# Chapter 15. Proven Practices and Innovative Technologies for On-Farm Crop Nitrogen Management

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# Chapter 15. Proven Practices and Innovative Technologies for On-Farm Crop Nitrogen Management

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Nitrogen (N) from soil, fertilizer, and manure sources is generally inefficiently used (30–60%) in most crop production systems. As a consequence, unused inorganic N can move off crop fields and contaminate surface and groundwater resources. Local and national governments have responded with guidelines, standards, regulations, and in some cases fines when off-field losses of N have not been reduced. Along with these environmental pressures, soaring energy costs have resulted in commensurate increased costs for N fertilizers. These factors are real for crop producers and are compelling them to scrutinize their crop N management more closely than in previous decades. Numerous time-proven practices, established by research and in crop production settings, are available that will result in improved crop N use efficiency. More emphasis should be given to these practices on farms throughout the world. Additionally, recent advances in sensor technologies are playing an increasing role in shaping the future of crop N management. We highlight some of these technologies available to help producers make better N management decisions. Both soil and crop measurements are considered and compared. Nonetheless, "on-farm" implies that producers will be at the center of implementing change, and change means N management options will motivate producers to action. Prerequisites for grower adoption require that technologies and practices be reliable, incur minimal additional expense (time and equipment), and integrate with ease into current operations. When these criteria cannot be met, external incentives (e.g., regulation or cost sharing) may be necessary.

## 1. INTRODUCTION

Modern agriculture has come to embrace the concepts of environmental stewardship as a necessary component of crop production. The stories and studies that have documented agricultural nutrients moving into and impairing ground and surface

waters and the environment in general (Vitousek, 1994; Delgado, 2002; Rabalais et al., 2002), an outcome which has in some cases been followed by stepped-up governmental regulation, have compelled producers to consider nutrient management as more than an production decision. And then recently, starting in about 2002, steep increases in worldwide energy costs, along with stagnant grain prices, have greatly altered how many farmers view N management. Today throughout much of the world, farmers are paying 2–4 times more for N fertilizer than they did 15 years ago, and yet grain prices are similar. Nitrogen will continue to be given special attention because of both environmental and economic pressures (Mosier et al., 2004).

As a nutrient, N is the main fertilizer with global environmental effects. In most agricultural settings, soil N is insufficient for healthy nonleguminous crop growth; consequently yield enhancement with N fertilizer typically ranges from 10% to 200%. The visual and subsequent yield response to historically inexpensive N fertilizer reinforces growers' reliance on it for profitable production. However, because of the inherent chemical properties of N, it plays a major role in dynamic, climate-mediated biological processes, all of which have the potential for adverse environmental outcomes. Nitrogen transformation and transport in soil and water along with plant N uptake is complex, making *efficient* management of N in the food, forage, and fiber production system difficult to achieve. Nevertheless, our hope is to do better. Developing more efficient N management systems for agriculture should be a quest pursued by producers, agribusiness, and researchers around the globe.

Crop N management – including crop need, N source, amount, placement, and timing issues – is difficult to anticipate because of spatial (within and between fields) and temporal (within and between growing seasons) variability. Because of this variability, N-management strategies have shown different levels of effectiveness in meeting crop needs while minimizing environmental losses. Seldom will a single N management plan used over multiple years result in optimal crop N use and protection against off-field N losses for each of those years. Nitrogen fertilizer use efficiency of crops varies greatly both between years and between different crops. It rarely exceeds 70% (Pierce and Rice, 1988) and more often ranges from 30% to 60% (Bock, 1984) for many crops. Globally, N fertilizer use efficiency is estimated to be closer to 30% (Raun and Johnson, 1999; Cassman et al., 2002). To improve N use efficiency, management needs to be time- and space-specific.

In essence, the N cycle is leaky (Figure 1). Losses to water and the atmosphere are part of the natural global N cycle. However, the conversion of stable atmospheric and organic N into reactive forms by energy production, fertilizer production, cultivation of legumes, plowing old grasslands, forest burning and land clearance, and the drainage of wetlands is reckoned to have doubled the amount of reactive N in the environment (Goulding et al., 1998). New reactive N when mobilized can be readily transported in solution or via the atmosphere so that local increases spread regionally and globally. The ultimate fate of this extra reactive N is uncertain. Much of it, as with much of the extra carbon dioxide, is "missing" (i.e., current measurements

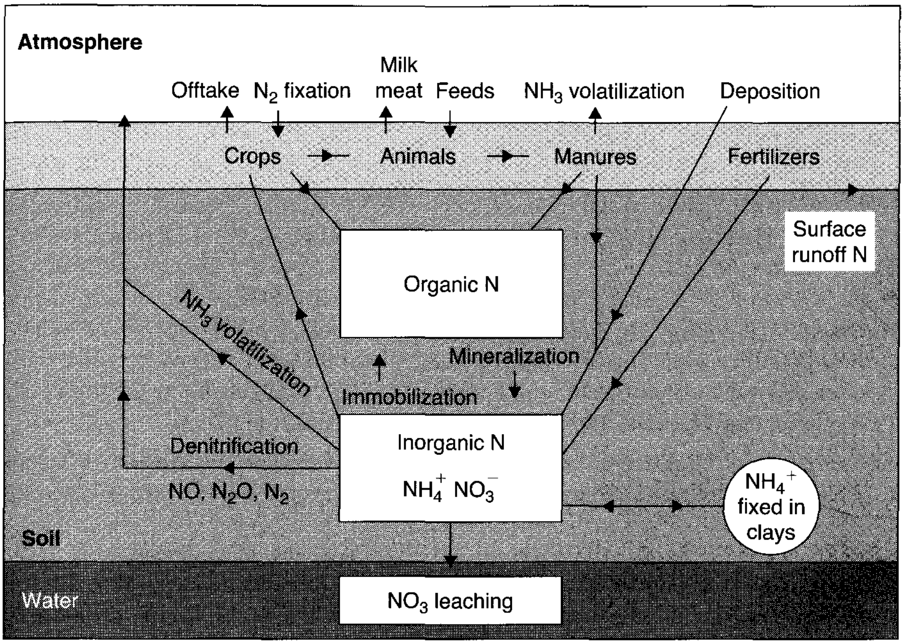


Figure 1. A simplified nitrogen cycle.

and calculations cannot account for missing N). It could be denitrified to $N_2$ or be accumulating in the atmosphere, soils, groundwater, land vegetation, oceans and marine sediments, changing ecosystems through eutrophication and acidification. The International Nitrogen Initiative addresses these problems at the broadest scale: http://www.initrogen.org/.

Given the instability of N and leakiness in the soil–plant system, many have asked, "Can we really do better?" We believe we can. Attention by producers, agribusinesses, and researchers should be heightened to develop and employ management practices proven to optimize N use efficiency. Some of the greatest improvements are likely to be found as new innovative technologies, and sensors are integrated into nutrient management plans. Of note are those technologies enabling timely and spatially accurate assessments of crop N need. Future management systems will rely upon a combination of these new technological tools along with time-proven practices that together are jointly responsive to the N dynamics in the crop–soil environment.

This chapter describes practices and technologies that have either helped producers use N more efficiently or shown promise in doing so. The phrase "nitrogen use efficiency" (NUE) is widely used in agricultural and ecological studies. However, it connotes various explicit meanings, depending on what measurements and calculations are made (Bock, 1984; Pierce and Rice, 1988). Since no standard

NUE definition is available for the myriad of practices and technologies discussed here, the phrase will be used in this chapter to mean a general concept of crop uptake and utilization of soil and fertilizer N. From a loss perspective, the primary pathways that lower NUE include nitrate leaching, denitrification, and ammonia volatilization (Cassman et al., 2002).

