Fertilizer Research **42**: 89–97, 1995.

Rational nitrogen fertilization in intensive cropping systems

Charles W. Rice[1], John L. Havlin[1] & James S. Schepers[2]
[1]*Department of Agronomy, Kansas State University, Manhattan, KS 66506-5501, USA and* [2]*USDA-ARS, University of Nebraska-Lincoln, Lincoln, NE 68583-0915, USA*

Key words: N mineralization, N use efficiency

Abstract

The objective of a rational N fertilization program is to account for the sources and fate of N while estimating crop N needs. Efficiency of N use will vary with cropping systems and N sources. Management technologies that affect N use efficiency include the amount of N applied, timing and placement of N fertilizer, and use of inhibitors. One of the main problems in making a fertilizer N recommendation is to account for the contribution of N mineralization to plant available N. Most laboratory procedures do not account for the environmental factors that affect N mineralization and only estimate the size of the mineralizable N pool. However, changes in soil moisture and temperature can dramatically affect the amount and rate of release of mineralized N. Field and modeling techniques are two possible techniques to estimate N mineralization. Field techniques can be divided into soil and plant approaches. Soil incubations in the field provide a quantitative approach while soil nitrate tests during the growing season provide a qualitative approach to estimating N mineralization. The plant is the ultimate integrator of N mineralization. Plant N uptake by an unfertilized crop can provide a quantitative approach with certain precautions. This approach may be costly, labor intensive, and site specific. Crop N uptake during the growing season can be estimated by measuring the tissue N content or using a chlorophyll meter. The chlorophyll meter measures the greenness of the plant and has been shown to be positively correlated to plant N status. Modeling may provide another option by including the factors that affect the rate of N mineralization from a known pool. The two most important variables include soil moisture and temperature. Realistic yield expectations and accounting for existing and projected amounts of available N can improve the accuracy of N recommendations.

Introduction

Production of food and its protein content are key components to sustaining the world population. In many cropping systems, N frequently limits crop yield and protein levels and additional N inputs are required to optimize productivity and profitability. Nitrogen availability to crops is regulated by a biologically dynamic soil N cycle; thus, it is subject to the environmental factors that regulate the activity of microorganisms. In general, a portion of the N applied in excess of crop requirements ultimately will be converted to NO_3^-, which may be leached to groundwater. Thus, it is important to develop rational practices for N fertilizer to ensure sufficient but judicious use of N for economic and environmental reasons. Previous N recommendations were based on inexpensive fertilizer, a lack of appreciation for spatial variability, and minimal environmental concerns. In some environmentally sensitive areas, future N recommendations need to be as site specific as possible.

Accurate recommendations for N fertilizer require knowledge of plant N requirements, external N sources, and N losses from the soil system. These components are represented by the equation:

$$N_f = N_c - (N_{sources} - N_{losses}) \tag{1}$$

where:

N_f = N fertilizer
N_c = N needed by the crop
$N_{sources}$ = N sources
N_{losses} = N losses

This apparently simple equation is very complex. The amount of N needed by the crop (N_c) is a function of dry matter yield and N concentration of the crop. The estimate of crop N requirement influences N recommendations more than any other factor. Overestimating the yield goal will result in a N recommendation that exceeds the actual crop N requirement; thus, establishing a realistic yield goal is important for reducing the environmental impact of N use (Jackson *et al.*, 1987). Power and Broadbent (1989) suggested using a yield goal that is 5 to 10% greater than average yield of the previous 5 to 7 years. It is unrealistic to expect precise estimates because of yearly variations in growing season weather. If the yield includes the entire plant, then the N concentration of that yield will determine the crop's N needs. In the case where only a portion of the crop is harvested (i.e. grain), an estimate of the N requirement for the entire crop should be used.

Exogenous N inputs include fertilizer, manure, and biologically fixed N. The contribution of biologically fixed N becomes more important in tropical systems, where free-living and associative N_2 fixation increases. Associative N_2 fixation with tropical grasses, including sugar cane, has been reported to be as much as 100 kg N ha^{-1} (Neyra and Dobereiner, 1977; Dobereiner, 1978). In rice production, the N contribution of *Azolla* has been reported to be equivalent to 30 kg urea-N ha^{-1} (Watanabe, 1987). Inputs from irrigation and precipitation also must be considered. Nitrogen inputs from precipitation normally are small, but localized sources can make a significant contribution. Nitrogen inputs from irrigation also are normally small, but when NO_3^- contaminates the groundwater, significant amounts of N can be added through irrigation. Schepers and Mosier (1991) reported that > 100 kg N ha^{-1} can be added during one growing season in the Platte River valley of Nebraska in the US, where the NO_3^--N concentration can exceed 30 mg N L^{-1}.

