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Nitrogen Management for Maize in Humid Regions: Case for a Dynamic Modeling Approach

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Abstract

This paper discusses the current approaches to estimating optimum N fertilizer rates for maize (*Zea mays* L.), and the main underlying cause for low precision in fertilizer recommendations and low N use efficiency in humid regions. Current approaches to estimation of N fertilizer rates are based on mass balances, average expected economic return based on field experiments, soil N tests, and crop leaf or canopy sensing. A 7-year study on the interacting effects of management practices and landscape position on seasonal soil mineral N and plant N dynamics showed high annual variability in plant available N. Yearly effects could mostly be explained by the interacting factors of early-season rainfall and soil organic matter content. A 5-year study on maize N response for different soil types and drainage classes showed that annual differences in late-spring rainfall were the greatest source of variability in optimum N rate, while wet years also experience greater spatial variability. Optimum N rate for maize is affected by the complex interactions of spring precipitation and temperature patterns, soil organic matter, and crop development. Highest precision in N management for maize may be achieved through in-season N applications that are based on information on early-season N dynamics. This can be accomplished through the use of models that dynamically simulate soil and crop processes, and possibly the use of crop optical sensors. We discuss the application of a dynamic simulation model to improve the prediction of optimum N fertilizer rates in a companion paper (Melkonian et al., this issue).

Introduction

Current environmental and economic concerns demand improved N use efficiency from cropping systems. Concerns exist related to excessive nitrate levels in groundwater and N-induced hypoxia in estuarine areas from agricultural sources (McIsaac et al., 2002), and also with the high energy consumption for N fertilizer manufacturing and greenhouse gas impacts from soil N₂O losses (Smith and Conen,

2004). Maize, a C₄ plant, is physiologically more efficient at utilizing N (more yield per unit N accumulation) than most other major crops, which are generally C₃ plants (Greenwood et al., 1990). But paradoxically, maize production systems as a whole generally have low fertilizer N uptake efficiency, or recovery efficiency (RE), which is the proportion of applied fertilizer that is taken up by the plant. Through on-farm experiments in six northcentral U.S.A. states, average RE was determined to be 37% with a standard deviation of 30% (Cassman et al., 2002). This suggests both low nutrient use efficiency and high potential N losses to the environment.

Precise estimation of the optimum N fertilizer rate is critical to reducing N leaching losses (Ostergaard, 1997). In a leaching study involving variable N fertilizer rates and two soil types (clay loam, loamy sand), van Es et al. (2002) showed considerable increases in N leaching losses, and decreased fertilizer N use efficiency when fertilizer rates exceeded crop N demands, as excess N is subject to environmental losses, mainly through leaching and denitrification. When 34 kg ha⁻¹ N was applied beyond the optimal rate, 15 kg ha⁻¹ (43%) of that amount was accounted for in leaching losses through drain lines. Randall (2006) reported similar increases in nitrate leaching with higher N rates. The average nitrate-N concentrations in subsurface drainage water remained well below the critical 10 mg L⁻¹ with low fertilizer rates (80 kg ha⁻¹ or less), but increased to 17 mg L⁻¹ at the 150 kg ha⁻¹ rate, suggesting that economic maize production may be difficult without significant N leaching losses.

Several studies have documented that nitrate leaching losses can be considerable under the major crop production systems (Robbins and Carter, 1980; Bergstrom, 1987; Randall et al., 1997). Maize production systems are very N-inefficient and stand out by generating the highest nitrate concentrations in leachate, followed by less-fertilized annual crops (e.g., soybean (*Glycine max* L), wheat (*Triticum aestivum* L.), and perennial crops (e.g., alfalfa (*Medicago sativa* L.) and grasses). This can be attributed to different fertilizer rates, fertilizer

Abbreviations: N, nitrogen; EONR, economically optimal N rate; PSNT, pre-sidedress nitrate test; PPNT, pre-plant nitrate test; ISNT, Illinois Soil Nitrogen Test; CDD, cumulative degree days; SMN, soil mineral N.

application schedules, timing of crop water and N uptake, and rooting depth (Randall et al., 1997; Bergstrom, 1987). Intensive maize production areas therefore pose a risk for N losses to surface and groundwater systems and have become the focus of policy debates on addressing eutrophication and hypoxia concerns (McIsaac et al., 2002).

