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ADAPT-N: ADAPTIVE NITROGEN MANAGEMENT FOR MAIZE USING HIGH-RESOLUTION CLIMATE DATA AND MODEL SIMULATIONS

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ABSTRACT

Current approaches to estimation of optimum 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. However, denitrification and leaching losses of nitrogen may occur from dynamic and complex interactions among weather, soil hydrology, crop water and N uptake, and management practices, and result in high variability in annual crop N needs in maize (*Zea mays* L.) production. Several studies have corroborated that weather impacts the soil N pool early in the growing season and contributes to the well-documented variability in economic optimum in-season N rates for maize. Increased climate variability will make the need for adaptive N management even more compelling. Higher precision in N management for maize in humid regions 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. We developed the Web-based *Adapt-N* tool, which is based on the *P*recision *N*itrogen *M*anagement model and near-real-time high resolution climate data from the Northeast Regional Climate Center.. It simulates soil N transformations and soil N/water transport and maize N uptake/growth in near-real time using soil and management information, and generates recommendations that allow for greatly increased precision of N management and improved response to the effects of climate change.

Keywords: Nitrogen, climate, adaptive management, precision agriculture.

INTRODUCTION

Improved N use efficiency from cropping systems has become a compelling issue with increased N fertilizer prices and concerns about environmental impacts. Excessive nitrate levels in groundwater and N-induced hypoxia in estuarine areas from agricultural sources (McIsaac et al., 2002) are persistent concerns, as well as the high energy consumption for N fertilizer manufacturing and greenhouse gas impacts from soil N_2O losses (Smith and Conen, 2004). Maize, a C_4 plant, is physiologically more efficient at utilizing N (more yield per unit N accumulation) than most other major crops, which are generally C_3 plants (Greenwood et al., 1990). But paradoxically, maize production systems as a whole generally have low fertilizer N uptake and recovery efficiencies (RE). Through on-farm experiments in six North-Central US 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 rates is critical to reducing N leaching losses (Ostergaard, 1997). Studies by van Es et al. (2002) and Randall (2006) reported rapid increases in nitrate leaching with N rates above the "optimum" and highlighted the importance of precise estimation of seasonal fertilizer N needs. 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 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.

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.

Early season weather, particularly precipitation, has been highly correlated with seasonal variation in optimum fertilizer N rates and nitrate (NO_3)-N export via subsurface drainage from crop fields (Balkcom et al., 2003; Mitsch et al., 2001; Sogbedji et al., 2001a). Current in-season N recommendations for maize production in most states are static and do not take into account the dynamic behavior of soil N (van Es et al., 2002). These recommendations can be up to 60 to 80 kg N ha^{-1} higher or lower than the economic optimum in-season N rate in any given year. Improving the current in-season N recommendations for maize is critical to the credibility of the fertility recommendation systems. Increased N use efficiency is expected to reduce unused N that becomes either stored in SOM or lost to other parts of the environment during the fall-winter-early spring period (van Es et al., 2002).

Estimating Optimum N Rates

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). In humid regions, however, yield patterns themselves are 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.

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. 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 spatial and temporal processes that affect N availability to maize.

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). 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.

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 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.

Fourth, recent advances in remote and proximal crop sensing are applied for estimation of crop N status during the growing season. Leaf chlorophyll meters (Sawyer et al., 2006b) or multi-band aerial or in-field 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. Crop sensing appears to be successfully applied for N management on other crops (esp. wheat) and shows promise for use in maize.

Temporal Dynamics in Soil N

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 USA (Ketterings et al., 2003). 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.

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), 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 static methods for determining fertilizer rates 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). 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).

Kay et al. (2006) measured maximum mineral soil N levels in late spring, after which above-ground plant N uptake increases rapidly. The variability in mineral soil N is a critical aspect as late spring levels in this study under 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 barley+clover. Much of the differentiation in available N occured early in the growing season (Kay et al., 2006). Regression analysis showed that organic matter content (an N source) and early-season rainfall (driving force for N losses) were the main predictors of season N availability.

(Sogbedji et al., 2001c) found that years with excessive wetness in late spring showed lower maize yields and higher EONRs that other years. A subsequent modeling effort was performed using LEACHM-N (Hutson and Wagenet, 1992), where soil N dynamics were simulated for the spring period in each of the five growing seasons. Estimated denitrification and leaching losses, and the total environmental losses corroborated the agronomic data in that higher environmental N losses were estimated for the years with wet early growing seasons and high EONRs, implying a greater need for supplemental fertilizer N in those years.