This chapter provides an overview of the situation primarily in Europe and North America. Those wanting more detail of the North American position can find this in Hargrove (1988), Follett et al. (1991), and Havlin and Jacobsen (1994). Those wanting to learn more about the European situation are directed to Romstad et al. (1997) or, for the United Kingdom alone, Davies (2000). For an analysis of N management under irrigated agriculture see Rauschkolb and Hornsby, 1994. The issues of fertilizers and the environment are dealt with in other chapters of this publication, as well as other recent works (Howarth, 1998; Rengel, 1998; Lægrid et al., 1999; Follett and Hatfield, 2001; Delgado, 2002; Mosier et al., 2004).

## 2. TRIED AND TRUE PRACTICES

The application of N fertilizer to agricultural crops is generally very cost-effective, that is, the fertilizer costs are far outweighed by the extra value of crop obtained. This has motivated farmers to apply abundant N to ensure high production levels. Yet, this often has created a surplus of inputs compared to outputs in grain/forage product, which leaves N at risk of loss to the environment. Figure 2 shows a graph of crop yield and quantity of N leached against each amount of N fertilizer applied. Applying more N than is needed for optimum yield greatly increases the potential for losses from the crop–soil system (Follett et al., 1991; Power et al., 2001). Farmers face pressure to move from the "Economic Optimum" to the "Environmental Optimum" (Figure 2). But at the Environmental Optimum, yields and profit as well as losses are reduced.

Nitrogen surpluses vary. Generally, the efficiency of conversion of N inputs into products for arable crops can be 60–70% or even more, but for livestock systems, 20% efficiency is good. Table 1 shows *average* N surpluses for some countries in the European Union (EU) and the United States in 1990/1991, expressed on an area basis. Those countries with the highest intensity of livestock production had the largest average surpluses, but the averages masked big differences between farms. Some farms in the EU had N surpluses of >1,000 kg/ha/year. Nitrogen surpluses in EU countries have been reducing because of environmental and economic pressures and improved technologies; Figure 3a shows some data for N and P (as $P_2O_5$) for The Netherlands as a whole, and Figure 3b shows a specific example for winter wheat in the United Kingdom in which a combination of improved yields and constant N fertilizer application has reduced the N surplus.

Factors that control N use efficiency under Northwest European conditions have been examined for the United Kingdom (Davies, 2000). The weather dominates N loss through the impact of rainfall and temperature on drainage, crop growth, and

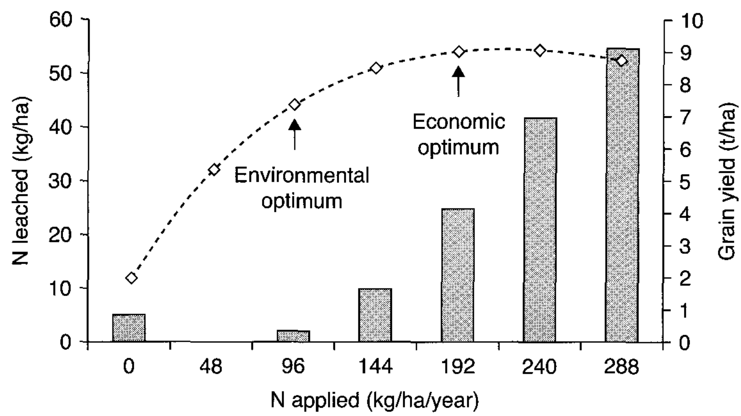


Figure 2. A nitrogen response curve and corresponding leaching losses from the 160-year-old Broadbalk Experiment at Rothamsted.

**Table 1.**
Country-wide N surpluses (annual fertilizer + manure applied − crop N removal in grain) for some EU countries and the U.S. (kg $ha^{-1}$ $yr^{-1}$) in 1990/91.

| | N Surplus |
|---|---|
| Netherlands | 321 |
| Belgium | 170 |
| Germany | 121 |
| France | 73 |
| United Kingdom | 59 |
| Portugal | 6 |
| United States | 3 |

N utilization. For livestock systems, the problem of the relative inefficiency of the animal in utilizing N is not easily overcome, and our understanding of N efficiency is far from complete. However, it is clear that better utilization of legumes and manures can have a major impact. Manipulation of diets also holds some promise.

The position is most clear for arable and horticultural systems (Goulding, 2000). A set of tested best management practices (BMPs) for optimum NUE are globally applicable, including:

- Farmers should choose the highest-yielding variety appropriate for the location to maximize the use of available N (bearing in mind quality, e.g., for milling).

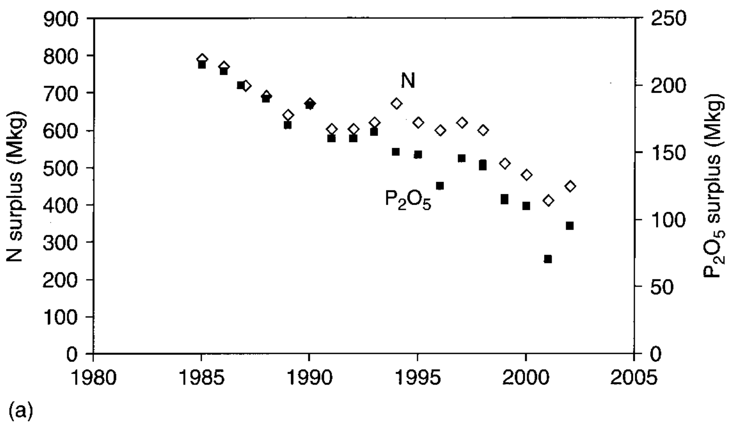


Figure 3a. Total nitrogen (N) and phosphorus (as $P_2O_5$) surpluses in the Netherlands from 1985 to 2002. In 2002 the average surpluses were 130 kg N per hectare and 28 kg $P_2O_5$ per hectare (Goulding et al., 2006).

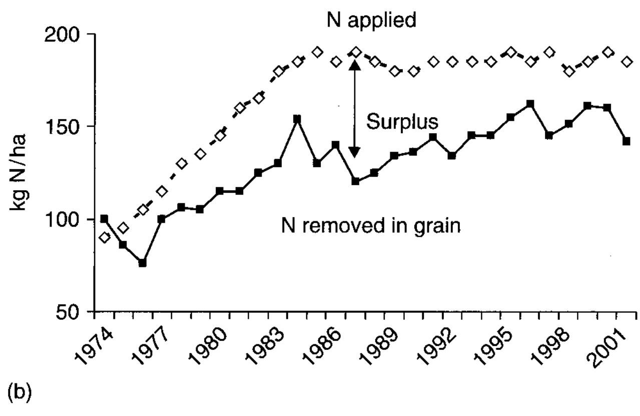


Figure 3b. The nitrogen surplus for winter wheat in England and Wales, shown as the difference between the nitrogen fertilizer applied and the nitrogen removed in harvested grain. The surplus has declined from a maximum of *c*. 75 kg $ha^{-1}$ in the late 1980s to *c*. 25–30 kg $ha^{-1}$ today (Goulding, 2000).

- Fertilizer recommendation should consider all potential N sources including soil inorganic N, potentially mineralizable N from soil organic matter (including crop residues and manures), and N in irrigation water.
- Nitrogen management strategies should start with a good understanding of precipitation patterns and variability in order to minimize N loss, but not be N deficient with the crop.

- As reasonable as possible, synchronize N applications with crop uptake. Nitrogen applications should be timed for optimal N use by the crop. Fall N should be applied only to those crops that need it or where long-term research has verified N loss from fall-applied N fertilizers is likely insignificant and improbable. Likewise, unnecessarily early spring applications should be avoided. Ideally, applications should be timed to provide N when the crop is growing rapidly.
- Splitting spring fertilizer applications may reduce leaching losses, but yield benefits should not be expected. For sandy soils, timing of N applications with crop need is crucial since leaching potential is high.
- When logistics make it impractical to synchronize fertilizer N applications with crop uptake, use of inhibitors or slow release formulations may help prevent N loss in some soil and cropping situations, but results will vary from year to year.
- For vegetable production, use of a starter and fertilizer banding can greatly increase the efficiency with which the N is used.
- For soils highly vulnerable to N leaching, a green cover should be maintained as much as practicable. Use a cover crop if necessary and drill autumn-sown crops early. A cover crop is particularly suitable following crop failure (e.g., drought) when high levels of nitrate-N remain in the soil after a growing season. However, this must be balanced against effective weed, pest, and disease control, and water storage for the following crop.
- Fertilizers and manures should be applied evenly with a properly calibrated spreader. When spreading, leave a buffer along the edges of watercourses.
- Appropriate controls to minimize pest, disease, and weed infestation are essential because a diseased crop is less able to use soil N.
- If irrigation is required, this should be done carefully, that is, only to support crop yield and using a scheduling system that accounts for precipitation.
- Irrigation systems that deliver water nonexcessively (irrigation rate $<$ infiltration rate) and evenly over the field can be used for spoon-feeding N in the irrigation water (i.e., fertigation).

