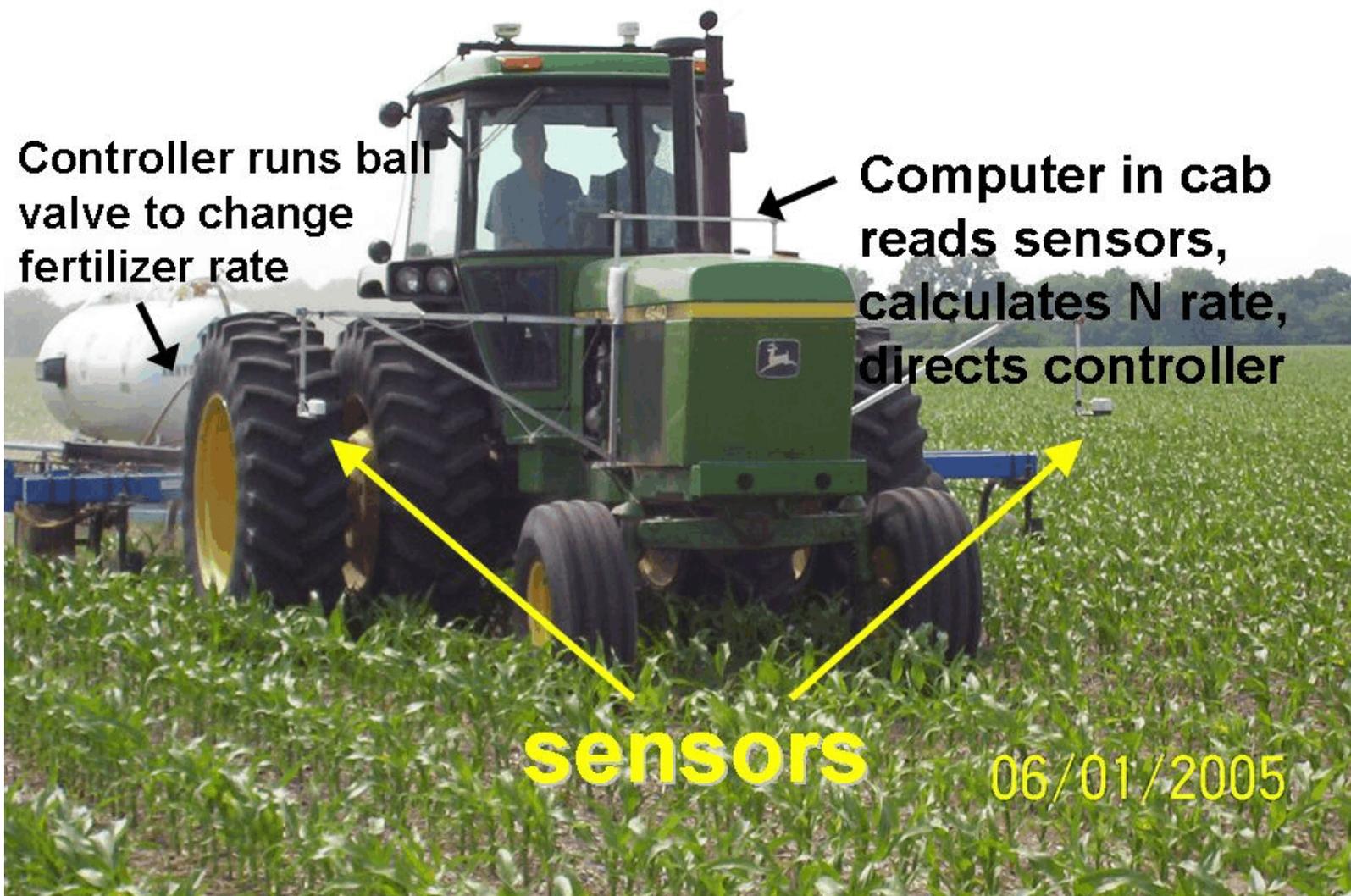


Managing Nitrogen with Crop Sensors: WHY and HOW

Peter Scharf
University of Missouri



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Brad Andrews
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Larry Mueller
Luci Oliveira
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Bill Holmes
Bob Benoit
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Brad Williams
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Overview

Systems for managing nitrogen (N) fertilizer rate based on crop reflectance sensors are increasingly available and well-developed. This manual covers fundamentals of why these systems are needed, what they can and can't do, and how to use them in a way that maximizes your odds of success. The material in this manual is based on a research program that was started in 1997 and a program of on-farm demonstrations that was started in 2004. As of this writing in March 2010, our experience includes 137 demonstration fields in Missouri—133 corn and four cotton.

