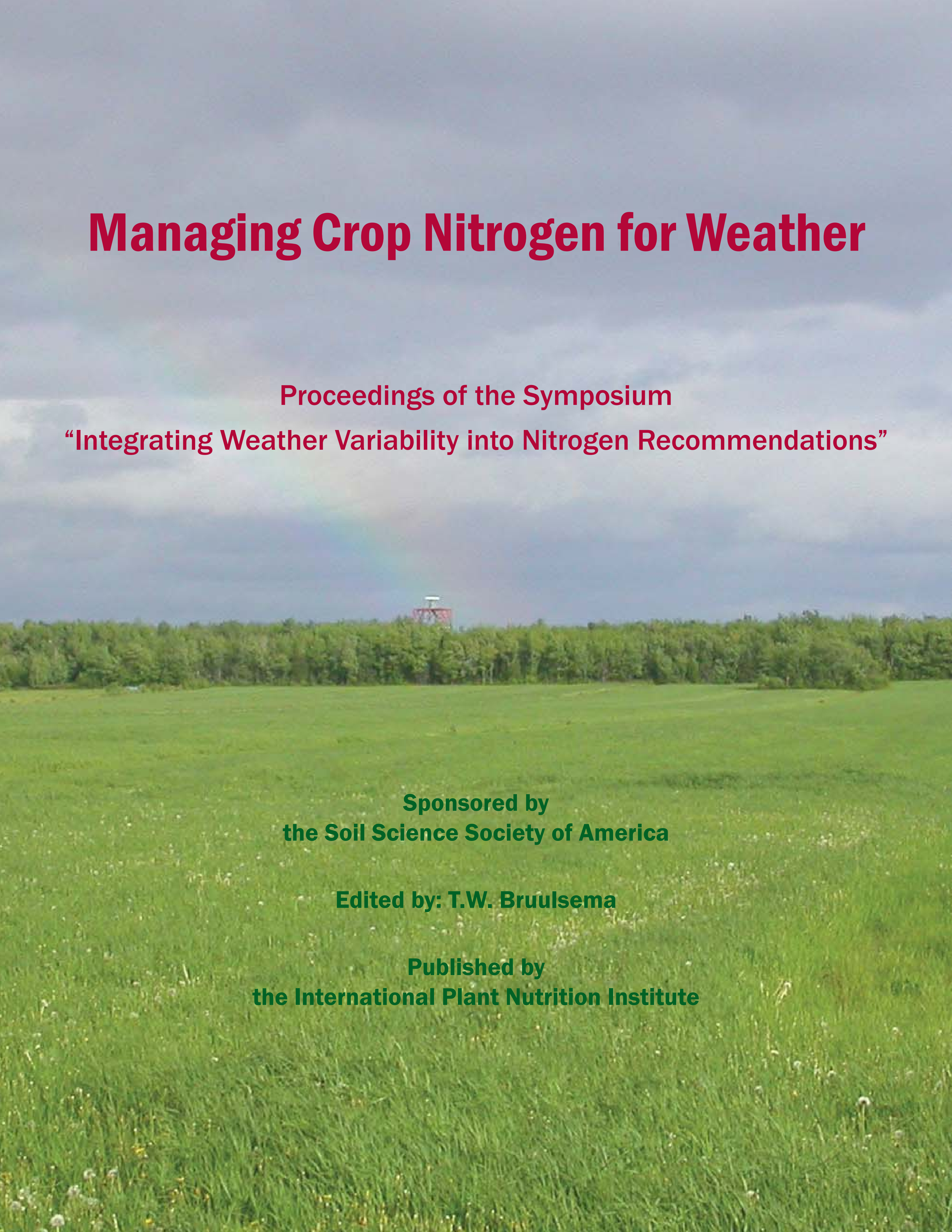

Managing Crop Nitrogen for Weather

Proceedings of the Symposium
"Integrating Weather Variability into Nitrogen Recommendations"

Sponsored by
the Soil Science Society of America

Edited by: T.W. Bruulsema

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Sponsored by Divisions S-4 and S-8 of the Soil Science Society of America
Indianapolis, Indiana, USA, 15 November 2006

The weather controls a great deal of the variation in crop response to nitrogen. The application of models integrating soil water flow, soil nitrogen dynamics, and plant uptake can potentially improve prediction of crop nitrogen needs in response to weather conditions. This book, based on the proceedings of a symposium at the 2006 meeting of the Soil Science Society of America, is intended to provide details of experimental data and experiences of those engaged in efforts to improve such predictions.

