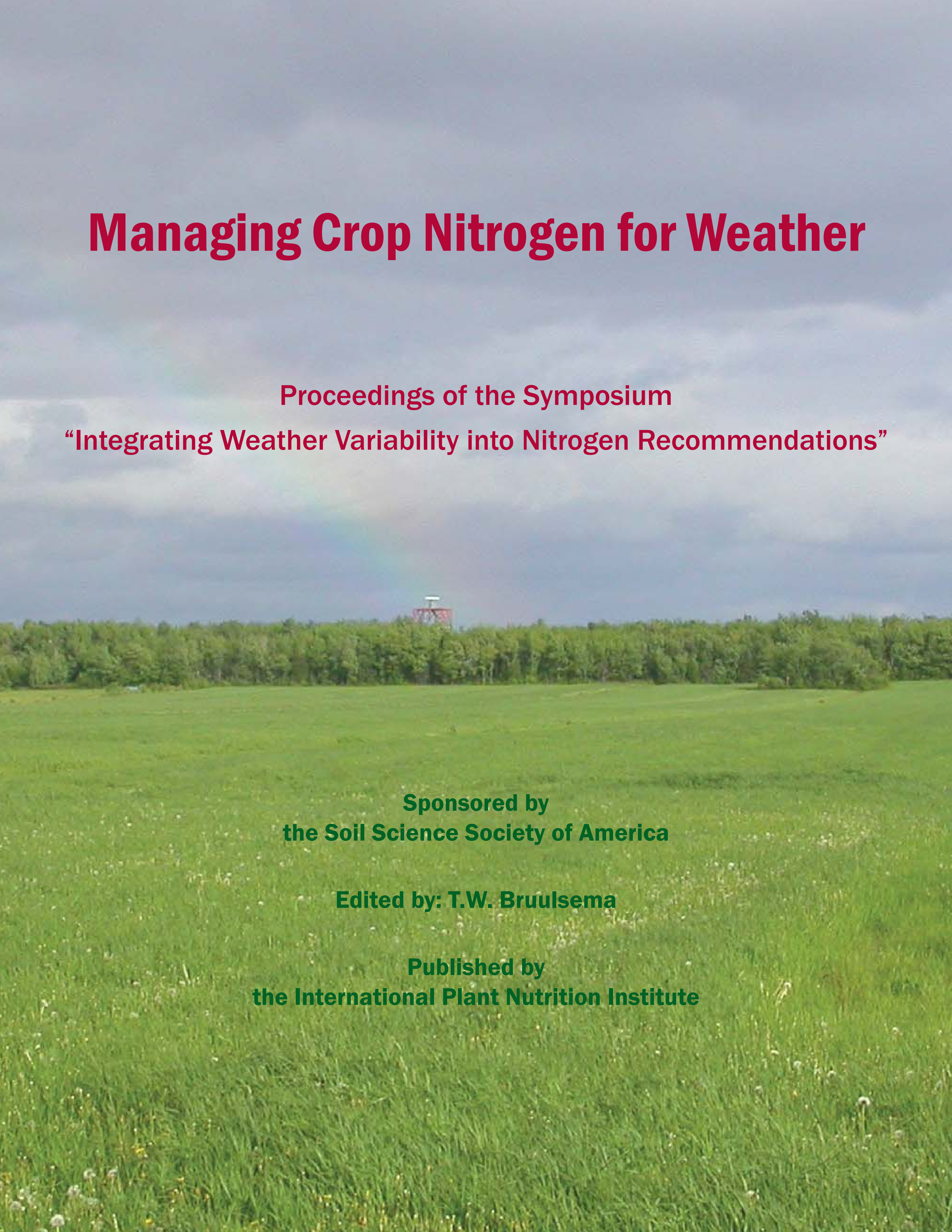

Managing Crop Nitrogen for Weather

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Application of Dynamic Simulation Modeling for Nitrogen Management in Maize

Jeff Melkonian*, Harold van Es, Art DeGaetano, Jean Sogbedji, and Laura Joseph

J. Melkonian and H. van Es, Department of Crop and Soil Sciences, Cornell University, Ithaca, New York 14853-1901, USA;
A. DeGaetano and L. Joseph, Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York 14853-1901, USA;
J. Sogbedji, Université de Lomé, Ecole Supérieure d'Agronomie, Lomé, Togo.
**Corresponding author: (jjm11@cornell.edu).*

Abstract

Denitrification and leaching losses of N in maize (*Zea mays* L.) production result from dynamic and complex interactions among weather, soil hydrology, crop water and N uptake, and management practices. Current tools for N management do not directly account for the dynamic behavior of soil N, limiting our ability to more efficiently manage N applications. Using dynamic simulation models as nutrient management tools represents a major step forward in the management of agricultural nutrient flows. We have developed the Precision Nitrogen Management or PNM model, composed of a dynamic simulation model of soil N transformations and soil N and water transport (LEACHN; Hutson, 2003) linked to a maize crop growth and N uptake model (Sinclair and Muchow, 1995). Our goal is to apply the PNM model to improve N use efficiency and reduce N losses in maize production. To achieve this goal, we are developing and testing new N management tools with the PNM model. One of these tools provides recommendations for in-season N applications for those growers who apply this N management practice. Current guidelines for these applications do not account for the impact of early season weather on soil N dynamics and the soil N pool available for crop uptake. Several studies have demonstrated 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. The response of the soil N pool to early season weather can be quantified with a well-calibrated dynamic simulation model such as the PNM model. Using this model, we generated adjustments to the recommended in-season N rates for maize in the 2004 to 2006 growing seasons for different climate regions in New York State. For 2007 and beyond, we are also developing a web-based version of this tool that will automatically access high resolution weather data from the Northeast Regional Climate Center at Cornell University. The availability of high resolution weather data will allow field-specific in-season N recommendations to be generated by the PNM model.

Introduction

In a companion paper in these proceedings, van Es et al. (2007) provided evidence that, in humid regions such as the northeast U.S.A. and southeastern Canada, N management tools have to account for the impact of early season precipitation and temperature on soil organic matter (SOM) mineralization and N losses. 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 New York State are static and do not take into account the dynamic behavior of soil N (van Es et al., 2002). These static 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 extension fertility recommendation system. These improved recommendations will allow producers to increase N use efficiency in maize production while maintaining or increasing crop productivity. 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).