Although mid- and late-season weather may still affect maize yields, *early*-season events appear to be the strongest determinant for N availability. 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 or environmental N losses.

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 1a). 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 soil mineral N (SMN) reside in the soil profile, mostly in the nitrate form and therefore subject to losses. 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 matter, 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 1a). 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 soil temperatures during those times of saturation (affecting denitrification rates; Figure 1a).

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, especially when fertilizer to crop price ratios are low, 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 with livestock farms. Organic N (manure, etc.) is commonly applied based on expected N release and maize N uptake during the following season (Figure 1b). 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.

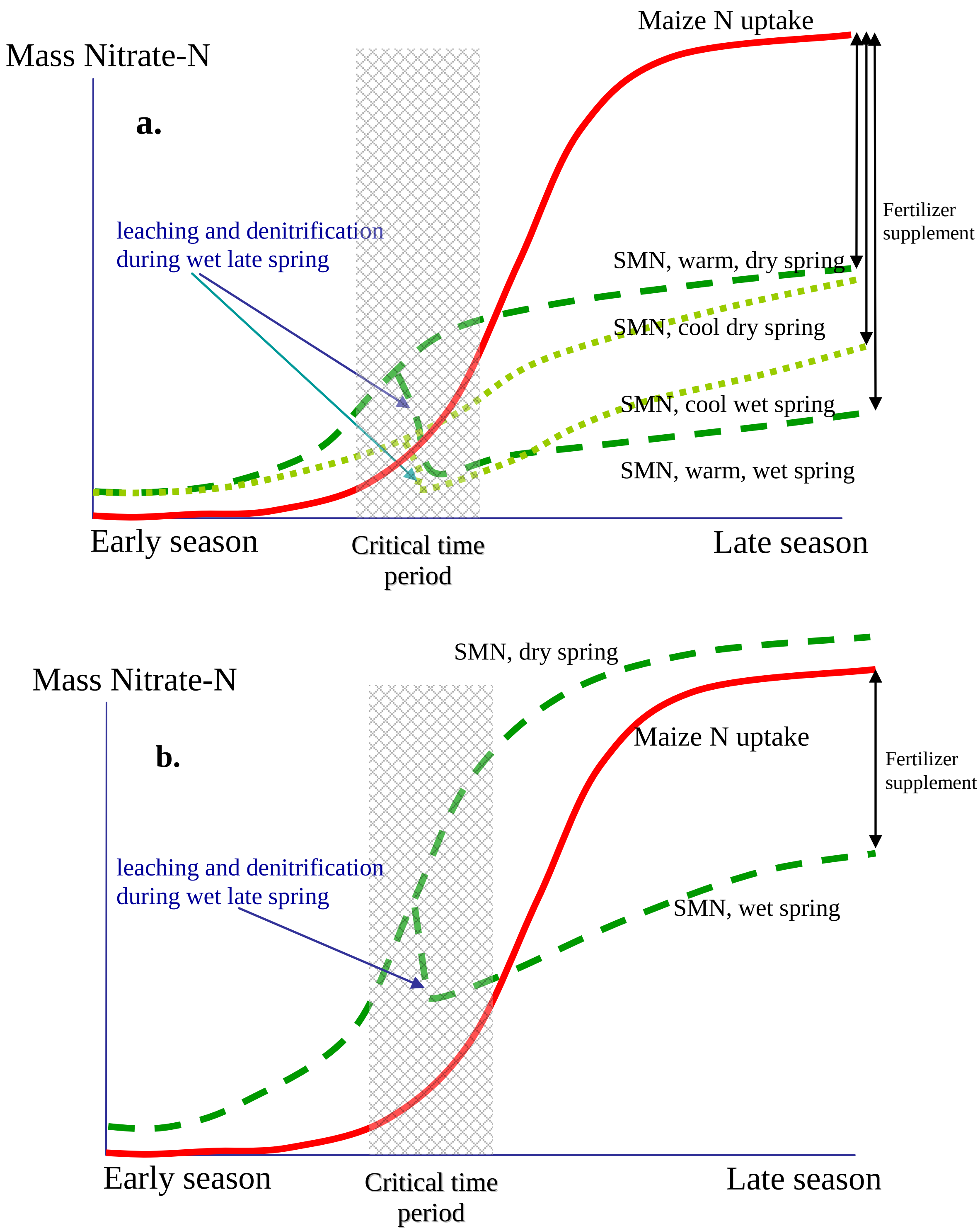

Figure 1. Conceptual gains and losses of soil mineral N and crop N over a growing season for a low soil N system (a), and a high soil N system (e.g., livestock; b). Broken and dotted lines represent SMN accumulations; solid line depicts maize N uptake.