The task of applying models and methods to manage nitrogen application rate, timing, and placement in a manner that addresses the variability imposed on the soil-plant system by the dynamics of weather is a challenging one. It is hoped that this publication will be of use to those attempting to go further in efforts to integrate the data required to adapt crop nitrogen management to constantly changing weather.

Acknowledgments

Appreciation is expressed to the Soil Science Society of America for providing funds for travel for invited speakers from overseas, and to each of the authors who have contributed to this symposium and to these printed proceedings. In addition, the following individuals are thanked for their contributions in providing reviews of the submitted manuscripts.

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Model-Based Nitrogen Fertilization Considering Agro-meteorological Data

Kurt Christian Kersebaum, H.I. Reuter, K. Lorenz, and O. Wendroth

The crop model HERMES was used to predict amounts of N to apply to winter wheat grown in specific field locations in Germany. The approach was based on winter wheat receiving a small basal dose at planting, followed by up to three further applications during the growing season. The model used actual weather data up to each date of application, followed by three scenarios projected to the end of the growing season. The three scenarios were selected from the past 30 years of weather data to represent wet, moderate, and dry conditions. Based on its estimation of available N in the soil and the crop growth potential, the model forecast the amount of N required to ensure against deficiency until the next time of application. Use of the model resulted in reductions in fertilizer applied when the weather limited wheat yield.

This work also demonstrated a benefit to dealing with variability within-field as well as variability from year to year. Both had a similar magnitude of effect on optimum rates. They also interacted, in that wet weather caused some parts of a field to yield more and others to yield less, with corresponding effects on N demand. Because of the capability to identify site and weather situations in which N rates could be reduced without reducing yields, the HERMES-based recommendations resulted in higher N use efficiencies. The model also predicts lower residual nitrate concentrations in the top meter of soil.

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

Harold M. van Es, B.D. Kay, J.J. Melkonian, and J. Sogbedji

Optimum N rates for maize are affected by complex interactions among spring rain and temperature, soil organic matter, and crop development. Precision management requires in-season applications based on information related to the dynamics of soil N in the spring. A 7-year study in Canada examined the amount of mineral N accumulated in the top 30 cm of soil at side-dress time for maize, when 700 growing degree-days have accumulated. Depending on the previous crop, its standard deviation among years ranged from 27 to 43 kg N ha^{-1}, indicating that a large component of year-to-year variability in N response could be due to variability in soil N supply, net of losses, in the spring. Much of this variability could be predicted from early season rainfall.

A 5-year study on soils of three drainage classes in New York, conducted from 1978 to 1982, found little variability in optimum N rate among the three drainage classes. However, variation among the five years was substantial, with a range of 65 kg N ha^{-1}. The two wettest years were associated with the highest optimum rates, particularly on the poorly drained soils. The LEACHN model corroborated the importance of losses of N in years with wet early growing seasons. The experimental data suggest that a model accounting for weather effects on soil N supply and losses in the spring would enable an improvement in the precision of N recommendations for maize.

Application of Dynamic Simulation Modelling for Nitrogen Management in Corn

Jeff J. Melkonian, H.M. van Es, A. DeGaetano, J. Sogbedji, and L. Joseph

The critical time period determining the contribution from the soil to the N needs of corn occurs when soils are warming up, the mineralization rate is approaching its maximum, and precipitation events may drive large losses of the accumulating mineral N. In the northeastern part of the Corn Belt, this period occurs between planting and side-dress time, largely May and June.

The Precision N Management (PNM) model links a crop growth and N uptake model to the LEACHN soil water and N model. It was applied using 40-year climate datasets for regional weather stations across New York State to predict Benchmark Net-N, the expected accumulation of mineral N in the soil based on normal mineralization, leaching and denitrification processes. It was also able to supply a prediction of Net-N for the current year at the end of June, using real-time climate data. Comparison of the two allowed for real-time weather-based adjustments to average recommended rates of N. Adjustments are specific to soil texture, and ranged from -15 to +35 kg N ha^{-1} in 2006.

