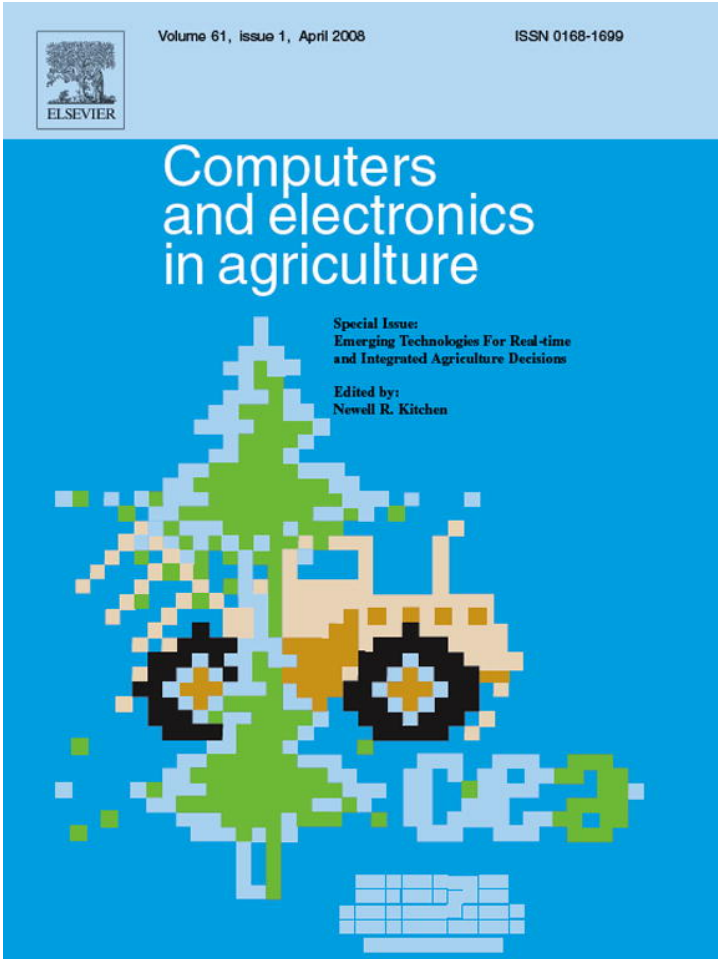
ELSEVIER
Volume 61, issue 1, April 2008
ISSN 0168-1699
Computers
and electronics
in agriculture
Special Issue:
Emerging Technologies For Real-time
and Integrated Agriculture Decisions
Edited by:
Newell R. Kitchen

computers and electronics in agriculture 61 (2008) 51–62

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/compag

Responsive in-season nitrogen management for cereals☆

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ARTICLE INFO

Article history:
Received in revised form
14 September 2006
Accepted 4 June 2007

Keywords:
Nutrient management
Remote sensing
Geospatial technology
Canopy sensors

ABSTRACT

Current nitrogen (N) management strategies for worldwide cereal production systems are characterized by low N use efficiency (NUE), environmental contamination, and considerable ongoing debate regarding what can be done to improve N fertilizer management. Development of innovative strategies that improve NUE and minimize off-field losses is crucial to sustaining cereal-based farming. In this paper, we review the major managerial causes for low NUE, including (1) poor synchrony between fertilizer N and crop demand, (2) uniform field applications to spatially variable landscapes that commonly vary in crop N need, and (3) failure to account for temporally variable influences on crop N needs. Poor synchronization is mainly due to large pre-plant applications of fertilizer N, resulting in high levels of inorganic soil N long before rapid crop uptake occurs. Uniform applications within fields discount the fact that N supplies from the soil, crop N uptake, and crop response are spatially variable. Current N management decisions also overlook year-to-year weather variations and sometimes fail to account for soil N mineralized in warm, wet years, ignoring indigenous N supply. The key to optimizing tradeoffs amongst yield, profit, and environmental protection is to achieve synchrony between N supply and crop demand, while accounting for spatial and temporal variability in soil N. While some have advocated a soil-based management zones (MZ) approach as a means to direct variable N applications and improve NUE, this method disregards yearly variation in weather. Thus, it seems unlikely that the soil-based MZ concept alone will be adequate for variable application of crop N inputs. Alternatively, we propose utilizing emerging *computer and electronic technologies* that focus on the plant to assess N status and direct in-season spatially variable N applications. Several of these technologies are reviewed and discussed. One technology showing promise is ground-based active-light reflectance measurements converted to NDVI or other similar indices. Preliminary research shows this approach addresses the issue of spatial variability and is accomplished at a time within the growing season so that N inputs are synchronized to match crop N uptake. We suggest this approach may be improved by first delineating a field into MZ using soil or other field properties to modify the decision associated with ground-based reflectance sensing. While additional adaptive research is needed to refine these newer technologies and subsequent N management decisions, preliminary results are encouraging. We expect N use efficiency can be greatly enhanced using this plant-based *responsive* strategy for N management in cereals.

☆ Mention of trade names or commercial products is done to provide specific information and does not imply endorsement by the U.S. Department of Agriculture.

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doi:10.1016/j.compag.2007.06.006

1. Introduction

In this paper we first review current nitrogen (N) management strategies for cereals (i.e. corn (*Zea mays* L.) and wheat (*Triticum aestivum* L.)), primarily focused on the Central Great Plains and Corn Belt region of the United States and other areas of the world with similar growing conditions. Additionally, we highlight problems associated with these strategies, and how *computer and electronic technologies* can be employed to address these problems. The consequence of current N management strategies is low N fertilizer use efficiency (NUE), leading to economic losses and environmental contamination (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005). In this paper, NUE is defined as the percent of applied fertilizer N recovered in the aboveground crop biomass during the growing season. Here we review the primary causes for low NUE in current systems. We then present our vision for development of alternative strategies, involving use of both soil-based management zones (MZ) and plant-based remote sensing of crop N status for in-season variable N applications. Successful deployment of these "approaches" will rely heavily upon utilizing emerging precision agriculture technologies, like on-the-go soil and crop sensors, data communication protocols between sensors, controllers, computers, and databases. Finally, we demonstrate that the proposed strategy directly addresses the fundamental problems associated with current practices. Preliminary research results indicate our proposed strategies hold promise for improving NUE over current approaches. Since corn and wheat provide a significant portion of human dietary calories (Cassman et al., 2002) and they account for a majority of global fertilizer N use, we conclude that adoption of our proposed strategies should lead to improved fertilizer NUE, reduced fertilizer costs, and diminished environmental impacts (Raun and Johnson, 1999).