Research on farms and experiment stations has shown that the economically optimal N fertilizer rate varies widely from field to field and from place to place within a field. Variability in how much N the soil is supplying to the crop appears to be the dominant factor controlling how much N fertilizer is needed.

How can this variable supply of N from the soil be understood and managed? Despite a tremendous research effort, the basic mechanisms controlling soil N availability are not understood well enough to make reliable predictions. Soil-based diagnostic tools are sometimes successful in identifying how much N is needed, but also frequently fail. Several sources suggest that plant-based measurements are much more accurate indicators of soil N supply than soil-based measurements.

Crop sensors are the most logistically practical way to take advantage of the plant's ability to indicate soil N supply. Sensor output can be translated into N rate control in a second or two, spatial variability in soil N supply is easily managed, and, unlike remote sensing, diagnosis can be done under any sky conditions.

Sensors take advantage of what all crop producers know from experience and common sense—crops with enough N are darker and taller crops that are N-deficient. When an applicator equipped with crop sensors comes to an area of short and light-green plants, N rate is increased. When it comes to an area of tall and dark plants, N rate is decreased.

Exactly how tall and dark a plant should be depends not only on having enough N but on stage of growth and genetics. In order to compensate for these effects, a high-N 'reference area' is needed. Sensor measurements from this area provide the 'yardstick' against which the rest of the field is measured in determining how much N is needed.

Although great progress has been made in using crop sensors to control variable-rate N applications, substantial obstacles remain. There is not yet wide agreement on the best approach or best equation for translating sensor measurements to N rates. Sensor values can drift during the day. Some controllers cannot accept external rate control commands. Liquid systems (UAN and anhydrous ammonia) have a limited range of N rates unless specially equipped. Risk of weather delays and the logistics of how to handle this risk are worrisome. Applying high-N reference areas is an added task. Skips in plant stand interfere with the sensors' ability to diagnose the correct N rate. Although all of these obstacles are real and should be understood by those attempting

sensor-based variable-rate N, all can be overcome. Good progress is being made to help producers overcome them.

The benefit of using crop sensors to control N rates is that these rates will match actual crop need much better than traditional N rate decision practices. This will save producers money in areas where less N is needed, protect yield in areas where normal N rates are needed, and make producers money in areas where actual need is above their normal rate. Although sensor predictions of optimal N rate are not perfect, they are closer to right than producer-chosen rates. In 55 on-farm demonstrations with side-by-side comparisons between sensor-based N rates and producer-chosen N rates, sensors have on average saved 14 lb N/acre and increased yield by 2 bushels/acre.

Why use crop sensors to manage N?

Wide variability in optimal N rate

Although the information is not widely publicized or widely available, a large database of N rate experiments suggests that the economically optimal N rate varies widely for many crops. I have personally found this to be true for corn, wheat, and cotton, regardless of previous crop or management system.

We studied eight corn fields in Missouri and found that the optimal N fertilizer rate varied widely from place to place within each field. Two examples are shown. Research in Minnesota, Kansas, and Pennsylvania produced the same conclusion, while one study in Wisconsin found minimal differences in N need within fields. All of this research was conducted in corn. Based on all available evidence, it appears that most corn fields have substantial variability within a single field in how much N is needed.

Variability in soil N supply

Soil N availability appears to be the controlling factor. Several lines of evidence lead to this conclusion:

- Spatial variability of yield is high when no N fertilizer is applied.
- Applying N cut this spatial variability of yield in half in most of our study fields (see example below).
- The final yield produced by the crop is poorly related to the optimal N rate, leading many midwestern universities to recently drop yield as a factor used to produce N rate recommendations for corn.
- The yield increase due to N fertilizer (difference in yield between fertilized and unfertilized) is a much better predictor of optimal N rate (than yield). The yield with no fertilizer accounts for the soil's N contribution.