The PMN model has been implemented and made available to crop advisers and producers through the Internet. Plans for future improvements include an implementation using weather data at higher spatial resolution (4 to 5 km) and an interface that delivers recommendations directly, rather than adjustments.

Optimum Nitrogen Rate for Corn Increases with Greater Soil Water Availability

John P. Schmidt, N. Hong, G. Folmar, D.B. Beegle, and H. Lin

Along a 300-m hillslope in Pennsylvania, optimal N rate for corn varied from 47 to 188 kg N ha^{-1} among 10 sampled sites within a field. Among many soil and landscape attributes examined, the gain in soil profile water during the month of July best explained the variation. This occurred in 2005, a year in which growing season precipitation was below normal in every month except July. As the gain in water in the top 90 cm of the soil increased from zero to 10 cm, the fitted linear regression predicts an increase in optimal N rate from 73 to 171 kg N ha^{-1}. Yields along this hillslope varied little (11.1 to 13.5 Mg ha^{-1}) and were not related to optimal N rate. The results demonstrate the close relationship between water availability and optimal N rates, and also the need to include landscape factors controlling lateral water transport when addressing site-specific impacts of weather.

Spring Rainfall Dictates Success of Nitrogen Applied to Corn in Fall or Winter

Jeffery R. Wessel, M.L. Ruffo, and F.E. Below

When applied in the fall or winter, N is susceptible to losses, and resulting corn yields are at times lower compared to those obtained with N applied in the spring. Across a range of locations in the state of Illinois (U.S.A.) over 3 years (1997, 1998, and 1999), a relationship was found between the yield loss associated with fall and winter N application, and the amount of rainfall in the spring (March through May). When spring rainfall amounts exceed 270 to 320 millimeters, yield loss was observed to increase above the 5% baseline to levels as high as 38%.

This information can be used to calculate probabilities of excess yield reduction associated with fall N application. It can also predict amounts of supplemental N for side-dress application in June to correct for spring rainfall-induced losses. The research underscores the influence of spring weather conditions on processes affecting the supply and losses of soil N.

Dynamic Site-Specific Fertilizer Management Triggered by Real-Time Simulations and Weather Conditions

Jetse J. Stoorvogel, M.P.W. Sonneveld, and E. Serrano

Three diverse case studies illustrate the need to include weather as a factor in making decisions on crop N management. The first, comparing two systems of N application for intensive wheat production in the Netherlands, showed that in-season applications can and should be varied to fit crop need, and prevent potential negative effects on crop disease and loss of excess N. Crop-model-based approaches provided site-specific recommendations for timing the applications to suit within-field management zones, but economics constrained applications to whole fields.

The second case study dealt with Costa Rican bananas, a crop for which no growth simulation model was available in a production system without mechanical site-specific application technology. Nevertheless, monitoring of crop performance and nitrate leaching in one-hectare blocks with three imposed levels of fertilization led to a system in which rates applied were specific to each of the three main soil types and to the yield performance of the crop.

The third case study dealt with a Netherlands dairy farm which had traditionally focused separate efforts on improving pasture and animal production. The separation of the two components of the farm system had led to poor overall N efficiency. The farm's N budget was improved by the combination of diet changes, storage methods, and application timing. Diet changes reduced the ammonia content of the manure. Better manure storage helped retain the N in the manure and allowed application at times that better matched weather conditions for efficient crop uptake. On-farm research showed that the availability of manure N differed for new versus old pastures.

In each of these three diverse case studies, improvement in N use efficiency depended on addressing both site-specific and weather-induced variability.