Dynamic Simulation Models as Management Tools for Improved Crop N Management

van Es et al. (2007, Chapter 2, this issue) reviewed current tools for crop N management including mass balance approaches, recommendations based on long-term field studies at multiple locations, the use of in-field canopy reflectance measurements, and soil N tests such as the Presidedress Soil Nitrate Test (PSNT), an evaluation based on measurement of NO_3-N in the top 30 cm

Abbreviations: ACIS, Applied Climate Information System; GDD, growing degree days; N, nitrogen; NO_3, nitrate; NH_3, ammonia: NHG_4^+, ammonium; NOAA, National Oceanic & Atmospheric Administration; NRCC, Northeast Regional Climate Center; PNM, precision nitrogen management; P, phosphorus; SOM, soil organic matter; Ts, transpiration; BNN, Benchmark Net-N; CNN, Current-year Net-N.

of the soil profile. All of these approaches have strengths and weaknesses. However, some of them do not dynamically account for the impact of early season weather on soil N dynamics to adjust in-season N recommendations, and the use of canopy reflectance and the PSNT are limited in this regard. Canopy reflectance measurements can indicate crop response to changes in soil N but, in maize, Karimi et al. (2005) found no clearly distinguishable differences in canopy reflectance in response to variable soil N near the time of anthesis. The PSNT does provide a 'snapshot' of soil N in the top 30 cm. However, multiple PSNT samples within a season to capture early season N dynamics is not practical nor is the test calibrated for such use.

We believe that the application of well-calibrated and tested dynamic simulation models of soil N dynamics and crop N uptake represents a major step forward in our ability to manage agricultural nutrient flows (van Alphen and Stoorvogel, 2000; Schaffer et al., 2001). Such models account for changes in soil N (sources, losses, and changes in soil N storage in the root zone) and crop N uptake. In theory, the output of these models can provide information for growers to adjust in-season N applications to more precisely match crop N demand (Kersebaum, 1995; Smith et al., 1997; van Alphen and Stoorvogel, 2000).

A simple representation of the impact of early season weather on the accumulation of NO_3-N in the soil is shown in **Figure 3** of van Es et al. (Chapter 2) where the NO_3-N pool is the result of the mineralization and nitrification of organic N in SOM. Our hypothesis is that early season weather can significantly affect this pool size, resulting in a variable supply of soil N for uptake by a maize crop. The largest impact of early season weather on soil N is during the critical time period when the soil NO_3-N pool is rapidly increasing in response to warmer soil temperatures, while crop N uptake is still low.

We have used dynamic simulation modeling to estimate the size of this early season soil N pool and adjust in-season N recommendations over the past several years for locations across New York state. We describe the dynamic simulation model that we used, linkage of the model to weather data, and the methods for improving current in-season N recommendations for New York state using modeling and weather data. The application of these recommendations is restricted to those growers who are able to practice in-season N applications in maize.

Model Development

We have developed a dynamic simulation model of soil N dynamics and maize N uptake, the Precision Nitrogen Management (PNM) model (Melkonian et al., 2005), for improving current in-season N recommendations for maize in the humid Northeast U.S. and Southeastern Canada. The PNM model has two components: LEACHN, the N (and P) 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). Components of LEACHN have been successfully incorporated into an N management tool for determining optimal topdress N rates for winter wheat (*Triticum aestivum* L.) crop production (van Alphen and Stoorvogel, 2000). We have also calibrated and tested the LEACHN model for applications in the humid Northeast U.S. (Sogbedji et al., 2001a,b).

Although LEACHN has a crop growth component, it was not intended as a crop growth model (Hutson, 2003). Therefore, in the PNM model, we replaced the LEACHN crop growth module with a more sophisticated crop model simulating maize N uptake and growth. This maize model is based on a recent maize N uptake, growth, and yield model developed by Sinclair and Muchow (1995). We focused on modeling maize in PNM model development because it is a major row crop in the northeast U.S.A. and southeast Canada, and the highest NO_3-N leaching potential has been found under this crop compared to less fertilized annual crops (e.g., soybeans and wheat), and perennial crops (e.g., alfalfa and grasses) [Randall et al., 1997; Mitsch et al., 2001, van Es et al., 2002; van Es et al., 2007 (Chpater 2)]. In particular, average annual groundwater NO_3-N levels have been measured that are generally well above the critical 10 mg L^{-1} level in areas under maize production even when growers applied N at the levels recommended by state extension services [van Es et al., 2002; van Es et al, 2007 (Chapter 2)]. This underlines the need for improved N management tools for maize production and/or a reassessment of the appropriateness of the nitrate standard in subsurface waters.

PNM Model Description

LEACHN and the maize N uptake, growth, and yield model (Sinclair and Muchow, 1995) were re-coded and linked in PYTHON, an interpreted, interactive, object-oriented programming language. The input and output interfaces of the PNM model were developed by reconfiguring the original LEACHN model interfaces using PYTHON. Flows between different pools of C and N are simulated in each soil segment as well as on the soil surface. The PNM model used the capacity water flow option in LEACHN to calculate water and N fluxes, and runs on a daily time step. Equations and descriptions of the processes in LEACHN are presented in Hutson (2003) and Hutson and Wagenet (1992). Critical outputs of the PNM model are the simulation of mineralized N and N 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 incorporated 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). Equations and descriptions of the processes in the model are presented in Sinclair and Muchow (1995). The maize N uptake, growth, and yield model has been well tested and provides a reasonable fit to data that were collected over a range of conditions and were independent of those used in model development (Sinclair and Muchow, 1995). As a note, PYTHON class structure allows for efficient implementation of additional crop models into the PNM model.

Linking the PNM Model to Weather Data

Currently, the PNM model utilizes temperature and precipitation data obtained from an operational real-time climate database maintained by the Regional Climate Center Program. This system is known as the Applied Climate Information System (ACIS) (Hubbard et. al., 2004). The model uses ACIS methods to request weather data, specifying weather station, weather variable and date range of interest. Both historical and current (real time) weather data are available from weather stations.

In the near future, the PNM model will utilize high resolution data provided by the Northeast Regional Climate Center (NRCC). The high resolution temperature data set is being developed from the National Oceanic & Atmospheric Administration's (NOAA) Rapid Update Cycle (RUC) weather forecast model and data obtained from ACIS (DeGaetano and Belcher, 2007). Temperature will be available at a 5-km resolution. The high resolution precipitation data set is being developed from data obtained from NOAA's operational Doppler radars and data obtained from ACIS (Ware, 2005). It will be available at a 4-km resolution.