Estimating Optimum N Rates

Maize generally shows high variability in N response, and economically optimal N rates (EONR) may range from zero to 250 kg N ha⁻¹ (Scharf et al., 2006). Therefore, the need for “precise” management of N fertilizer is compelling, but the ability to estimate the true EONR has remained relatively elusive. Whelan and McBratney (2000) asserted the need to test the ‘null hypothesis of precision agriculture management’, i.e., whether “precision” management truly provides benefits over uniform management. By inference, this requires an accounting of the relevant processes that cause such variability.

Mass-Balance Approach

Historically, the mass-balance approach has been the most widely-used method for making N fertilizer recommendations (Stanford, 1973). It is generally based on a yield goal and associated N uptake, minus credits given for non-fertilizer N sources such as mineralized N from soil organic matter (SOM), preceding crops, and organic amendments. Several studies have documented, however, that the relationship between yield and EONR is very weak or non-existent for humid regions (Lory and Scharf, 2003; Vanotti and Bundy, 1994; Katsvairo et al., 2003, Sawyer et al., 2006a). The increased use of yield monitors for site-specific yield measurement and grid-based soil sampling with SOM assessment have generated renewed interest in combining spatial yield data with the mass-balance approach for the purpose of variable rate fertilizer application technology (Ferguson et al., 2002, Khosla et al., 2002). However, most efforts have shown limited results in humid areas. Other studies, e.g., Mamo et al. (2003), claim better results with site-specific N management, although they often evaluate EONR *ex post* from strip plots, which is not necessarily a good indicator of predictive capability. For N applications the relevant yield variability is not in the past, but the immediate future (Scharf et al., 2006). Yield patterns themselves are in fact highly variable from year to year (Katsvairo et al., 2003; Kahabka et al., 2004), and any mass balance approach to N fertilizer recommendations therefore would pose the challenging task of predicting yields in the early growing season.

Maximum Return to N Approach

In recent years, several leading US maize producing states have adopted the maximum return to N (MRTN) approach (Sawyer et al., 2006a), which largely abandons the mass-balance method. It provides relatively generalized recommendations based on extensive multi-year and multi-location field trials, curve-fitting, and economic analyses (Vanotti and Bundy, 1994). The rate with the largest average net return is the MRTN, and the recommendations vary with grain-to-fertilizer price ratio. This has provided a more realistic and simpler approach, and has generally resulted in reductions in recommended N fertilizer rates. Adjustments based on realistic yield expectation are sometimes encouraged. Northern states (e.g., Minnesota, Wisconsin) generally recommend lower N rates than southern states due to higher N gains from soil organic matter mineralization. The MRTN approach may be an improvement over the mass balance approach, since it is based on more recent and more comprehensive field-response datasets, and by using the more conservative quadratic-plateau curve-fitting technique it may better serve the goal of environmental impact reduction. However, owing to its generalization over large areas and across seasons, it does not address or account for dynamic processes that affect N availability to maize.

Soil Testing

A third general approach is the use of various types of soil tests to estimate crop N needs. Magdoff et al. (1984) developed the pre-sidedress nitrate test (PSNT), which can be used to estimate crop N availability and allows for adjustment of in-season N applications (Blackmer et al., 1989). It is generally recognized as being successful in identifying N-sufficient sites and in some cases for making N fertilizer rate recommendations when soil nitrate levels are low (Fox et al., 1989; Blackmer et al., 1989; Magdoff et al., 1990; Binford et al., 1992; Klausner et al., 1993). Durieux et al. (1995) and Sogbedji et al. (2000) found that the use of the PSNT method resulted in lower N fertilizer rates and nitrate leaching losses while maintaining yields compared to traditional yield goal based methods. Concerns associated with the test are the extensive sampling requirement (due to common high soil nitrate variability; Ma and Dwyer, 1999) during a short time window, and its sensitivity to early-spring weather conditions. The PSNT is often effectively used to evaluate N sufficiency levels in high-nutrient soils, as common in livestock systems (Klausner et al., 1993).