Optimizing Nitrogen Management for Rainfed Wheat and Maize in Africa

Upendra Singh, P. Wilkens, and M. Naimi

Crop management decisions can be complex in rainfed environments with high climate variability. Crop growth simulation models provide tools that can be used for decision support. The DSSAT version 3 wheat model was applied to calculate optimum N rates, based on prices for fertilizer and wheat, soil water-holding capacity, expected rainfall, and yield potential within the province of Settat in Morocco. Recommendations provided by this model ranged from zero to 140 kg N ha^{-1}. The DSSAT maize model, applied in Togo, indicated that N fertilizers strongly limited yields across a wide range of planting dates, and that while optimum N rates were lower for a maize-mucuna rotation, a maize-maize rotation fertilized at higher levels of N could produce at least 67% more on an annual basis. While the N response component of these models requires further validation, and other constraints including price uncertainty further limit attained farm yields, the application of these models demonstrates considerable potential to improve production.

Growing Season and Soil Factors Related to Predicting Corn Nitrogen Fertilization in Quebec

Nicolas Tremblay, E. Fallon, C. Bélec, G. Tremblay, and É. Thibault

Optimal N rates are determined by the combination of crop N demand, soil N supply, and losses of N from the soil. Weather affects all three. Analysis of three multi-year databases of corn responses to applied N in Quebec indicates that geographic regions can be grouped into four categories, which differ in responsiveness to N and in the degree to which year-to-year differences in weather affect such responsiveness. A province-wide database indicates that the median optimal N rate varies strongly from year to year, ranging from 70 to 170 kg N ha^{-1} in the extremes of a nine-year period but usually falling within the range of 100 to 150 kg N ha^{-1}. A range of similar extent (86 to 184 kg N ha^{-1}) was also seen at a single research station over a 7-year period. Evidence of interaction between weather and soil texture was also seen. The preferred method of dealing with this variability is to apply only part of the N requirement at planting, and base the supplemental dose at side-dress time on some measure of crop canopy or chlorophyll. Optimal rates tend to be higher in wetter years, particularly in medium- to fine-textured soils.

In-Season Real-Time Plant Analysis for a more Flexible Nitrogen Recommendation System

Axel Link and J. Lammel

European cereal producers are finding advantages to applying N in multiple small doses through the growing season. The advantages include increased yields as well as enhanced N use efficiency. In-season applications need to be adjusted to suit the needs of the crop, which are best determined by analysis of crop N status. Such analysis can be done by analysis of plant tissue, tissue sap, or measures of leaf or canopy reflectance related to chlorophyll content. The key advantage of multiple applications is that more knowledge of the weather and its impact on crop nutritional need is obtained before the last decision on the final total N dose.

Fifty Years of Predicting Wheat Nitrogen Requirements in the Pacific Northwest U.S.A.

William Pan, W. Schillinger, D. Huggins, R. Koenig and J. Burns

In the Columbia Plateau that resides in the rain shadow of the Cascade mountains, variations in dryland wheat yield across large land areas and year-to-year are related to available water, defined as spring soil water plus rainfall during the growing season. N requirements vary with yield, and to some extent with protein content. As yields have increased over the past 50 years, water use efficiency has increased, while N use efficiency has been assumed constant.

Within-field variation in wheat yield has been observed to be only weakly related to available water. Landscape-scale processes including redistribution of water result in site-specific relationships of yield to available water. This redistribution of soil water also influences N availability, movement, and losses, and thus affects the relationship of yield to available N. Precision agriculture technology to enable site-specific N management can potentially improve overall N use efficiency. However, its application will require weather-based crop modeling that integrates diagnosis, application timing, and in-field measures of N use efficiency.

A Water-Use-Based System for Deriving Nitrogen Recommendations in the Canadian Prairies

Rigas E. Karamanos and J.L. Henry

Since water availability governs most of the variability in crop yield across the Canadian prairies and from one year to another, much of the challenge in recommending N is to accurately forecast yield. The soil and climate zones of the Canadian prairies have been refined over the years. The current system uses climate-based rainfall probabilities and soil water storage to predict crop yield. Adding an N balance to those data allows a systematic approach to making N recommendations. Rainfall probabilities are related to crop yield, soil N mineralization and losses of N from the soil. The N balance includes target levels of protein for wheat crops.

The empirical equations relating crop yield to available water are well-validated. They explain a large amount of variability in crop yield, provided that rainfall for the growing season can be predicted. The N recommendations provided by the system are reasonable in proportion to the yields obtained, but insufficient data exists to truly validate them. The evolution of the system over the years demonstrates the intricate involvement of weather, and its interaction with soils, in the core processes controlling the optimum rate of N for crop yield and protein.