Since it is variability in soil N supply that creates variability in optimal N rate, the research from corn probably applies for other crops as well. I would expect optimal N rate to vary widely for most crops in most fields in humid regions. There's not much evidence about spatial variability of optimal N rate in dry regions (less than 30 inches of rain).

Spatial diagnosis needed—but how?

Once you understand how widely optimal N rate varies, you can see the need to diagnose where to put more N fertilizer, and where to put less. Putting less where less is needed will save money and reduce N loss from the field to water. Putting more where more is needed will increase yield and the efficiency of all the other production inputs. The question is: How?

Not yield

Historically, yield has been used to predict N rate more than any other factor. Varying N rates based on historical yield maps or on 'yield zones' based on a variety of factors has probably been tested more than any other system for guiding variable-rate N applications. Rarely has this approach produced good results, and in some cases has resulted in lost yield. In the eight fields that we studied intensively, the expense and

trouble of varying N rate based on yields returned only \$1/acre, much less than the cost of implementing the system.

Not soil testing

Soil testing is another method to diagnose crop nutrient needs that has been around for a long time. However, no direct measure of soil N availability is made in most soil tests.

Why not? Nitrate is the dominant form of plant-available N in soil. But nitrate-N can be lost (with water) or gained (from soil organic matter) quickly, making it difficult to get a reliable indicator of soil N supply from a single soil nitrate measurement. Soil nitrate testing is most common in the Great Plains, where lower rainfall reduces the chances that N will be lost between testing and uptake. Even there, samples need to be two or three feet deep to be useful, which is enough of a barrier that most producers don't use the test.

In the 1980s, some advances were made in using in-season soil nitrate testing in humid regions. The reduced time between sampling and crop use cut down on problems with N loss after sampling, but increased the logistical difficulties of using the test. Only a small percentage of producers in humid regions have used soil nitrate tests for whole-field N rate decisions, much less for variable-rate N decisions. Zone soil nitrate samples (either preplant or in-season) did a poor job of predicting where to put more N and where to put less in our eight intensively-studied fields. Soil nitrate, soil ammonium, and ten other soil tests designed to measure soil N availability were never more than 25% right in diagnosing which fields needed more N and which needed less in a network of 66 experiments in seven midwestern states.

Crop color is most accurate

In the same 66 experiments, chlorophyll meter values were between 50 and 67% right in diagnosing which fields needed more N and which needed less. While this is far from perfect, it was 2 to 2.5 times better than the best soil test. In 23 on-farm experiments in Missouri, chlorophyll meter values were about 50% right in diagnosing which fields needed more N and which fields needed less, while N rates chosen by producers had almost no relationship to actual N needed.

Crop color is the most promising approach to correctly diagnose how much N to apply, and offers the potential to substantially improve N rate decisions compared to current practices.

How to succeed with sensor-based N management

Steps to successful sensor-based N management:

- 1. Broadcast any preplant N at no more than half of the normal total rate.**
- 2. Apply a high rate of N to a small area of each field four weeks or more before the sensor-based N application.**
- 3. With corn, don't start sidedressing until the corn is 12" tall or taller.**
- 4. Sensor-based variable-rate N application can be used with any N form and any style of applicator (as long as it has the right hardware & software).**
- 5. On the day of application, measure the high-N reference area with the sensors before starting to fertilize.**
- 6. Re-read a high-N reference area at least every two hours.**
- 7. Have a plan for how you can be sure to get N applied to every field even under the most adverse weather conditions. This may require availability of high-clearance or aerial application, or using sensor-based N management on only part of your fields.**
- 8. Be aware of the strengths and weaknesses of available sensors and systems for translating sensor measurements to N rates.**

Preplant N management

Applying 1/3 of a normal total N rate as a preplant broadcast application is ideal to maximize the benefit of using sensors in a nitrogen management system. This practice:

- maintains the potential to save N fertilizer in areas where the soil is providing substantial amounts of N to the crop;
- provides enough N to nearly eliminate any chance of yield loss due to early-season N stress; and
- avoids N enrichment in the early-season root zone, which can cause the plant's appearance to suggest a better season-long N supply than really exists.

