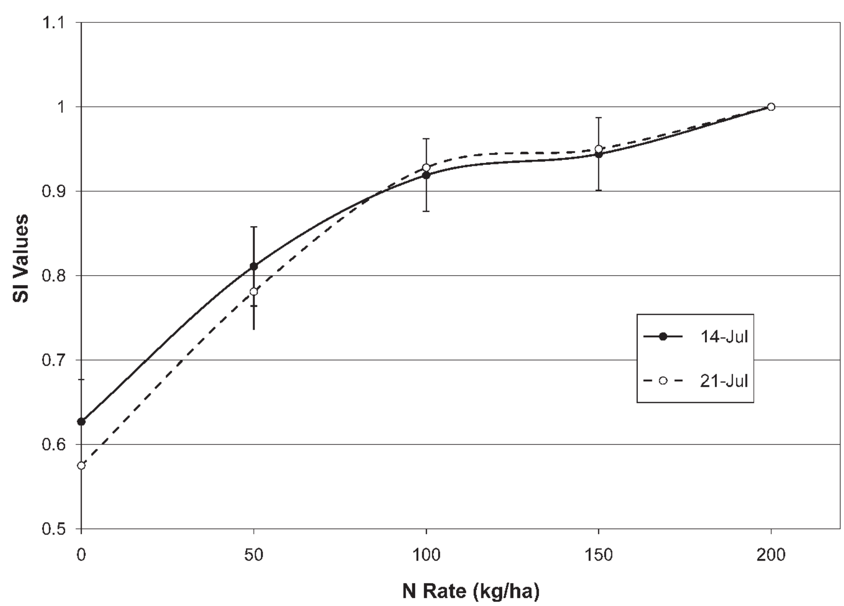

Fig. 4. Sufficiency index (SI) values for irrigated corn as a function of fertilizer N rate for two dates (V9 and V12) in 2009.