Exploring the Effect of Weather Forecast Accuracy on Nitrogen Fertilizer Recommendations

A. Gordon Dailey, A.P. Whitmore, and J.U. Smith

While models of the soil-plant system relate N availability to weather conditions, future weather based on forecasts is known only poorly. This study assessed the benefit of foreknowledge of weather when using the crop and soil model SUNDIAL to make N recommendations.

Even a limited 3-week weather forecast, 70% accurate, could benefit arable farming in England and Wales by £15M per year. The benefits were based on small reductions of N losses and small increases in crop yields, since with better knowledge of coming weather, both over- and under-applications were less frequent. Using accurate foreknowledge of weather (60% accuracy for a 7-week projection), compared to climate-based probabilities, reduced losses by 0.1 kg N ha^{-1} from denitrification and by 1.2 kg N ha^{-1} from leaching, and increased crop N removal by 2 kg N ha^{-1} of crop N removal, corresponding to a yield increase of 110 kg ha^{-1}. While these predicted changes are small, they justify a considerable investment into improved weather forecasting when integrated across the country.

Science and Education Needs to Reconcile National Environmental and Energy Goals with Current Nitrogen Recommendations

Raymond E. Knighton and M. O'Neill

Agronomic research based only on economics falls short of social and environmental goals for N management. The combination of new concerns with ammonia as a criteria air pollutant, with the longer-known issues including groundwater nitrate contamination, eutrophication by airborne and waterborne N, and greenhouse gas emissions means that environmental impacts must be a large part of the evaluation criteria for new N management tools. Prediction of these impacts must be part of the crop N model output. Simultaneously, national energy goals demand that biofuel crops produce a net energy surplus, making energy efficiency an additional issue. New regulations will be applied to crop N management. Creative thinking is needed to apply "green payments" as incentives for adoption of advanced N management methods.

Crop Simulation Models and Decision Support Systems

Gerrit Hoogenboom, U. Singh, P. Wilkens, J.W. White, J.W. Jones, K.J. Boote, and L.A. Hunt

Computer models of plant growth and development can be a valuable tool to relate the growth of crops to daily changes in weather. Models fundamentally make predictions of the effects of sub-systems on whole systems, using known linkages between lower level processes (physics, chemistry) on higher level processes (physiology, plant-soil interactions, crop performance, and cropping system dynamics). The nutrient cycling in a cropping system is governed by many physical, chemical, and biological factors. Physics of water flow are important. Chemistry of nutrient transformations in soil is important. And multiple organisms affect transformation processes and the uptake of nutrients from soil into crop plants. Many complexities of plant regulation of growth, development, and nutrient uptake are not yet understood.

In-Season Prediction of Yield Potential for Nitrogen Management in Irrigated Corn

Achim Dobermann, H. Yang, K. Cassman, and D. Walters

The Hybrid-Maize crop growth model is used to predict corn yields based on weather. Using historical weather, it projects a range of scenarios beyond any point in the growing season. This approach results in an accuracy in predicting N requirement prior to silking no better than ±23 kg N ha^{-1}. Crop models still are challenged to accurately predict date of maturity. In Nebraska, yields of irrigated corn range from 14.1 to 14.8 t ha^{-1} while those for rainfed corn range from 8 to 10 t ha^{-1}. Integration of a yield-limiting N component to the model is a work still in progress, but in areas where optimum N rates can be expected to be a function of potential yields, the current Hybrid-Maize model can be an effective tool in N management.

Linking In-Season Fertilizer Decisions to Weather-Based Yield Predictions

N. Derby, Francis Casey, R.E. Knighton, and D. Steele

In an experiment with four irrigation methods conducted over six growing seasons in North Dakota, optimum N rates showed a positive relationship with grain yields, within a multivariate linear model including weather, soil, irrigation and fertility parameters. Weather induced variations in yield potential should enter into the decision-making process when making fertilizer recommendations. A model was developed to predict final corn grain yields based on conditions prevailing up to 10 July. Its predictions fitted observed final yields with an R-square of 0.80. This model could provide a season-specific yield potential used to modify N application during the growing season, which could result in fertilizer savings in cool years or fertilizer increases to take advantage of optimum growing conditions and increase yields.