PNM Model Calibration

LEACHN Component

Hutson and Wagenet (1991), Jemison et al. (1994a), and Lotse et al. (1992) reported that LEACHN model output was sensitive to changes in the rate constants for equations describing nitrification, mineralization, and denitrification. Sub-surface NH_3 volatilization had little impact on model output. As a note, LEACHN does not currently account for NH_3 volatilization from the soil surface. This will be added to the LEACHN component of the PNM model in 2007. 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. The experiments included a range of N management practices for maize production that are typically found in the northeast United States. Nitrate-N leaching, crop N uptake, and changes in soil NO_3-N and NH_4-N levels were intensively monitored. Estimates of denitrification were obtained by the difference between N inputs and N losses. We note that N flux to SOM was not accounted for, and consequently, denitrification may be overestimated. Calibration efforts focused on the nitrification, denitrification, manure mineralization, and plant residue mineralization rate constants for the LEACHN component of the PNM model (Sogbedji et al., 2001a; Sogbedji et al., 2006). Simulation of SOM mineralization was slightly modified from the original LEACHN. In the PNM model, SOM mineralization was 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. The decision to use two SOM mineralization rate constants was based on examination of data from a long-term study of SOM mineralization in a maize-barley rotation (Dharmakeerthi et al., 2005) and several years of soil N measurements from fallow plots that had previously been in maize (Schindelbeck and van Es, unpublished). Both studies reported a rapid early season accumulation of soil N from SOM mineralization with little additional accumulation after approximately mid-July. Values for the two rate constants were calibrated to provide a good fit between simulated and reported soil N levels and crop N uptake from studies involving second year or more of maize rotations (Cox et al., 1993; Singer and Cox, 1998; Cox and Cherney, 2001) where inputs for these simulations were obtained from the reported studies. We have several field studies currently underway to better quantify SOM mineralization in a maize rotation in relation to tillage practice, soil texture and soil temperature/moisture. These data will be used to refine the SOM mineralization rate constants. The SOM mineralization rate constant was calibrated based on data from a long-term study of SOM mineralization in a maize-barley rotation (Dharmakeerthi et al., 2005).

Maize N Uptake, Growth, and Yield model

Several components of the maize N uptake, growth, and yield model (leaf appearance, sensitivity of leaf area development to soil water content and specific leaf N, and crop transpiration) were slightly modified to improve PNM model performance. The parameters for leaf appearance as a function of growing degree days (GDD) (Muchow and Carberry, 1989) were adjusted from the original model based on data from Cox et al. (1990a). In the PNM model, GDD is calculated as mean daily temperature over a base (10ºC) for mean daily temperatures between 10ºC and 30ºC. Mean daily temperatures above or below this range are set to 30 ºC and 10 ºC, respectively (Sinclair and Muchow, 1995). We also adjusted parameters in the equation calculating transpiration (Ts) from biomass accumulation (Amir and Sinclair, 1991; Muchow and Sinclair, 1991) to produce daily Ts values typical for maize at Northeastern U.S. and Southeastern Canada latitudes (Jara et al., 1998). The equation describing the theoretical relationship between specific leaf N and canopy radiation use efficiency (Sinclair and Horie, 1989) was modified based on measured data reported by Muchow and Sinclair (1994). Parameters in the equation describing leaf area development as a function of soil water status (Muchow and Sinclair, 1991) were modified based on field measurements relating leaf area index to soil water status for maize grown in the northeast U.S. (Cox et al., 1990b).

PNM Model Performance

Sogbedji et al. (2001b) reported on the performance of the LEACHN component of the PNM model after calibration based on data from Sogbedji et al. (2000). Statistical tests comparing measured and simulated NO_3-N leaching data indicated that calibration of the model was necessary by broad soil texture class (coarse, medium, fine) and where significant organic N inputs were affecting N dynamics. Based on this information, Sogbedji et al. (2006) recalibrated the LEACHN component of the PNM model using data from van Es et al. (2006) who reported on a multi-year study tracking N flows on different soils and timings of manure applications to maize. Following model calibration, Sogbedji et al. (2006) compared simulated vs. measured monthly drain flow NO_3-N concentrations. Statistical tests comparing simulated and measured data using a linear regression model with a slope of 1.0 and an intercept of 0 (a 1:1 line) indicated quite low prediction errors. Correlation coefficients for the tests ranged from 0.63 to 0.96 (Sogbedji et al., 2006).

Sinclair and Muchow (1995) and Muchow and Sinclair (1995) examined the performance of the maize N uptake, growth, and yield model incorporated into the PNM model. They found excellent agreement between simulated and measured N uptake, total biomass and grain yield (from experiments independent of those used in model development) for N applications of up to 240 kg N ha^{-1}. We have also found good agreement between measured and PNM model-simulated maize N uptake and yield for a number of locations in New York state.

Model Application for In-Season N Recommendations

Starting in 2004, we developed PNM model-generated adjustments to the current in-season N recommendations (Ketterings et al., 2003) for maize production in New York State. These adjustments were calculated twice a week during June, the peak time for in-season N applications to maize in the state. PNM model simulations were done for three soils representing the range of soil textural classes found under maize production in New York State. Model-generated adjustments by soil textural class were developed for each of the 16 climate regions of New York State where the climate regions are defined based on differences in long-term precipitation and temperature averages (**Figure 1**).

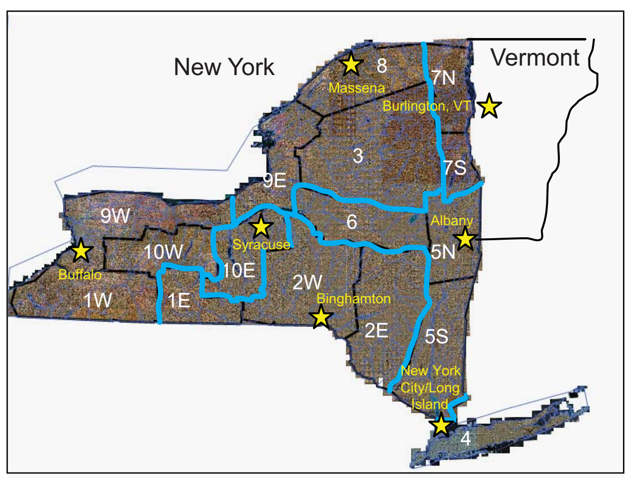


Figure 1. Climate regions of New York state, defined by historical precipitation and temperature averages. The stars (☆) indicate locations where mean Benchmark Net-N (BNN) was calculated from 35 climate year simulations. The climate regions where the BNN for a particular location were applied are outlined (—). The BNN was used to calculate adjustments to current in-season N recommendations for maize in New York state.

These model-generated adjustments to current N recommendations were intended for producers with maize that followed one or more previous crops of maize in the rotation, where the N sources were inorganic fertilizer and SOM mineralization. In future years, we will provide model-generated N recommendations for the first year of maize in a rotation, as well as maize grown after one or more previous crops of maize. We will also include both inorganic and organic sources (SOM, manure and a previous perennial legume or grass crop).