2. Problems of current N management strategies

Current N management strategies for world cereal production systems have resulted in low NUE, averaging only around 33% of fertilized N recovered (Raun and Johnson, 1999). At $850 per metric tonnes of N fertilizer, the unaccounted 67% represents a $28 billion annual loss of fertilizer N (assuming fertilizer–soil equilibrium). While it is impossible to achieve 100% efficiency for N fertilizer use in any crop production system, these numbers suggest there is significant opportunity for reducing N losses associated with current management practices. Pathways for N losses from agroecosystems include gaseous plant emissions (Daigger et al., 1976; Francis et al., 1993), soil denitrification, surface runoff, volatilization, and leaching (Raun and Johnson, 1999). With the exception of N denitrified to N_2, these pathways lead to an increased load of biologically reactive N into external environments (Cassman et al., 2002). In the U.S. for example, the amount of biologically reactive N delivered from the land to coastal waters has increased noticeably over the past century (Turner and Rabalais, 1991), and has been proposed as a primary causal factor in oxygen depletion of coastal waters (Rabalais, 2002). Current fertilizer N management practices in the U.S. Corn Belt, especially when N fertilizer is applied at rates greater than crop needs (Burwell et al., 1976), have lead to nitrate-N being a major contaminant found in the surface and ground waters of the region (Schilling, 2002; Steinheimer et al., 1998; CAST, 1999). In summary, current N management strategies for cereal production systems in the U.S. and around the world are characterized by low N use efficiency (NUE), environmental contamination, and considerable ongoing public debate regarding use of N fertilizers in crop production. Hence, development of alternative N management strategies that maintain crop productivity, improve NUE, and minimize environmental impact will be crucial to sustaining cereal production systems worldwide.

2.1. *Causes of low NUE for current N management strategies*

One of the major causes for low NUE of current N management practices is poor synchrony between soil N supply and crop demand (Raun and Johnson, 1999; Cassman et al., 2002; Fageria and Baligar, 2005). Poor synchronization is mainly due to large pre-plant applications of fertilizer N. Cassman et al. (2002) estimated, from USDA survey data that typical N application amounts in the U.S. Corn Belt region over last 20 years averaged approximately 150 kg ha^{-1}, with farmer surveys (USDA data) indicating that around 75% of the N applied occurs prior to planting (including the previous fall) and only 25% of the N applied after planting. These large pre-plant N applications result in high levels of soil profile inorganic N, well before rapid crop uptake occurs, resulting in poor synchrony between soil N supply and crop demand as depicted in Fig. 1. Efficiency of use from a single pre-plant N-fertilizer application typically decreases in proportion to the amount of N fertilizer applied (Reddy and Reddy, 1993). Other studies have substantiated that

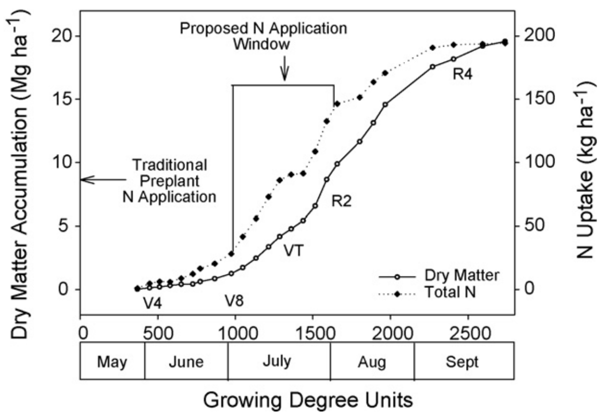

Fig. 1 – Corn dry matter and N uptake vs. accumulated growing degree units. From unpublished research with six hybrids grown under irrigated conditions over two growing seasons at Shelton, NE in replicated plots in 1992. Crop dry matter and N accumulation were determined on a weekly basis throughout the entire growing season. Calendar dates and important phenological dates are depicted. Timing of N application for current vs. proposed in-season management scheme is also shown in the figure.

in-season applied N resulted in a higher NUE than when N is pre-plant applied (Miller et al., 1975; Olson et al., 1986; Welch et al., 1971; Randall et al., 2003a,b). Collectively, these results agree with the recommendations of Keeney (1982), who advocated that the most logical approach to increasing NUE is to supply N as it is needed by the crop. This reduces the opportunity for N loss because the plant is established and in the rapid uptake phase of growth. Thus, while research is rich with results supporting the point that NUE is improved by synchronizing applications with crop N use, adoption by farmers with this as an impetus has been minor. The barrier, as suggested by Cassman et al. (2002), has primarily been a lack of cost-effective and/or practical technologies to implement in-season N applications.

Another major factor contributing to low NUE in current strategies has been uniform application rates of fertilizer N to spatially variable landscapes, even though numerous field studies have indicated economic and environmental justification for spatially variable N applications in many agricultural landscapes (Mamo et al., 2003; Hurley et al., 2004; Koch et al., 2004; Scharf et al., 2005; Shahandeh et al., 2005; Lambert et al., 2006; Hong et al., 2007). Uniform applications within fields discount the fact that N supplies from the soil, crop N uptake, and response to N are not the same spatially (Inman et al., 2005). Without tools to address spatially variable crop N need, farmers tend to apply enough N, at uniform rates, to meet crop needs in the more N-demanding areas of the field, resulting in greater risk of N loss from field areas needing less N (Hong et al., 2007). Thus, N applied at field-uniform rates ignores spatial differences and is at considerable risk for environmental loss.