The Pre-Plant N Test (PPNT; Bundy et al., 1995) measures soil nitrate or soil nitrate-plus-ammonium in the soil (typically from 0 to 60 cm) early

in the season to guide N fertilizer applications at planting. It is generally recommended for cases with either high residual inorganic N from the previous season, or with organic N inputs such as manure, where it provides some guidance for adjusting early N fertilizer application rates. Its accuracy, however, is deemed limited for determining EONR in humid regions where the inorganic N is highly susceptible to losses during the early season.

More recently, the Illinois Soil Nitrogen Test (ISNT) has been advanced as a tool to identify sites that are non-responsive to N fertilizer (Khan et al., 2001; Mulvaney et al., 2001). It is intended to estimate the organic N fraction (presumably amino sugars) that contributes to crop-available N in the following growing season. It has an advantage that it samples a more stable N fraction than the PSNT, and therefore allows for early-spring or late-fall sampling. Mulvaney et al. (2005) determined the test to be generally successful at identifying non-responsive sites in Illinois, and Williams et al. (2007) found good predictability of the ISNT for determining maize optimum N rates for Southeastern soils when accounting for different soil types. However, Osterhaus and Bundy (2005) found no relationship between the test and EONR; Laboski (2004) showed a poor relation between ISNT and corn N response; Barker et al. (2006) found no correlations of the ISNT with several yield indicators and EONR; and Klapwyk and Ketterings (2006) concluded that the test was unsuccessful at identifying N responsive sites, although inclusion of organic matter content improved predictability.

Crop Leaf or Canopy Sensing

Recent advances in remote and proximal crop sensing allow for estimation of crop N status during the growing season. Leaf chlorophyll meters (Sawyer et al., 2006b) or multi-band aerial or in-field remote sensing (Sripada et al., 2006) are used for assessing leaf or canopy N status, typically for the purpose of mid-season N applications. Effective use of the method is best obtained for late applications during the V10 to R1 stage of maize development, which implies the use of high-clearance fertilizer application equipment or overhead fertigation, although earlier sensing may provide guidance on yes/no decisions for supplemental fertilization. The methodology generally requires a reference strip that has received high levels of N fertilization. A concern is that some yield potential may already be lost by the time the N stress can be effectively measured. It also appears more suitable for evaluation of relative differences within fields, i.e., for site-specific application. Crop sensing appears to be successfully applied for N management on other crops (esp. wheat, this issue). It shows

promise for use in maize, but is still being actively researched.

Temporal Dynamics in Soil N

The dynamics of plant N uptake are quite complex as plants absorb more nutrients at certain growth stages than others. Dinnes et al. (2002) concluded that N dynamics in humid regions are affected by a multitude of factors including tillage, drainage, crop type, soil organic matter content, and weather factors. Others claim that the effects of weather may be larger than other attributes (Lamb et al., 1997; Eghball and Varvel, 1997; Sogbedji et al., 2001), as it influences rates of N mineralization and losses through leaching and denitrification. It appears therefore that variation in both space (site-specific-based) and time (primarily as defined by variation in weather conditions) in the use of N fertilizer need to be considered. The current methods for determining fertilizer rates mostly neglect the annual variations in yield response to N and may result in overfertilization in some years (leading to excess residual soil nitrate) and underfertilization in other years (leading to unattained yield goals).

Magdoff (1991) suggested that soil and crop simulation models may be applied to extending N-rate predictions to various soil and weather scenarios and estimate the need for modification of N fertilizer recommendations. Van Alphen and Stoorvogel (2000) used the mechanistic WAVE model (vanClooster et al., 1994) to fine-tune N fertilization on wheat and demonstrated increased fertilizer use efficiency. MANAGE-N has been used to optimize both the timing and rate of N fertilization for irrigated rice (*Oryza sativa* L.; ten Berge et al., 1997).