Calculation of Benchmark Net-N (BNN)

Multiple climate year simulations were done at each location to obtain long-term averages for root zone N (NH_4-N + NO_3-N). We refer to these average root zone N contents as BNN since they represent long-term average root zone N for current N management in maize. The rationale for using BNN based on PNM model simulations is that these values are model estimates of the average N available to the crop under current N management guidelines. Values of BNN were calculated from model simulations over 40 climate years for the following locations in New York state: Buffalo, Binghamton, Syracuse, Albany, Massena, and Islip, and one location in Burlington, Vermont (**Figure 1**). These sites were selected based on their proximity to major maize production areas in New York state and availability of at least 40 years of complete climate records. BNN was calculated from the root zone soil NO_3-N + NH_4-N at planting (kg N ha^{-1}) plus N additions (fertilizer and N from mineralization of SOM in the root zone, kg N ha^{-1}) minus N losses from the root zone (ammonia volatilization, denitrification, leaching and crop uptake, kg N ha^{-1}). Values of BNN by location and soil textural class were calculated for the following dates: 1, 8, 15, 22, and 29 June for each year in the 40-year simulations. For each location, mean BNN across climate years were then calculated for each date and by soil textural class from the past 35 climate years (data from the first 5 years of the simulations were not used for calculating the mean BNN; these years were used to initialize the N and water content distributions in the root zone for the particular scenario [**Table 1a**]).

The purpose of doing a large number of climate years was to quantify the impact of weather variability, at each location, on early growing season soil N dynamics and crop N uptake. The crop input data (a mid-maturity maize cultivar, 10 May planting date, and a plant density of 7.2 plants m^{-2}) were typical for New York state. Soils input data required by the LEACHN component of the PNM model were obtained from Sogbedji et al. (2001a) and Sogbedji et al. (2001c) for the soils in the three soil textural classes. We selected an in-season N rate of 125 kg N ha^{-1}, the recommended in-season N rates for continuous maize (Cherney et al., 2004, p. 43). This recommended rate varied by 10 to 20 kg N ha^{-1} with soil texture, so we tested simulations with in-season rates of 100 and 150 kg N ha^{-1}. These gave similar results to the 125 kg N ha^{-1} rate, so only the 125 kg N ha^{-1} in-season N simulations were used in the BNN calculation for a given location. N contributions from soil organic matter, organic carbon, and N maize stover following grain harvest were reset each year. This was done to avoid possible carryover effects of these factors on soil N dynamics and crop N uptake that would be independent of seasonal weather.

Table 1a. Mean Benchmark Net-N (BNN) used in the calculation of the 30 June 2006 adjustments to current in-season N recommendations for maize in New York State.

Location	Mean BNN by soil texture		
	Fine	Medium	Coarse
	- - - - - - kg N ha-1 - - - - - -		
Albany, NY	67	69	71
Binghamton, NY	62	65	66
Buffalo, NY	65	67	70
Massena, NY	67	68	71
Islip, NY	67	68	69
Syracuse, NY	63	66	67
Burlington, VT	66	68	69

Adjustments to Current In-Season N Recommendations to Maize

The overall procedure for adjusting current in-season N recommendations was to simulate root zone N contents (kg N ha^{-1}) for different times in June and for selected locations across New York State using model inputs representing the current management practices for maize following one or more previous crops of maize (Ketterings et al., 2003). Current year net-N (CNN) were calculated similarly to mean BNN, except that only the current year's data were used (**Table 1b**). CNN and mean BNN were compared twice a week for each of the 16 climate regions during June of 2005 and 2006 where the climate regions associated with the different BNN location are shown in **Figure 1**. The assumption we made is that when CNN deviated from

Table 1b. Current Net-N (CNN) by soil texture on 30 June 2006 for the 16 climate regions in New York state.

Climate Region	Precipitation (June, 2006)	CNN by Soil Texture		
		Fine	Medium	Coarse
	(mm)	- - - - - - - - kg N ha^{-1} - - - - - - - -		
1 East	163	50	58	60
1 West	68	75	76	75
2 East	277	35	43	46
2 West	239	45	52	57
3 (Adirondacks)	258	27	34	40
4	151	52	61	65
5 North	233	37	45	50
5 South	216	39	47	50
6	251	39	46	49
7 North	88	59	66	61
7 South	187	47	53	58
8	135	54	61	61
9 East	128	65	71	67
9 West	67	81	80	83
10 East	148	51	60	58
10 West	97	80	82	80

mean BNN by at least ±10 kg N ha^{-1}, adjustments needed to be made to recommended sidedress rates (**Table 2**). Deviations in a given year represented the effect of early season weather in that year on root zone N content. This is the same general approach to the calculation of the current sidedress N recommendations for maize in New York state (Ketterings et al., 2003) with the critical exception that we dynamically account for the impact of early season weather on soil N in the current year rather than rely on an efficiency factor for crop N uptake that is constant for a given soil texture regardless of early season weather.

Bulletins were sent to Cornell Cooperative Extension field crop extension staff and crop consultants in New York state that included the suggested adjustments (**Table 2**). In addition, these bulletins contained summaries of early season weather for different regions in New York State with particular reference to possible impacts on N losses. Early spring (March – May) 2006 was generally cooler and drier for most of the climate regions when compared with the 30-year averages of the locations shown in **Figure 1**. SOM mineralization was lower resulting in moderate N losses and upward adjustments (**Table 2**) for the climate regions that experienced high June precipitation (**Table 1b**). For these regions (largely in central and eastern New York), individual growers would have had to determine if the upward adjustments were significant enough to justify the cost of the additional N at sidedress.

We expect to include information on the costs and benefits of the suggested adjustments in future years. Similarly, climate regions in western New York that experienced lower precipitation in June 2006 than the 30-year average (1W, 9W, 10W; **Table 2**) generally had more moderate downward adjustments than if the early spring temperatures had been higher. Although these downward adjustments were modest, the cost savings for a farm with 300 ha of grain maize would have been approximately $3000 to $3500 at the average 2006 price for liquid urea ammonium nitrate ($0.77/kg N) typically applied at sidedress. This does not include the benefits of reduced N losses to the environment. The bulletins also included information to guide interpretation of PSNT values for maize production systems with organic N inputs, where the information was based on the extent of simulated N losses for each climate region. Field crop extension staff were encouraged to contact us if the rainfall totals in their area were significantly different from the weather data used in the simulations for their climate region. When such a case arose, we ran model simulations using weather data from weather stations suggested by the staff that were more representative of their area, calculated CNN, and provided more site-specific suggested adjustments to the current in-season N recommendations.

