Precision nitrogen fertilizer management of maize and cotton using crop sensors

Peter C. Scharf[A,F], Newell R. Kitchen[B], Kenneth A. Sudduth[B], John A. Lory[A], W. Gene Stevens[C], Luciane F. Oliveira[A], D. Kent Shannon[A], Harlan Palm[A], J. Glenn Davis[D], Earl D.Vories[E], David J. Dunn[C] and Andrea P. Jones[C]

[A]University of Missouri, Plant Sciences Division, Columbia, MO 65211.
[B]USDA-ARS, Columbia, Missouri 65211.
[C]University of Missouri, Plant Sciences Division, Portageville, MO 63873.
[D]USDA-NRCS, Columbia, Missouri, 65201.
[E]USDA-ARS, Portageville, MO 63873, U.S.A.
[F]Corresponding author. Email Scharfp@missouri.edu.

Abstract
Nitrogen fertilizer greatly increases crop yields but requires large amounts of energy to produce and has undesirable off-site effects when it escapes from agricultural systems. Precisely matching N fertilizer rates to crop needs maximizes benefits while reducing negative impacts. Soil N supply to crops is spatially variable, so spatial diagnosis is needed to apply optimal N rates. Crop reflectance sensors provide an accurate and spatially-intensive method for diagnosing and applying the correct N rate. We have developed calibrations relating optimal N rate to reflectance ratios for maize and cotton. These calibrations require that sensor reflectance measurements be expressed as a ratio with measurements from high-N areas that are matched in growth stage, genetics, and environment. We have used these calibrations in demonstrating sensor-guided N applications to maize and cotton producers. Side-by-side replicated comparisons of sensor-based variable-rate N and producer-chosen N rates for 53 maize fields resulted in N savings of 16 kg N/ha and a yield increase of 110 kg grain/ha. Results from our first four demonstrations in cotton fields should be available by the time of the congress. Drift of sensors during the course of a day has been an unexpected obstacle and requires frequent re-measurement of the high-N reference area.

Key Words
Spatial variability, diurnal variability, crop circle, greenseeker, cropscan.

Introduction
Nitrogen fertilizer is a crucial input for production of many of the world's major crops—maize, wheat, rice, cotton, potatoes, sorghum, and more. Smil (2001) estimates that 40% of the current human population would not be alive if the Haber-Bosch process for industrial fixation of nitrogen had not been invented.

Our research with maize suggests that it is common for economically optimal nitrogen rates to vary widely within a field (Figure 1) (Scharf *et al.* 2005; Mamo *et al.* 2003). Uniform application of the producer's normal N fertilizer rate to the field shown in Figure 1 would have resulted in both under- and over-application of N in various regions of this field. This conclusion agrees with most of the limited research on this subject to date. In our study, standard deviation for yield across landscapes was often much greater for unfertilized plots than for fertilized plots. This suggests that the soil's ability to supply N to the crop varies spatially. Coupled with a weak relationship between yield and optimal N rate, this suggests that soil N availability was the dominant factor controlling spatial variability in optimal N rate in our studies.

Characterizing soil N availability to the crop using soil tests has proven to be quite difficult, especially in humid regions. Scharf *et al.* (2006), in a network of 66 experiments over a large geographic area, found that chlorophyll meter readings (sensitive to leaf spectral properties) were a far better predictor of optimal N rate than were any of 16 soil mineral N measurements or 10 soil quick tests. Thus crop spectral properties appear to be one of the most promising methods for diagnosing optimal N rate. Reflectance sensors allow real-time measurement of crop spectral properties with nearly immediate translation into N rate decisions. Our objective was to develop calibrations relating sensor measurements to optimal N rates for maize and cotton, and to apply those calibrations in on-farm demonstrations of this technology.