A third reason for low NUE is attributed to the way N fertilizer requirements are commonly derived. Many current fertilizer N recommendation procedures are “yield-based”, meaning a yield goal is set before the crop is planted and multiplied by some constant factor to estimate the N fertilizer requirement. This calculation produces a number that is, in essence, an estimate of the amount of N that will be removed from the field at harvest, N associated with biomass production, and an estimate of fertilizer NUE (Stanford and Legg, 1984; Meisinger and Randall, 1991). Adjustments to the calculated fertilizer recommendation are often made for various N credits, such as previous crop and recent use of manure (Mulvaney et al., 2005). While this “mass balance” approach is simple and holds considerable appeal, it is not without its shortcomings. One major weakness inherent in this approach is that it assumes a constant fertilizer NUE (Meisinger, 1984; Meisinger et al., 1992), even though research has shown that NUE varies significantly from site to site and year-to-year. From plot research, NUE rarely exceeds 70% (Pierce and Rice, 1988) and more often ranges from 30 to 60% (Bock, 1984). The other difficulty is in deriving an accurate and realistic estimate of the yield goal, particularly for rain-fed cropland with precipitation varying seasonally as well as annually. A number of approaches for determining yield goal have been considered. Averaging yields over a number of years can be used, but this method may result in inadequate N for years when conditions provide better than average yield. A yield goal that is based upon only the best recent years will generally meet crop N needs, but potentially will leave inorganic N in the soil when growing conditions have not been ideal. Yield goal is often determined by adding 5–10% to the average yield of the most recent 5–7 years (Rice and Havlin, 1994).

Surveys have demonstrated that many producers overestimate their yield goal when determining N recommendations (Schepers and Mosier, 1991; Goos and Prunty, 1990), because of the historic low cost of N fertilizer, and not wanting to limit yields, regardless of the type of year. Inflated yield goals may also suggest that producers do not use actual whole-field averages, but rather rely upon yield expectations from the highest producing field areas. Even before the availability of combines with yield monitoring systems, farmers intuitively knew that areas of their fields yielded 10–20% or more than the average.

The deficiencies of the yield-based approach in making N recommendations is substantiated in a study conducted by Lory and Scharf (2003), where data from 298 previously reported experiments in five Corn Belt states in the U.S. were combined to evaluate corn yield response to fertilizer N. In this study, recommended N rates, as determined by actual yield, exceeded the economically optimum N rate (EONR) by up to 227 kg ha^{-1} and on average by 90 kg ha^{-1}. Furthermore, recommended N rates were not highly correlated ($r = 0.04$) with EONR. Thus, using yield goal would have resulted in inappropriate N recommendations on these study areas, and N over application in many instances. Researchers in Iowa (Blackmer et al., 1997), Wisconsin (Vanotti and Bundy, 1994; Bundy, 2000), Pennsylvania (Fox and Piekielek, 1995), and Ontario (Kachanoski et al., 1996) also identified concerns about the reliability of using expected yield in making N recommendations.

2.2. *Responding to complex interactions*

Generally, crop-N demand is related to biomass yield and the physiological requirements for tissue N, with C_4 crops (e.g., corn) requiring less N to produce a given level of biomass than C_3 crops (e.g., wheat) (Gastal and Lemaire, 2002). Crop-management practices and weather have a major influence on biomass yield and thus N demand. Weather during the cropping cycle can vary significantly from year-to-year, which causes large differences in yield potential. In irrigated systems, the yield potential of a specific crop is largely determined by solar radiation and temperature. In many rain-fed cropping environments, rainfall amount and seasonal distribution, as well as available soil moisture storage capacity, have the greatest influence on yield potential. While solar radiation, temperature, and moisture regimes determine the genetic yield ceiling, actual crop yields achieved by farmers are generally far below this threshold because it is neither possible, nor economical, to remove all limitations to growth from sub optimal nutrient supply, weed competition, and damage from insects and diseases. Hence, the interaction of weather and management causes tremendous year-to-year variation in crop N requirements within fields.

In summary, it is not surprising that current N management strategies have resulted in such low NUE values, given that current practices typically disregard the effects of weather in estimating crop fertilizer N requirements, make use of large pre-plant N applications (i.e., lack of synchrony), and ignore within-field variability in N fertilizer need. The key to optimizing the trade off amongst yield, profit and environmental protection for future N management practices is to achieve better synchrony between applied fertilizer N and crop N demand, accounting for landscape spatial variability in soil N supplies and crop N uptake. This would result in less dependence on large pre-plant applications of uniformly applied N and greater reliance on a "reactive approach" that involves in-season estimates of crop N needs with the ability to adjust for both temporal and spatial variability effects on soil and crop N dynamics. To accomplish this task, it will be necessary to utilize various precision agriculture tools like on-the-go soil and crop sensors that have the ability to "sense" crop N status in "real-time", and deliver spatially variable N applications based on crop N need.

3. Innovative nitrogen management strategies using precision agriculture information

Precision agriculture includes a wide range of geospatial technologies that have become available to agriculture since the mid-1990s. These technologies have been made possible by low cost global positioning systems (GPS) and mobile data processing equipment capable of storing and retrieving large databases. Some of these developments have provided detailed spatial databases for traditional elements of the N recommendation algorithms such as soil survey maps, yield maps, previous crops, and soil tests results. Satellites and aircraft can also provide remotely sensed data on soil moisture content, residue cover, and crop stress. On-the-ground soil sensors have also been developed for assessing soil electrical conductivity, sub-soil compaction, and soil organic matter. Real-time crop sensors have also become available utilizing passive and active light technologies to ascertain crop stress (such as apparent N status) through reflectance measurements in visible and near-infrared wave bands.