We have confidence in the application of BNN for dynamic adjustments to current year in-season N applications. Our 35-year average simulated N in the top 30 cm at sidedress (mean BNN) is very similar to 6-year average PSNT values for 27 sites in New York State that were in continuous maize (with no organic inputs) production using recommended N management practices (Klausner et al., 1993).

2007 Growing Season and Beyond

We will continue to offer adjustments to current in-season N recommendations by climate region for New York state. These will be provided via bulletins and as a web-based interactive map where users can click on their climate region, select a soil texture from a pull-down menu, and receive the suggested adjustments. The adjustments will be updated twice weekly during June based on PNM model simulations. This information is primarily intended for inorganic N for maize following one or more years of maize. We will also run 40-year simulations and current-year simulations by climate region for a

Table 2. Late June (30 June 2006) adjustments to the current in-season N recommendations for maize for three soil textures in the 16 climate regions of New York state. These adjustments were included in a bulletin sent to Cornell Cooperative Extension Field Crop staff and crop consultants. Adjustments were based on model-generated information in Tables 1a and 1b.

Climate Region	Recommended adjustments to current in-season N rates by soil texture		
	Fine	Medium	Coarse
	- - - - - - - - kg N ha^{-1} - - - - - - - -		
1 East	+10	+10	+10
1 West	-10	-10	-10
2 East	+20	+20	+30
2 West	+20	+15	+15
3 (Adirondacks)	+35	+35	+35
4	0	+10	+15
5 North	+20	+30	+35
5 South	+20	+20	+30
6	+20	+20	+30
7 North	+10	0	+10
7 South	+10	+15	+20
8	+10	+10	+15
9 East	0	0	0
9 West	-15	-15	-15
10 East	+10	+10	+10
10 West	-10	-15	-15

limited range of manure application scenarios and scenarios for first year maize following an alfalfa sod, since alfalfa is typically grown in rotation with maize in New York state. Values for BNN will be compared with CNN by climate region as described above.

From 2004 to 2006, we have only been able to offer adjustments to the current sidedress N recommendations by climate region because weather station data are not at a high enough resolution (approximately one station per 1500 km^{-2}) to allow farm- or field-specific applications of the model. There can be significant local variations in temperature – and, in particular, precipitation – that are not reflected in the weather station data due to local topography and the complex nature of weather systems in New York state. This local variability in temperature and precipitation has a significant enough effect on soil N dynamics, crop growth, and N uptake that, without higher resolution weather data, we have only been able to offer adjustments to current in-season N recommendations by climate region and not for individual fields up to this time. In the near future, we will have access to high resolution weather data from the NRCC at Cornell (DeGaetano and Belcher, 2007). These will be available on 5 km grids for temperature and 4 km grids for precipitation. This is a high enough resolution that we can make field-specific adjustments in addition to the more general climate region adjustments already in place.

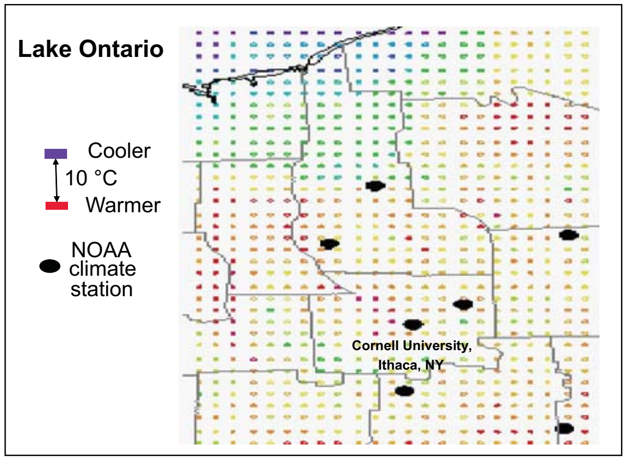


Figure 2. Maximum temperature data at 5-km grid resolution for 1 June 2006 for central New York state. The color code represents a temperature range of 10 ºC. Overlaid on the grid are the NOAA weather stations in that region, represented by the large black ovals.

High Resolution Weather Data

Gridded high resolution maximum temperature range for 1 June 2006 is shown in **Figure 2.** Also included are the weather station locations. Close inspection of the gridded data shows that maximum temperature can vary significantly (> 3 to 5ºC) within the expected reporting range of an individual weather station. Differences in air temperature of this magnitude will affect soil temperature and, therefore, the N transformation processes in the LEACHN component of the PNM model, since these processes are dependent on soil temperature through the calculation of a temperature correction factor (Hutson, 2003).

Figures 3a and b show daily total precipitation (cm) on 28 June 2006 for the Northeast U.S. obtained from weather stations (Figure 3a) and high resolution precipitation fields generated from Doppler radar and ACIS data (Figure 3b). The color-coded daily precipitation totals generated by the processed and interpolated radar data compare well to the daily precipitation totals reported by the station data across the region. Note that the radar-generated data provide finer resolution than the station data where daily precipitation totals change over relatively short distances. This can be seen in the area to the north and west of the main