N Mineralization and Uptake

Multiple N sources may contribute to maize N uptake. Approximately 190 kg N ha⁻¹ is needed to produce a maize crop of 10 Mg ha⁻¹ of grain (Cassman et al., 2002). Mineralization of SOM can supply a significant fraction, with a typical value of 130 kg N ha⁻¹ for Midwestern soils (range of 50 to 250 kg N ha⁻¹; Cassman et al., 2002), and lower estimated values (average of about 80 kg N ha⁻¹) for soils in the eastern U.S.A. (Ketterings et al., 2003). Nitrogen mineralization rates during the growing season generally range between 0.7 and 1.0 kg ha⁻¹ d⁻¹ in humid temperate regions (Jokela and Randall, 1989; Greenwood et al., 1985; Magdoff, 1978). Higher rates are measured in the first weeks following incorporation of green and animal manures, but they subsequently decrease to rates less than 1 kg ha⁻¹ d⁻¹ (Magdoff, 1991; Utomo et al., 1990; Wagger, 1989). The difference between the crop requirement (which itself is affected by

seasonal developmentally-related environmental stresses) and the soil supply is ideally provided by fertilizer. But the precise estimation of this differential and the associated fertilizer use efficiency remains a challenge due to numerous sources of variability.

A seven year study of soil and maize N dynamics was conducted by Kay et al. (2006) from 1997 to 2003 in Southern Ontario (Canada) involving different soil and crop management systems, landscape positions and N rates. **Figure 1** plots the quantities of soil mineral N (SMN) from organic matter accumulation on the unfertilized plots with cumulative degree days (CDD). CDD is calculated from mean daily air temperature ($^{\circ}\text{C}$) accumulated from the early spring after three successive days in which the mean daily air temperature was above 0°C . CDD represents “thermal time” to describe the accumulation of plant available N through the growing season, as microbial activity generally begins as soil temperature increases above 0°C .

Maximum mineral soil N levels are generally observed at 1000 to 1200 CDDs (late spring), after which above-ground plant N (PN) uptake increases rapidly (**Figure 1**). The plant-available N (PAN), the sum of SMN and PN, also increases throughout the growing season, indicating a continuous release of N from the soil system. Most, but not all, mineralized soil N has accumulated in the plant by the end of the growing season. The remaining soil N is subject to leaching in humid regions, and good environmental stewardship therefore aims for the residual N to be minimal.

The variability in SMN and PAN is a critical aspect of this data set. At pre-sidedress time (late spring), the SMN for plots in maize following barley showed a large range from 25 to 175 kg ha^{-1} , and even 37 to 271 kg ha^{-1} for maize following

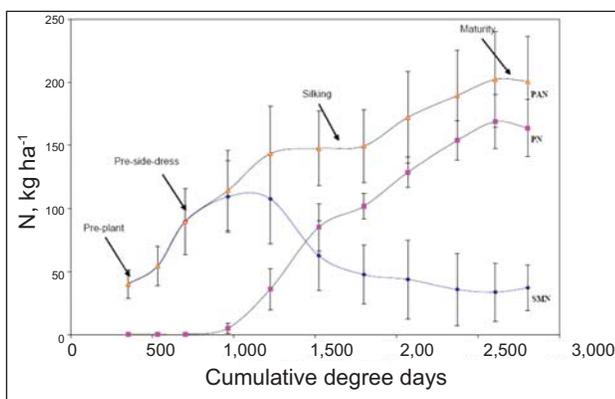


Figure 1. Accumulation of soil mineral N (SMN), total shoot N (PN), and plant available N (PAN) in the ON plots over the growing season. Bars describe standard deviations among years (from Kay et al., 2006; reprinted with permission).

barley+clover. At maturity, PAN ranged for 63 to 309 kg ha^{-1} for maize after barley and 93 to 333 kg ha^{-1} for maize after barley+clover. Much of the differentiation in available N therefore occurs early in the growing season (Kay et al., 2006).