3.1. *Management zone approach*

To accommodate spatially variable landscape conditions and better match fertilizer N supply with crop N requirements, some (Franzen et al., 2002; Ferguson et al., 2003) have advocated a soil-based approach involving delineation of spatial variability into management zones (MZ) as a means to direct variable N applications and improve NUE. Management zones, in the context of precision agriculture, are field areas possessing homogenous attributes in landscape and soil condition. When homogenous in a specific area, these attributes should lead to similar results in crop yield potential, input-use efficiency, and environmental impact. Approaches to delineate MZ vary, but typical procedures involve acquiring various geo-referenced data layers (i.e., topography, soil color, electrical conductivity, yield, etc.), traditional and geospatial statistical analyses on these layers, and delineation of spatial variation from these layers into MZ, as outlined by Schepers et al. (2004) and illustrated in Fig. 2. Soil map units (Wibawa et al., 1993), topography (Kravchenko et al., 2000), remote sensing (Schepers et al., 2004), electrical conductivity sensors (Kitchen et al., 2003; Heiniger et al., 2003; Johnson et al., 2003), crop yield (Flowers et al., 2005; Kitchen et al., 2005) and producer experience (Fleming et al., 2004) have all been used with varying success to delineate MZ. While these data sources for MZ delineation can be used to consistently characterize spatial variation in soil physical and chemical properties that partially affect crop yield potential, they are less consistent in characterizing spatial variation in crop N requirements because of the apparent effect of temporal variation on expression of yield potential (Schepers et al., 2004; Lambert et al., 2006). Therefore, the soil-based MZ concept alone will not be adequate for improving variable application of crop inputs like N, primarily because it does not address weather-mediated variability in crop N demand.

3.2. *In-season crop monitoring approach to N management*

Crop plant leaves or canopy measurements have long been known to serve as an indicator for nutrient needs. Since plants integrate soil, climate, management, and other environmental influences on crop N health, they provide an opportunity for targeting N fertilizer inputs. When fertilizer N can be targeted at rates that meet but do not exceed crop N requirements, residual soil N after harvest is minimized (Hong et al., 2007). We contend that responding to the plant as the basis for N inputs will improve NUE. Here we discuss four different ways in-season crop assessment can facilitate N management decisions.

With all four approaches, the assessment of crop N status is accomplished by comparing the crop plants yet to be fertilized with crop plants where N is not a limiting factor. Plants adequately fertilized through the growing season constitute a *sufficient-N reference*, and are based on principles established by Schepers et al. (1992a,b). In essence, the greater the difference between *sufficient-N reference* plants and un-fertilized or deficiently fertilized plants, the more N fertilizer is needed. Without this reference to determine a relative difference, there is little basis for making N rate recommendations.

3.2.1. *Visual assessments using calibration reference plots*

Scientists at Oklahoma State University developed the "Ramped Calibration Strip" (RCS) to visually assess in-season N requirements (Raun et al., 2005). An automated programmable N-fertilizer-strip applicator was designed that can apply pre-plant rates ranging from 0 to 300 kg N ha^{-1}, in progressively incremental rates as low as 10 kg N ha^{-1} over user defined distances (50–300 m per sequence). The highest N rate and the rate increments can be adjusted to the crop and the expected N need. The system has been used in winter wheat with N ramps from 0 to 150 kg ha^{-1} in increments of 10 kg N ha^{-1} and that changed every 3 m. The RCS is specifically designed to assist producers in visually estimating the optimal mid-season fertilizer N rate by inspecting differences in growth and color during the season across the range of pre-plant N rates. The RCS approach offers particular advantages for large acreages where pre-plant soil tests and in-season soil tests are simply too labor intensive for the producer. For example, if no visual in-season growth differences are observed across the RCS (0–150 kg N ha^{-1}), it is unlikely that