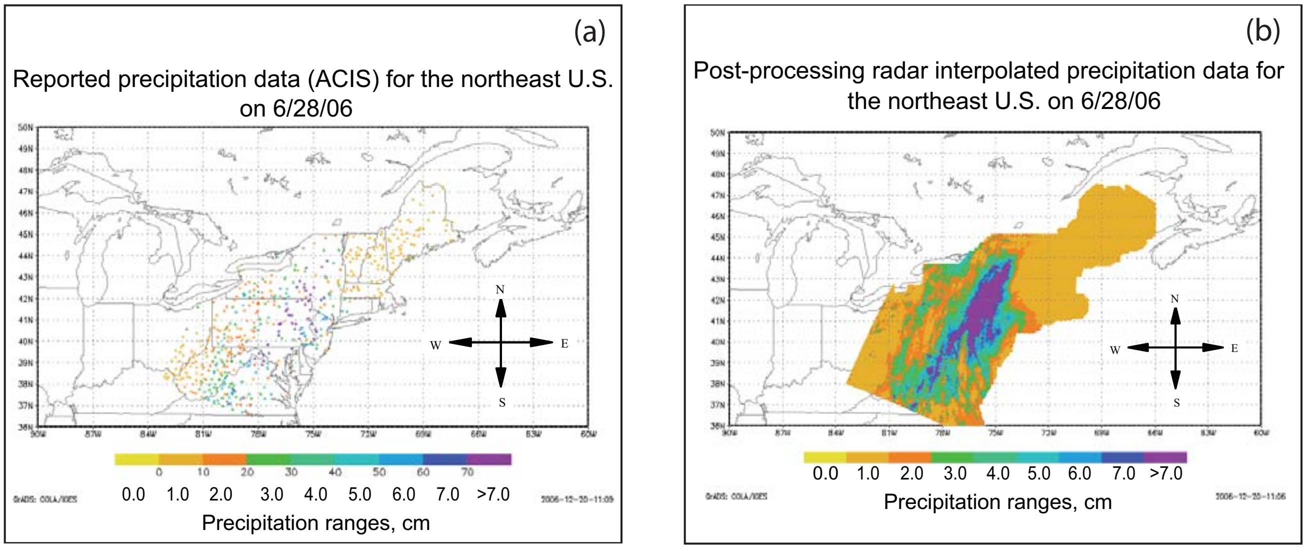


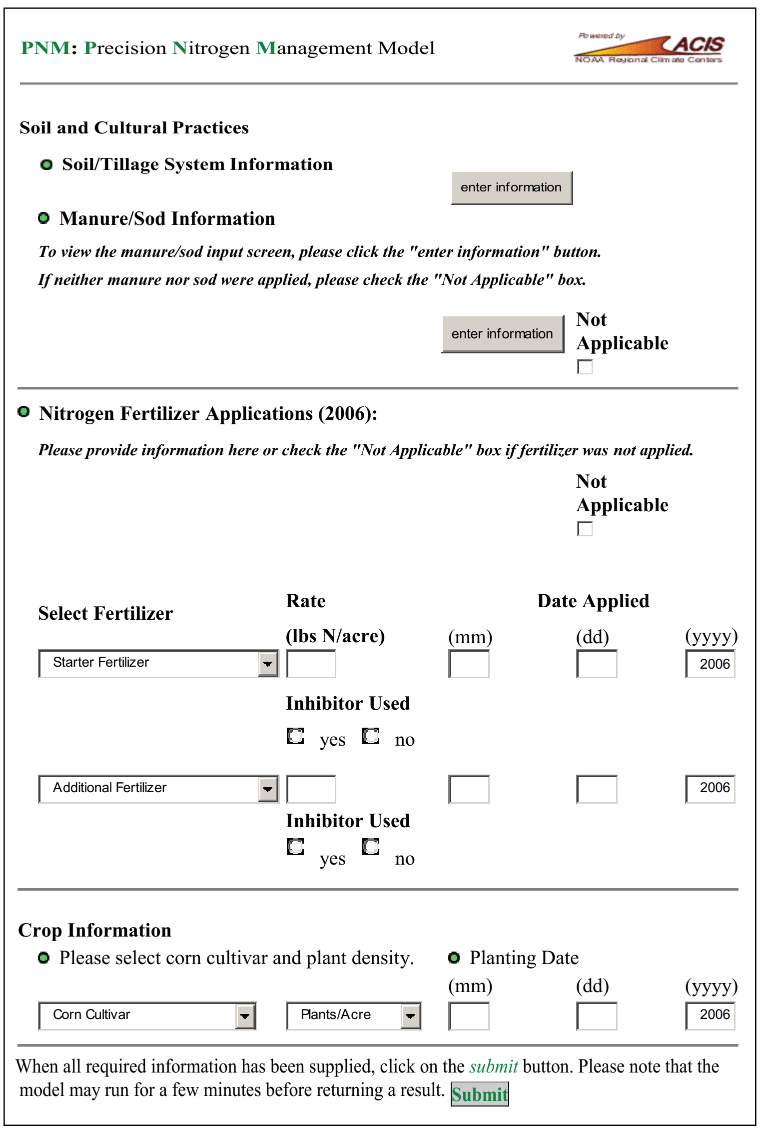
Figure 3. (a) Weather station precipitation totals for 28 June 2006 in the northeast U.S. obtained from an operational real-time climate database maintained by the Regional Climate Center Program using Applied Climate Information System methods, and (b) post-processing interpolated radar-based high resolution precipitation totals for the same day over the same location. The color code for the daily precipitation totals are the same in both figures.

precipitation front (shown in purple). In these locations, weather station data can under- or over-estimate radar-generated daily precipitation totals for nearby locations (10 to 20 km) by up to 2 cm.

PNM model Web interface

Once the high resolution weather data become available, we will offer field specific in-season N recommendations through a PNM model web interface. Users (producers, crop consultants and extension staff) will be able to obtain these field specific recommendations by providing relatively simple information on soil texture, cultivar, and N additions (organic and inorganic). The main input page of the Web interface is shown in **Figure 4**. The inputs from the interface are linked to the appropriate input parameters in the PNM model. We will link the high resolution temperature and precipitation data to the model as these data become available (spring 2007). We will also maintain PNM model access to the operational real time climate database maintained by the Regional Climate Center Program via ACIS.

At present, PNM model Web interface users will be provided with suggested adjustments to current sidedress N recommendations using the same process described for 2004 to 2006. Over the next 3



PNM: Precision Nitrogen Management Model

Powered by ACIS
NOAA Regional Climate Centers

Soil and Cultural Practices

- **Soil/Tillage System Information** [enter information]
- **Manure/Sod Information**

To view the manure/sod input screen, please click the "enter information" button.
If neither manure nor sod were applied, please check the "Not Applicable" box.

[enter information] **Not Applicable** ☐

- **Nitrogen Fertilizer Applications (2006):**

Please provide information here or check the "Not Applicable" box if fertilizer was not applied.

Not Applicable ☐

Select Fertilizer	**Rate** (lbs N/acre)	**Date Applied** (mm)	(dd)	(yyyy)
Starter Fertilizer				2006
	Inhibitor Used ☐ yes ☐ no			
Additional Fertilizer				2006
	Inhibitor Used ☐ yes ☐ no			

Crop Information

- Please select corn cultivar and plant density.
- Planting Date (mm) (dd) (yyyy)

Corn Cultivar | Plants/Acre | | | 2006

When all required information has been supplied, click on the *submit* button. Please note that the model may run for a few minutes before returning a result. [Submit]

Figure 4. Main page of web interface for providing PNM model-generated field specific in-season N recommendations for maize.

years (2007 to 2009) we will also generate in-season N recommendations calculated directly from PNM model output rather than using model output to adjust current in-season N recommendations for maize. The PNM model-generated recommendations will be developed from a comparison of the size of the current soil N pool available for crop uptake, the pool of potentially mineralizable soil N, current crop N uptake and crop N uptake at maturity. These data will be obtained from the 40-year simulations used to calculate the BNN for different locations across New York state. We will be field testing the PNM model in-season N recommendations to determine if these can directly replace the current in-season N recommendations. The replicated field trials will compare maize growth and N uptake for a range of in-season N applications including the current in-season N recommendations and PNM model-generated in-season N recommendations.