Internal inputs include residual soil inorganic N and N mineralized from crop residues, soil organic matter, and manure that decompose during the growing season. In perennial crops, root N that will be translocated to the shoots also should be considered.

Nitrogen losses include leaching of NO_3^-, gaseous N losses from soil through denitrification, volatilization of N from fertilizers and vegetation, and erosion. The quantity of N lost through these pathways greatly depends on the local conditions of soil, crop, and climate

Our simple equation now takes the form:

$$N_f = N_c - [(N_m + N_{in} + N_r + N_{fix}) - (N_l + N_d + N_v + N_e) - N_{im}] \quad (2)$$

where,

N_m = N mineralization from soil organic matter
N_{in} = residual inorganic soil N
N_r = N from residue
N_{fix} = biologically fixed N
N_l = N loss from leaching
N_d = N loss from denitrification
N_v = N loss from volatilization
N_e = N loss from erosion
N_{im} = temporary N loss from immobilization

The ultimate goal of a N management program is to accurately supply the crop requirement, while minimizing N losses through leaching, denitrification, volatilization, and erosion. Minimizing N losses and maximizing crop recovery of applied N will enhance N use efficiency and reduce environmental risk inherent with the use of external N inputs.

Efficiency of N use

Implicitly included in a N fertilizer recommendation is the efficiency of N use by the crop. Each of the N sources identified in Equation 2 will have an associated efficiency that is a function of losses. Management systems that dramatically change N use efficiency require that the N recommendation model be recalibrated. Nitrogen use efficiency is a function of climate; soil properties; crop and soil management; and management of the N applied (time, form, and placement). Although we often have very little control of climate, changes in precipitation amounts and timing will alter N transformations and subsequent availability. Myers (1988) reported N fertilizer efficiencies ranging from 12 to 74% for arable crops in the tropics. Poor recovery could be due to leaching and denitrification in wet climates and poor N uptake in dry climates. Crop and soil management practices are important considerations in management of N inputs, e.g. the effect tillage systems have on fertilizer transformations and microbial activity. For example, Phillips *et al.* (1980) reported that no-tillage corn production required more N fertilizer compared to plowed systems. This conclusion is based

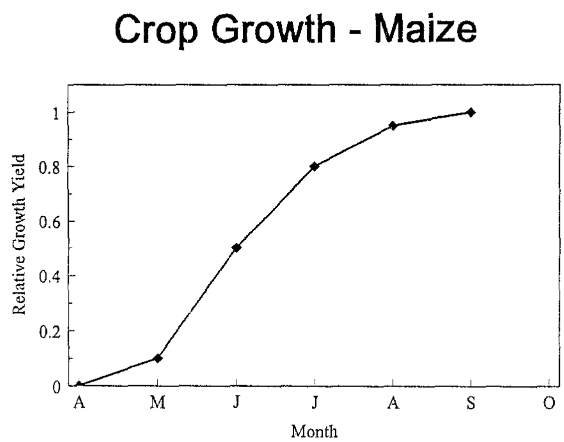

Fig. 1. Typical growth of maize in the central US.

on the premise that fertilizer N is used less efficiently under a no-tillage system. In reality, no-tillage systems generally exhibit higher denitrification (Rice and Smith, 1982) and greater potential for immobilization (Rice and Smith, 1984) and leaching (Thomas *et al.*, 1973). Crop recovery of applied N sometimes can be enhanced by adopting new technologies that improve the synchrony between crop needs and N supply.

Nitrogen management technologies have been developed to reduce N contact with soil microorganisms, N leaching, and N volatilization. Reducing N contact with soil microorganisms can reduce denitrification and immobilization. Nitrification inhibitors also can be used with N sources to temporarily reduce microbial activity responsible for the oxidation of NH_4^+. Nitrogen management technologies incompass application timing and placement of fertilizers and manures, use of inhibitors and N amount.

Timing

Maximum crop recovery and use of applied N require that N available be synchronous with plant growth and N demand (Fig. 1). Nitrogen synchrony often is not practical or possible. Supplying N after the crop reaches full canopy without damage to the crop can be difficult unless it is supplied by fertigation, a high-clearance vehicle, or aerial application. The timing of N availability must consider N mineralization as well as external N inputs. McGill and Myers (1987) discussed this relationship using a moisture-temperature index as an indicator of microbial activity and N mineralization. For example, the semi-arid tropical climate