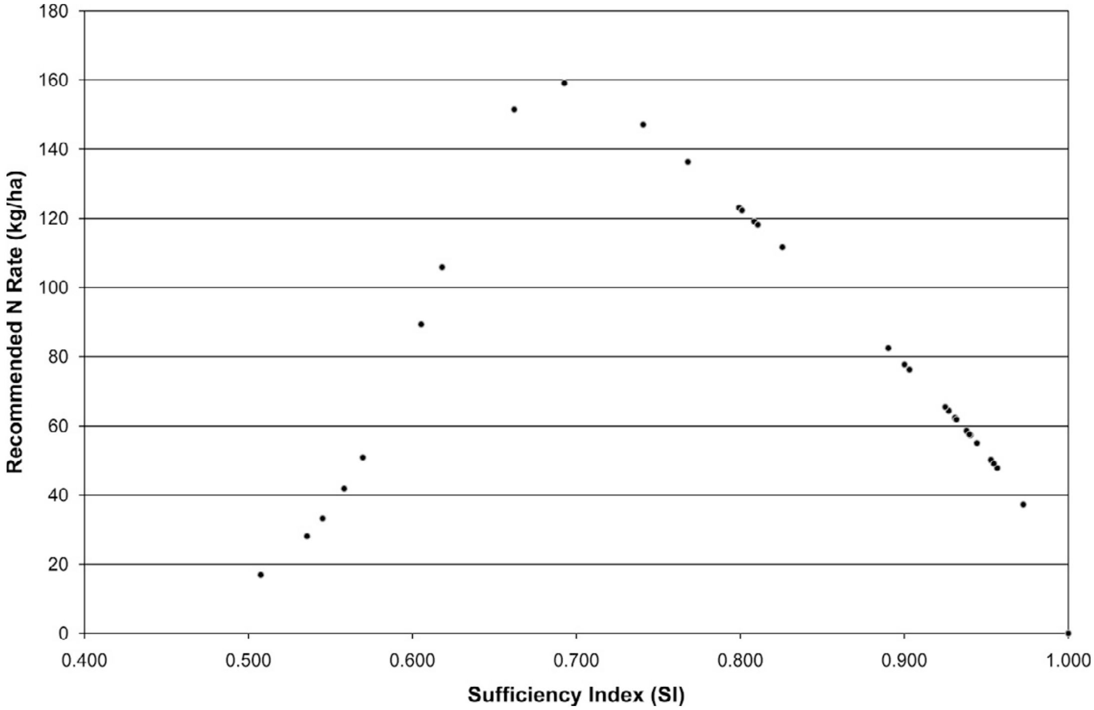

Fig. 5. Recommended N application rates using sufficiency index (SI) values for irrigated corn at the V12 growth stage. Sufficiency index values were based on the red-edge chlorophyll index and reflectance data were collected with Crop Circle 470 canopy sensors. The simulation used an EONR value of 175 kg N ha^{-1} and a preplant N rate of 56 kg N ha^{-1}. Back-off function was implemented to limit N application for SI values <1 – ΔSI. Note, parameters in Eq. [16] are set as follows: MZ_i = 1.0, $N_{PreFert}$ = N_{CRD} = 0, NUE = 0.5, N_{UPT} ≈ 0.45, ΔSI = 0.3.

N uptake as a function of SI are embedded in the model (Eq. [15]). Beyond the N recommendation generated by the model, it is envisioned that producers would be able to set upper and lower limits on the amount of N that would be applied via the fertilizer rate controller.

Implementation

The magnitude of ΔSI is, in part, dependent on the sensor measurement method. Proximal canopy sensors measure reflected light from a crop canopy at distances typically >0.5 m. For corn sensed with proximal crop canopy sensors having red-edge (730 nm) and NIR (800 nm) measurement bands, the ΔSI value is roughly equal to 0.3 ± 0.1. Contact type measurements, such as those performed by a SPAD meter, involve a different measurement methodology than that of proximal crop canopy sensors. The SPAD measurement involves the absorption of light, at two different wavelengths, through the leaf tissue of the crop. The ratio of the two wavelengths is proportional to the chlorophyll content of the tested leaf. For SPAD measurements, the ΔSI values are slightly lower than those of proximal sensors and have values that range from 0.1 to 0.3.

Selection of ΔSI terms for the N rate model can be determined by establishing a check strip (zeroN) next to a reference strip (high N) at planting. Data may be collected throughout the growing season to establish growth related ΔSI values. Computation of the SI value for these strips will result in an SI value that represents the point where the crop's growth response intersects the *y* axis as shown in Fig. 1. Computing the difference between an SI equal to 1.0 and SI(0) (check plot) value will result in a ΔSI term for use in Eq. [15]. It should be noted that ΔSI will typically increase as the vegetative growth stages progress unless the crop encounters an untimely environmental stress, for example, under water stress. This phenomenon is demonstrated by the data for growth stages V9 and V12 as shown in Fig. 4. The value for ΔSI at V9 was 0.37 while the value for ΔSI increased to 0.42 at V12. These values compare favorably with those reported by Roberts (2009) who broke five irrigated corn fields into two management zones each and measured the CI (590 nm and NIR) between V10 and V14. The more fertile management zones had an average ΔSI of 0.23 and the less fertile zones averaged 0.37. Another observation, with respect to the ΔSI value, involves its sensitivity to corn hybrid. Values for the ΔSI term seem to be somewhat invariant with respect to corn hybrid (Varvel et al., 2007) but more research needs to be conducted to establish this observation. This is most likely due to that fact that the ΔSI is derived from normalized sensor data rather than from absolute sensor measurements.