The PNM model web interface for field specific in-season N recommendations will be offered through the Cornell Theory Center (CTC) (**Figure 5**). The CTC provides web services for outreach to users for applications like the PNM model web interface. The CTC also provides the computational and data storage capacities that are necessary for producing the high resolution temperature and precipitation data. In spring and summer 2007, we will begin extensive testing of the Web interface with appropriate stakeholders including extension staff, crop consultants, and selected growers.

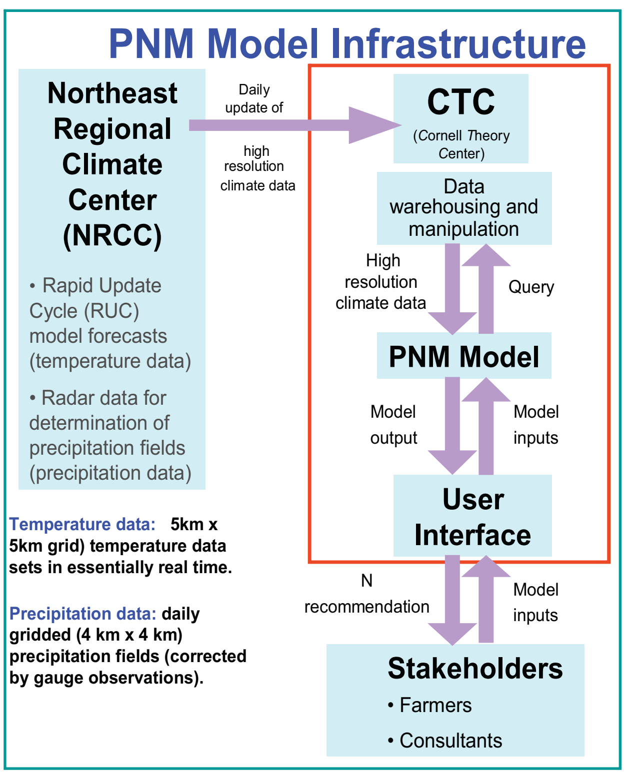


Figure 5. Infrastructure of the PNM model web interface for providing field specific in-season N recommendations for maize, including links to the Northeast Regional Climate Center.

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References

Amir, J. and T.R. Sinclair. 1991. A model of water limitation on spring wheat growth and yield. Field Crops Res. 28:59-69.

Balkcom, K.S., A.M. Blackmer, D.J. Hansen, T.F. Morris, and A.P. Mallarino. 2003. Testing soils and cornstalks to evaluate nitrogen management on the watershed scale. J. Environ. Qual. 32: 1015-1024.

Cherney, J.H., W.J. Cox, R.R. Hahn, E.Z. Harrison, Q.M. Ketterings, M.B. McBride, W.S. Reid, R.R. Schindelbeck, H.M. van Es, E.J. Shields, M. Smith, W.D. Pardee, G.C. Bergstrom, K.J. Czymmek, and J.K Waldron. 2004. Cornell guide for integrated field crop management. Cornell Cooperative Extension, 365 Roberts Hall, Ithaca, NY, U.S.A. 112 p.

Cox, W.J., R.W. Zobel, H.M. van Es, and D.J. Otis. 1990a. Growth development and yield of maize under three tillage systems in the northeastern U.S.A. Soil & Tillage Res. 18:295-310.

Cox, W.J., R.W. Zobel, H.M. van Es, and D.J. Otis. 1990b. Tillage effects on some soil physical and corn physiological characteristics. Agronomy J. 82:806-812.

Cox, W.J., S. Kalonge, D.J.R. Cherney, and W.S. Reid. 1993. Growth, yield, and quality of forage maize under different nitrogen management practices. Agronomy J. 85:341-347.

Cox, W.J. and D.J.R. Cherney. 2001. Row spacing, plant density and nitrogen effects on corn silage. Agronomy J. 93:597-602.

DeGaetano, A.T. and B.N. Belcher. 2007. Spatial Interpolation of Daily Maximum and Minimum Air Temperature Based on Meteorological Model Analyses and Independent Observations, J. Applied Meteorology and Climatology, [In press].

Dharmakeerthi, R.S., B.D. Kay, and E.G. Beauchamp. 2005. Factors contributing to changes in plant available nitrogen across a variable landscape. Soil Sci. Soc. Am. J. 69:453-462.

Hubbard, K.G., A.T. DeGaetano , and K.D. Robbins. 2004. SERVICES: A modern applied climate information system. Bulletin of the American Meteorological Society, 85:811-812.

Hutson, J.L. and R.J. Wagenet. 1991. Simulation nitrogen dynamics in soils using a deterministic model. Soil Use and Management 7:74-78.

Hutson, J.L. and R.J. Wagenet. 1992. LEACHM: Leaching Estimation And Chemistry Model: A process-based model of water and solute movement, transformations, plant uptake, and chemical reactions in the unsaturated zone. Continuum Vol. 2, Version 3. Water Resources Institute, Cornell University, Ithaca, NY, U.S.A.

Hutson, J.L. 2003. Leaching Estimation And Chemistry Model: A process-based model of water and solute movement, transformations, plant uptake, and chemical reactions in the unsaturated zone. Version 4. Dept. of Crop and Soil Sciences, Research series No. R03-1. Cornell University, Ithaca, NY, U.S.A.

Jabro, J.D., J. Lotse, D.D. Fritton, and D.E. Baker. 1994. Estimation of preferential movement of bromide tracer under field conditions. J. Hydrology 156:61-71.

Jara, J., C.O. Stockle, and J. Kjelgaard. 1998. Measurement of evapotranspiration and its components in a corn (Zea mays L.) field. Agric. and Forest Meteorology 92:131-145.

Jemison, J.M. Jr., J.D. Jabro, and F.H. Fox. 1994a. Evaluation of LEACHM: simulation of cumulative drainage, bromide leaching, and corn bromide uptake. Agronomy J. 86:843-851.

Jemison, J.M. Jr., J.D. Jabro, and F.H. Fox. 1994b. Evaluation of LEACHM: simulation of nitrate leaching from nitrogen-fertilized and manured corn. Agronomy J. 86:852-859.