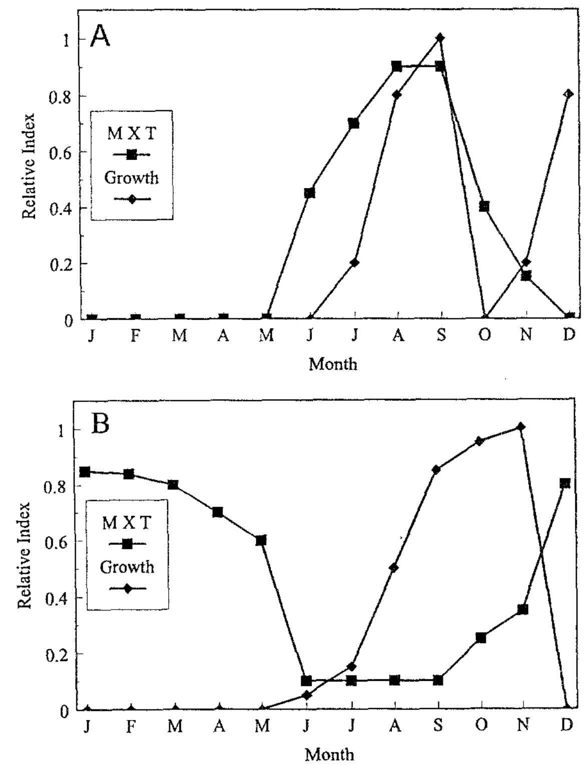

Fig. 2. Moisture-temperature index (■) for N mineralization and relative growth (♦) for (**A**) a semi-arid, tropical site with *kharif* and rubi at Hyderabad, India and (**B**) a subtropical site with wheat at Darling Downs, Australia (McGill and Myers, 1987).

of Hyberabad, India, creates conditions conducive for synchrony between N mineralization and kharif and rabi crops (Fig. 2A). An example of a nonsynchronous relationship between N mineralization and crop N demand occurs in sub-tropical Queensland Australia with spring wheat (Fig. 2B). To improve the recovery of fertilizer N, some producers will split their N fertilizer application or delay the application into the growing season. This practice can successfully increase N fertilizer use efficiency and potentially reduce N fertilizer inputs. Studies have shown a 10 to 30% decrease in the amount of N fertilizer needed by the crop from this practice (Wells, 1984).

Placement

Adoption of N placement technologies can reduce N losses and increase plant N uptake. Placement of N becomes more important as reduced tillage systems are adopted. In the United States of America, common placement methods for maize include either sur-

Table 1. Fertilizer N recovered by corn as affected by tillage (1985–1986 average)

N Placement	Time Applied	Tillage System (%) Plowed	No-till
Broadcast	At planting	46	36
	Delayed	56	44
Injected	At planting	59	52
	Delayed	56	56

Pierce and Rice (pers. commun.).

Table 2. Grain yield response of maize to urease inhibitor

Treatment	Irrigated ($Mg\ ha^{-1}$)	Dryland
Urea	7.02a	3.16a
Urea + NBPT	8.28b	4.30b
NH_4NO_3	8.28b	3.85b

Lamond *et al.* (1994).

face or subsurface banding of the N fertilizer (Lamond *et al.*, 1991). Placement of fertilizer N is even more critical with the use of urea in rice production. Volatilization losses are extremely high (up to 96%) unless deep placement of urea is used (Watanabe *et al.*, 1981; Zhao-liang, 1981). Subsurface placement of manure N can reduce N volatilization losses of surface-applied manure. Often, timing and placement interact positively (Table 1). These data show greater fertilizer N recovery by maize when the N application was delayed to the sixth leaf stage or subsurface banded at planting. In this example, no benefit resulted from subsurface banding with a delayed application. Other studies have shown the benefit of banded fertilizer on recovery of applied N (Murphy *et al.*, 1978; Mengel, 1982).

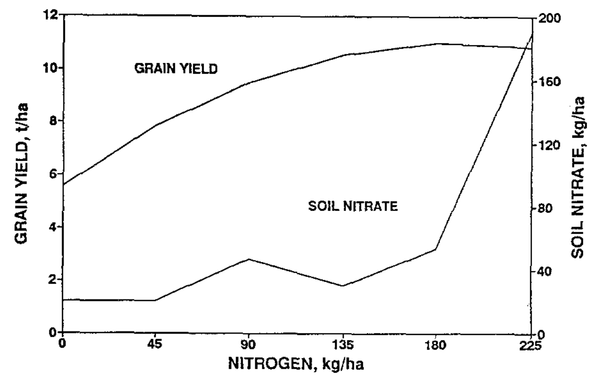

Fig. 3. Nitrogen response curve for maize. Soil nitrate concentrations in the surface 3.2 m. N rate for economic optimum yield was about 180 kg N ha^{-1}.