Accuracy of the N application model is dependent, in part, on the selection of the ΔSI term in Eq. [15]. Improper selection of the term can cause the calculated N rate to be higher or lower than the nominal rate. Application errors are typically minimal and do not appreciably diminish the performance of the model because the net effect on N rate involves the square root of the error in ΔSI. Table 2 shows the errors associated with ΔSI magnitude errors of ± 0% and ±20% as compared with a nominal ΔSI value. The assumed nominal ΔSI value for purposes of comparison was set to 0.3. At an SI value of 0.7, the nominal N rate would be 175 kg ha^{-1}. For ΔSIs at the ±20% error extremes, the maximum application error is –15 kg/ha and +21 kg ha^{-1}, respectively and for ΔSIs at the ±10% error extremes, the maximum application error is –8 kg ha^{-1} and +9 kg ha^{-1}, respectively. It is interesting to note that a 20% error in the ΔSI term results in <12% error in the nominal application rate and approximately 5% for a 10% ΔSI error.

Table 2. Effect of error in ΔSI term on model performance for an N_{OPT} equal to 175 kg ha^{-1}. Parameters in Eq. [15] are set as follows: $MZ_i = 1.0$, $N_{PreFert} = N_{UPT} = N_{CRD} = 0$.

SI	ΔSI error				
	–20%	–10%	0%	10%	20%
	kg N ha^{-1}				
0.6	24	11	0	–9	–18
0.7	21	9	0	–8	–15
0.8	17	8	0	–7	–12
0.9	12	5	0	–5	–9
1	0	0	0	0	0

Another issue regarding the value of the ΔSI term pertains to the spectral components used to calculate the vegetative index that is used to calculate ΔSI. Generally, red wavebands (660–690 nm) will produce larger ΔSIs than red-edge wavebands (710–750 nm) or green-yellow wavebands (520–600 nm). Selection of wavebands is based primarily on the growth stage of the crop and sometimes the cropping system implemented. It is best to sense crops having low LAI values with red bands due to the high efficiency by which chlorophyll in the crop's leaf tissue scavenge light. As the crop's LAI increases, less and less red light is reflected back from the crop/soil scene and measurement sensitivity to increasing crop biomass decreases. This phenomenon is demonstrated by the corn data measured at V12 in Fig. 6. The biomass of the corn generally increases with applied N. As shown, the NIR reflectance continues to increase as crop LAI increases, that is, with increasing N rate. Similarly, the red-edge band (730 nm) follows the same trend as the NIR band. However, the red band (670 nm) is unresponsive to increasing crop biomass. Two waveband vegetation indexes calculated from NIR and red-edge bands (or green-yellows bands) will typically be better indicators of crop chlorophyll content at high LAIs than indexes calculated from red and NIR bands. Red/NIR indexes will be primarily responsive to changes in NIR reflectance for LAIs greater than ~2 (Gitelson and Merzlyak, 1996).

Regarding N application to crops having SI values below the lower bound of SI(0), N rate should be modified so as to conserve N. Low SI valued crops (SI ≤ SI(0)) most likely will not respond to additional N application as prescribed by the model. As such, a method to appropriately manage N application, so as to conserve N and not to over-apply to crops that cannot use the additional N, should be implemented. There are various methods to address N application for low SI values. One method involves simply limiting the N rate to a predetermined maximum value. A more conservative method involves the use of a back-off function. This function can take on various mathematical forms and may be as basic as a simple linear line that decreases applied N for SI values below SI(0). As a rule, the function will generally fall to zero N somewhere between the bounds of 1 – ΔSI and 1 – 2 · ΔSI. The closer to the 1 – ΔSI boundary that the function falls to zero, the more aggressive the N conservation will be. This function may also plateau to a nonzero N value so as to allow the VRA system to apply a sustaining base N rate to the poor performing portions of the field.