These BMPs have been proven throughout the world. In the United Kingdom, limitations on total N application rates and the timing of manure applications were tested in nitrate sensitive areas (NSAs). In December 1998, enforcement was initiated in 68 nitrate vulnerable zones (NVZs) covering 600,000 ha. Results from measurements and modeling studies in NSAs showed a significant reduction (about 20%) in N usage and losses (Dampney et al., 2000). Experiments at the International Maize and Wheat Improvement Centre (CIMMYT), Mexico, showed that changing N application and irrigation schedules allowed inputs to be reduced by almost 30% (from 250 down to 180 kg/ha) and leaching losses reduced by 49–70 kg/ha, while yields were maintained (Rauschkolb and Hornsby, 1994). For horticultural crops,

research has shown that fertilizer applications to brassica rotations can be reduced by 50% without loss of yield if residual N is taken into account, and using starter or banded fertilizers on vegetable crops can reduce leaching losses by up to 75% (Rahn et al., 1993).

On a larger spatial and temporal scale, a change of rotation or type of farming system can reduce losses. Organic farming can result in smaller leaching losses over a rotation (Goulding et al., 2000), but careful management during the plowing out of the leguminous phase is required because this releases large amounts of N through mineralization. Some crops may not be able to utilize the entire amount of N released, resulting in large losses in that year. A very thorough review of N efficiency in organic agriculture was made by Kristensen (1995). Integrated crop and animal farming systems are proving to be both profitable and less polluting, but evidence suggests that the system must be tailored to the local conditions (Goulding et al., 1999).

Some other specific management practices for improving N efficiency deserve special mention. Crop yield and N use efficiency has been improved under some field conditions with nitrification (Prasad and Power, 1995) or urease (Schlegel et al., 1986) inhibitors, but results are inconsistent. Coarse textured soils appear to be best suited for inhibitor use. A review of the nitrification inhibitor DCD (Dicyandiamide) in the United States found increased rice (*Oryza sativa* L.) yield under a variety of cultural practices (Wells et al., 1989). Inhibitors have not been extensively adopted in Europe. A recent review of inhibitors (McCarty, 1999) did not even address practical issues, but only modes of action. Prasad and Power (1995) pointed out that the need for a 270–450 kg/ha increase in yield to cover the inhibitor costs had prevented many from reaching the farm. Similarly, N fertilizers formulated to be "slow release" synchronize solubility of the fertilizer prill to coincide with crop N need (Hauck, 1985). Slow release formulations have successfully been used in high-value crops and horticultural situations, but historically also cost prohibitive with grain crops. With increasing N fertilizer prices in recent years, interest in N inhibitors and slow release fertilizers has been renewed, with products being targeted for grain crop production. One such product is a polymer-coated urea, shown to increase corn yield by 0.4 and 0.7 Mg/ha over the same rates of preplant urea and solution N, respectively (Blaylock et al., 2005). Nitrate leaching and nitrous oxide emissions were also reported to be less with this slow release fertilizer.

Experiments have shown that planting a cover crop [such as rye (*Secale cereale* L.), white mustard, (*Brassica phaecelia* L.), or hairy vetch (*Vicia villosa* Roth)] between harvest and planting a late winter or spring crop is the single most effective way of retaining N, as reviewed in several chapters in Hargrove (1988). However, when the cover crop is killed its N is released back into the soil at a rate that depends on climate and management. This re-mineralized N can be effectively used by the following crop, but can also be leached in subsequent seasons (Harrison and Peel, 1996).

The introduction of buffer strips between agricultural land and water courses or bodies can help prevent the movement of nitrate, phosphate, and pesticides

into water courses at some sites (Leeds-Harrison et al., 1999). They have proved to be very effective in some circumstances (e.g., for New Zealand see Downes et al., 1997 and for the United States see Dickson and Schaeffer, 1997). However, buffer strips remove nitrate by denitrification; this increases nitrous oxide emissions – swapping one pollutant for another (Goulding et al., 1996). Such measures are, at best, short-term and are better replaced by actions that reduce off-field N losses. In other words, remediation efforts will likely always be needed, but the best solutions prevent the problem altogether.

Multiple cropping, those systems with an average of more than one crop per year, includes sequential crops, intercrops, or combinations of the two. Multiple crop systems are most effective in improving both N and water use efficiency for climatic regions where precipitation and temperature allow an effective growing season beyond the time needed for monocrop culture (Hook and Gascho, 1988). Crops and crop rotations that are designed to minimize erosion and nitrate leaching, to utilize crops capable of biological fixation of N, and to allow for timely N application (whether with fertilizer, manure, or crop residue management) will generally achieve efficient N use (Kurtz et al., 1984).

## 3. YIELD AS A DETERMINANT FOR NITROGEN FERTILIZER REQUIREMENT

For decades, a starting point for producers in determining crop N need has been to multiply a target crop yield (sometimes call "yield goal" or "expected yield") by the concentration of N in the harvested plant material. This calculation produces a number that is, in essence, an estimate of the amount of N that will be removed from the field (Stanford and Legg, 1984; Meisinger and Randall, 1991). This mass-balance approach excludes the unharvested plant material left in the field since it decomposes over time and releases N to the soil for subsequent crops. When N is not a limiting factor for crop growth, the amount of N removed from the field with harvest will, even under ideal conditions, be 30–50% less than the sum of available soil and fertilizer N (Hauck, 1973; Pierce and Rice, 1988). This lack of crop usage results from a plethora of interacting soil, climate, and management factors that either causes N loss from the crop–soil system (through processes such as denitrification, leaching, and volatilization) or change N into forms unavailable to the crop (such as immobilization).

The crop N-fertilizer requirement (NFR) (i.e., the amount of fertilizer or manure N needed so that it is not limiting for the crop, but that inorganic N is not in excess) is usually adjusted for the lack of 100% efficiency. Input recommendations typically include a crop NUE for the soil and fertilizer N of around 50–70% (Dahnke and Johnson, 1990). In the United Kingdom, fertilizer recommendations for arable crops, issued by the Department for the Environment Food and Rural Affairs, are based on measured N use efficiencies of 55–70%, varying with soil type (UK Ministry of Agriculture, Fisheries and Food – MAFF, 2000). Producers

generally want a simplified crop-specific equation for estimating the N input requirement. As an example, many corn producers in humid regions of the United States have used a rule of applying about 23 kg N for every Mg of target grain yield. Based on average corn grain N content (16.5 g $kg^{-1}$, dry weight basis), this rule assumes an N use efficiency of about 60%. When deriving a fertilizer rate from target yield, adjustments are made to account for the contribution of soil N as well as other credits, such as the N available from a preceding leguminous crop, manure, or irrigation water.

While we recognize that plant uptake from each source of N has a unique NUE (Pierce and Rice, 1988), a simplified calculation for determining the NFR as follows:

$$\mathrm{NFR} = \frac{[(\mathrm{TY})(\mathrm{CNC}) - \mathrm{SN} - \mathrm{NC}]}{\mathrm{NUE}} \tag{1}$$

where NFR = crop N fertilizer input requirement; TY = target yield (as dry matter); CNC = crop N concentration in the harvested portion of the crop; SN = soil N measured or estimated to be available for the crop; NC = N credits from other potential sources; and NUE = N use efficiency (expressed as a fraction).