Inhibitors

Specific inhibitors of biological N processes have been developed and can be used to increase N use efficiency and decrease leaching losses. The most common and effective products inhibit nitrification and urea hydrolysis. Nitrification inhibitors temporarily inhibit the nitrification process when crop N uptake is low and denitrification and leaching potentials are high. Several compounds have been reported to inhibit nitrification, but only three have been developed commercially: nitrapyrin, N serve, [2-chloro-6-(trichloromethyl)pyridine]; etridiazol, Dwell, [5-thoxy-3-(trichloromethyl)-1,2,4-thiadiazaole]; and dicyandiamide, DCD, (Peterson and Frye, 1989). The extent of nitrification inhibition depends upon the amount and time of N application, soil temperature, and precipitation patterns (Frye, 1981). Generally, conditions conducive for leaching and denitrification will enhance the effectiveness of nitrification inhibitors. A more complete discussion of nitrification inhibitors is presented by Sahrawat (1994).

Urease inhibitors reduce urease activity, resulting in delayed hydrolysis of urea or urea-based fertilizers that will increase transport of surface-applied urea into the soil. Movement of urea into the soil can significantly reduce volatilization losses of applied urea. This can translate to greater grain yields (Table 2) (Lamond *et al.*, 1994). A more complete discussion of urease inhibitors is presented by Bremner (1994).

Amounts of N applied

Identifying the precise amount of external N applied to a crop is extremely important in maximizing crop recovery of N and minimizing environmental risk associated with N use. A typical N response curve is illustrated in Figure 3. The largest incremental response to applied N occurs at the lower amounts of N application. More importantly, the final 10% yield response to applied N uses approximately 35% of the N fertilizer required for maximum profit (Schlegel and Havlin, 1994). These data also show that increasing the amount of N applied beyond the economic optimum amount dramatically increases profile N content and NO_3^- leaching potential.

One of the main problems in developing an accurate N recommendation is to quantify the contribution of N mineralization, because it is an important source of plant N. Accurately assessing N mineralization is difficult and has been the subject of research for almost 100 years. Universal procedures to quantify N mineralization still have not been developed. Early research focused on developing a laboratory test to determine the N mineralization potential of soils. Laboratory procedures can be divided into chemical and biological indices. These are reviewed and discussed elsewhere (Keeney, 1982; Meisinger, 1984; Rice and Havlin, 1994; Stanford, 1982). Generally, the laboratory procedures have not been adopted widely, because they do not predict N mineralization under field conditions. These laboratory procedures generally have been unsuccessful, because they fail to consider the dynamics of the factors that regulate the rate of N mineralization. These factors are substrate quality; moisture; substrate accessibility (clay content, tillage; wetting and drying cycles, freeze-thaw cycles); temperature; and pH. A complete discussion of these factors is given by Rice and Havlin (1994).

The nature and complexity of these regulatory factors complicate assessment of N mineralization in the laboratory. Field techniques and modeling are two other possible choices. Field techniques include soil sampling and incubations over time and plant sampling. Field techniques integrate many of the regulatory factors noted above, as well as crop and soil management factors that affect N mineralization. A disadvantage of the field techniques is that they are often site specific. Field techniques can be divided into quantitative or qualitative approaches and have been discussed in greater detail by Schepers and Meisinger (1994).

Assessment of nitrogen mineralization

Soil incubations

A quantitative approach to field N mineralization is the use of fallow soil. This approach avoids the disturbance that occurs with laboratory techniques. The lack of disturbance can emulate conditions that occur in the field with differing soil management systems, such as reduced tillage and residue management. Other physical conditions also are preserved. The soil in conservation tillage systems, often is more dense, cooler, and wetter than plowed soil. To eliminate large leaching and denitrification losses, the fallow technique can include a cover (Rice *et al.*, 1987). Rice *et al.* (1987) reported differences between tillage systems and soil drainage classes under the covered fallow soils that were not shown by laboratory techniques. One potential disadvantage of covering the soil is that it would not undergo the same wetting and drying cycles that occur under normal field conditions. A more detailed discussion of this technique is presented by Schepers and Meisinger (1994).