Many producers would prefer to apply a higher N rate pre-plant, then use sensors to decide where they need a 'top-up' sidedress N application. Unfortunately, our research suggests that sensors cannot determine that a crop doesn't need any additional N. Even when the corn is as dark green as it can be at the time of sidedress N application, it may run short later and need a small additional amount of N. For this reason, we never recommend less than 50 lb N/acre for corn that is less than waist high, even if its appearance is excellent. Corn that looks good at this stage will never need a high N rate, often needs a low N rate, and will sometimes need a zero or medium N rate. The low N rate is most often the right decision.

In 55 on-farm demonstrations of sensor-based N management, **half of the profit associated with sensors came from saving N. The other half came from**

increasing yields in fields and parts of fields that needed more N than the producer chose to apply. A producer who applies a near-full rate of N before planting, then follows our recommendation to always apply at least 50 lb N/acre when sidedressing based on sensors, will have no potential to save money on N. This cuts out half of the potential profit associated with using sensors.

Banded pre-plant N also creates some difficulties for sensor-based N

management, regardless of whether it is applied with the planter or in a separate operation. If the band of N is near the seed bed (applied with the planter or as part of a strip-till operation), the young plant will take up water that contains a high concentration of N. It will have an excellent appearance, even though it may run short of N later unless more is supplied. Since the sensors diagnose what the soil is providing by looking at the appearance of the plant, they will diagnose that the soil is providing a lot, and direct the applicator to apply a low rate. But this is likely to be the wrong diagnosis. As the roots grow into soil without the banded N, the supply will be much lower and the crop's appearance will decline to reflect the total soil N availability. This probably won't happen until after the sidedress operation.

When N is banded preplant, but not near the rows, the planting operation will place some seeds nearer to the band, and some seeds farther away. The plants near the band will look better than if the same rate had been broadcast, and the plants between the band will look worse. If the bands are angled to the planter rows, and the sensors are set to average several seconds worth of readings, these effects should cancel out and sensor-based sidedressing should perform well.

In-season variable-rate N: Any type of N, any type of applicator

We have demonstrated variable-rate, sensor-based N applications in 143 fields in Missouri and have used all four major N sources and every major type of applicator. I will list these below with some tips for success.

- Dry N with a spinner cart. The cart needs to have hydraulic belt control that can vary belt speed. Quality of the dry N material is crucial to success. Poor-quality material with lots of dust will spread unevenly and streak up the crop. If urea is used, it should be treated with Agrotain to prevent volatile loss. This is an economical approach that is fairly fast but with clearance limitations that limit how many acres can be covered, especially for corn.
- Dry N with a high-clearance spinner. See above. Higher cost but higher speed and higher clearance. When used on corn that is three feet tall or taller, Agrotain is no longer needed.
- Dry N with an air-boom machine. See above. Slower than a spinner, but quality of the dry fertilizer material is not as crucial.
- Liquid N injected with a tractor-drawn applicator. Can operate either with a variable-speed piston pump or a variable-speed hydraulic pump controlled by feedback from a flow meter. With most liquid N applicators that have a simple orifice system, hydraulics limits the range of effective N rates that can be used. Careful choice of orifice size is important. You should choose the orifice to put out the highest rate

that you'd like to be able to apply at the highest pressure that you're comfortable with (probably 80 to 100 psi) at your normal operating speed. Then the lowest rate you can effectively apply will be half of your highest rate. If you go lower than half, pressure will be so low that you are in danger of uneven distribution of N along your toolbar. If you want to be able to apply a wider range of N rates, you will need to have either a pulse-width-modulated system (Capstan) or nozzle bodies with spring-loaded orifices (Veriflow or Greenleaf). The Capstan system is more expensive but has proven itself over an extended time period. The spring-loaded orifices open farther as pressure increases, making it possible to achieve a much wider range of rates at acceptable operating pressures. They are much cheaper than the Capstan system but have been available for only a few years. Our experience with them so far has been good.