On the average, lower landscape positions accumulated more PAN than upper positions, which can in part be explained by higher levels of organic matter (**Figure 2**). In all, year effects, as well as year by position by N rate were of similar magnitude, indicating that N management would need to be adjusted in response to changing weather conditions. Cumulative rainfall during the early season (period 200 to 700 CDD) showed a strong correlation with PAN at 2000 CDD (mid maturity), indicating the strong influence of early-season rainfall on plant N availability. **Figure 2** suggests that higher early-season rainfall requires greater supplemental fertilizer N due to losses of mineralized N, but with an interaction based on landscape position. Regression equations to estimate PAN developed by Kay et al. (2006) included early-season rainfall and multiplicative terms with organic carbon as predictor variables, providing relatively high predictability ($R^2 = 0.63$ to 0.70).

Yearly Optimum N Rate and Rainfall

Several studies in the Northeast U.S.A. determined that spatial variability in maize N response was minimal in most years, but poorly-drained areas justified higher N rates in excessively wet years, despite higher SOM levels (Katsvairo et al., 2003; van Es et al., 2005). A field study was conducted

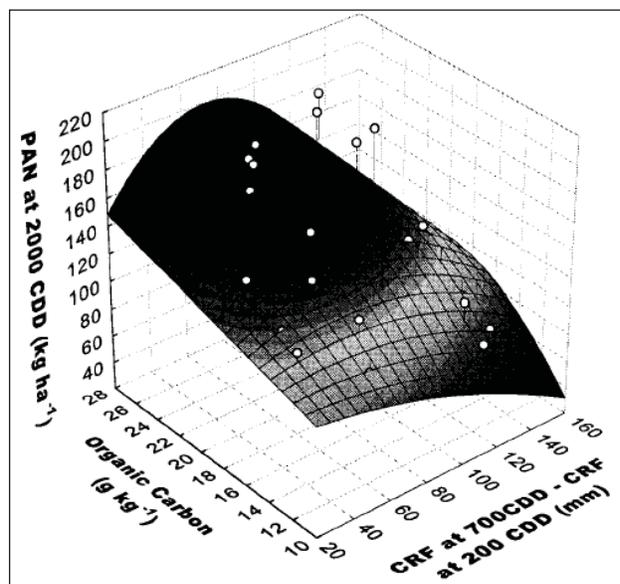


Figure 2. Variation in plant available N at 2000 CDD with organic carbon content and cumulative rainfall in the period 200 to 700 CDD for the barley-NT treatment, based on a regression equation with $r^2=0.63$ (from Kay et al., 2006; reprinted with permission).

Table 1. Optimum economic N rate for 5 years and three soil types of different drainage class expressed as deviations from the grand mean (adapted from Sogbedji et al., 2001).

| Soil type | Year | | | | | Mean deviation |
|-----------------------------------|------|------|------|------|------|----------------|
| | 1978 | 1979 | 1980 | 1981 | 1982 | |
| ----- kg N ha ⁻¹ ----- | | | | | | |
| Honeoye-Lima (mod. well drained) | -15 | -29 | 13 | -17 | 15 | -7 |
| Kendaia (swh. poorly drained) | -19 | -28 | 26 | -14 | 54 | 4 |
| Lyons (poorly drained) | -12 | -20 | 12 | -15 | 48 | 3 |
| Mean deviation | -15 | -26 | 17 | -15 | 39 | |

in New York State for a 5-year period from 1978 to 1982 involving three soil types of different drainage classes (moderately well, somewhat poorly, poorly) grown to maize (Sogbedji et al., 2001). For the 5 consecutive years, four rates of sidedress N (0, 55, 110, and 220 kg N ha⁻¹) were applied to multiple replicates on the three soil types. Maize grain yield response data were used to determine EONR using quadratic models, and assuming a fertilizer-to-grain price ratio of 3.3.