### 3.1. Deriving Target Yield

In Eq. 1, target yield influences NFR more than any other term. Deriving an accurate and realistic (unbiased by false hopes and a desire to keep up with neighboring farmers) estimate of the target yield is challenging, particularly for rain-fed cropland with precipitation varying seasonally as well as annually. A number of approaches for determining target yield have been considered.

#### 3.1.1. Historical yield

Averaging yields over a number of years can be used, but this method will inevitably result in inadequate N for years when conditions provide better than average yield. A target yield 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. In dryland agriculture where nitrate-N leaching is minimal, leftover N is not considered problematic, particularly since it can be accounted for with soil sampling and credited toward subsequent crops (Hergert, 1987). In humid areas, such as eastern United States and Western Europe, leftover N has a much greater potential for loss from the crop–soil environment and thus a much less chance of being available for subsequent crops.

Target yield 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 a majority of producers overestimate their target yield when determining N recommendations (Goos and Prunty, 1990; Schepers and Mosier, 1991) because of the

historic low cost to apply ample N fertilizer to insure it will not be limiting, regardless of the type of year. Inflated target yield may also suggest 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 have known that, for a field-average 10 Mg/ha corn yield, there were areas within that same field that probably produced 12–14 Mg/ha (personal experience of authors). Nitrogen fertilization at or even only slightly higher than actual field-average levels can underestimate NFR for the most productive soils of a field and overestimate NFR for chronic poor producing soils of a field.

### 3.1.2. Yield mapping

Yield variation within fields is a major disadvantage of using a single target yield to represent the entire field. If yield variability could be predicted, it potentially would be a basis for variable application of N. Since the early 1990s, yield monitoring and mapping have offered producers a direct method for measuring spatial variations in crop yield (Lark and Stafford, 1996). Yield mapping has shown within-field variation as high as 200% or more (Kitchen et al., 1999). Producers view these maps and intuitively see an opportunity for variable-rate N applications. However, yield maps are confounded by many potential causes of yield variability (Pierce et al., 1997) as well as potential error sources from combine yield sensors (Arslan and Colvin, 2002). Using yield maps to predict crop production for N management without also relying on spatial measurement of soil/landscape properties, as well as other potential and often transient yield-limiting factors (e.g., pest incidence, other nutrients, and management variation), is almost certainly futile. Averaging multiple years of yield maps has been suggested as one way of establishing stable yield productivity patterns related to soil properties (Kitchen et al., 1995; Stafford et al., 1996; Colvin et al., 1997). However in some regions, high producing areas of a field during "dry" years can be low producing areas of the same field in "wet" years (Wibawa et al., 1993; Colvin et al., 1997; Sudduth et al., 1997). Averaging yield maps may also "neutralize" the information needed to better understand the interaction between soil/landscape properties and climate for crop production (Sawyer, 1994).

### 3.1.3. Remote sensing for yield

High-resolution remote sensing from airborne or satellite systems has also been used with varying success in quantifying within-field yield variation (Moran et al., 1997; Shanahan et al., 2001). Yield prediction accuracy is greatly improved when early to mid-season remotely sensed images are used to estimate vegetative growth, such as normalized difference vegetation index (NDVI), and then are combined with agrometerological models. Since images taken late in the growing season express the cumulative seasonal effects of soil, pest, management, and climate, these can be used to predict crop yield maps using simple regression techniques

(Moran et al., 1997). Remotely sensed data for yield mapping have advantages over on-the-go combine yield monitoring including higher resolution and with less error associated with data collection (e.g., time lags from harvest point to sensor, combine speed variation, combine vibration). While a certain amount of ongoing ground calibration may also be necessary, Pierce and Nowak (1999) have speculated that remotely sensed data for constructing yield maps may someday replace combine yield monitors.

### 3.1.4. Yield potential from soil and landscape maps and measurements

Soil types have been used as a guide for describing field yield variation. Traditional soil surveys usually report the target grain yield of major crops by soil map unit. Soil surveys in the United States have not been conducted at a scale precise enough for effective use of site-specific N management (Mausbach et al., 1993). In the United Kingdom, recommendation systems are still largely based on soil-based target yields, as explained in the *Fertilizer Recommendations* (MAFF, 2000). The procedure links an established requirement for optimum yields of a particular crop to a soil supply index based on soil type and previous cropping. However, the most progressive recommendation systems in the United Kingdom use computer models (Dampney et al., 2000) and some scientists are moving away from a yield-based system toward one based on crop canopy management (Gillett et al., 1999) (discussed more later).

Slope position and landform characteristics are topographic features that also have been used to explain crop productivity (Hanna et al., 1982; Gantzer and McCarty, 1987; Jones et al., 1989; McConkey et al., 1997; McGee et al., 1997; Timlin et al., 1998; Kitchen et al., 2003). Generally, footslope positions out-yield upslope positions unless poor drainage causes ponding. Real-Time Kinematic (RTK) GPS receivers have made possible the automated collection of highly accurate elevation data, thus providing an efficient way of obtaining high-resolution digital elevation models (DEM) of agricultural fields (Clark and Lee, 1998). Field topography plays an important role in the hydrological response of rainfall catchment and has a major impact on water availability to crop production. The increasing availability of DEMs and the advent of computerized terrain analysis tools have made it possible to quantify the topographic attributes of a landscape (Weibel and Heller, 1991).

Soil productivity indices have also been developed using specific soil properties to characterize the suitability of the root zone for crop growth (Pierce et al., 1983; Scrivner et al., 1985). However, the measurements that are required to calculate soil productivity indices on individual fields are expensive, time consuming, and require follow-up laboratory analysis.

Rapid spatial measurement of soil profile apparent soil electrical conductivity ($EC_a$) has potential for predicting variation in crop production potential as caused by soil differences (Jaynes et al., 1993; Kitchen et al., 1999, 2003, 2005; Lund et al., 1999). For example, soil $EC_a$ has been used to estimate topsoil thickness (i.e., depth to first Bt horizon) on claypan soils (Doolittle et al., 1994; Kitchen et al., 1999).

For these soils, crop yield is depressed with decreasing topsoil thickness for average and below-average precipitation years (Thompson et al., 1991). Predicting target corn yields from $EC_a$-predicted topsoil thickness is illustrated in Figure 4. The top map displays actual soil $EC_a$ values obtained for a 14-ha field. On the same day that $EC_a$ measurements were taken, points selected to span the field's range of $EC_a$ values were soil sampled with a soil probe to determine topsoil thickness. A regression equation relating $EC_a$ to topsoil thickness was obtained for the calibration dataset ($R^2 = 0.84$). The bottom map is the resultant target yield derived from $EC_a$-estimated topsoil depth, and from which a variable-rate N application was conducted. Variable-rate N application compared to adjacent strips of conventional single-rate N treatments (one-yield goal) was equal in corn yield where topsoil thickness was <38 cm, but variable-rate N produced about 0.5 Mg/ha more where topsoil thickness areas were >38 cm.

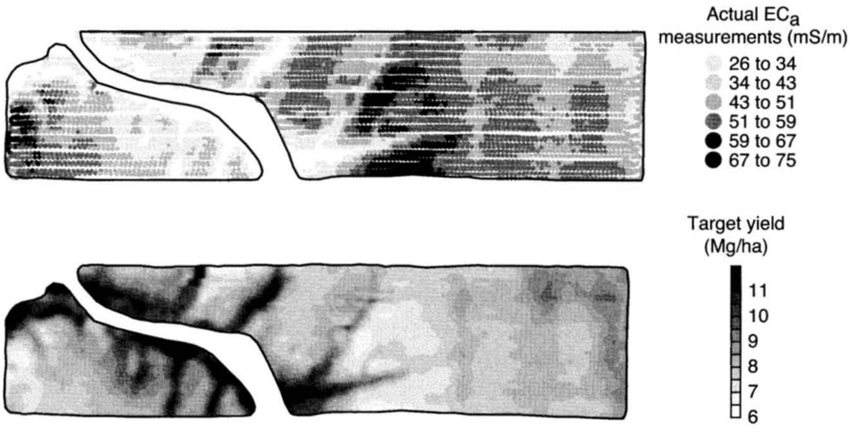


Figure 4. Soil $EC_a$ measurements on 1 s intervals along 5 m transects for a 14 ha claypan soil field in Missouri (top); and corn target yield derived from soil $EC_a$ (bottom).