The Challenge: a Research Agenda for Managing Crop Nitrogen for Weather

Tom Bruulsema

A research agenda to further the development of integrated model-based N recommendations should include:

- Participatory research with producers and advisers to test feasibility of integrated N management tools, using on-farm weather monitoring;
- Development of models of weather impact on crop growth, soil N supply, and soil N losses;
- Further exploration of datasets of past response research, assembling the necessary soil and weather data to run models to estimate the movement and transformation of soil N;
- Increased use of real-time remote sensed data to detect N status of plants and gauge need for additional N application;
- Development of simplified means to characterize soil physical properties that impact water and nutrient movement in soil for practical management, using principles from the sciences of soil physics and agro-meteorology;
- Spatial analysis and description of nitrate transport and transformation within agricultural fields;
- Identifying genetic traits influencing the physiology of crop growth, to select genotypes that capture more of the nutrients made available through the season by mineralization.
- Field validation of soil-crop-water-nutrient models.
- Increased accessibility of real-time weather data.

Model-Based Nitrogen Fertilization Considering Agro-Meteorological Data

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Abstract

The spatial and temporal coincidence of nutrient supply to the demand of crops is especially important for N, to enhance N use efficiency and to protect water resources from contamination. Temporal dynamics of relevant state variables of soil-crop N dynamics are simulated in agricultural system models using agro-meteorological data and temporally stable basic soil characteristics. The model HERMES was used within different places of Germany to derive field-specific fertilizer recommendations for cereal crops by sequential model runs at different development stages combining actualized real weather data and a typical weather scenario of each specific site for a predictive calculation of N deficiency. The annual variability of model recommendations was analyzed for different locations within a heterogeneous field using 30-year weather data. The temporal variability of the recommendations were in the same order of magnitude as the spatial variation within the field. The potential error of the predictive simulation is shown using different weather scenarios covering the variability of that specific site. Results of real-time model applications for entire fields and site-specific application ? within the framework of precision agriculture are shown in comparison with other recommendation methods. Yields achieved with the model recommendations were not significantly different from methods based on soil and crop analysis, but tend to give lower recommendations for fertilization resulting in a higher use efficiency.

Introduction

Weather has a strong impact on crop growth and water and nutrient dynamics in soil-crop systems. Due to the various processes and their interactions, N fertilization of agricultural crops is still a challenge. High N surpluses in national N balances of industrialized countries and related problems of water quality are indicating low efficiency of N applications (e.g., Isermann, 1990). Best management practices require a spatial and temporal adaptation of nutrient supply to the demand of the crops to improve N use efficiency and to prevent contamination of water resources with nutrients.

Nitrogen fertilizer recommendations are usually based on measurements of soil mineral N, nowadays supported by optical sensors detecting crop N status at advanced development stages. Nevertheless, both methods are just snapshots of a present situation, which are neither able to explain an observed phenomena nor to predict a probable development for the future. Recent agro-technical development using global positioning systems enables farmers to differentiate their crop management within fields considering the variability of relevant site conditions. This site-specific crop management potentially provides better efficiency of applied nutrients combined with lower emissions of agro-chemicals. High spatial and temporal variability of soil mineral N would require a frequent and spatially dense soil sampling, which is not realistic under practical conditions due to high costs. Therefore, methods are needed to estimate the N demand considering both the soil supply and the crop demand as a function of the actual and probable weather conditions. Agricultural system models transfer time-stable soil and terrain attributes, which have to be estimated once for a field, into relevant state variables of the soil-crop N dynamic using real time agro-meteorological data.

We investigated the spatial and temporal variability of model-based fertilizer recommendations of

Abbreviations: N, nitrogen; Kc, crop coefficient or crop water requirement (?) [Tom verify] the model HERMES within a heterogeneous field in Germany using 30-year weather data. The potential error of the prediction was assessed by using different annual weather data sets representing a dry, a medium, and a wet year for the specific site. To show the practical potential of the model, results from real-time applications on field trials are compared to other methods of recommendation.