June precipitation amounts for this study were 112, 64, 144, 97, and 137 mm for 1978, 1979, 1980, 1981, and 1982 respectively. Both 1980 and 1982 experienced periods of excessive wetness, and yields were generally lower for those years (Sogbedji et al., 2001). **Table 1** lists the EONR for the three soil types and five growing seasons, expressed as deviations from the grand (overall) mean. Averaged across 5 years, EONR for each of the three drainage classes only ranged 11 kg N ha⁻¹, with the better-drained Honeoye-Lima areas requiring less N on the average than the other soils (**Table 1**). Most of the variability was associated with the poorly-drained soils (Kendaia and Lyons) requiring more N in one year (1982), which experienced excessive wetness in June. This suggests that EONR was minimally affected by drainage-related field variability, except for one out of five years when the poorly drained areas required higher N rates.

Generally, the optimum rates were similar for the 1978, 1979, and 1981 years (with dry springs), being 15 to 26 kg N ha⁻¹ below the grand mean for all drainage classes. In 1980 and 1982 (with wet late springs), optimum N rates were much higher, from

Table 2. Variance component analysis for year and drainage class effects (from Sogbedji et al., 2001).

| Source | Variance Component, kg N ha ⁻¹ | CV, % |
|-----------------|---|-------|
| Year | 501 | 12.4 |
| Drainage class | 0 | 0 |
| Year* dr. class | 73 | 4.7 |

17 to 39 kg N ha⁻¹ above the grand mean (**Table 1**), indicating that in these years significantly more N was needed to achieve optimum maize yields. For the 5-year period of this study, the field-averaged EONR had a range of 65 kg ha⁻¹. A variance component analysis (**Table 2**) corroborates that annual variability was the dominant source of variation for EONR, that drainage class (soil type) effects were insignificant, and that drainage class by soil type effect was significant in

that EONR was higher (about 50 kg N ha⁻¹ above the grand mean) on poorly drained soils in years with wet springs (Sogbedji et al., 2001).

A subsequent modeling effort was performed using LEACHM-N (Hutson and Wagenet, 1992), where soil N dynamics were simulated for the period March 1 to June 30 in each of the five growing seasons (assuming no fertilizer applied). Estimated denitrification and leaching losses, and the total environmental losses, were affected by both drainage class (soil type) and year (**Table 3**; Sogbedji et al., 2001). On an annual basis, LEACHM-N environmental N loss estimates within each drainage class were similar for the 1978, 1979, and 1981 years, but higher for 1980 and 1982. The model estimates therefore corroborate the agronomic data in that higher environmental N losses were estimated for the years with wet early growing

Table 3. LEACHM-N simulated environmental losses based on March 1 to June 30 simulations for three drainage classes and five growing seasons.

| Year | Environm. Losses | | (leach+denitr.) |
|--|------------------|---------|-----------------|
| | Denitrified | Leached | |
| ----- kg ha ⁻¹ ----- | | | |
| Honeoye-Lima (moderately well drained) | | | |
| 1978 | 5 | 14 | 19 |
| 1979 | 5 | 14 | 19 |
| 1980 | 12 | 40 | 52 |
| 1981 | 6 | 11 | 17 |
| 1982 | 15 | 35 | 50 |
| Kendaia (somewhat poorly drained) | | | |
| 1978 | 14 | 10 | 25 |
| 1979 | 16 | 1 | 27 |
| 1980 | 51 | 15 | 65 |
| 1981 | 17 | 7 | 24 |
| 1982 | 55 | 11 | 65 |
| Lyons (poorly drained) | | | |
| 1978 | 16 | 9 | 25 |
| 1979 | 17 | 9 | 26 |
| 1980 | 53 | 14 | 67 |
| 1981 | 21.0 | 5 | 26 |
| 1982 | 56 | 12 | 68 |

seasons and high EONRs, implying a greater need for supplemental fertilizer N in those years. Total losses were in general similar among the drainage classes but the denitrification process dominated for the poorly-drained soils (Kendaia and Lyons), while leaching was estimated to be more significant for the moderately well-drained soil.