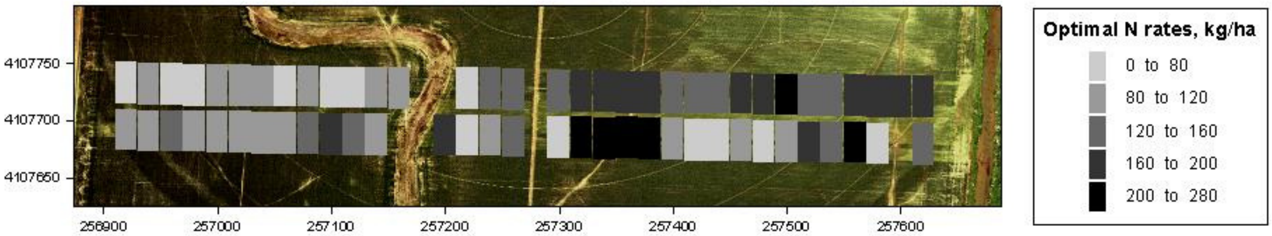

Figure 1. Spatial variation in economically optimal N fertilizer rate for maize. Each gray rectangle contained six N rate treatments (0, 55, 110, 165, 220, 275 kg N/ha) and yields associated with each N rate were measured. Yield response to N was modeled separately for each gray rectangle as a quadratic-plateau function. Economically optimal N rate was calculated from this function and prevailing prices for maize and N fertilizer at the time of the experiment. Economically optimal N rate for each experimental area is coded by the shade of gray. Optimal N rate in this field ranged from 50 to 230 kg N/ha, which was the smallest range among eight fields that we studied. Uniform application of the producer's normal N rate would have resulted in both under- and over-application of N in this field. Ticks are position coordinates (Universal Transverse Mercator) in meters.

Methods

Calibration of reflectance measurements against economically optimal N fertilizer rates was accomplished using a network of N rate response experiments for maize and for cotton. In each experiment, 40 or more plots were used to measure yield response to N rate, which was described using a quadratic-plateau model. Economically optimal N rates were calculated from these yield response functions using representative prices for N, maize grain, and cotton lint.

Reflectance was measured using one or more of three reflectance sensors:
Cropscan (Cropscan Inc., Rochester, MN, U.S.A.)
Crop Circle (Holland Scientific, Lincoln, NE, U.S.A)
Greenseeker (NTech Industries, Ukiah, CA, U.S.A)
The latter two sensors are termed 'active' based on having an internal pulsed light source.

Reflectance measurements were made at the stage of the main N application (V6 in maize—6 collared leaves and 30 cm height, early square in cotton—first flower buds appearing) in plots receiving 0 N at planting, low to moderate N rates at planting, and high N rates at planting. Later measurements were made on the same groups of treatments that had not received any in-season N applications.

Relative reflectance values were calculated for treatments receiving 0, low, or moderate N rates at planting by dividing their average reflectance by the average reflectance for high-N treatments.

Linear regression was used to relate economically optimal N rates to reflectance measurements. Each experiment produced 2 (maize) or 3 (cotton) data points for this regression, corresponding to the number of preplant N rates for which independent optimal in-season N rates were calculated and for which independent sensor measurements were collected.

The resulting calibration equations were used to control variable-rate N applications in field-scale demonstrations using fertilizer applicators owned by producers or agricultural service providers. At least three replications were used in each field to compare variable-rate N applications (controlled by sensors) to uniform applications at a rate chosen by the cooperating producer. Yield monitors were used to collect yield data for both crops, and N rate, yield, and profitability were calculated for both treatments.

Results

A wide range of optimal N rates was observed for both crops. This facilitated the development of good calibrations between optimal N rate and sensor measurements. Visible/NIR reflectance, relative to the same measurement from high-N plots, successfully predicted optimal N rate in both crops and all sensors. In maize, useful predictions could be made as early as the V6 stage (Figure 2), which was the earliest stage studied. In cotton, relationships at the early square stage (the earliest stage studied) mostly had r^2 values of 0.3 or less, but useful relationships were found at the mid-square and early flower growth stages (Figure 3).

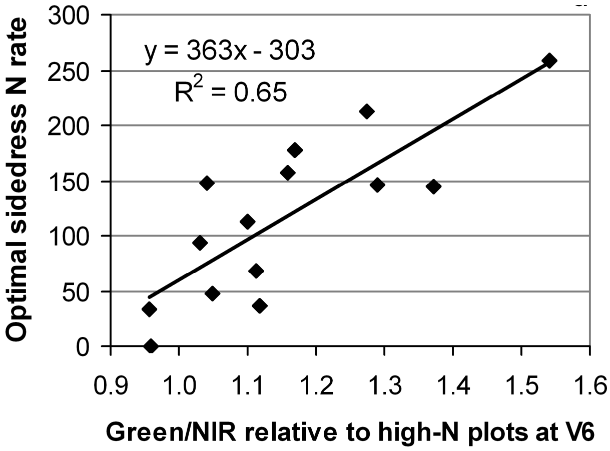

Figure 2. Optimal N rate for maize was reasonably well related to green/NIR reflectance (relative to the high-N treatment) measured with the Cropscan radiometer at the V6 stage. The equation shown was used in translating sensor measurments to N rates in subsequent field-scale demonstrations of sensor-guided N application.