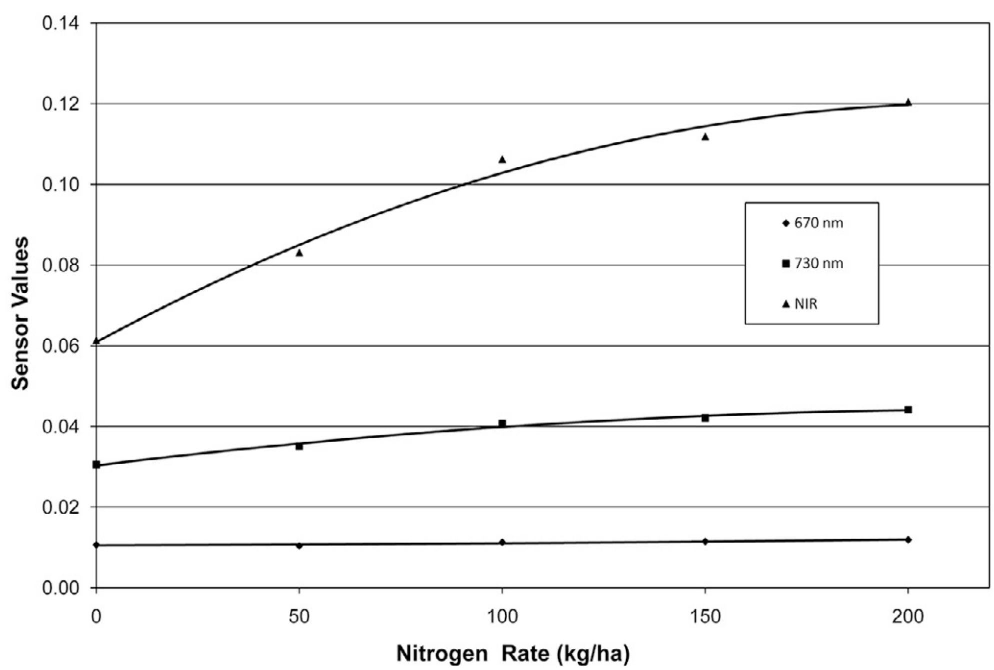

Fig. 6. Sensor values vs. N rate for irrigated corn at V12. Graph demonstrates the effect of high leaf area on sensor reflectance values for red (670 nm), red-edge (730 nm), and NIR (>760 nm) wavebands.

By way of example, consider the N application model incorporating a back-off function shown in Eq. [16] below

$$N_{APP} = \left(N_{OPT} - N_{PreFert} - N_{CRD} + N_{COMP}\right) \cdot \sqrt{\frac{(1-\mathrm{SI})}{\Delta\mathrm{SI}\cdot\left(1+0.1\cdot e^{m(\mathrm{SI}_{Threshold}-\mathrm{SI})}\right)}} \quad [16]$$

where N_{OPT} is the EONR or the maximum N rate prescribed by producers; $N_{PreFert}$ is the sum of fertilizer N applied before crop sensing and/or in-season N application; N_{CRD} is the N credit for the previous season's crop, nitrate in water, or manure application; N_{COMP} is the N in excess of N_{OPT} required by the crop under soil limiting conditions at a given growth stage; SI is the sufficiency index; m is the back-off rate variable ($0 < m < 100$); and $SI_{Threshold}$ is the back-off cut-on point.

The back-off function used in this N application model has a sigmoidal response. The aggressiveness of the function's N conservation is controlled by the back-off rate (m) and the SI trigger threshold ($SI_{Threshold}$) parameters. The back-off rate parameter m controls how rapidly N_{APP} decreases with decreasing SI values. Control of where the back-off function begins to engage is determined using parameter $SI_{Threshold}$. $SI_{Threshold}$ is usually set to coincide with the SI(0) point. Figure 7 demonstrates the effect