Soil nitrate tests

Soil nitrate tests provide a relative index of *in situ* N mineralization. Specific soil NO_3^- tests have many variations that are dependent on climatic conditions, crop, and soil type. In the humid temperate regions of the US, the pre-sidedress nitrate test (PSNT) for maize is being evaluated. This test measures the amount of NO_3^- in the top 30 cm of the soil profile when the corn is at the 6-leaf stage or approximately 30 cm tall (Bock *et al.*, 1992). The PSNT was proposed first by Magdoff *et al.* (1984) to identify situations where fertilizer would not be needed to attain optimum maize yields. The PSNT integrates residual NO_3^- from the previous season, N losses, and spring N mineralization until the time sampled. The intent of this test is to allow N mineralization to proceed as long as possible before the accumulated NO_3^- is measured and yet allow enough time to apply sidedress N before the crop grows too tall to prevent access to the field. The advantage is that, in the eastern two thirds of the US, the PSNT can separate sites that have sufficient N (> 20–25 mg NO_3^--N kg^{-1}) from those that require additional fertilizer N inputs for maize production. The PSNT does not quantitatively measure N mineralization. For the PSNT to be useful, a standard sampling time and rapid analysis are important so that sidedress fertilizer N can be applied in a timely manner. Presently, the PSNT has been evaluated only for maize and needs to be evaluated for other crops. Neteson *et al.* (1989) reported that soil profile inorganic N currently is being used in the Netherlands to adjust N fertilizer recommendations for several crops. Including soil profile inorganic N was either equally effective or decreased N fertilizer requirement when compared to using a fixed N rate.

Plant N status

The plant is the ultimate integrator of environmental variables controlling the N transformations within the soil N cycle and, ultimately, the N available to it. Two approaches will be discussed: a qualitative approach involving chlorophyll meters and a quantitative approach using N uptake by an unfertilized crop. Crop N uptake provides an estimate of N availability during the growing season. The N status of the crop can be quantified by determining the tissue N content or using a chlorophyll meter. The chlorophyll meter measures the chlorophyll content or greenness of the plant that is correlated positively with crop N status. The chlorophyll meter is ideal for real time analysis of the crop N status and indicates N stress. The principle is discussed further by Schepers *et al.* (1992a,b) who had success comparing chlorophyll meter readings of an area requiring N to an area where N is nonlimiting because of application of adequate N fertilizer. Some of the disadvantages discussed by Schepers and Meisinger (1994) are that the data generated are site and plant (variety) specific. This makes calibration of the meters difficult unless a sufficiency index is calculated.

Plant N uptake

Nitrogen uptake by an unfertilized crop represents the best method for quantifying net N mineralization. The advantages of this approach are that it integrates field temperature, moisture, and aeration conditions that greatly influence N mineralization potential and can be adapted easily to include many crop and soil management practices. Nitrogen uptake in unfertilized plots also includes the normal rooting depth of the crop being studied and integrates spatial and temporal influences on N mineralization. Accurate measures of crop N uptake must include total biomass N and not just grain yield. One problem with estimating total N mineralization is accounting for root N content. A constant shoot:root N ratio cannot always be assumed and must be validated. Other disadvantages of this technique are costs, labor requirements, and site specificity. Information derived from one site may not be transferable to another site, unless some other nonsite-specific parameters can be correlated to N mineralization or can be used to predict it.

Models

Modeling techniques are other options that could directly incorporate the factors affecting microbial activity and N mineralization, as well as the other factors affecting N availability and losses. Current attempts to model N mineralization for field situations include the rate factor (k) and the size of the mineralizable pool (N_0). Most studies suggest use of first order kinetics (Broadbent, 1986; Juma *et al.*, 1984; Stanford and Smith, 1972). A few studies have suggested a two-pool model to predict N mineralization (Molina *et al.*, 1980; Deans *et al.*, 1986). For use under field conditions, the rate then is adjusted for moisture and temperature (Campbell *et al.*, 1981; Myers *et al.*, 1982). However, Campbell *et al.* (1988) reported that their model underestimated N mineralization during the growing season. They attributed the underestimate to flushes of N mineralization during rewetting of dry soils. For temperature, Honeycutt *et al.* (1988) suggested using accumulated heat units to predict N mineralization; however, the heat unit concept is unable to predict N mineralization under dry soil conditions (Doel *et al.*, 1990). Such models need to include climatic parameters and soil properties. Neeteson *et al.* (1989) have successfully used a N fertilizer recommendation model for potatoes in the Netherlands.

Fertilizer N recommendation

Fertilizer N recommendations need to be calibrated across broad areas, even though site-specific information is used to develop the appropriate algorithms. To calibrate N recommendations, knowledge of the crop response to N fertilizer is required. Critical variables for determining the N rate need to be identified and measured. Important site variables include texture, pH, and organic matter content. Management variables include tillage systems, irrigation, and rotations. Once the crop response and the important variables are identified, then the recommendation model should be tested over a range of environmental conditions and N components.