- Liquid N with a sprayer-type applicator and drop nozzles. Same limitations on N rates (and same potential solutions) as above. Drops should extend to well below the ear.
- Liquid N with a sprayer-type applicator and injection toolbar. Same limitations on N rates (and same potential solutions) as above. Depending on depth of 'injection', N may be more immediately available to the crop (compared to other application methods) when soil conditions are very dry.
- Anhydrous ammonia with a tractor-drawn toolbar. Ammonia has the same limitations on N rate described for the liquid N systems above—from your highest to lowest rate shouldn't be more than a factor of 2. Only the Capstan system (Nject) can be used to expand this range with ammonia. Ammonia is typically the cheapest N source, placed where it is immediately available to the crop, and resistant to loss during wet weather. It is also the slowest to apply and dangerous to handle.

High-N reference area

Our research in Missouri and a large body of additional research suggests that **a high-N reference area is needed for all crops** to succeed with sensor-based N applications. The same is true of any other diagnostic system based on crop color, such as aerial photographs or hand-held color meters. Values measured by sensors are sensitive to growth stage, genetics, and possibly other environmental conditions of the field or the weather experienced that year. Determining the value that the sensor measures on a high-N area establishes what value should be expected for the particular growth stage and genetics when N supply is good. This is the 'yardstick' by which the rest of the field will be measured.

The high-N reference area should be applied well ahead of the planned N application. I would suggest four weeks as ideal timing. If the N is applied too soon before the N application, the crop will not be as dark as it could be, and the 'yardstick' will be too short. This will result in under-application of N.

If the high-N reference area is applied too far ahead, or if weather is especially wet between reference N application and sensor-based N, **it can sometimes happen that the 'high-N' area no longer has enough N.** If this is the case, the reference area

should not be used. Often only part of the reference area will have experienced enough N loss to cause a problem. The remaining part that looks N-sufficient can still be used. Good judgement and common sense are required in deciding whether to use a high-N reference area, or which part to use. If there is no good reference area, it is probably better to abandon plans for sensor-based N management and instead choose a uniform N rate to use. In our many field demonstrations of sensor-based N applications for corn, **problems with the reference area is the only factor that consistently is associated with unprofitable N rate decisions.**

Any size of high-N reference area can be used. The larger the area is, the more stable the average value is, but we have done many profitable field demonstrations using small (30 by 50 feet) high-N reference areas. When using a small reference area, it is particularly important to pick an area that is average for the field. Areas near the edge of the field where grain carts or trucks have trafficked should be avoided, along with high areas, low areas, disturbed areas, and areas with above- or below-average yield history or potential.

Any N source and application method can be used in applying a high-N reference area. However, if any type of banded N is used, the N should be applied near the crop row. If the N is too far away, the crop may not have enough N to make it as dark green as it could be at the time of the sensor-based N application. The 'yardstick' will be too short, causing under-application of N.

Logistical difficulties of getting a high-N reference area applied to every corn field is a significant barrier to adoption of sensor-based N management. Taking a fertilizer applicator to every field solely to apply reference areas is not a good option. In my opinion, aerial application of the reference areas has great logistical advantages. It's fast, easy to apply field-length strips, and the limited amount of material being spread keeps the cost reasonable. Another advantage to aerial application will be presented in the section on sensor drift. For producers who are already taking a fertilizer applicator to the field for both preplant and sidedress applications, increasing the rate on a few strips, or double- or triple-applying those strips is not much trouble. If the preplant N is mixed with chemical or P and K, this presents some barriers (cost, label restrictions) to increasing the material rate to create a high-N reference area. A spinner applicator mounted on a four-wheeler or a hand-crank spinner are ways to get high-N reference areas applied that are logistically much easier and/or cheaper than a full-size applicator, especially for producers whose fields are spread over a large area.

The location of the high-N reference area should be clearly recorded or marked in a way that will be easy to find and use during the sensor-based N application.. Preferably reference areas should be placed so that it will be easy during sidedressing to re-measure a reference area at least every two hours.