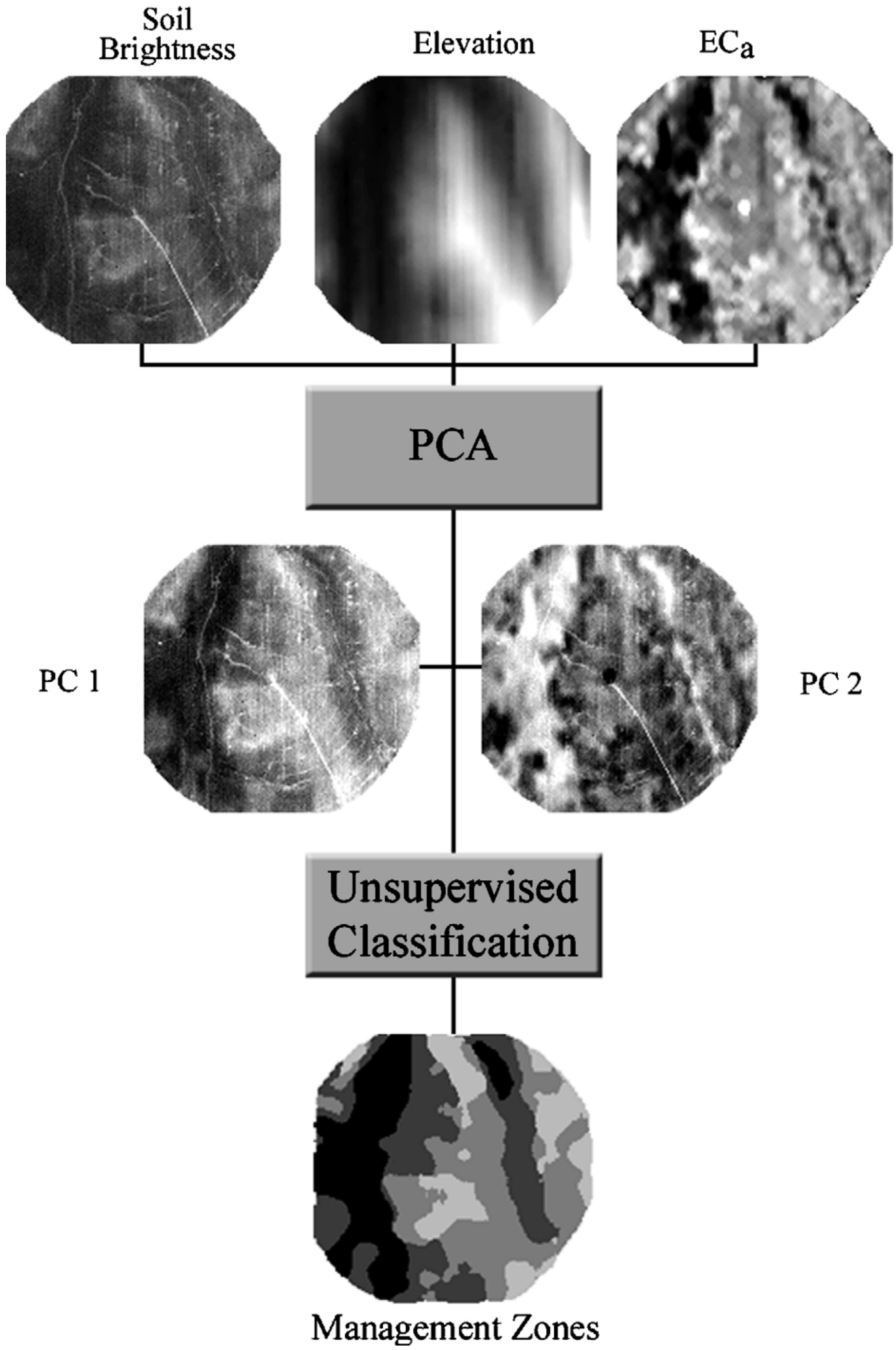

Fig. 2 – Depiction of procedures for delineating management zones (MZ), showing gray scale maps of five landscape attributes acquired at the Gibbon, NE corn study site consisting of red, green and blue bands (shown in one map) of soil brightness image, elevation and apparent electrical conductivity (EC_a), with variations in color, from dark to light, corresponding to increasing values for all landscape attributes (Schepers et al., 2004). Gray scale maps of principal component (PC) scores for PC's 1 and 2, resulting from principal component analysis (PCA) of five landscape attributes, with variations in color, from dark to light, corresponding to decreasing PC scores. Gray scale map of MZ, resulting from unsupervised classification of PC scores for two PC's, with variations in color, from dark to light, corresponding to MZ 1 through 4.

there will be added response to fertilizer N. However, if growth peaked at 100 kg N ha^{-1} with discernable differences from 0 to 100 kg N ha^{-1} (no differences from 100 to 150 kg N ha^{-1}), then the top-dress rate would be around 100 kg N ha^{-1}. It is important to note that the RCS must be applied "on-top" of the normal farmer practice and would thus reflect the N contributed from other sources such as residual soil nitrate, manure, soil mineralization, rainfall, etc. However, in order to be useful for applying supplemental N for long-season crops (e.g., corn) based on early-season observations, it is likely that crop developmental stage and total crop N need will also need to be considered.

An advantage of the RCS is that it is a within-field visual indicator, giving direct educational value to the producer because of the easily recognized signs of N stress or N adequacy. It is timely in that it provides a visual guide at the time in the growing season a decision needs to be made as to what N rate should be applied. This approach may also be useful with calibrating real-time crop canopy sensors to the in-season N rate for maximum growth and yield (discussed more in a latter section). A potential disadvantage of the RCS would exist for fields exhibiting significant spatial variability in N fertilizer need because of large differences in N coming from the soil and crop N need. In these cases, multiple strips within fields might be required to make appropriate soil-specific N fertilizer rate decisions.

3.2.2. *Leaf chlorophyll meter sensing*

Previous work by Blackmer and Schepers (1994), Blackmer et al. (1993) and Blackmer and Schepers (1995), using the Minolta SPAD 502 chlorophyll meter (CM) to monitor crop N status and applying fertilizer N, showed that crop-based approaches to manage N would be an improvement over current soil-based approaches. This work demonstrated under a fertigation cropping system that detection of a crop N stress using a CM for determining N applications could maintain crop yields with less N fertilizer. Nitrogen stress and grain yield losses were observed to occur whenever CM readings declined below 95% of the meter values for reference area corn receiving adequate to excess N at planting time. They suggested that the 95% value (referred to as a “sufficiency index”) would be a reasonable “trigger point” to apply additional N. Subsequently, Varvel et al. (1997) confirmed these findings in a small plot study involving N applications directed by CM assessments from early vegetative growth (V8, Ritchie et al., 1997) through silking (R1). Furthermore, they noted that when the sufficiency index at V8 was below 90%, maximum yields were not achieved with in-season N fertilizer applications, in part because early season N was below that needed for optimum growth and yield potentials had already been reduced. In another study involving 66 N rate experiments conducted in seven north-central states in the U.S. over a 4-year period, Scharf et al. (2006) found that CM readings at all growth stages from V5 to R5 were significantly correlated with the economically optimal N rate and yield response to N applied at growth stage V7 or earlier. They concluded that CM readings are a good predictor of corn yield response to N over a wide range of soil types, geography, landscape forms, weather environments, corn hybrids, and management practices, and would be useful in making N-fertilizer management decisions. Collectively, this cited research demonstrates (1) that monitoring the plant using the CM can be used as a tool to maintain an adequate but not over-supply of N for the corn crop, and (2) that yields can be maintained with less N than is typically used with single pre-plant applications.