Karimi, Y., S.O. Prasher, H. McNairn, R.B. Bonnell, P. Dutilleul, and P.K. Goel. 2005. Discriminant analysis of hyperspectral data for assessing water and nitrogen stresses in corn. Trans. of the ASAE. 48:805-813.

Kersebaum, K.C. 1995. Application of a simple management model to simulate water and nitrogen dynamics. Ecological Modelling 81: 145-156.

Ketterings, Q.M., S.D. Klausner, and K.J. Czymmek. 2003. Nitrogen guidelines for field crops in New York. Department of Crop and Soil Sciences, Extension Series E03-16, Cornell University, Ithaca, NY, U.S.A.

Klausner, S.D., W.S. Reid, and D.R. Bouldin. 1993. Relationship between late spring soil nitrate concentrations and corn yields in New York. J. Prod. Agric. 6:350-354.

Lotse, E.G., J.D. Jabro, K.E. Simmons, and D.E. Baker. 1992. Simulation of nitrogen dynamics and leaching from arable soils. J. Contaminant Hydrology 10:183-196.

Melkonian J., H.M. van Es, and L. Joseph. 2005. Precision Nitrogen Management model: simulation of nitrogen and water fluxes in the soil-crop-atmosphere continuum in maize (Zea mays L.) production systems. Version 1.0. Dept. of Crop and Soil Sciences, Research series No. R05-2. Cornell University, Ithaca, NY, U.S.A.

Mitsch, W.J., J.W. Day, J.W. Gilliam, P.M. Groffman, D.L. Hey, G.W. Randall, and N. Wang. 2001. Reducing nitrogen loading to the Gulf of Mexico from the Mississippi river basin: Strategies to counter a persistent ecological problem. BioScience 51:373-388.

Muchow, R.C. and P.S. Carberry. 1989. Environmental control of phenology and leaf growth in a tropically adapted maize. Field Crops Res. 20:221-236.

Muchow, R.C., T.R. Sinclair, and J.M. Bennett. 1990. Temperature and solar radiation effects on potential maize yield across locations. Agronomy J. 82:338-343.

Muchow, R.C. and T.R. Sinclair. 1991. Water deficit effects on maize yields modeled under current and “greenhouse” climates. Agronomy J. 83:1052-1059.

Muchow, R.C. and T.R. Sinclair. 1994. Nitrogen response of leaf photosynthesis and canopy radiation use efficiency in field-grown maize and sorghum. Crop Sci. 34:721-727.

Muchow, R.C. and T.R. Sinclair. 1995. Effect of nitrogen supply on maize yield: II. Field and model analysis. Agronomy J. 87:642-648.

Randall, G.W., D.R. Huggins, M.P. Russelle, D.J. Fuchs, W.W. Nelson, and D.L.Anderson. 1997. Nitrate losses through subsurface tile drainage in conservation reserve program, alfalfa and row crop systems. J. Environ. Qual. 26:1240-1247.

Shaffer, M.J., L. Ma, S. Hansen. 2001. Introduction to simulation of carbon and nitrogen dynamics in soils. In: Shaffer, M.J., L. Ma, and S. Hansen (eds.) Modeling carbon and nitrogen dynamics for soil management. Lewis Publishers, New York. p. 1-11.

Sinclair, T.R. and T. Horie. 1989. Leaf nitrogen, photosynthesis, and crop radiation use efficiency: a review. Crop Sci. 29:90-98.

Sinclair, T.R. and J. Amir. 1992. A model to assess nitrogen limitations on the growth and yield of spring wheat. Field Crops Res. 30:63-78.

Sinclair, T.R. and R.C. Muchow. 1995. Effect of nitrogen supply on maize yield: I. Modeling physiological responses. Agronomy J. 87:632-641.

Singer, J.W. and W.J. Cox. 1998. Corn growth and yield under different crop rotation, tillage and management systems. Crop Sci. 38:996-1003.

Smith, J.U., A.G. Dailey, M.J. Glendining, N.J. Bradbury, T.J. Addiscott, P. Smith, A. Bide, D. Boothroyd, E. Brown, R. Cartwright, R. Chorley, S. Cook, S. Cousins, S. Draper, M. Dunn, A. Fisher, P. Griffith, C. Hayes, A. Lock, S. Lord, J. Mackay, C. Malone, D. Mitchell, D. Nettleton, D. Nicholls, H. Overman, J. Purslow, A. Scholey, S. Senior, L. Sim, P. Taylor. 1997. Constructing a nitrogen fertilizer recommendation system using a dynamic model: what do farmers want? Soil Use Manage. 13:225-228.

Sogbedji, J.M., H.M. van Es, C.L. Yang, L.D. Geohring, F.R. Magdoff. 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. J. Environ. Qual. 29:1813-1820.

Sogbedji, J.M., H.M. van Es, J.L. Hutson. 2001a. N fate and transport under variable cropping history and fertilizer rate on loamy sand and clay loam soils: I. Calibration of the LEACHMN model. Plant & Soil 229: 57-70.

Sogbedji, J.M., H.M. van Es, J.L. Hutson, and L.D. Geohring. 2001b. N fate and transport under variable cropping history and fertilizer rate on loamy sand and clay loam soils: II. Performance of LEACHMN using different calibration scenarios. Plant & Soil 229:71-82.

Sogbedji, J.M., H.M. van Es, S.D. Klausner, D.R. Bouldin, and W.J. Cox. 2001c. Spatial and temporal processes affecting nitrogen availability at the landscape scale. Soil & Tillage Res. 58:233-244.

Sogbedji, J.M., H.M. van Es, J. Melkonian, R.R. Schindelbeck RR. 2006. Evaluation of the PNM model for simulating drain flow nitrate-N concentration under manure-fertilized maize. Plant & Soil 282:343-360.

van Alphen, B.J. and J.J. Stoorvogel JJ. 2000. A methodology for precision nitrogen fertilization in high-input farming systems. Precision Agric. 2:319-332.

van Es, H.M., K.J. Czymmek, and Q.M. Ketterings. 2002. Management effects on nitrogen leaching and guidelines for a nitrogen leaching index in New York. J. Soil Water Cons. 57:499-504.

van Es, H.M., J.M. Sogbedji, and R.R. Schindelbeck. 2006. Effect of manure application timing, crop, and soil type on nitrate leaching. J. Environ. Qual. 35:670-679.

van Es, H.M., B.D. Kay, J. Melkonian, and J.M. Sogbedji JM. 2007. Nitrogen management under maize in humid regions: Case for the dynamic approach. (this issue).

Ware, E.C. 2005. Corrections to Radar-Estimated Precipitation Using Observed Rain Gauge Data. Master degree thesis, Cornell University