Towards Dynamic N Recommendations

The above-discussed research, as well as other studies (e.g., Katsvairo, 2003, Kahabka et al., 2004; van Es et al., 2005, Scharf et al. 2006) demonstrate the significance of early-season weather conditions on the seasonal EONR. Although *mid-* and *late-*season weather may still affect maize yields, *early-*season events appear to be the strongest determinant for N availability. This is largely explained by the water and temperature dynamics during that period (**Figure 3**). In normal years, SOM mineralization generates an accumulation of mineral N in the soil, which may eventually contribute to about half of the required crop N (**Figure 3a**). The maize N uptake curve lags behind the SOM mineralization curve until the rapid uptake phase during the late vegetative period. During the late spring, high quantities of SMN reside in the soil profile that are mostly in the nitrate form and therefore subject to losses (**Figure 3a**). This is a critical period for N losses and seasonal N availability. If excessive rainfall occurs during this time, significant N losses may occur from leaching or denitrification (with warm soil). SMN accumulation is generally higher for soils high in organic carbon, but this may be subject to losses as well (Kay et al., 2006).

Losses are also affected by the accumulation of heat units over the first months of a growing season. In the case of a cool spring, N mineralization is slow, and the accumulation and subsequent loss of SMN is smaller when excessive wetness occurs

(**Figure 3a**). In all cases, the end result is that the supplemental N fertilizer rate varies greatly depending on water and temperature conditions during the entire early season, including the accumulated heat units, the occurrence and timing of excess wetness, and the soil temperature during those times of saturation (affecting denitrification rates; **Figure 3a**).

The low impact of mid- and late-season weather conditions on N rate is explained by the low probability for leaching and denitrification. The crop's water transpiration rate significantly increases once it enters the mid vegetative stage (rapid growth phase), greatly exceeding precipitation amounts in all but the most extreme wet years. Therefore, soils are being depleted of water, and high rainfall recharges a dry soil profile without causing excess wetness. This soil-water-N dynamic is in principle similar for other warm-season crops that are grown at the mid-level latitudes. Cool-season crops (e.g., winter cereals) on the other hand have higher synchronicity between soil N mineralization and crop uptake.

When maize N fertilizer recommendations are based on average or modal crop response using methods like MRTN (Sawyer et al., 2006a), this will generally result in excessive fertilization in years with dry springs, and inadequate fertilization in years with high early season N losses. In many cases, farmers opt to use higher rates (insurance fertilizer) for the uncommon case where they experience a wet early season. In the majority of years this results in excessive fertilizer application, unnecessary expense, and increased losses potentially impacting the environment (Sogbedji et al. 2000; Randall et al., 2006).

An analogous process occurs when additional organic N inputs are applied, as is often the case