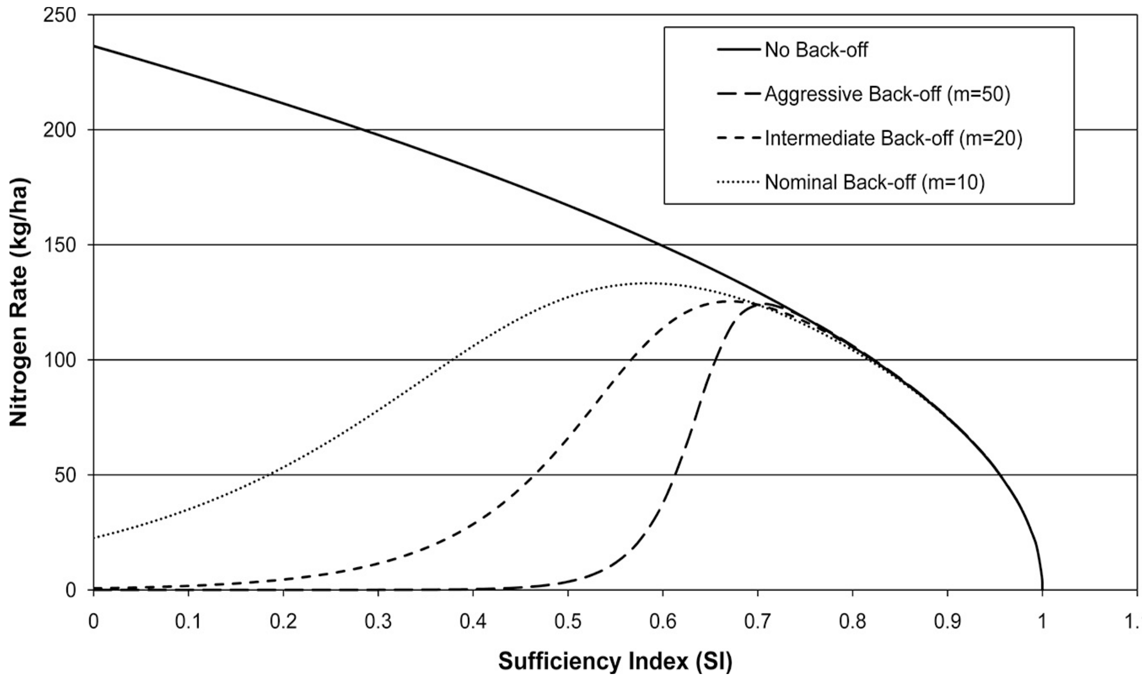

Fig. 7. Comparision of simulated N application using the proposed algorithm incorporating a sigmoidal back-off function. The simulation used an N_{OPT} value of 130 kg N ha^{-1}. Back-off function was implemented to limit N application for SI values <1 – ΔSI. Note, parameters in Eq. [16] are set as follows: MZ_i = 1.0, $N_{PreFert}$ = N_{CRD} = 0, NUE = 0.5, N_{UPT} ≈ 0.45, $SI_{Threshold}$ = 0.7.

of three different back–off scenarios with an $SI_{Threshold}$ of 0.7. The N_{App} model in Eq. [16] can be easily controlled to modify applied N for crops having SI values below the SI(0) point, that is, 1-ΔSI. Crop SI values <1 – ΔSI are attenuated by the model so as to conserve N since values below this bound correspond to crop stress beyond the VRA system's ability to correct for N deficiencies.

CONCLUSIONS

The experimental results indicate that the model is a practical method for making in-season fertilizer N recommendations because only sufficiency index and growth stage data are required. The in-season N recommendation model developed from a generalized N fertilizer response function uses: (i) information pertaining to the economic optimum N rate or the optimum N rate offered by producers, consultants, or extension specialists; and (ii) spatially variable vegetation index data acquired via crop canopy sensors or remotely sensed imagery. The resulting model embeds local production attributes like soil type, cultural practices, and climate through the economic optimum N rate or optimum N rate provided by the producer. These considerations alleviate the need to estimate potential yields that are known to vary over time and space because of the unpredictability of weather. The spatially variable in-season N recommendation generated by the model readily accommodates N supplied via manure applications, legume credits, preplant N applications, and anticipated N supplied in irrigation water. The in-season N recommendation is flexible in terms of producer preferences and climatic conditions through a function that considers the portion of total N uptake that has accumulated at the time of sampling.

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