# *ADAPT-N*: A COMPUTATIONAL TOOL FOR PRECISE N MANAGEMENT IN CORN

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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. 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. 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.

## 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. 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.

In a recent policy report, Ribaudo et al. (2011) emphasized the significant role of corn in the nitrogen problem: "Corn is the most widely planted crop in the United States and the most intensive user of nitrogen. In 2006, corn accounted for an estimated 65 percent of the total quantity of nitrogen applied to major U.S. field crops. Corn also accounted for half of all nitrogen-treated crop acres that were not meeting the rate, timing, or method of application criteria used in this analysis to define acceptable nitrogen management […] In addition, recent demand pressures due to the biofuels mandate, as well as increasing international demand for feed grains, suggests that corn acreage and the intensity of corn production are likely to increase. Together, these factors increase the importance of raising the NUE in corn production in the United States, especially on farms that raise livestock and apply manure to their fields."

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. Similar concerns with N management have also been raised in the context of greenhouse gas emissions. Hoben et al. (2010) and van Groenigen et al. (2010) determined that nitrous oxide ($N_2O$) losses increased exponentially when crops are fertilized beyond crop uptake needs. The global warming impact of this is very significant and for maize this accounts for a disproportionate contribution to total agricultural greenhouse gas emissions (Ribaudo et al., 2011).

**Annual Variability**

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; Mullen et al., 2011). The need for "precise" management of N fertilizer is compelling, but the ability to estimate the true EONR has remained relatively elusive. 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 for the dynamic behavior of soil N (van Es et al., 2002). Improving the current in-season N recommendations for maize is critical to the credibility of 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).

In recent years, several leading US maize producing states have adopted the maximum return to N (MRTN) approach (Sawyer et al., 2006a). 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. 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.

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 stages 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. Mineralization of SOM can supply a significant fraction, with a typical value of 100 lbs/ac for Midwestern soils (Cassman et al., 2002), and lower estimated values (average of about 70 lbs/ac) 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).

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 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). Losses are also affected by the accumulation of heat units over the first months of a growing season, which interact with the occurrence of precipitation events, as well as management factors like date-of-planting, early fertilization, manure application, tillage, rotation, etc.. The end result is that the supplemental N fertilizer rate varies greatly depending on management as well as water and temperature conditions during the early season. Sogbedji et al., (2001c) found that years with excessive wetness in late spring showed lower maize yields but higher EONRs than other years, which is paradoxical to the mass-balance concept discussed above. 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.

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. 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.

## ***Adapt-N* Tool**

More precise management of N in corn production in humid regions requires the explicit consideration of several interacting factors, including weather, into the recommendation system. 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.

We have developed the Web-based *Adapt-N* tool (http://adapt-n.cals.cornell.edu; Fig. 1) to provide improved in-season N recommendations based on simulation of soil N dynamics and maize N uptake. In 2010, the tool was available for fields in the Northeast USA and Iowa, and will be available for the entire eastern USA by the 2012 growing season. 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 2 shows a schema for the model implementation infrastructure. PNM has two components: LEACHN, the N (and phosphorus) module of LEACHM (Hutson, 2003) 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; 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 lysimeter plots located on two contrasting soil textural classes.

The crop component of PNM is based on a maize N uptake, growth and yield model developed by Sinclair and Muchow (1995). 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. 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.

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.), crop maturity class, crop density, and tillage and planting dates (http://adapt-n.cals.cornell.edu/; Fig. 1). 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 (Graham et al., 2011).

**High Resolution Climate Data**

The *Adapt-N* tool 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 growing seasons are highly variable at short distances. The Northeast Regional Climate Center (NRCC) and the Cornell Center for Advanced Computing (CAC) 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 (Fig. 2). 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).

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.