### 3.1.5. Mounting evidence for not using yield

While expected yield as a basis for N recommendations is based on sound mass-balance principles, growing evidence indicates it is an unreliable way to estimate NFR for many environments (Bundy, 2000; Lory and Scharf, 2003; Mulvaney et al., 2005). Averaged over large areas, target yield tends to correlate with NFR, but at the scale of individual fields or even within fields, yield may not be a very good predictor of NFR at all (Vanotti and Bundy, 1994b). Also of concern are the too high or too low calculated N recommendations when yields are much higher or

lower than average (Nafziger et al., 2004). For these reasons, some recommendations have shifted to approaches that do not use yield goal but instead utilize soil-specific N recommendations based on soil productivity classification (Vanotti and Bundy, 1994a) or set ranges for specific rotations (Blackmer et al., 1997). This shift and diversity in recommendation approaches across the Corn Belt in the United States of America has raised questions about the reliability of using yield in the N rate recommendation.

## 4. SOIL NITROGEN ASSESSMENT

Soil contribution of N for crops varies across the globe. For example, farm sites under rice production in Asia were contrasted with maize fields in North-Central United States and shown to annually have 50–140kg/ha less N come from the soil (Cassman et al., 2002). Likewise, soil N available for crop uptake and growth within the same field will fluctuate within and between growing seasons because of climatic and landscape factors (including soil moisture, organic matter quality, temperature, pH, and oxygen). Yet, to optimize N inputs producers need accurate and cost-effective tools for directly or indirectly estimating soil N available for crop growth.

### 4.1. Potential Mineralizable Nitrogen

Nitrogen availability tests employing biological assays, where net mineralization is measured after incubation under controlled soil moisture and temperature, have been explained extensively earlier (Stanford and Smith, 1972; Stanford and Epstein, 1974; Keeney, 1982; Stanford, 1982; Meisinger, 1984; Campbell et al., 1994). Since N mineralization in the field is largely controlled by unpredictable factors, such as temperature and soil moisture, correlation with incubation tests can be inconsistent (Fox and Piekielek, 1984).

Procedures for *in situ* measurement of N mineralization, such as enclosing a soil sample in a buried polyethylene bag or tube for incubation under ambient conditions, have been shown to correlate well with season-long mineralization (Eno, 1960; Poovarodom et al., 1998). The advantages of these methods include the prevention of nitrate leaching and the control of N mineralization rates at field temperatures. Various methods of chemically or physically extracting that fraction of soil organic matter which will most easily decompose and make N available (Keeney, 1982; Christensen, 1992) are less time consuming than incubation tests. These procedures also vary in their agreement to field measurements of N mineralization because of year-to-year climatic variation (Fox and Piekielek, 1984; Gelderman et al., 1988). In recent years, development of a technique for determination of amino sugar N in soil hydrolysates (Mulvaney et al., 2001) has shown promise for identifying Illinois soils responsive to corn N fertilization (Mulvaney et al., 2005), but evidence is lacking for universal use. While biological and chemical extraction tests are routinely used in research, their application for on-farm decisions has seen limited use.

### 4.2. Inorganic Nitrogen

Inorganic N soil tests – referred to as soil mineral N (SMN) measurements in Europe and parts of North America – assess soil nitrate-N and sometimes ammonium-N from soil samples, either taken in the fall (for arid and colder regions) or just before planting or early in the growing season (for humid and warmer regions), and have been widely used for N fertilization decisions (Magdoff et al., 1984; Blackmer et al., 1989; Fox et al., 1989; Magdoff, 1991; Andraski and Bundy, 2002). In Europe samples for SMN are generally sampled in spring for modifying N recommendations. The UK recommendations (MAFF, 2000) advise farmers to measure SMN rather than use tables of soil N supply, especially in fields where manures have been applied regularly or large crop residues remained.

Soil sampling depth for these tests varies from 30 to 90 cm; sample depth guidelines depend upon a variety of factors, including crop, climate, soil type (Dahnke and Johnson, 1990), and producers' willingness to obtain subsoil samples. Under arid conditions, inorganic N soil tests are used to determine the mass of available N and could be used as the SN parameter in Eq. 1 (Westfall, 1984; Peterson and Voss, 1984). Elsewhere inorganic tests are more often used as indicators of soil N sufficiency. In this way, the test is calibrated with N fertilizer response and used directly for making N recommendations, as opposed to the mass-balance approach of Eq. 1. Tests of soil N sufficiency include the preplant soil nitrate test (PPNT) and the presidedress soil nitrate test (PSNT). Variations of these two tests are used in humid and semi-humid regions of North America and Europe. Calibrations with the PSNT found that nitrate-N levels >20 to 25 mg N/kg typically show little or no response to the application of additional N fertilizer (Blackmer et al., 1989; Fox et al., 1989; Meisinger et al., 1992; Andraski and Bundy, 2002).

The PPNT and PSNT have been simultaneously evaluated under various management practices at more than 300 sites in ten US Corn Belt states (Bundy et al., 1999). They concluded that a more practical way of assessing the economic and environmental consequences of management decisions made with these two tests was based on the *rate of failure* by the tests to predict non-N-responsiveness (Table 2). Two types of failure were identified. Type A failure resulted when the soil test predicted a non-N-responsive site, but the site actually responded to N fertilization (an economic loss due to lost yield). Type B failure resulted when the soil test predicted a N-responsive site, but the site did not respond to N fertilization (both an economic loss from applying unneeded N and increased risk for environmental loss due to excess N). Incidence of Type B failure occurred more frequently than Type A failure, but was much less with latter soil sampling (PSNT) and deeper soil sampling (0–60 cm sampling depth). Sampling later and deeper was also especially important in corn cropping systems that included manuring and/or a preceding alfalfa crop.

Since the spatial variation of inorganic N can be high (Cahn et al., 1994; Cambardella et al., 1994; Selles et al., 1999), producers are encouraged to composite a minimum of 15–20 cores. For fields with obvious landform variation, subdivision following soil and landscape patterns will likely improve accuracy in predicting

**Table 2.**
Critical soil nitrate-N levels and percent of sites where soil tests failed to predict N response, derived from linear response plateau models using all observations.

| Previous crop or cropping system | Time of soil sampling | Soil depth | N | Critical soil nitrate-N level (ppm) | Failed soil test[a] | |
|---|---|---|---|---|---|---|
| | | | | | Type A (% of sites) | Type B (% of sites) |
| All observations | PPNT | 0 | 292 | 15.7 | 1 | 35.3 |
| | | 0–60 | 292 | 9.3 | 6.8 | 22.6 |
| | PSNT | 0 | 301 | 16.9 | 2.3 | 25.2 |
| | | 0–60 | 239 | 12 | 4.6 | 18 |
| Corn (without manure in study year) | PPNT | 0 | 127 | 19.2 | 1.6 | 26.8 |
| | | 0–60 | 126 | 16.1 | 11.1 | 14.3 |
| | PSNT | 0 | 125 | 18.9 | 3.2 | 21.6 |
| | | 0–60 | 115 | 14.2 | 3.5 | 11.3 |
| Corn (with manure in study year) | PPNT | 0 | 28 | 11 | 3.6 | 42.9 |
| | | 0–60 | 28 | 12.2 | 3.6 | 14.3 |
| | PSNT | 0 | 29 | 16.6 | 3.5 | 24.1 |
| | | 0–60 | 24 | 22.4 | 8.3 | 16.7 |
| Alfalfa | PPNT | 0 | 27 | na | 0 | 92.6 |
| | | 0–60 | 27 | na | 0 | 77.8 |
| | PSNT | 0 | 28 | na | 0 | 39.3 |
| | | 0–60 | 26 | na | 0 | 38.4 |

Adapted from Bundy et al. (1999).