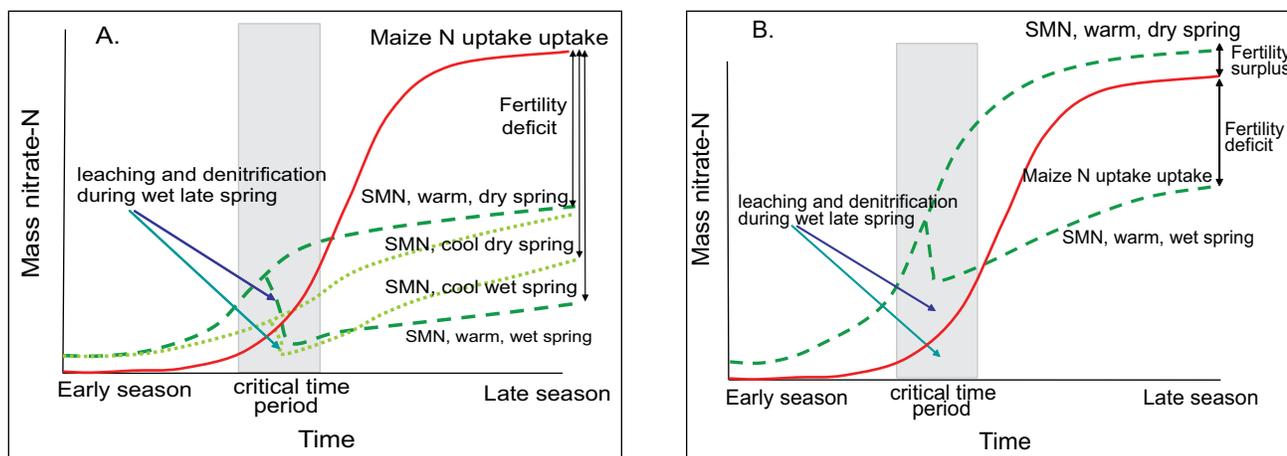


Figure 3. Conceptual gains and losses of soil mineral N and crop N over a growing season for a low soil N system (a), and a high soil N system (e.g., livestock; b). Broken and dotted lines represent SMN accumulations; solid line depicts maize N uptake.

with livestock farms. Organic N (manure, etc.) is commonly applied based on expected N release and maize N uptake during the following season (**Figure 3b**). This results in even higher SMN accumulations in the late spring and a greater potential for loss from excessive soil wetness. Livestock farmers then often face the challenge to decide on applying expensive supplemental sidedress N.

Modeling Approach

The EONR is strongly influenced by soil organic matter, soil water/temperature dynamics, and crop development during the early growing season. More precise management of N requires the explicit incorporation of these factors into the recommendation system. The current mass-balance and MRTN approaches fail to do so and are therefore implicitly limited in the achievable level of precision. One cannot accurately predict N fertilizer needs for maize at the beginning of the growing season (even less so during the previous fall), because one of the main determining factors (late-spring weather) is still unknown. Therefore, early-spring N applications cannot be precise, even with slow-release or nitrification-inhibition technology, and early season soil testing (e.g., ISNT and PPNT) can only achieve limited accuracy. Also, tools like lower-stalk nitrate tests are only useful as *ex-post* evaluations of crop N sufficiency and have limited use for predictive purposes.

It appears that late-spring assessments and subsequent applications have the most potential for improving N fertilizer management for maize. The PSNT is designed for that purpose, but has shown to be expensive, mainly due to sampling requirements, and somewhat imprecise. This is mainly due to the complexity of early-season N dynamics and the fact that the test only provides a “snapshot” assessment without incorporating temporal processes. Leaf and canopy sensing may ultimately show promise, but will similarly be limited by the instantaneous scope, as well as the fact that early-vegetative maize has small canopies available for sensing.

Our preliminary work indicates that dynamic simulation models allow for the incorporation of all relevant processes (soil water, temperature and N transformation processes; crop growth and water and N uptake) and their space and time dynamics for assessing maize N fertilizer needs. Melkonian et al. (2007; this issue) describe the development and implementation of such technology in New York State. The effective use of this approach requires (i) N fertilizer application in late spring (at least in some years), (ii) a well-validated dynamic soil-crop model, (iii) the availability of high quality climate and soil data, and (iv) a user-friendly framework for the use of the model. We postulate that the

prediction accuracy of the model may be further enhanced by information from other N management methodologies, including data on soil N availability from ISNT, PPNT, or PSNT.

Conclusion

The EONR for any field is not a fixed quantity, but varies as a result of several interacting factors. The most significant among those are early-season weather (precipitation and temperature), N mineralization from organic sources, and crop development. Most currently-used N fertilizer recommendation systems ignore these dynamic processes, and are therefore inherently limited in achieving precision. We propose to incorporate the complex interactive processes that affect soil mineral N availability into the recommendations. The PSNT and emerging crop sensing methods aim to address this need, but do not allow for time integration. The use of a process-based dynamic simulation soil-crop model appears to be the most promising approach, because it allows for the incorporation of multiple interacting factors and temporal processes.

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