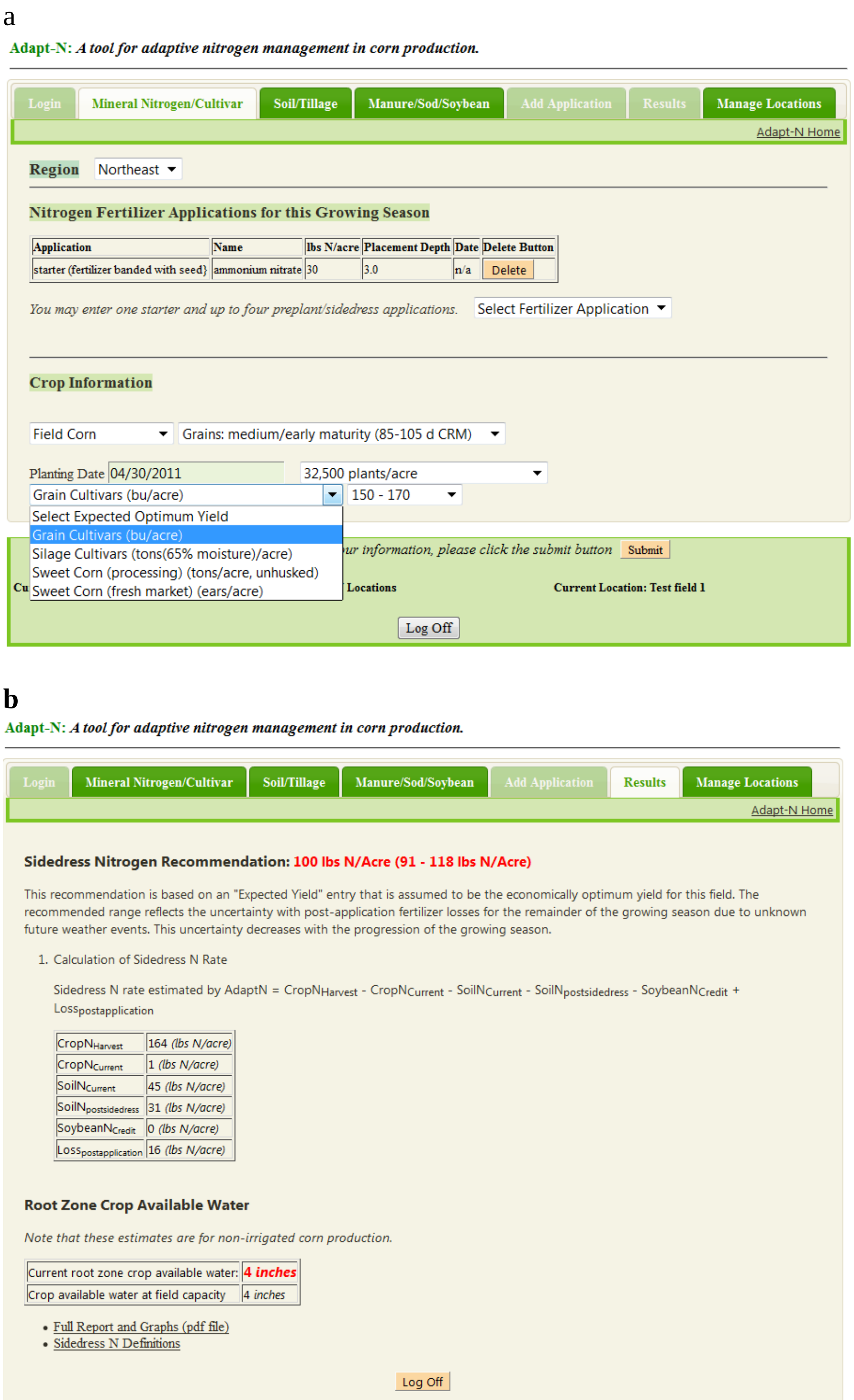


Figure 1. Web user interface for the *Adapt-N* tool: One of the input tabs (a) and the results tab (b).

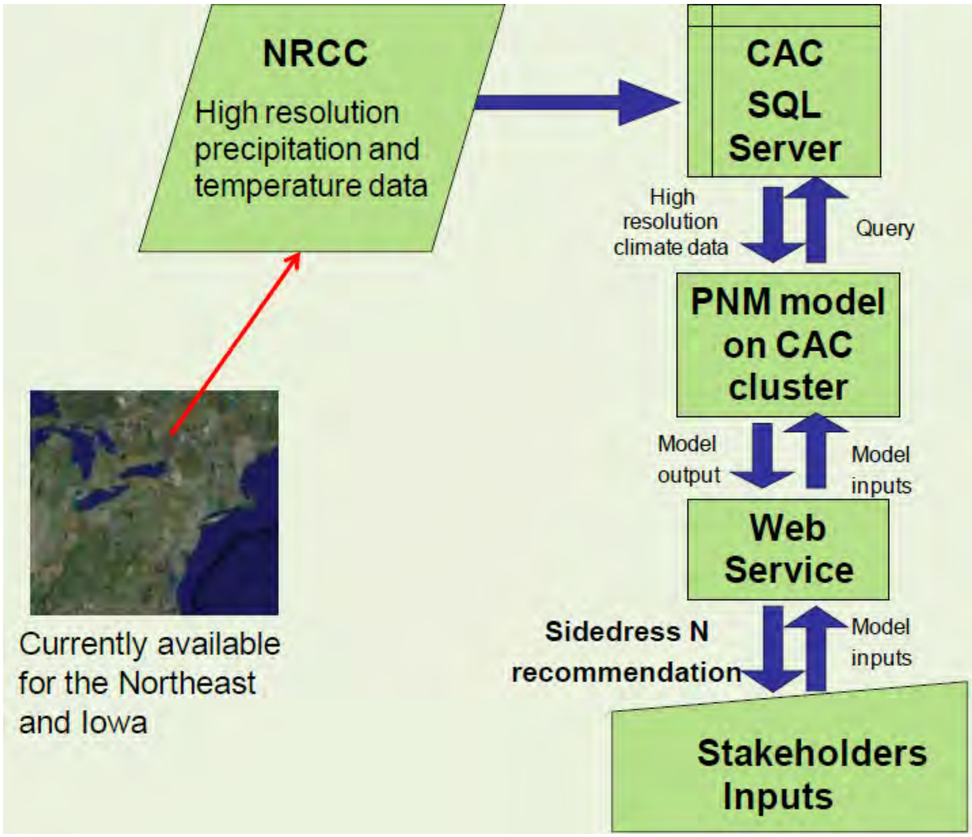


Figure 2. *Adapt-N* model infrastructure for use of near-real-time N recommendations.