Extending this tool and concept to whole-field management is problematic since it is extremely difficult to collect sufficient data using a hand-held device to manage large fields (Schepers et al., 1995). Yet these findings identified the need for technologies that would provide similar information on whole fields as that generated by the CM. While the CM is logistically restricted to small areas, the concepts established for its use have helped open the doors for the development of similar technologies suitable for production-scale conditions, from which uniform early season N management can be replaced by a more crop responsive evaluation and N application (Schepers et al., 1995; Raun and Johnson, 1999).

3.2.3. *Aerial and satellite remote sensing*

Remote sensing – the process of acquiring information about objects from devices not in contact with those objects – is an option for obtaining information on crop N status for portions of or an entire field (Moran et al., 1997; National Research Council, 1997). This technique has been used by many scientists to characterize spatial variability in fields (Bhatti et al., 1991; Atkinson et al., 1992).

For N status in crop plants, the relationship to remote sensing has been well studied. Plants with increased levels of available N typically have greater leaf N concentrations, more chlorophyll (Inada, 1965; Al-Abbas et al., 1974; Wolfe et al., 1988), and greater rates of photosynthesis (Sinclair and Horie, 1989). Chlorophyll in leaves absorbs most strongly in the blue (around 450 nm) and red (around 670 nm) light, and reflects in the green (around 550 nm) region of the light spectrum. The Minolta SPAD 502 CM, discussed in the previous section, measures light transmission in the red (650 nm) and near-infrared (940 nm) parts of the spectrum to estimate leaf chlorophyll content (Blackmer et al., 1994; Markwell et al., 1995). The positive relationship between leaf greenness and crop N status means it should be possible to assess crop N needs from remotely sensed reflectance measurements of the crop canopy (Walburg et al., 1982; Hinzman et al., 1986) and leaves (Dwyer et al., 1991; McMurtrey et al., 1994).

There are technical concerns regarding the use of imagery data (satellite or aerial) for assessing canopy N status, particularly for canopies with incomplete closure and/or exposed soil. For example, Shanahan et al. (2001) collected aerial imagery data with a 12-bit four-band [blue, green, red, and near-infrared (NIR)] digital camera system periodically through the growing season. They showed that reflectance in the green and NIR bands in the form of the GNDVI (green normalized difference vegetation index), as proposed by Gitelson et al. (1996), had greater potential for assessing canopy variation when collected after tasseling than before tasseling. This is because of the confounding effect of soil background in aerial imagery data collected before canopy closure. Other researchers (Huete, 1988; Rondeaux et al., 1996; Baret et al., 1989) have attempted to remove the soil background effect through mathematical manipulations of the various reflectance bands (i.e., soil-adjusted vegetative index (SAVI) or transformed soil-adjusted vegetative index (TSAVI)). However, Shanahan et al. (2001) indicated that the TSAVI equation was no better, and often worse, than the GNDVI in detecting variation in canopy vigor or greenness during early season growth. Although aerial imagery appears to have limited potential for use early in the growing season for evaluating crop N status, it holds more promise after canopy closure. However it should be noted that both aerial and satellite imagery can be compro-

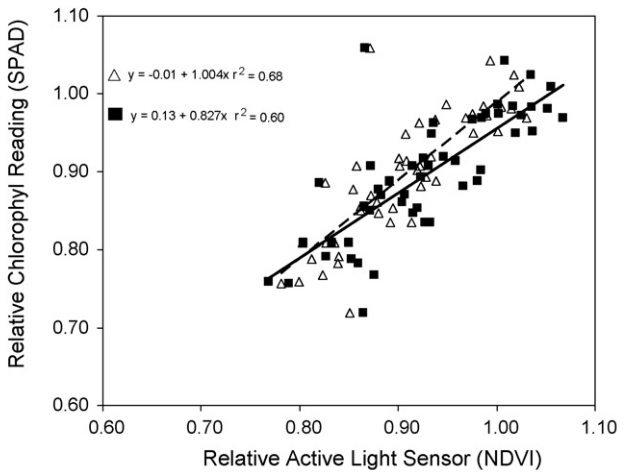

Fig. 3 – Readings from two different active-light sensors (■: Greenseeker™, NTech Industries, Inc., Ukiah, CA; △: Crop Circle™ Holland Scientific, Lincoln, NE) are related to SPAD chlorophyll meter readings for corn at the V10 growth stage. Both NDVI and SPAD are shown as a fraction relative to readings taken from an N reference area (corn with sufficient N).

mised by cloud cover, especially in regions where this climatic feature is common in spring and summer months.

3.2.4. *Ground-based remote sensing*

Ground-based crop canopy reflectance sensing, technically a type of remote sensing, has also been used to assess crop N condition and determine N input recommendations. Unlike aerial or satellite sensing, ground-based sensing need not be compromised by clouds and the sensors can be attached directly to an applicator so that the fertilization can be accomplished within seconds of crop sensing. A four band (blue, green, red and near-infrared or NIR) passive-light sensor system was shown to be capable of detecting variations in corn leaf chlorophyll content similar to the CM, and thus could potentially be used in directing rate changes for an in-season N applicator (Shanahan et al., 2003). Active-light sensor measurements have also been shown to be associated with CM readings (Fig. 3), and have been successfully used in determining variable-rate N applications in wheat (Raun et al., 2002). Sensor reflectance measurements of winter wheat converted to NDVI were used to calculate a response index (determined by comparing to a non-N limiting reference strip) and showed that early-season sensing and treatment of each 1 m^2 resulted in NUE increases of 15% over that of current whole-field techniques based on mass-balance approaches. The commercially available GreenSeeker (NTech Industries, Ukiah, CA) active-light sensor used in this work is self-illuminated in red (650 ± 10 nm FWHM, full width, half magnitude) and NIR (770 ± 15 nm FWHM) bands. The sensor measures the fraction of the emitted light in the sensed area that is returned to a detector, which is then used to compute NDVI. The NDVI is the difference between the NIR and red reflectance divided by the sum of these two values. Biermacher et al. (2006) conducted an economic analysis of 65 site-years of data from winter wheat N fertility studies in the Southern Plains of the U.S. to estimate the expected returns from uniform N versus a system using the GreenSeeker sensor and a variable-rate applicator. They showed variable-rate N applications would result in significant N savings compared to uniform N application, when using N priced at \$0.55 kg^{-1}. Researchers in Europe and elsewhere (Schroder et al., 2000; Olfs et al., 2005; Berntsen et al., 2006; Tremblay and Belec, 2006; Zillmann et al., 2006) have also shown that this approach can be used to direct variable in-season N applications in cereal grains that improves NUE, crop harvest ability, and/or quality. Some of the aforementioned research involved use of the Yara N sensor system for variable N applications, which has been available for about a decade in Europe (Yara UK Limited, Lincolnshire, UK) as a commercialized service, and is being adopted by growers. Early Yara sensors relied on passive light (sunlight) but newer devices use an active light technique, similar to the GreenSeeker system. Together, the results from Europe, the U.S. and elsewhere with cereal grains suggests that this "reactive approach" holds considerable promise for improved N management.