The high-N reference area should always be at the **same growth stage** as the crop to be fertilized, and preferably should be the same genetics. Sensor values are particularly sensitive to growth stage. For corn that is knee high or less, sensor values

change enough from one day to the next to change N rate recommended by 10 to 15 lb N/acre. For corn beyond knee high, this value increases to 15 to 20 lb N/acre/day. This means that it is critical to use a high-N reference area that is at the same growth stage as the corn that will be fertilized. If a high-N reference area is used that has the same genetics but is three days ahead or behind the crop to be fertilized, this will introduce an error of 30 to 60 lb N/acre in the N rate prediction.

Once corn gets to about chest-high, values don't change much until tassels emerge, so if sensors are being used to guide N applications after corn is chest-high, the growth stage of the reference area is no longer so critical.

Virtual reference strip

Some people are advocating the concept of a 'virtual reference strip' and saying that it eliminates the need to go out and apply an actual high-N reference area. This concept is based on the idea that if you drive the length of the field and back measuring sensor values of the crop, somewhere in that trip you will find plants that have enough N to produce full yield, and this can be your 'yardstick' for guiding N applications. Advocates of this approach have shown that it is true for some fields. The problem is that it is not true for all fields.

I chose one of our sensor demonstration fields that had an average of 75 lb N/acre applied preplant (partly variable-rate DAP, so some areas were higher). In this field, it was more likely to find N-sufficient corn during a trip down and back than in the many demo fields that had lower preplant rates. Nonetheless, using two different approaches to selecting a 'virtual reference value' from the sensor measurements during the trip down and back, neither produced a value as good as the real high-N area. Fertilizing based on the virtual reference approaches would have given average N rates 25 and 50 lb N/acre below the average N rate with a real high-N reference, and reduced yield by an estimated 12 and 28 bushels per acre. It doesn't take many fields with this kind of outcome to kill the idea that a virtual reference approach can work.

Spatial variability in high-N values

High-N corn does not necessarily appear the same over an entire field, and the same is probably true for other crops. Differences in growth stage are probably the biggest reason. Wet areas remain cold longer, growth is slower, and the plants are smaller and lighter even if they have enough N. At some point in the future, we will probably create a map of high-N sensor values to use in sensor-based N applications. This will increase the accuracy of N rate diagnosis by correcting for spatial variations in size and stage.

Variability over time in sensor values

Drift in sensor values is an important problem that is not widely recognized, so little has been done to solve this problem. Being aware of the problem and some simple steps that you can take to counter it will increase your success with sensor-based N management.

One factor that changes sensor values for all sensors we have tested is leaf wetness.

When leaf wetness changes, the high-N reference area should be re-measured before continuing to apply fertilizer. This will re-set the ‘yardstick’ of what the crop should look like with high N under current conditions. Re-measuring the high-N area should be done either when leaves get wetter (for example, a rain shower passes through) or drier (dew evaporates from leaves).

Even without any obvious change in field conditions, sensor values often change (for the same plant) during the course of a day. **I recommend that a high-N reference area should be re-measured at least every two hours, and should be re-measured every hour if Greenseeker sensors are used.** This will adequately correct for any drift that occurs so that the accuracy of N rate decisions will not be impaired.

The Greenseeker sensor appears to be sensitive to some environmental condition that causes the NDVI (an index used to calculate N rate) to start high in the morning, drop toward mid-day, then increase again in the afternoon. This drift can lead to serious errors in N rate if the high-N reference is not re-measured regularly. The cause of this predictable daily change in Greenseeker values is not known at this time, but potentially can be corrected once it is understood.

There is additional sensor drift that can't be accounted for by changes in leaf wetness or the consistent pattern of change seen with the Greenseeker sensor. More study is needed to understand the source of this drift. It's likely that at least some of the drift is related to changes in plant appearance, such as drooping leaves during high water-demand conditions (hot, sunny, windy). Re-measuring the high-N reference area is the only way to account for this type of change.

One way to make re-measuring the high-N reference area easy is to apply the high-N reference area as a strip that crosses the rows, so that the N applicator goes over it every time it goes the length of the field. This area can be georeferenced and mapped, and the system programmed to update the high-N value each time the applicator crosses it. Although this feature is not yet available commercially, we have programmed our custom software with this feature and it has worked very well. Aerial application is, logistically, a good option for establishing high-N reference areas and can easily be used to apply strips that cross the rows.