For making fertilizer N recommendations, at least two strategies emerge, depending on other characteristics of the production system. The main distinction between these strategies is the ability of the producer to apply N fertilizer easily at any time during the growing season versus situations that essentially require all the fertilizer to be applied while the plants are small

Table 3. An example data set from Nebraska to determine N fertilizer recommendations for corn with two irrigation systems

Data	Conventional	Center-Pivot
Residual soil N		
0–20 cm (mg kg^{-1} nitrate-N)	13.5	12.3
20–90 cm (mg kg^{-1} nitrate-N)	7.2	4.5
0–90 cm (wt. average, mg kg^{-1} nitrate-N)	8.8	6.2
Organic matter		
0–20 cm (%)	1.77	1.9
Irrigation water (mg l^{-1} nitrate-N)	30	30
Expected yield (mg ha^{-1})	12.6	12.6
Estimated water application (cm)	25	25
Estimated crop N need (kg ha^{-1})	309	309
21.4 (expected yield) + *39*		
N credits		
Residual soil N (kg ha^{-1})	79	56
9 (mg nitrate-N kg^{-1})		
Organic matter (kg ha^{-1})	56	60
2.5 (expected yield)(% organic matter)		
Irrigation water (kg ha^{-1})	75	75
0.1(cm depth)(mg l^{-1} nitrate-N)		
Others		
Soybeans (50 kg ha^{-1})	0	0
Alfalfa (135–170 kg ha^{-1})	0	0
Manures (variable	0	0
Fertilizer N required (kg ha^{-1})	99	118

to avoid mechanical damage. Situations that are limited to preplant or sidedress N application involve a greater degree of anticipation on the part of the farmer, because they provide little opportunity to compensate for atypical climatic conditions. In contrast, situations where fertigation or other means of N application (i.e. high clearance vehicle, foliar application, etc.) are possible throughout the growing season allow producers to move closer to spoon-feeding their crops. As it turns out, the greater flexibility a producer has in terms of N application times and forms, the more decisions that must be made about fertilizer costs, labor, and convenience. The two scenarios for N recommendations that follow are for irrigated corn in Nebraska (Table 3). One field is under conventional furrow irrigation and the other adjacent field has been under center-pivot irrigation for several years. Because of the methods of irrigation and past fertilizer N management practices, the levels of residual soil N are different for the two fields.

Conventional field

Consider applying approximately 20–30 kg N ha^{-1} as a starter fertilizer at planting and the remainder as preplant or sidedress application. Local regulations require preplant applications in excess of 90 kg N ha^{-1} use a nitrification inhibitor. The credit given for the amount of N supplied in irrigation water is conservative, because the amount of water applied by furrow irrigation can be quite variable within a field, ranging from 60–90 cm. However, because a considerable portion of the irrigation water is applied to corn after silking, a portion of the N in the irrigation water will not be utilized by the crop. The value of 25 cm water application is based on the evapotranspiration minus long-term average precipitation during the growing season.

Center-pivot field

Consider applying approximately 20–30 kg N ha^{-1} as a starter fertilizer at planting and 50–75% of the remainder as preplant or sidedress application. Use chlorophyll meters or other means to monitor crop N status during the growing season. If an N deficiency appears to be developing, apply 20–30 kg N ha^{-1} as urea ammonium nitrate in the irrigation water as needed. No N should be applied in the water beyond 3 weeks after silking.

One future N management scenario under development involves the use of equipment to apply variable rates of N. This approach will depend on a field location system, typically a global positioning system (GPS), to identify the position of the fertilizer applicator in the field. The variable-rate map of fertilizer N recommendations will be generated based on a variety of factors, such as residual soil N, organic matter content, and yield goal, for each part of the field. This is an emerging technology that offers the potential to reduce N applications in fertile areas of the field and maintain productivity in less fertile areas.

Conclusions

Our ability to make fertilizer recommendations is becoming more sophisticated, as we learn more about the soil/plant/water system. In the past, yield was the only measure of crop N need; however, this has contributed to some environmental problems. We now know that accounting for existing and projected amounts of available N in the root zone can improve the accuracy of N recommendations. Biologically fixed N, from associative and free-living systems, needs to be quantified, especially in tropical systems. In most cases, maximum yield is not desirable, because it results in economic and environmental risks. Realistic yield expectations should be stressed when making N fertilizer recommendations. We should realize that we cannot achieve or expect 100% efficiency from N fertilizers. Some losses through denitrification and leaching must be expected, and, in some years, unusual weather events will create situations that can significantly reduce or increase N use efficiency.

Acknowledgments

This paper was partly supported by a specific cooperative agreement from the USDA-ARS No. 58-5440-2-105. Contribution No. 94-577-J from the Kansas Agric. Exp. Stn., Manhattan, KS.