The methodology developed for wheat by Raun et al. (2002) relies on the ability to estimate crop N demand from early season growth. This is done by dividing the sensed NDVI by the days from planting to the day of sensing (http://www.nue.okstate.edu), which is essentially the early-season growth rate or biomass production per day. This can, in essence, provide an estimate of yield potential. Unlike the pre-plant yield goal approach, this method projects yield after the crop is well established and as is nearing the rapid vegetative growth stage. The sensor-based fertilizer N recommendation is accomplished by subtracting the projected N uptake for the predicted yield in the sensor area from the projected N uptake in the non-N limiting reference strip, and then dividing by an NUE factor (usually between 0.6 and 0.7 for in-season N applications) to obtain the in-season top-dress N rate. The main advantages of the ground-based sensor approach over the current pre-season "yield-goal" approach is the ability to obtain spatial difference in crop N need and assess climatic conditions encountered from planting to the time of in-season N application before making N recommendation. The weakness of this system lies in the uncertainty in estimating yield from mid-season sensor measurements and the use of a fixed NUE factor, a value that varies spatially within fields (Scharf et al., 2005).

In-season crop sensing to estimate yield potential allows N rates to be tailored and adjusted for N responsive- or non-responsive conditions. Using contributions from scientists all over the world, several unique crop and/or region-specific algorithms are being evaluated using these concepts, including, for example, irrigated corn, dryland corn, winter wheat, spring wheat, sorghum, and Bermuda grass (http://www.nue.okstate.edu). Each algorithm requires pre-plant establishment of the non-N-limiting reference strips as proposed by Schepers et al. (1992a,b), in-season sensor readings from the N rich strip and farmer practice, knowledge of planting dates, and regional yield limits (http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php). These algorithms are free on the web, and all mathematical components of each algorithm are public property. The majority of these algorithms have been tested experimentally and validated in multi-year on farm trials. Additional experiments are currently underway across a wide array of soil, climate, and cropping systems to refine many of these algorithms and generate new ones, which will account for some of the problems encountered in making variable N applications (http://nue.okstate.edu/Conferences_Workshops.htm).

Changing from uniform field-scale N applications to variable-rate applications based on sensor-determined crop need offers producers a significant opportunity for improving NUE. However, as already mentioned, a major constraint to the practical adoption of variable-rate in-season N application is having robust sensor algorithms for making N recommendations that are appropriately responsive to soil–climate interactions. In-season N management involving sensors will need to be flexible to accommodate equipment availability, weather uncertainties, and acceptable risks. Managing N in winter versus summer annual crops will likely involve different approaches in order to interpret sensor data with variation in factors such as bare soil color, vegetative cover, chlorophyll content, leaf area index, biomass, plant height, etc. As such, in-season technologies and management decisions will need to accommodate variable amounts of vegetation and different growth stages. In the end, a variety of vegetative indices may be needed that account for specific crops under specific production practices. Ideally, the procedures and algorithms will be inclusive of as many environmental (e.g., weather, soil organic matter, soil texture) and managerial (e.g., cropping system, hybrid, tillage, etc.) factors as possible.