Growth stage at time of sensor-based N application

We have successfully and profitably used sensor-based N applications to corn at corn heights from 12 inches (stage V6) to 7 feet (stage V15). Although it would be logistically advantageous for producers who use tractor-drawn sidedress applicators to start before the corn is 12 inches tall, I do not recommend it. The corn is too small for the sensors to get an accurate measurement of their color, and they are too small to have adequately explored the root zone. Crop sensors use plant color as an indicator of how much N is available from the soil, so adequate root development is needed before sensing can reliably indicate soil N supply.

Producers who have tractor-drawn sidedress N applicators must deal with the risk of not getting all of their corn acres applied if they wait until corn is 12 inches tall to start sidedressing. They have two reasonable ways to address this risk:

- 1) Arrange reliable access to high-clearance or aerial N application for those years where rain prevents all fields from being sidedressed with the tractor; or
- 2) Prioritize the most variable fields, or fields where the probability of low optimal N rate is highest, as being most suited for sensor-based application. Sidedress other fields before corn is 12 inches tall without using the sensors.

As corn gets bigger, it gets darker, and the difference in appearance between N-sufficient and N-stressed corn widens. The rate recommendation system that you use should be able to adjust for growth stage. This will be discussed more in the section on recommendation systems.

Similarly, our research shows that sensors cannot reliably predict the optimal N rate for cotton at the early square growth stage (typically 10-12 inches tall), but can predict optimal N rate beginning 7 to 10 days after the early square stage. We refer to this stage as 'mid-square', and cotton is typically 14-16 inches tall. From mid-square at least until the early flower stage sensors can provide a good estimate of how much N is needed.

Although Missouri research on using sensors to guide N rates for wheat is still limited, my best guess is that sensors will work well and that they will be most useful for applications from 7 to 10 days before the first joint forms until 4 to 7 days after.

In all three crops, many producers prefer to make in-season N applications slightly before the window in which sensors perform well. Adapting management systems to accommodate slightly later applications is a crucial step in successful N management using crop sensors.

Available crop sensors to support variable-rate N applications

Active-light sensors dominate the ag market. These sensors have pulsed light sources, and can sense how much of the pulsed light (both visible and near-infrared) bounce back from the canopy. Active-light sensors can be used at night (probably with greater accuracy than during the day due to less interference from sunlight) and have been claimed to be more resistant to the effects of changing sun angle and cloud cover than earlier sensors that relied on sunlight. Evidence for this claim is weak or nonexistent, but these are the sensors that have been developed and marketed.

Currently there are three brands of active-light sensors to support variable-rate N on the market: **Greenseeker** (sold by Trimble), **OptRx** (sold by Ag Leader), and **CropSpec** (sold by Topcon Ag). A fourth sensor on the market is the **Crop Circle 210** (sold by Holland Scientific and precursor to the OptRx sensor) and although it can support variable-rate application it is no longer being marketed with that goal in mind.

Greenseeker is the only brand that was commercially available as an agricultural instrument before 2010 and has a considerably greater experience and research base than the other two sensors. Greenseeker has introduced a map feature that allows N rate recommendations to be modified based on field maps (yield zones, for example). The consistent pattern of change in Greenseeker values from morning to noon to evening (mentioned in the section above on variability) is its biggest drawback but probably can and will be solved. Greenseeker values fluctuate more widely than other sensors in the sub-second time scale, but I do not view this as a major issue—enough measurements are taken and averaged that the averages appear to be stable.

The OptRx sensor is a second-generation sensor designed by Holland Scientific, so there is considerable design and operation experience behind it, but research experience remains lacking. As of this writing in June 2010, I am hearing that the OptRx system is using N rate equations that we developed for the first-generation Holland sensor (Crop Circle 210), which used quite different wavelengths. The OptRx and Crop Circle sensors may need to be interpreted with different equations, as is true for Crop Circle and Greenseeker (see table in next section). Additional comparison and evaluation is needed before this can be considered a reliable system. We have noticed some condensation in the OptRx sensor and in its predecessor, the Crop Circle 210, sometimes to the point of shorting out the sensor. Condensation could also interfere with the optical system and affect measurements.