References

Bock BR, Kelley KR and Meisinger J (1992) Predicting N fertilizer needs for corn in humid regions: Summary and future directions. *In*: Bock BR and Kelley KR (eds) Predicting N fertilizer needs for corn in humid regions. Bull. Y-226, pp 115–127. National Fertilizer and Environmental Research Center, Tennessee Valley Authority, Muscle Shoals, AL

Bremner J (1994) Problems in the use of urea as a nitrogen fertilizer. *In*: Ahmad N (ed) International Symposium on Nitrogen Economy in Tropical Soils. 9–14 Jan. 1994. Port of Spain, Trinidad. Univ. West Indies, Trinidad, West Indies (*In press*)

Broadbent FE (1986) Empirical modeling of soil nitrogen mineralization. Soil Sci 141: 208–213

Campbell CA, Jame YW and De Jong R (1988) Predicting net nitrogen mineralization over a growing season: Model verification. Can J Soil Sci 68: 537–552

Campbell CA, Myers RJK and Weier KL (1981) Potentially mineralizable nitrogen, decomposition rates and their relationship to temperature for five Queensland soils. Aust J Soil Res 19: 323–32

Deans JR, Molina JAE and Clapp CE (1986) Models for predicting potentially mineralizable nitrogen and decomposition rate constants. Soil Sci Soc Am J 50: 323–326

Dobereiner J (1978) Potential for nitrogen fixation in tropical legumes and grasses. *In*: Dobereiner J *et al.* (eds) Limitations and Potentials for Biological Nitrogen Fixation in the Tropics, pp 13–34 Plenum Publishing Corp., New York

Doel DS, Honeycutt CW and Halteman WA (1990) Soil water effects on the use of heat units to predict crop residue carbon and nitrogen mineralization. Biol Fertil Soils 10: 102–106

Frye WW (1981) Nitrification inhibitors. Soil Sci News and Views 2 (10). Dept. of Agronomy, Univ. of Kentucky, Lexington

Honeycutt CW, Zibilske LM and Clapham WM (1988) Heat units for describing carbon mineralization and predicting net nitrogen mineralization. Soil Sci Soc Am J 52: 1346–1350

Jackson G, Keeney D, Curwen D and Webendorfer B (1987) Agricultural management practices to minimize goundwater contamination. Environ Resources Center, Univ WI, Dept. Nat Resources, Madison, WI. 114 p.

Juma NG, Paul EA and Mary B 1984 Kinetic analysis of net nitrogen mineralization in soil. Soil Sci Soc Am J 48: 753–757

Keeney DR (1982) Nitrogen availability indices. *In*: Page AL *et al.* (eds) Methods of Soil Analysis, part 2, 2nd Ed. Agronomy 9: 711–733

Lamond R, Whitney DA, Hickman JS and Bonczkowski LC (1991) Nitrogen rate and placement for grain sorghum production in no-tillage systems. J Prod Agric 4: 532–535

Lamond RE, Whitney DA, Maddux LD, Gordon B, Key O and Koch S (1994) Nitrogen management for no-till corn and grass sorghum production. *In*: Lamond RE (ed) Kansas Fertilizer Research 1993. Rep. Pro. 697, pp 93–97 Kansas Agric Exp Stn. Manhattan, KS

Magdoff FR, Ross D and Amadon J (1984) A soil test for nitrogen availability to corn. Soil Sci Soc Am J 48: 1301–1304

McGill WB and Myers RJK (1987) Controls on dynamics of soil and fertilizer nitrogen. *In*: Follett RF *et al.* (eds) Soil Fertility and Organic Matter as Critical Components of Production Systems. Soil Sci Soc Am Spec Pub 19, pp 73–99. Soil Sci Soc Am, Madison, WI

Meisinger JJ (1984) Evaluating plant-available nitrogen in soil-crop systems. *In*: Hauck RD (ed) Nitrogen in Crop Production, pp 391–416. Am Soc Agron Madison, WI

Mengel DB, Nelson DW and Huber DM (1982) Placement of nitrogen fertilizers for no-till and conventional till corn. Agron J 74: 515–518

Molina JAE Clapp CE and Larson WE (1980) Potentially mineralizable nitrogen in soil: The simple exponential model does not apply for the first 12 weeks of incubation. Soil Sci Soc. Am. J 44: 442–443

Murphy LS, Leikam DF, Lamond RE and Gallagher PJ (1978) Applying N and P at the same time into the same soil shows promise for winter wheat. Better Crops 62: 16–23

Myers RJK (1988) Nitrogen management of upland crops. From cereals to food legumes to sugar cane. *In*: Wilson JR (ed) Advances in Nitrogen Cycling in Agricultural Ecosystems. CAB International, Walling Ford, UK

Myers RJK, Campbell CA and Weier KL (1982) Quantitative relationship between net nitrogen mineralization and moisture content of soils. Can J Soil Sci 62: 111–124

Neeteson JJ, Dilz K and Wijnen G (1989) N-fertilizer recommendations for arable crops. *In*: Germon JC (ed) Management Systems to Reduce Impact of Nitrates, pp 253–264 Elsevier, New York NY