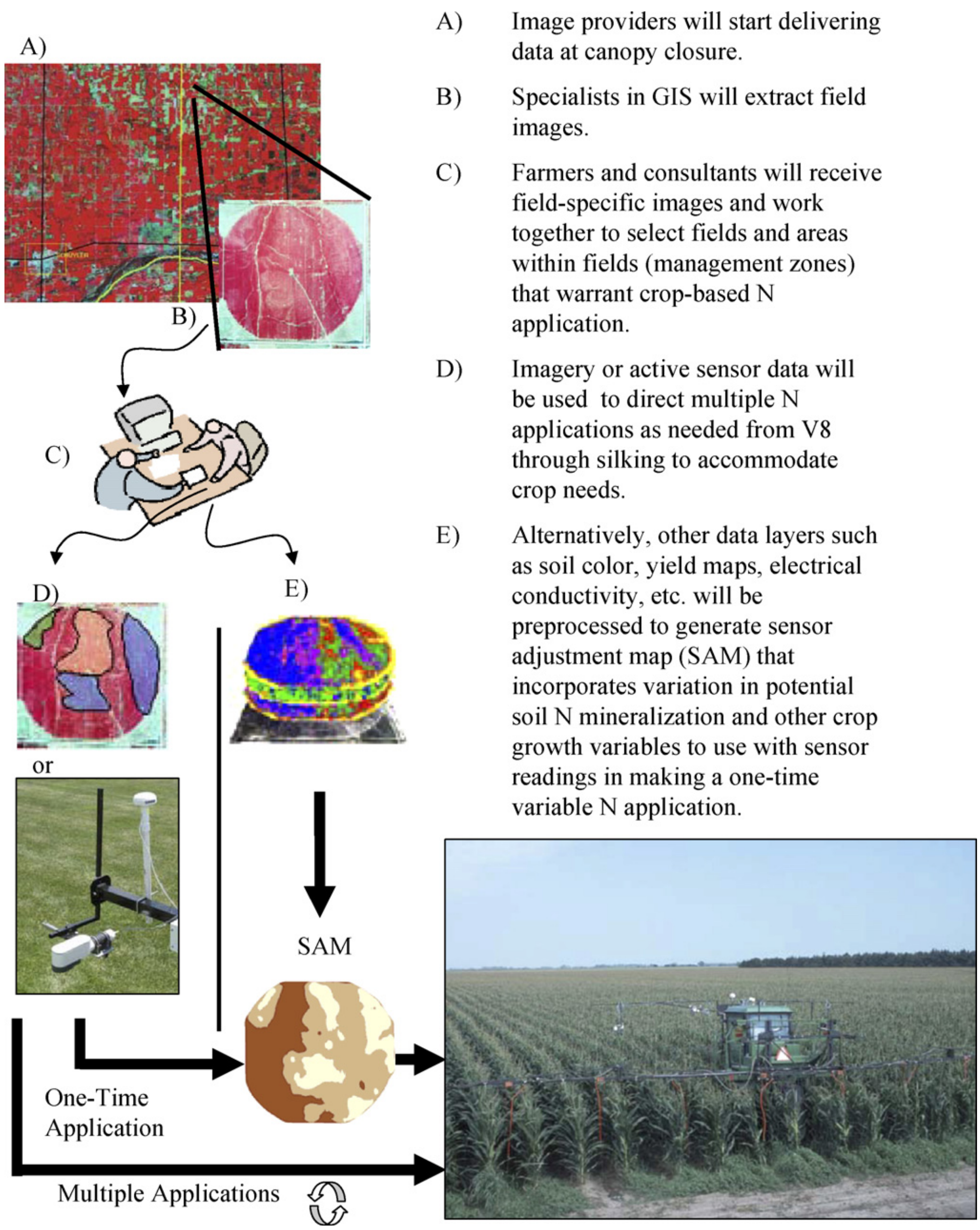

Fig. 4 – An example describing the integration of soil and crop information into a responsive N management system.

3.3. *Integrating soil and crop sensing information into N management*

Through sensors and improved algorithm development, we expect to see a better understanding of soil-crop N dynamics in the future. This in turn may enhance responsive in-season sensing and N management. For example, we envision a flexible management system for N that will enable producers to make intelligent (economically and environmentally sound) decisions for cereal production using a variety of inputs. In the example illustrated in Fig. 4, producers could use some type of remote sensing (satellite or aircraft) to provide imagery of large areas and determine large scale within-field variation in vigor, nutrient, status, etc. Ag consultants would more than likely be needed to manage these large spatial image databases, extract/georectify individual fields, and examine/interpret for signs of variable need. Producers and consultants would verify the likely causes of the observed variability and, if desired, process the imagery to assign MZ within the field (based on producer and consultant inputs and other data). The resulting treatment map would serve as input along with the responsive ground-based sensor information to generate variable-rate instructions for the controller. Sometimes the spatial resolution, timeliness, or clarity of the imagery may not be adequate because of cloud cover or other reasons, in which case the producer may opt to only use active sensors as input for the controller. Another controller input strategy may involve using imagery/sensor data along with other preprocessed spatial information (see sensor adjust map (SAM) in Fig. 4), providing many options for directing in-season N applications.

4. Conclusions

We discussed three managerial factors that contribute to low NUE-poor synchrony of N inputs with timing of crop demand for N, uniform fertilizer applications to landscapes with spatially variable crop N need, and failure to account for variable weather influences on yield potential and N need. Management strategies that do not account for these factors will fall short of increasing NUE beyond the current levels. Addressing these factors for improving NUE will require approaches that are *responsive* to the soil-crop-management system. Our conclusion is that in-season plant-based strategies offer the best opportunity for doing this, and is the reason our research programs are working to develop and refine these technologies.

Several responsive plant-based approaches are in various stages of development. With each, a *sufficient-N reference* is needed to determine mid-season fertilizer N recommendations, regardless of the cereal crop in question. The reference clearly identifies the need for additional N above that available to the crop up to the point in the growing season when the mid-season N management decision is made. Examination of the crop at this stage using human observations (e.g., Ramped Calibration Strips) or sensor technology (e.g., chlorophyll meter, above ground imagery, or ground-based reflectance sensors) relative to the *sufficient-N reference* provides the means for the decision of how much additional N is needed to complete the crop. In contrast to responsive approaches, soil testing lacks a visual check for assisting farmers in the decision making process. We suggest this is one reason adoption of soil testing methods for N management is low. Visual appraisals of crop N response (N Reference, or N Ramps) lures farmers into being involved, and if nothing else it encourages them to think about agronomic principles relative to their N management. Sensor-based methodologies are progressive, but adoption of these new approaches will likely be accelerated as they are embedded within some kind of strategy that provides positive visual feedback to farmers.

Algorithms for processing sensor information into N input decisions have been developed, but refinements are needed in order to account for management, soil, and climate differences. Some of these algorithms have successfully been employed in production-scale cropping. More research is needed to understand the implications of *sufficient-N reference* placement within fields, and if spatial variability of *sufficient-N reference* has a significant impact on determining optimal N rates.

Finally, while there is clearly need for additional adaptive research to further refine sensor technologies and decision algorithms, preliminary results are encouraging and we expect NUE can be significantly enhanced using a *responsive* strategy, particularly for regions similar to the Great Plains and Corn Belt of the U.S. Nevertheless, we acknowledge there are areas where the *responsive* approach may not be appropriate, such as rain-fed areas where precipitation from the proposed time of in-season N applications to the end of the growing season is low and/or erratic. Under these circumstances, in-season N applications made to the soil surface may be unavailable for crop uptake and thus limit yields; in which case current pre-plant N applications would likely be more suitable.

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