The CropSpec instrument has the weakest experience and research base (at least in the U.S.) of the three sensors, but I've heard positive comments from the few researchers I know who have had their hands on one.

Greenseeker and OptRx sensors can be purchased in combination with variable-rate controllers from the same companies. If you already have a variable-rate controller with serial input capability, Greenseeker can also be used with a broad range of controller makes and models.

Translating sensor measurements to N rate recommendations

Many crop researchers have studied the relationship between nitrogen rates and crop sensors. Quite a few have developed systems for translating sensor measurements to N rate recommendations. In some cases, the N rate recommendations produced from the same sensor readings may be very different. Time and experience will help to develop our understanding of which systems perform well, and in which environments. Your choice of system will affect your degree of success with sensor-based N management.

The Greenseeker system offers a wide variety of crops and rate recommendation systems. This provides flexibility but can be quite confusing. Which one should you use? Everything else being equal, a system developed near where you are using the sensors (or at least in a similar climate) would be preferable. Regional differences in yield potential, soil N mineralization, potential for N loss, and other climate-related

factors are probably at least partly accounted for by using 'local' systems. However, just because a system is local does not mean that it will perform well in your field.

Missouri system

I and co-workers in Missouri have developed equations for translating sensor measurements to N rates for corn and cotton, and are working on developing equations for wheat. These equations (shown in the table below) are different for different sensors, and in corn are different for different growth stages. In all cases, the N rate is calculated from the sensor value divided by the value from the high-N reference area. This is why a good high-N reference area is so important—the value measured there has a big impact on N rates used in the rest of the field.

Crop	Sensor	Stage	Missouri N rate equation
Corn	Greenseeker	V6-7 (12" to knee high)	(220 x ratio*) - 170
Corn	Greenseeker		(170 x ratio) - 120
Corn	Greenseeker	V11+ (chest high or taller)	(160 x ratio) - 130
Cotton	Greenseeker	mid-square to early flower	(122 x ratio) - 95
-----	OptRx	-----	not available
-----	CropSpec	-----	not available
Wheat	-----	-----	not available
Corn	Crop Circle 210	V6-7	(330 x ratio) - 270
Corn	Crop Circle 210	V8-10	(250 x ratio) - 200
Corn	Crop Circle 210	V11+	(240 x ratio) - 210
Cotton	Crop Circle 210	mid-square to early flower	(178 x ratio) - 156

*Ratio = (Target visible/near-infrared) / (High-N visible/near-infrared)

Missouri's equations were developed from a series of N rate experiments in producer fields. Yield response was measured, optimal N rate was calculated, sensor measurements were taken, and the equation that best related sensor measurements to optimal N rate over all sites was determined. Pennsylvania has used a similar approach and produced a similar equation. Other researchers have used a more indirect approach, using sensor values to predict yield potential, then combining yield potential and sensor values to predict yield response to N, then predicting N rate from yield response using an efficiency factor supplied by the user.

Visible/near-infrared is the sensor measurement used in our equations. Missouri

equations for corn and cotton are available with the Greenseeker system but are calculated from an index called NDVI. We have worked with Greenseeker to develop equations that are, as closely as possible, equivalent to the equations in the table. Missouri equations for the Crop Circle 210, the first-generation sensor from Holland Scientific, have been used for the Ag Leader OptRx sensor through a 2-year testing phase and into commercialization. These equations may or may not be appropriate for the OptRx and so far not enough testing has been done to resolve this issue. Our equations for the Crop Circle 210 sensor have been extensively tested in field-scale demonstrations with good results, and our Greenseeker equations have been tested in quite a few fields as well.

Comparing, choosing, moving forward

Different systems may recommend very different N rates from the same data. In a 2008 test in Iowa, the default Greenseeker equation for corn applied an average of 16 lb N/acre, which came out N-deficient and 24 bu/acre lower yield than the producer rate. The Missouri recommendation for the same sensor data would have averaged 76 lb N/acre, nearly five times as much, with total N used at 10 lb/acre above the producer's rate. This illustrates how far we still need to go to get agreement and good performance.

Additional research, development, and experience is needed to select and perfect equations translating sensor values to N rates. This is the heart of successful sensor-based N management.