[a]Type A failure = soil test predicted non-N-responsive, but was responsive Type B failure = soil test predicted N-responsive, but was not responsive.

crop NFR and N use efficiency (Dahnke and Johnson, 1990; James and Wells, 1990; Franzen et al., 1999b; Walters and Goesch, 1999).

The successful use of inorganic N soil tests has not been universal. Some soils are too stony to make sampling practicable. Following a crop such as potato that is expected to supply significant N to the next crop, the spatial variability of soil test N may not be as important to predicting N supplying capacity of the soil as the spatial

variability of potentially mineralizable N remaining in roots and plant residues (Franzen et al., 1999a). Calibration efforts under similar soil, climate, and cropping systems help establish the conditions under which the tests are most successful (Bundy et al., 1999). In some situations, grower adoption of SMN tests is enhanced by governmental policy. As an example, in central Nebraska, groundwater nitrate contamination in the Platte River aquifer has resulted in the Central Platte Natural Resources District requiring soil nitrate sampling on corn production fields. Use of the soil test has helped producers identify those fields high in residual soil N contributing to groundwater contamination and adjust N inputs accordingly (Schepers et al., 1997). Adoption of N soil tests has been high for crops such as sugar beets where close scrutiny is needed to maintain crop quality (Ulrich et al., 1993).

### 4.3. Spatial Variability of Soil Nitrogen

As previously noted, soil N availability is often highly variable within fields. Schepers and Meisinger (1994) succinctly captured the reason for this variability:

> Nitrogen mineralization is a complex process that involves a vast collection of microorganisms (bacteria, fungi, and actinomyces) acting on a wide array of substrates (crop residues, soil humus, dead microbial tissue, and manure) under varying soil environments (temperature, water content, and aeration) to produce a remarkably simple product (nitrate-N) that can be used by plants, lost to the atmosphere as N gases, immobilized, accumulated in soil, or leached from the soil-crop system.

Little doubt is left as to why soil N – in both its organic and inorganic forms – is spatially variable as we consider that each condition and process mentioned varies within fields. From such dynamic processes the NFR within fields has been shown to be quite variable within fields and difficult to predict (Malzer et al., 1996; Moore and Tyndale-Briscoe, 1999; Mamo et al., 2003; Scharf et al., 2005).

With inexpensive tools (such as GPS) available to make the spatial soil and plant measurements and from maps created, interest in quantifying patterns of within-field availability of soil N has been spurred (Pierce and Nowak, 1999; Raun and Johnson, 1999). Variable-rate N application maps derived from root-zone nitrate-N grid soil samples on a field considered uniform resulted in a 60% increase in area correctly fertilized over fields of fixed-rate applications (Ferguson et al., 1996). Yet, mapping soil N variability has not proven successful everywhere. In humid environments, sampling of the PSNT in concert with yield mapping was tested and found to be insufficient information for variable-rate N management (Katsvairo et al., 2003). For fields with areas of high leaching potential, profile nitrate-N can be highly variable within short-scale (e.g., $<5$ m) spatial structure, rendering spatial soil sampling for N-management decisions ineffective (Everett and Pierce, 1996). Under some conditions soil sampling intensity can be reduced and still provide accurate N availability maps with "targeted" soil sampling, meaning like soil areas are grouped into zones

and sampled and analyzed independently. Success with target sampling has been achieved using aerial image/spectral reflectance data (Diker and Bausch, 1999; Franzen et al., 1999a) and soil $EC_a$ (Franzen and Kitchen, 1999) to derive sampling zones.

While the soil sampling density required for accurate N-application maps varies from field to field, time and expense constraints limit use of spatially dense sampling for N in most crop production systems (Ferguson et al., 1996). Exceptions are with those high-value crops such as potatoes and sugar beets where profit margins permit the additional expense. Alternatively, new technologies and tools may allow for on-the-go *in situ* measurement of soil N. For example, near-infrared (NIR) soil sensing has been effectively used in predicting inorganic N content as long as a calibration set included the same interfering soil constituents as the unknown samples (Ehsani et al., 1999). Further development is needed in sensors that can rapidly measure soil properties associated with estimating soil N.

## 5. PLANT NITROGEN MEASUREMENTS

Plant measurements for determining crop N status are generally a sufficiency–deficiency strategy, not a mass-balance strategy as shown in Eq. 1. Plant measurements serve as indicators for within-season N additions, or if measured at crop maturity to diagnose whether or not conditions provided deficient, sufficient, or excessive N for the crop. Since plants integrate soil, climate, management, and other environmental influences on crop N health, they provide an opportunity for improving NUE over relying only on yield prediction and preplant or early season soil N measurements. However, issues related to plant N measurements need to be considered before including these tools in the N-management plan, including (1) uncertainty of determining full-season N status and fertilizer needs from young crop plants, when an opportunity for N addition still exists; (2) a reported wide range in sufficiency critical values; (3) varying sufficiency critical values as the crop matures; (4) varying critical values from various plant parts (e.g., leaves versus stems); and (5) the need for maintaining a N-sufficiency block or strip for reference that adequately represents N needs of the remaining field (Schröder et al., 2000).

Plant tissue sampling for N-management decisions has previously been extensively reviewed (Westerman, 1990; Bennett, 1993; Barraclough, 1997) and will not be detailed here. Generally, tissue N tests are highly variable and unstable indicators for within-season N decisions (Schröder et al., 2000). Exceptions exist on a crop-by-crop and region-by-region basis, particularly when a specific plant sampling procedure can be identified. Successful examples include petiole sampling for potatoes (Westermann and Kleinkopf, 1985; Williams and Maier, 1990a, b) and sugar beets (Ulrich et al., 1993), wheat tissue sampling combined with tiller density measurements (Scharf and Alley, 1993), end of growing season corn stalk nitrate test (Binford et al., 1990 and as reviewed by Schröder et al., 2000), preharvest plant tissue and postharvest grain N for spring wheat (Peltonen, 1992), and stem testing for linola (Hocking, 1995).

### 5.1. Leaf and Canopy Greenness

Since N is a primary constituent of plant chlorophyll pigments, leaf or crop canopy greenness can be used to evaluate crop N health for within-season N-input decisions. An obvious advantage of using plant greenness is that there is little time delay between measurement and interpretation, such as that occurs in soil sampling and analysis. Further, since each plant expresses crop N status for its given location, greenness sensing provides the best opportunity for quantifying detailed spatial variability of crop N needs. The human eye is one of the best sensors for detecting greenness variations and has been the basis for N recommendations using color charts (Shukla et al., 2004) or in-field N-rate calibration stamps (Raun et al., 2005).

### 5.2. Chlorophyll Meter Sensing

A hand-held chlorophyll meter (Minolta SPAD-502) measures leaf transmittance centered at red (650) and NIR (940 nm) wavelengths and has been shown to be sensitive to N stress in corn (*Zea mays* L.) (Dwyer et al., 1991; Schepers et al., 1992; Wood et al., 1992; Piekielek et al., 1995), wheat (*Triticum aesitivum* L.) (Follett et al., 1992; Fox et al., 1994), rice (*Oryza sativa* L.) (Turner and Jund, 1991), and tall fescue (Kantety et al., 1996). The meter has been shown to be an effective tool in identifying and correcting N deficiencies as well as improving NUE for both irrigated corn (Blackmer and Schepers, 1995; Varvel et al., 1997) and rice (Cassman, et al., 1998); but under rain-fed conditions the meter may not always be useful (Bullock and Anderson, 1998). Corn growth stage, variety (Sunderman et al., 1997; Varvel et al., 1997; Bullock and Anderson, 1998), and water stress (Schepers et al., 1996) are factors that will influence chlorophyll readings. To minimize the impact of these non-N effects on chlorophyll meter readings, a normalized measurement (referred to as a N-sufficiency index) can be calculated by dividing the readings from N-deficient plants by readings from N-sufficient plants (Piekielek et al., 1995; Varvel et al., 1997). To operate, the SPAD-502 is clamped onto a single leaf to prevent interference from external light. The meter is limited to sensing transmittance through a very small area of leaf (about 6 $mm^2$) with each reading. The practical use of the meter for N management appears to vary between corn and rice production systems, with greater on-farm adoption of this technology in rice than corn systems (Cassman et al., 2002). This is likely due to differences in field size on typical corn versus rice farms, with average cornfields being considerably larger than typical rice paddocks. While individual readings can be rapidly obtained in smaller rice paddocks, acquiring a representative value for large cornfields is time consuming and for fields with significant spatial variability in soil N it is difficult to obtain representative measurements (Schepers et al., 1995). For this reason, chlorophyll meter sensing to assess production scale crop N health is not practical for most producers. The SPAD-502 will continue to aid N research primarily as a diagnostic tool, but has limited use in N-management decisions for large-scale production agriculture.