Figure 2. Web user interface for the *Adapt-N* tool.

MODELING APPROACH

More precise management of N under maize in humid regions requires the explicit consideration of several interacting factors, including weather, 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. In humid regions, 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 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.

Adapt-N Tool

We have developed the Web-based *Adapt-N* tool (http://adapt-n.eas.cornell.edu/, Figure 2) to provide improved in-season N recommendations based on simulation of soil N dynamics and maize N uptake for conditions in the Northeast U.S.A. It is based on the Precision Nitrogen Management (PNM) model (Melkonian et al., 2005; Melkonian et al., 2007) and input of near-real time high-resolution climate data. Figure 3 shows a schema for the model implementation infrastructure. PNM has two components: LEACHN, the N (and phosphorus) module of LEACHM (Hutson, 2003; Hutson and Wagenet, 1992) and a maize N uptake, growth and yield model (Sinclair and Muchow, 1995). LEACHN is a process-based, one-dimensional model that simulates water and solute transport, and chemical and biological N transformations in the unsaturated soil zone (Hutson, 2003). LEACHN is well suited for simulating soil N processes and has been extensively used and tested in several studies (Jabro et al., 1994; Jemison et al., 1994a,b; Lotse et al., 1992; Sogbedji et al., 2001a,b; Sogbedji et al., 2006). The rate constants in the equations describing nitrification, denitrification, manure mineralization and plant residue mineralization were calibrated based on multi-year, replicated field experiments (Sogbedji et al., 2000; van Es et al., 2006). These field experiments were conducted on large, hydrologically isolated lysimeter plots located on two contrasting soil textural classes. Calibrations were based on a range of N management practices for maize production that are typically found in the Northeast U.S. Nitrate-N leaching, crop N uptake, and changes in soil NO_3-N and NH_4-N levels were intensively monitored (Sogbedji et al., 2001a; Sogbedji et al., 2006). In the PNM model, SOM mineralization is simulated using two rate constants instead of one as in LEACHN: a higher rate constant for early season SOM mineralization (up to July 15) and a lower rate constant later in the season, based on studies by Dharmakeerthi et al. (2005).

The crop component of PNM is based on a recent maize N uptake, growth and yield model developed by Sinclair and Muchow (1995). The models were re-coded and linked in PYTHON, an interpreted, interactive, object oriented programming language. Flows between different pools of C and N are simulated in each soil segment as well as on the soil surface.