Neyra CA and Dobereiner J (1977) Nitrogen fixation in grasses. Adv Agron 29: 1–38

Peterson GA and Frye WW (1989) Fertilizer nitrogen management. *In*: Follett RF (ed) Nitrogen Management and Ground Water Protection, pp 183–219 Elsevier, New York

Phillips RE, Blevins RC, Thomas GW, Frye WW and Phillips SH (1980) No tillage agriculture. Science 208: 1108–1113

Power JF and Broadbent FE (1989) Proper accounting for N in cropping systems. *In*: Follett RF (ed) Nitrogen Management and Ground Water Protection, pp 160–181. Elsevier, New York

Rice CW, Grove JH and Smith MS (1987) Estimating soil net nitrogen mineralization as affected by tillage and soil drainage due to topographic position. Can J Soil Sci 67: 513–520

Rice CW and Havlin JH (1994) Integrating mineralizable N indices in fertilizer N recommendations. *In*: Havlin *et al.* (eds) New Directions in Soil Testing for Nitrogen, Phosphorus, and Potassium. Soil Sci Soc Am Spec Publ 40, pp 1–13. Soil Sci Soc Am, Madison, WI (*In press*)

Rice CW and Smith MS (1982) Denitrification in no-till and plowed soils. Soil Sci Soc Am J 46: 1168–1173

Rice CW and Smith MS (1984) Short-term immobilization of fertilizer nitrogen at the surface of no-till and plowed soil. Soil Sci Soc Am J 48: 295–297

Sahrawat KL (1994) Nitrification inhibitors and persistence of fertilizer nitrogen in the soil system. *In*: Ahmad N (ed) International Symposium on Nitrogen Economy in Tropical Soils. 9–14 Jan. 1994. Port of Spain, Trinidad. Univ. West Indies, Trinidad, West Indies (*In press*)

Schepers JS, Blackmer TM and Francis DD (1992a) Predicting N fertilizer needs for corn in humid regions: Using chlorophyll meters. *In*: Bock BR and Kelley KR (eds) Predicting N Fertilizer Needs for Corn in Humid Regions. Bull. Y-226, pp 103–114. National Fertilizer and Environmental Research Center, Muscles Schoals, AL

Schepers JS, Francis DD, Vigil M and Below FE (1992b) Comparison of corn leaf nitrogen and chlorophyll meter readings. Commun Soil Sci Plant Anal 23: 2173–2187

Schepers JS and Meisinger JJ (1994) Field indicators of nitrogen mineralization. *In*: Havlin *et al.* (eds) New Directions in Soil Testing for Nitrogen, Phosphorus, and Potassium. Soil Sci Soc Am Spec Publ 40, pp 31–47. Soil Sci Soc Am, Madison, WI (*In press*)

Schepers JS and Mosier AR (1991) Accounting for nitrogen in nonequilibrium soil-crop systems. *In*: RF Follet *et al.* (eds) Managing Nitrogen for groundwater Quality and Farm Profitability, pp 125–138. Soil Sci Soc Am, Madison, WI

Schlegel AJ and Havlin JL (1994) Corn response to long term nitrogen and phosphorus fertilization. J Prod Agric (*In press*)

Stanford G (1982) Assessment of soil nitrogen availability. *In*: Stevenson FJ (ed) Nitrogen in Agricultural Soils, pp 651–688. Soil Sci Soc Madison, WI

Stanford G and Smith SJ (1972) Nitrogen mineralization potentials in soils. Soil Sci Soc Am Proc 36: 465–472

Thomas GW, Blevins RL, Phillips RE and McMahon ME (1973) Effect of killed sod mulch on nitrate movement and corn yield. Agron J 65: 736–739

Watanabe I (1987) Summary report of the *Azolla* program of the international network on soil fertility and fertilizer evaluation for rice. *In*: *Azolla* Utilization. Int Rice Res Inst, Los Banos, Philippines

Watanabe I, Craswell ET and App AA (1981) Nitrogen cycling in wetland rice fields in south-east and east Asia. *In*: Wetselaar R *et al.* (eds) Nitrogen Cycling in South-East Asian W Monsoonal Ecosystems, pp 4–17. Aust Acad Sci, Canberra, Australia

Wells KL (1984) Nitrogen management in the no-till system. *In*: Hauck R (ed) Nitrogen in crop production, pp 535–550. Am Soc Agron, Madison, WI

Zhao-liang Z (1981) Nitrogen cycling and the fate of fertilizer nitrogen in rice fields of the Suchow district, Jiangsu Province, China. *In*: Wetselaar R *et al.* (eds) Nitrogen Cycling in South-East Asian Wet Monsoonal Ecosystems, pp 73–80. Aust Acad Sci, Canberra Australia