### 5.3. Spectral Reflectance Sensing

Measurement of crop canopy reflectance, either from ground-based or airborne platforms using image and photographic cameras, can provide a valuable measure of potential N status of the crop. Plant transformation of light energy to chemical energy (photophosphorylation) is most efficiently accomplished in chloroplasts by absorbing red (630–680 nm) and blue (450–520 nm) wavelength light. Green light (520–600 nm) is absorbed much less by plants, producing higher reflectance in this wavelength range. Hence sensing reflectance at these three wavelengths (RGB light) provides a measure of leaf chlorophyll content.

By definition, crop reflectance is the ratio of the amount of light leaving the canopy to the amount of incoming light. Digital reflectance sensors (spectral radiometers) and photographic images are commonly calibrated against a standardized reference panel to assess the amount of incoming light. This is needed because radiometers vary in wavelength discrimination and light intensity sensitivity. Film types also vary in sensitivity to different light. Reflectance can also be successfully calculated for crop N status by obtaining a relative reference by comparing reflectance leaving the crop canopy of an area known to be nonlimiting in N to reflectance from the test area. This relative reflectance approach has been accomplished with both spectral radiometer measurements (Chappelle et al., 1992; Blackmer et al., 1996; Shanahan et al., 2003) and photography (Blackmer et al., 1996; Flowers et al., 2001; Scharf and Lory, 2002). Image interpretation is merely qualitative unless referenced with standardized panels under the same light conditions, or nonlimiting N reference is obtained. Reflectance measurements are affected by many environmental factors other than N such as canopy architecture (Jackson and Pinter, 1986) and hybrid (Blackmer et al., 1996). Referencing reflectance to a nonlimiting N area within the same field can account for many of these factors (Blackmer et al., 1996). Also for ground-based reflectance sensing of corn prior to tasseling, a 75° view angle allowed for more plant and less soil reflectance and was more accurate in predicting plant N than reflectance measurements taken from a nadir view (Bausch et al., 1996).

Green and red light reflectance alone can be a strong indicator of plant N content (Blackmer et al., 1994, 1996). From digitized film images RGB wavelength can be separated and intensity counted (0–255) for analysis with crop N (Blackmer et al., 1996; Flowers et al., 2001, 2003). Brightness of red light was shown to be a better indicator of corn N deficiency than chlorophyll meter readings (Blackmer and Schepers, 1996).

Inclusion of other reflectance information related to plant biomass has often been shown to be a better index for assessing crop N health and making management decisions than just using RGB reflectance. Plants absorb much less NIR light (700–1,400 nm) than does soil. This difference in absorption between soil and plants provides a contrast that has been the basis for numerous biomass or vegetative indices (e.g., NDVI) as reviewed (Myneni et al., 1995; Moran et al., 1997; Pinter et al., 2003). Calculations combining visible light reflectance (a measure of the plant's photosynthetic health) with NIR reflectance (a measure of the plant's structure and

capacity to assimilate carbon) have been successfully used in evaluating crop N health and making N fertilizer additions. Stone et al. (1996) were able to reduce N fertilizer input and increase NUE for wheat by variably applying N using a plant N spectral index derived from red and NIR reflectance values. Transformation of reflectance into a biomass indicator (such as NDVI) puts the information into potential yield terms and allows for N requirements to be calculated on a mass-balance basis (Raun et al., 2002; Mullen et al., 2003). Corn canopy NIR and green reflectance were used to develop a N-reflectance index that was strongly correlated to chlorophyll meter readings (Shanahan et al., 2003), plant N content (Bausch et al., 1996) and within-season soil N (Diker and Bausch, 1999).

To remove the varying effects of sunlight (e.g., sun angle and cloudiness) on reflectance measuring, an active type of reflectance sensor system has been employed that emits its own source of modulated light onto the crop canopy at user determined wavelengths using light emitting diodes (LEDs) and then detects with photodiodes canopy reflectance at those same wavelengths (Stone et al., 1996). These sensors provide both visible and an NIR wavelength reflectance assessment and vegetative indices are calculated (e.g., NDVI). Measurements taken with these active light sensors are highly correlated with chlorophyll meter SPAD measurements (Figure 5). Like described with other sensing methods, crop reflectance readings from an area adequately fertilized with N is used as a reference to compare unfertilized areas to, in order to generate an in-season N fertilizer rate recommendation. Operationally, these sensors can be mounted (~0.6 m above canopy) on N-fertilizer applicators equipped with computer processing and variable-rate controllers so that sensing and fertilization are done in one pass. Research results using this type of sensor suggest that the sensor system is capable of detecting variations in chlorophyll content and could potentially be used in controlling an in-season N applicator. Algorithms for N recommendations for wheat have been identified (Raun et al., 2002), with ongoing studies being conducted in the United States and elsewhere assessing this technology for corn, cotton, rice, and other crops (see http://www.soiltesting.okstate.edu/SBNRC/SBNRC.php).

Aerial images of crop fields are also appealing to producers because it is low cost, has quick turn around, provides whole-field information that is spatially accurate, and can be used as a diagnostic tool for assessing many different types of crop stress. They give producers an immediate visual assessment of conditions. With well-known field landmarks also visible on an image (such as field boundaries, trees, or structures), producers are quickly able to estimate the extent of the crop stress as well as associate stress areas with soil and landform features. However to date, photographic images have mainly provided qualitative assessment of those fields that are N deficient (Blackmer and White, 1996). Verification of crop N deficiency has been needed since other environmental stresses can produce a similar reflectance signature. An exception has been where NIR photographs taken during early spring accurately estimated soft red winter wheat tiller density and aided in correct N-fertilizer recommendations (Flowers et al., 2001).

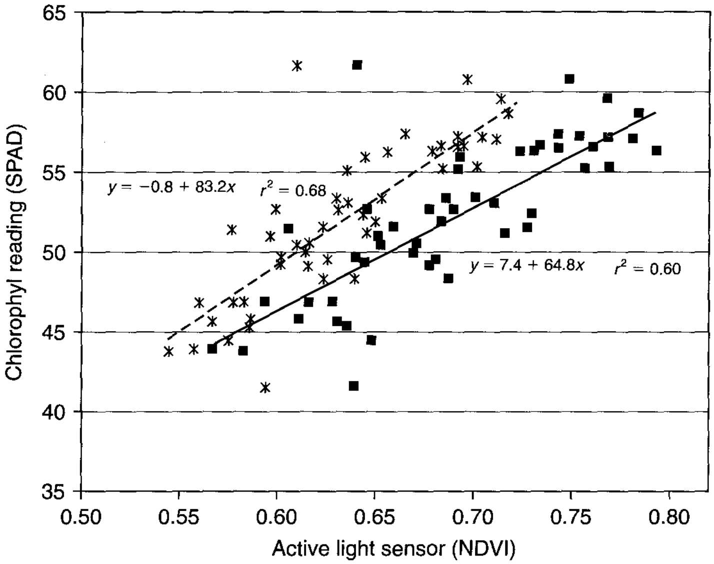


Figure 5. Two types of active light sensors correlate well with SPAD chlorophyll meter readings for corn at the V10 growth stage (N.R. Kitchen).