**Adapt-N Outputs**

The Adapt-N tool provides a multitude of outputs that provide specific N management recommendations, as well as additional simulation results that offer insights into various process components that affect N dynamics. The results page (Fig. 1b) shows an N rate recommendation and the components of the N budget from which it is derived. In addition, profile water availability is provided. The report function (Fig. 1b) generates a report that includes input information, recommendations, and graphical simulation results in pdf format, which is useful for record keeping. Graphs that are generated include the following: 1. cumulative N mineralization, 2. cumulative N uptake by the crop, 3. cumulative total N losses (gaseous and leaching) from the root zone (Fig. 3), 4. cumulative N leaching losses from the root zone (Fig. 3), 5. nitrate N in the root zone (real time LSNT), 6. inorganic N in the root zone, 7. growing season daily and cumulative rainfall, 8. post-emergence growing degree days, 9. corn vegetative stage, and 10. growing season daily average temperature. These graphical results allow users to gain additional insights into N dynamics for the growing season at any time. Planned features for the Adapt-N tool include automated email or texting alerts, and incorporation of irrigation and cover crop inputs.

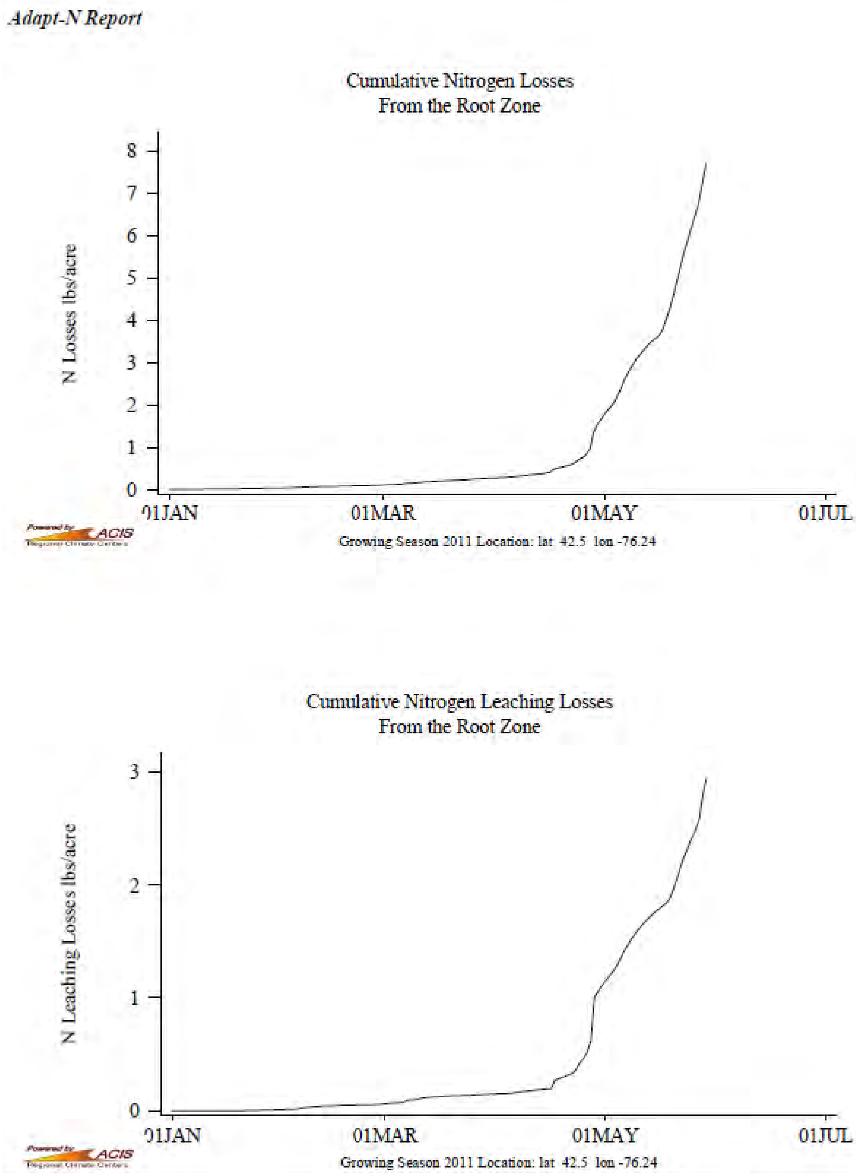


Figure 3. Example graphical results from Adapt-N tool.

## 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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