Improving nitrogen efficiency of maize (corn) using crop sensors

Peter Scharf [1]

[1] University of Missouri, 108 Waters Hall, Columbia, MO, 65211, U.S.A., http://plantsci.missouri.edu/nutrientmanagement/, http://nvisionag.com/, scharfp@missouri.edu

Abstract
Nitrogen fertilizer has a tremendous impact on crop growth and is essential for feeding the 7.4 billion people on Earth. It is also the most energy-intensive input to crop agriculture, has a proclivity to escape from ag systems, and has negative off-site impacts when it escapes. For all of these reasons, efficient use of N fertilizer is essential. Crop sensors are a promising approach to optimize N fertilizer application rate and timing. Three separate experiments with maize (corn) helped to define the N efficiency gains to this approach. One experiment group involved 55 field-scale experiments in which the farmer's N rate was compared to variable-rate N based on crop sensors. System efficiency (N removed in grain/[N applied as fertilizer + manure]) was 0.68 with the farmer's chosen rate, and increased to 0.78 with sensor-chosen N rates. A second experiment was initiated in 2007 to compare N fertilizer rate and timing decision systems. For 2007-2014, the most profitable pre-plant N rate (200 kg N ha^{-1}) gave system N efficiency of 0.43, while sensor-based N rate gave system N efficiency of 0.74. The third experiment was initiated in 2012 and compared a pre-plant N rate of 155 kg N ha^{-1} with sensor-based variable-rate N. System efficiency for pre-plant N was 0.51, and for sensor-based N was 0.57. In the latter two experiments, pre-plant N treatments had low efficiency in years with high spring rainfall. Timing of N probably improved N efficiency more than improved N rate.

Key Words
Efficiency, sensor, reflectance, variable-rate, nitrogen

Introduction
Nitrogen fertilizer is one of the most disruptive technologies in history. Plant growth in nearly all terrestrial and marine environments is nitrogen-limited. The use of nitrogen fertilizer has increased food production so much that Smil (2001) estimates that 40% of the current human population would not be alive without it.

The optimal N fertilizer rate varies widely from place to place within fields (Mamo et al., 2003; Scharf et al., 2005). This appears to be mainly due to spatially variable N contribution from soil organic matter, which can vary over years in the same field due to weather (Mamo et al., 2003).

Nitrogen is also disruptive in environments that are not agricultural for the same reason: it increases plant growth. Excess growth in marine environments ultimately leads to low-oxygen conditions (especially in confined waters), disrupting animal life. Nitrogen additions to sensitive terrestrial systems (deserts and alpine areas, for example) can create a competitive advantage for invasive species that crowd out natives.

In addition to its biological effects, nitrogen gases derived from human activity can have disruptive effects in the atmosphere. A substantial proportion of global nitrous oxide emissions are derived from N fertilizer, increasing the heat-trapping capacity of the atmosphere. Nitrous oxide is also expected, indirectly, to be the largest anthropogenic disruptor of the stratospheric ozone layer in this century, which limits the amount of ultraviolet radiation reaching the Earth's surface.

Figure 1. Crop Circle ACS-210 sensors on dry fertilizer spreader, variably applying N based on crop color.

Methods
For all three experiments/experiment groups, sensor measurements were acquired and interpreted as described by Scharf et al. (2011). Crop Circle ACS-210 sensors (Figure 1) were used in all experiments except for six of the on-farm experiments where Greenseeker sensors were used. System N efficiency was defined as nitrogen removed in grain divided by nitrogen applied as fertilizer and manure.

On-farm experiments

55 experiments were carried out from 2004 to 2008 on commercial farms in Missouri, U.S.A. Elements in common over all 55 experiments include:

1. A farmer-chosen N fertilizer rate was compared with variable-rate N application based on crop canopy sensors.
2. Variable-rate N application was carried out in real time based on crop canopy reflectance readings, with fertilizer rates adjusted each second.
3. On each farm, only one N fertilizer source and one N fertilizer timing were used for these two treatments.
4. At least three replications were used, with an average of 5.6 replications.
5. A high-N reference area was established at least 4 weeks prior to sensing and fertilization.
6. A reference reflectance value from this high-N area was measured before variable-rate N application, and used in the equation for calculating N rate.

Urea-ammonium nitrate solution (either injected or dribbled) was used as the N source in more than half of the experiments; broadcast urea was also used as the N source in some experiments, and injected anhydrous ammonia in others. Time of application ranged from stage V6 to stage V16. Average plot length was 450 m, average plot width was 10.7 m, and average number of replications was 5.6.

Long-term N systems experiment

Figure 2. Late August aerial photo of the experiment. Light-colored plants are experiencing N deficiency.

This experiment was initiated in 2007 at the Bradford Research Center near Columbia, Missouri, U.S.A. Cropping system is continuous no-till maize (corn). The soil is a Vertic Epiaqualf.