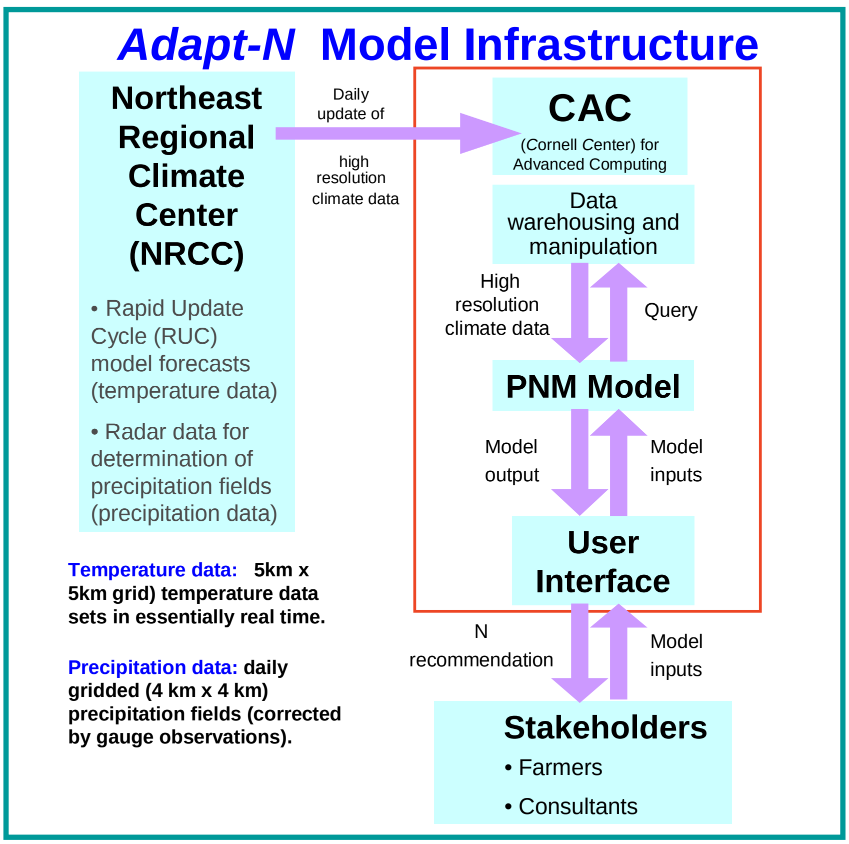

Figure 3. *Adapt-N* model infrastructure for use of near-real-time N recommendations.

Critical outputs of the PNM model are the simulation of mineralized N and losses through leaching, denitrification, and volatilization, as well as crop N uptake and biomass (vegetative and grain) accumulation. The subroutines of the maize N uptake, growth, and yield model incorporate the effects of temperature, solar radiation, water supply and parameters influencing the crop N budget during the three major phases of maize development: vegetative growth, anthesis, and grain fill (Muchow and Sinclair, 1991; Muchow et al., 1990; Sinclair and Amir, 1992; Sinclair and Muchow, 1995).

In order to effectively simulate N processes, the *Adapt-N* tool requires user information on relevant soil and crop input data, including soil textural class (fine, medium, coarse), drainage class, slope, tillage practices, organic matter content, timing and amounts of previous N inputs (fertilizer, manure, sod, compost, etc.), soil nitrate data (if available), crop maturity class, crop density, and tillage and planting dates (http://adapt-n.eas.cornell.edu/). This also allows for site-specific management by performing simulations for areas with different soil organic matter contents and drainage and textural classes in a field.

High Resolution Climate Data

In the *Adapt-N* tool the PNM model accesses the most up-to-date high-resolution climate data as input information by asking the user to provide latitude and longitude information for the field under consideration. The availability of such high-resolution data was deemed essential to the successful adoption of adaptive N management strategies, because spatial patterns of precipitation (especially) and temperature during Northeast USA growing seasons are highly variable at short distances. The commonly-used Applied Climate Information System (ACIS; Hubbard et. al., 2004 is based on weather station observations that are generally located 30 to 60 km apart. This is of inadequate resolution to capture local weather dynamics and therefore of limited use for farm-level simulation of N processes. The Northeast Regional Climate Center and the Cornell Center for Advanced Computing have developed methods to produce and distribute high resolution (4 x 4 km gridded) temperature and precipitation data for the Northeast. These data are updated daily on advanced database servers and can be automatically accessed by the *Adapt-N* tool for the location (longitude and latitude) inputted by the user (Figure 3). The high resolution temperature data are being derived from processing routines using the National Oceanic & Atmospheric Administration's (NOAA) Rapid Update Cycle (RUC) weather forecast model and data obtained from ACIS (Belcher and DeGaetano, 2005). The high resolution precipitation data are being developed from data obtained from NOAA's operational Doppler radars and data obtained from ACIS (Ware, 2005; Wilks, 2008). Simulating early-season soil N levels with high-resolution climate data allows for quite precise estimates of sidedress N needs and can improve N use efficiency in corn production systems (whether involving manure applications or not).

An additional dimension of the use of high-resolution climate data for adaptive N management is the ability to incorporate climate change into N management. Future climates are generally predicted to involve more extreme events and periods of excessive wetness and prolonged drought. The *Adapt-N* approach allows for accounting of such extremes and incorporation into N management.

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 promote an adaptive N management approach that incorporates the complex interactive processes that affect soil mineral N availability. The *Adapt-N* tool uses process-based dynamic simulation of soil-crop processes and inputs of high-resolution climate data towards this goal and allows for the incorporation of multiple interacting factors and temporal processes.

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