## 6. NUTRIENT BUDGETS

Nutrient budgets have been compiled around the world, using a variety of scales and methodological approaches (Meisinger and Randall, 1991; Watson and Atkinson, 1999). Nutrient budgeting is an extension of the mass-balance approach as shown in Eq. 1. They measure or estimate the inputs and outputs of nutrients (usually N, P, and K) to a field, farm, or system, usually at the farm gate. Nutrient budgeting may operate on daily, monthly, or annual time frames. More frequent tracking requires more user input, but also provides the greatest opportunity for synchronizing nutrient inputs with crop needs. Farm gate budgets usually include inputs in feed, fertilizers, manures, composts, and bedding and outputs in saleable produce. They do not usually include the necessarily very detailed measurements of losses such as leaching, denitrification, and ammonia volatilization, consider each field separately, or measure transfers between fields. Nor do they provide information on soil processes or biological inputs and outputs of nutrients, which are particularly important for N. By their nature they cannot improve N use efficiency but only highlight problems and raise awareness of the need for better techniques. For many producers and agronomists, however, raising awareness is an essential first step. In the United Kingdom, a standard nutrient budget system has been developed

for use within the computerized version of its Fertiliser Recommendations (MAFF, 2000) called PLANET (see http://www.planet4farmers.co.uk/welcome/index.html). The budget includes benchmarks for N, P, and K for all major farm types, based on the measured budgets from >170 farms.

To counter their large N surpluses (see Table 1) the Netherlands have introduced a compulsory nutrient budgeting policy, Mineral Accounting System (MINAS). This required nutrient budgets to be made on all farms with >2.5 livestock units per hectare and set allowed surpluses (Table 3). If these values were exceeded, farmers

**Table 3.**
Allowed N surpluses in the Netherlands, MINAS Nutrient Budgeting Scheme (kg N/ha/year).

| Year | Arable | Grassland |
|---|---|---|
| 1998 | 175 | 300 |
| 1999 | 175 | 300 |
| 2000 | 150 | 275 |
| 2002 | (125) | (250) |
| 2005 | (110) | (200) |
| 2008 | (100) | (180) |

Figures in parentheses were not agreed upon when the scheme began.

were taxed about 75c (£0.5 or €1) for each kilogram N above the limit. However, it should be noted that farmers did not have to include atmospheric deposition or fixation by legumes in their calculations of inputs, and some ammonia losses are allowable. Despite these relatively generous regulations, Dutch farmers were not happy with the arrangements and had great difficulty meeting the requirements. MINAS has not delivered the environmental improvements required and so is being replaced by limits on inputs: a maximum of 170 kg N/ha can be applied as manure (but with a derogation to 250 kg/ha on farms with >70% grass) and a target of zero P surpluses by 2050 (Goulding et al., 2006).

## 7. CONSIDERATIONS FOR DEVELOPING NEW ON-FARM TECHNOLOGIES

Some of the diagnostic tools for assessing crop N needs discussed here have been available to producers for several decades. Researchers and extension agronomists have advocated the adoption of such tools, but with limited success. For example, in 1999 knowledgeable representatives from the United States were asked what

percentage of their state's corn acreage was tested annually using the preplant nitrate test (PPNT), PSNT, early-season chlorophyll meter sensing, and stalk nitrate testing. These diagnostic tests were designed to help producers make better N-management decisions. A summary of their responses (Table 4) indicates that adoption has been generally low, but high where adaptive into specific cropping systems. In the humid regions of the northeastern United States, the PPNT test has been put

**Table 4.**
From a survey about corn grain grown in the US, what percentage of the acreage in 1999 used these soil and plant diagnostic tools for N management? (Numbers represent the upper limit when a range was given).

| Diagnostic test | New England/ Mid-Atlantic region (11 states) representing 4.2 M acres (% of acres) | North Central region (13 states[a]) representing 61.2 M acres (% of acres) |
|---|---|---|
| Pre-plant soil nitrate test | 13.3 | 1.8 |
| Pre-sidedress soil nitrate test | 0 | 14.0* |
| Early-season chlorophyll meter | 0 | <1 |
| Stalk nitrate test | <1 | <1 |

[a]Includes one Canadian providence.
*Primarily from states with a majority of irrigated acreage (e.g., Kansas, Nebraska).

into practice on about 13% of that region's corn acreage, but this area represents a very small percentage of corn grown nationally. The PSNT has also seen significant use in the north-central region, predominantly on irrigated acres in the western portion of the region (reaching a high of about 30–40% of irrigated corn acreage in Nebraska). Many may find this level of adoption discouraging until they reflect upon the nature of N in a biologically complex agricultural production system. One test, one technology, or one practice should not be the goal. Instead the goal should be a myriad of options from which N management can be tailored. A review of the potential use of precision agriculture technologies in Northern Europe (Sylvester-Bradley et al., 1999) concluded that they were most likely to be adopted where prior knowledge identified large heterogeneity and predicted treatment zones, but that the main obstacle was the lack of appropriate sensors.

In decades past, timing of N fertilization has largely been a function of convenience, that is, N was applied when it was least interfering with other operations.

This "convenience perspective" was shaped by the relative low cost of N fertilizer and ignorance to environmental consequences of fertilizer N moving off fields into ground and surface waters and as greenhouse gases. These shaping factors are now disappearing and emerging is the compelling principle to time or synchronize N inputs when crops utilize N (Raun and Johnson, 1999; Cassman et al., 2002). Synchronizing N inputs is one of the best opportunities for improving NUE, particularly in areas of the world where farming is done on large fields (Cassman et al., 2002). Normally in areas of the world where fields are small, inputs are less mechanized and in many cases the practice to synchronize N is already a part of the culture.

"On farm" implies that producers will be at the center of implementing changes; but "change" also means there will be attractive new choices available to motivate producers. Many N-management technologies and practices, though soundly developed and tested, have been left on the shelf by producers. Prerequisites for grower adoption requires that new and innovative practices be reliable, incur minimal additional expense (time and equipment), and integrate with ease into current operations. When these cannot be met, external incentives (e.g., regulation, private or government cost-sharing programs) may be needed.

## 8. CONCLUSIONS

Modern agriculture is increasing in complexity as demands for more food, feed, and fiber, at higher quality, while concurrently safe-guarding the environment are requested by the consumer. The economics of food, feed, and fiber production are now embracing the costs of environmental impact. Fine-tuned N management that minimizes off-field losses remains a challenge for farmers and agronomists. Tried and tested old practices as well as new technologies offer ways of increasing NUE, sometimes by significant amounts. Tools that indicate N in excess of crop needs for the year in question may have little economic appeal to producers, because of N costs, but these same tools used under these conditions will grant the greatest environmental benefit. Opportunity for improvement largely lies with technologies that enable timely, quick, and accurate measurement of the spatial variability of crop yield potential, soil N availability, and within-season indication of crop N health. Soil N excess and deficiency can exist on the same field. "Thus, it is the variability in space and time of the processes that regulate the availability of N to plants and the fate of N in soil that make precision N management attractive" (Pierce and Nowak, 1999). Ground or airborne sensing is being aggressively tried. In most cases, the decision rules for transforming images into N-management decisions are not well developed or validated yet, but limitations of remotely sensed data are likely to be remedied soon. We predict within a few decades reflectance sensing will be commonly used in crop N management in the United States and European countries.

Environmentally, some of the biggest problems of poor NUE are associated with poor utilization of animal manures, and here progress has been slow. Nutrient

heterogeneity within stockpiled manures along with transport logistics are issues that magnify in significance as animal confinement operations become larger and more concentrated. Whenever animal feeding is a component of an agriculture production operation, we strongly encourage whole-farm nutrient budgeting and planning.

One final point, a focus just on increasing NUE can lead to, in some situations, other environmental problems. For example, early sowing to obtain effective crop cover and an increase in N uptake and reduction in N losses can promote the risk of pest and disease carry-over and pesticide use. The overriding need is for technologies that embrace all aspects of farm efficiency to ensure long-term improvements.

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