Eight N management systems were compared in a randomized complete block experiment with six replications (Figure 2). Systems varied in N rate and timing only; N source for all systems was broadcast ammonium nitrate. Plot dimensions were 3 m by 15 m. Only two systems will be discussed in this paper, the high N rate (200 kg N ha-1) applied pre-plant, and the sensor-based N rate at stage V7 (about 40-50 cm height).

Nitrogen management and drainage experiment

This experiment was initiated in 2012 at the Bradford Research Center near Columbia, Missouri, U.S.A. Cropping system was continuous no-till maize (corn). The soil is a Vertic Epiaqualf.

Treatments were nitrogen management and drainage in an incomplete factorial design. Only nitrogen management treatments will be reported in this paper. There were two nitrogen management treatments:
1) 157 kg N ha^{-1}) applied pre-plant, and 2) sensor-based N rate at stage V7 (about 40-50 cm height). Both treatments were applied as urea-ammonium nitrate solution injected to a depth of about 5 cm. The sensor-based N treatment was applied as a real-time variable-rate N application with N rate based on the stream of sensor data. Plot dimensions are 12 m by 60 m (Figure 3), large enough to manage spatial variability within plots.

Figure 3. Aerial photo of the experiment with plot boundaries overlaid.

Results

On-farm experiments

Average N fertilizer rate chosen by the farmer was 194 kg N ha^{-1} over the 55 on-farm experiments. This includes estimated manure-N contributions. Average N fertilizer rate when using crop sensors to control variable-rate N application was 179 kg N ha^{-1}, a reduction of 15 kg N ha^{-1} ($p = 0.015$).

Reducing N rate usually increases N efficiency, but sometimes at the cost of yield. However, in this case the evidence was that this reduction in N rate was accompanied by, if anything, an increase in yield. Yield with sensor-based N rate was 110 kg ha^{-1} higher ($p = 0.18$) than with the N rates chosen by farmers. Although this is weak evidence, it is corroborated by weather and individual-year analyses. 2008 was a wet year, resulting in loss of soil N and preplant N. It is also the only year in which sensor-based N rates exceeded farmer-chosen N rates, resulting in 526 kg ha^{-1} higher ($p = 0.007$) yield.

The combination of lower N use and higher yield resulted in both higher N efficiency (78% vs 68%, $p = 0.0011$) and higher profitability ($42 ha^{-1} advantage, $p = 0.0007$).

Long-term N systems experiment

During the 8-year period 2007-2014, we had 5 wet springs (2008-2010, 2013-2014, 39 to 51 cm rainfall April-June) and one severe drought (2012, 18 cm rainfall May-September). Data from 2011 are not presented here, due to stand loss early in the season and a hailstorm at midseason that resulted in high yield variability that was not related to treatments.

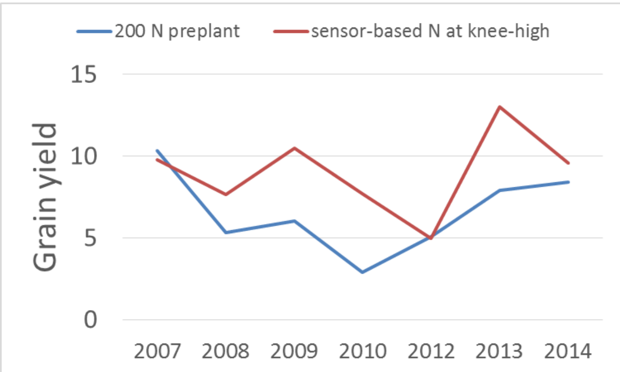

Figure 5. Yields for pre-plant and sensor-based N management over years.

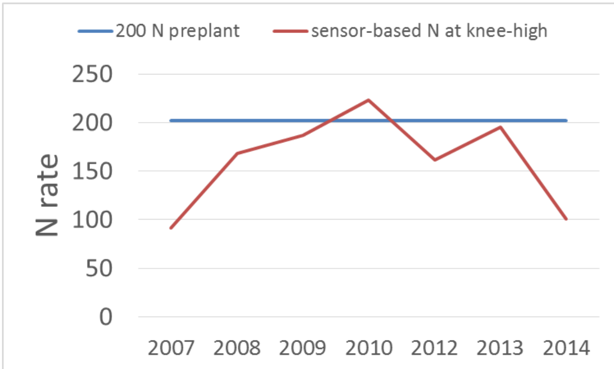

Figure 4. N fertilizer rates for pre-plant and sensor-based N management over years.