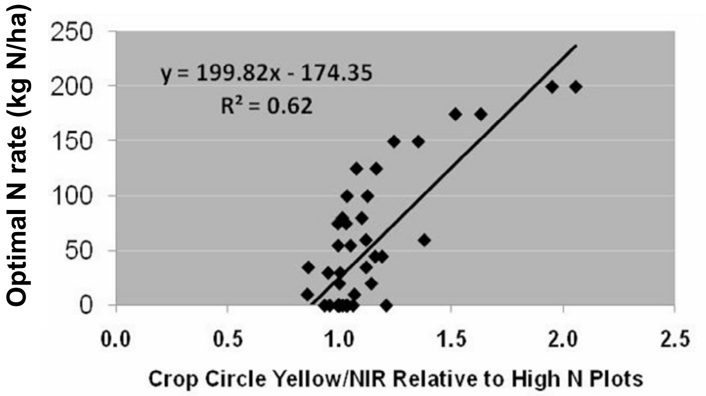

Figure 3. Optimal N rate for cotton was reasonably well related to yellow/NIR reflectance (relative to the high-N treatment) measured with the Crop Circle radiometer at mid-square/early flower stages. The equation shown was used in translating sensor measurments to N rates in subsequent field-scale demonstrations of sensor-guided N application.

In field-scale demonstrations of sensor-guided variable-rate N for maize using the calibrations reported above, sensor-based rates out-performed N rates chosen by cooperating producers (applied at the same time). For the period 2004-2007, the economic advantage of sensor-based management was due to the ability to reduce N rate, relative to the producer rate, without suffering any yield penalty (Table 1). This was average behavior, while in fact the use of sensors decreased yield in some demonstrations and increased yield in others, with a net effect of zero.

In 2008, with an unusually wet spring, much background soil nitrate and ammonium were lost. More N was applied using sensors than using the rate chosen by the producers. This turned out to be a correct decision, increasing yield and profit relative to producer-chosen rates (Table 1).

Similar field-scale demonstrations have been carried out in cotton in 2009. We should be able to report those results at the congress.

Table 1. Average outcome of sensor-based N management in 53 field-scale demonstrations in maize. Effect on profit is based only on yield and N use. Cost of implementation is difficult to calculate and is not included.

Period	# Fields	Effect of sensor management[A] on:		
		Yield	N rate	Profit
		Mg/ha	Kg N/ha	$/ha
2004-2007	41	0	-27	+30
2008	12	+0.6	+18	+72

[A]Relative to N rates chosen by cooperating producers.

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We have found that sensor measurements drift during the day when mounted in a stationary position over the same plant all day long. This is true for both maize and cotton. One factor in this drift can be leaf wetness, as demonstrated by spraying water on leaves while taking measurements. However, a great deal of the variation that we have observed cannot be attributed to this source and we do not know the source. Greenseeker sensors repeatably have low visible/NIR values in morning and evening, with higher values at mid-day, and are the most variable of the three sensors we have studied (Figure 4).

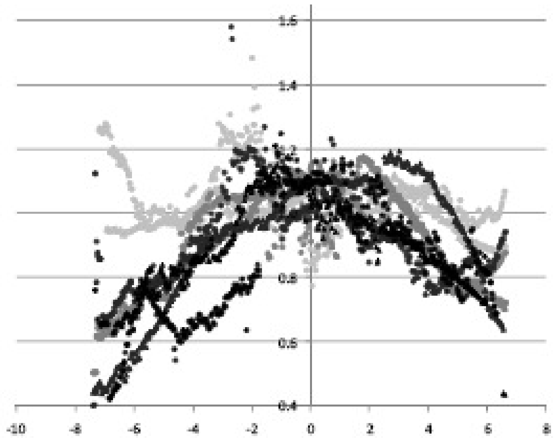

Figure 4. Normalized visible/NIR for the Greenseeker sensor as a function of time (0 = solar noon, and visible/NIR value at solar noon was defined as 1.0 in normalizing the day's data). Data were collected on eight separate days from a stationary position above a single cotton plant.

Conclusions

- We were able to calibrate reflectance sensors to predict optimal N fertilizer rates for both maize and cotton.
- Using these calibrations to control N rate in field scale demonstrations produced at least some success in diagnosing and responding appropriately to differences in soil N supply to the crop. Sensor-based N management used less N and produced more yield and profit than producer-chosen rates in 53 demonstration fields.
- Additional work to eliminate or compensate for sensor drift will be important to successful deployment for wide-scale nitrogen fertilizer management.

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