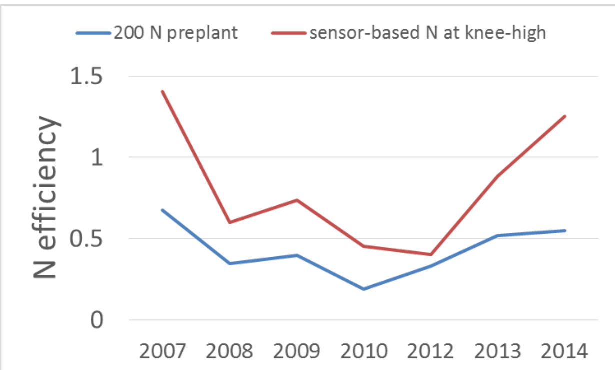

Figure 6. System N efficiencies for pre-plant and sensor-based N management over years.

Among pre-plant N rates, the 200 kg N ha^{-1} rate was chosen to present here because it gave greater yield and greater profit than the other preplant N rates, which were lower.

Sensor-based N rates (Figure 4) were higher in wetter years (2008, 2009, 2010, 2013; 2014 is the exception). Loss of soil-derived N in wet years was expressed in plant size and color and detected by sensors, leading to higher N rate recommendations. Even in wet years, sensor-based N rates were nearly always lower than the 200 kg N ha^{-1} rate applied before planting.

Grain yield (Figure 5) was equal for the two selected N management systems in years with drier springs (2007 and 2012). In the 5 years with wet springs, yield with sensor-based N management was substantially higher than with 200 kg N ha^{-1} before planting. Nitrogen deficiency symptoms were observed in the plots with preplant N management to a much greater extent than in plots with sensor-based management, despite the fact that N rate was usually lower in the plots with sensor-based N management. **Loss of N from wet soils between planting and the time of sensor-based N applications (when corn was knee-high) can explain all of these observations**.

The combination of lower N application rates and higher yields resulted in an efficiency advantage for sensor-based N applications (Figure 6). Efficiency was statistically higher ($\alpha = 0.05$) every year except 2012. **Over all years, average system N efficiency was 0.74 with sensor-based management; with 200 kg N ha^{-1} preplant, efficiency was 0.43**. The low efficiency of preplant N application was due mostly to loss of fertilizer N before crop uptake in wet years. Timing of sensor-based N applications (6 to 7 weeks after planting) reduced the period during which N loss could occur, leading to better delivery to the crop and higher efficiency. Optimizing N fertilizer rate using sensors probably also contributed to higher efficiency.

Nitrogen management and drainage experiment

A severe season-long drought in 2012 limited yields to below 2 Mg ha^{-1}. Under dry conditions, differences in reflectance between the high-N reference area and the plots to be fertilized were relatively small, leading to low average N rates based on sensors. This could have been detrimental if precipitation after sensing had been plentiful. In our climate, average rainfall is lower after sensing than before, and evapotranspiration after sensing is higher; water stress will in nearly all cases be greater midsummer than at the time of sensing.

In 2013 and 2014, early-season rainfall was plentiful or excessive, leading to some loss of preplant N. Yields were average for our climate and this soil. In both years, sensor-based N rates exceeded the preplant N rate by about 10% (Table 1). This may mean that sensors were detecting the effects, in plant appearance, of the loss of soil-derived N and compensating for it.

Yields with sensor-based N management were also around 10% higher in 2013 and 2014 (Table 1). This indicates that yields with preplant N management were N-limited. This was due to some combination of longer exposure to N loss conditions and lower N rates than the sensor-based N system. System efficiency was about equal for the two N management systems in these two years.

Table 1. Yield, N rate, and system efficiency for 2 N management systems over years.

Year(s)	N management system	Yield (Mg ha^{-1})	N rate (kg ha^{-1})	System efficiency
2012	157 kg N ha^{-1} preplant	1.9	157	0.16
	Sensor-based at knee high	1.9	114	0.22
2013	157 kg N ha^{-1} preplant	7.8	157	0.66
	Sensor-based at knee high	8.9	174	0.68
2014	157 kg N ha^{-1} preplant	8.3	157	0.70
	Sensor-based at knee high	9.5	177	0.70
2012-2014	157 kg N ha^{-1} preplant	6.0	157	**0.51**
	Sensor-based at knee high	6.8	155	**0.58**

When averaged over the 3-year period, the two N management systems used almost exactly the same total amount of N, but sensor-based management produced higher yield, resulting in higher system efficiency ($p = 0.03$): 0.58 for sensor-based variable-rate N, compared to 0.51 for preplant N at a fixed rate.

Summary

Over 3 multi-year experiments with a total of 65 site-years, sensor-based variable-rate N applications to maize (corn) resulted in higher system N efficiency than alternative management systems. In two of the experiments, this was due to both higher yield and lower N use with sensor-based N rates; in the third, yield was higher and N rate was not changed.

Crop sensors show great promise for diagnosing crop N status as influenced by soil N contribution, allowing farmers to apply N at a rate to match crop need at a time when uptake will be efficient.

Sensors can play an important role in increasing N use efficiency, ensuring an adequate supply of food and fiber while shrinking the energy and environmental footprint of agriculture.

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