Material and Methods

Model description

For the simulation of crop growth and N dynamics and the estimation of N fertilizer recommendations the process-oriented model HERMES (Kersebaum, 1995) was used. The model consists of sub-modules for water balance, N transport and transformations, crop development, and growth including N uptake. The fundamentals of the model are described here only briefly. More details can be found in Kersebaum (1995) and Kersebaum and Beblik (2001).

Soil water is simulated by a simple capacity approach deriving the capacity parameters automatically from soil texture information according to the German soil taxonomy (AG Bodenkunde, 1994). These basic values are modified by organic matter content, bulk density, and hydromorphic indices. For groundwater-influenced sites, capillary rise is calculated depending on soil texture and distance to groundwater using tabulated values of AG Bodenkunde (1994). Potential evapotranspiration was calculated according to Haude (1955) using crop-specific factors during the growing season (Heger, 1978) and bare soil factors between harvest and crop emergence. Alternatively, the model can use reference evaporation calculated externally by other methods and crop-specific Kc factors to estimate the potential crop-specific evapotranspiration. The calculation of actual evaporation and transpiration considers the soil water status and time-variable vertical root distribution of crops. The release of mineral N is simulated as net mineralization from two pools of potentially decomposable N according to first order reactions. The initial size of a slowly mineralizable pool is derived from soil organic N (Nuske, 1983). Resistant compounds from crops or manure are added to that pool at harvest or manure application. A smaller easily decomposable pool is fed by easily decomposable compounds of the same crop residues and manure. Nitrogen in crop residues recycled to the soil is calculated automatically using simulated N uptake and a crop-specific N harvest index to subtract N exported with the yield, allowing simulation of complete rotations. Daily mineralization coefficients are calculated depending on mean air temperature (Nuske, 1983; Nordmeyer and Richter,1985) and soil moisture (Myers et al.,1982). Denitrification losses from top soil are calculated by a Michaelis-Menten kinetic modified by reduction function depending on water filled pore space and temperature (Richter and Söndgerath, unpublished, cited in Schneider, 1991):

$$N_{den} = \frac{V_{max} * (NO_3)^2}{(NO_3)^2 + K_{NO3}} * f(\Theta_r) * f(T) \qquad (1)$$

with a maximum denitrification rate Vmax (kg N ha^{-1} day^{-1}), the soil nitrate content NO_3 (kg N ha^{-1}) and the Michaelis-Menten coefficient for nitrate (kg N ha^{-1}) and functions for water content and temperature:

$$f(\Theta_r) = 1 - e^{-\left(\frac{\Theta_r}{\Theta_{crit}}\right)^6} \qquad (2)$$

$$f(T) = 1 - e^{-\left(\frac{T}{T_{crit}}\right)^{4.6}} \qquad (3)$$

Critical values T_{crit} for temperature and Θ_{crit} for water filled pore space are set to 15.5 °C and 76.6 cm^3 (100 cm)$^{-3}$, respectively.

The sub-model for crop growth was developed on the basis of the SUCROS model (Keulen et al., 1982). Driven by global radiation and temperature, daily net dry matter production is simulated. The partitioning of the assimilates to different crop organs is determined by the phenological development of the crops, which is calculated by a cumulative biological time based on thermal time (°C * day) modified by day length and vernalization. Root dry matter is distributed over depth by an empirical function according to Gerwitz and Page (1974) with an increase of rooting depth with biological time. Dry matter production is reduced if water or N are limiting. Water logging situations can be considered reducing crop growth according to Supit et al. (1994) if air filled pore space in soil falls below a crop specific critical air content. Stress by oxygen shortage increases with the duration of limited air filled pore space and reduces the actual transpiration and consequently crop growth. Water uptake is calculated proportional to the vertical distribution of roots and the available water in each layer. During dry periods, the potential transpiration is reduced to an actual transpiration according to the water availability in the rooted soil layers. Water stress is estimated by the ratio between actual and potential transpiration. To consider N stress, a crop specific function of a critical N content in the crop depending on the stage of development is defined (Kersebaum and Beblik, 2001). For N uptake, the demand of the crop is calculated from the difference between the actual N content of the crop and a maximum N content which is also related to biological time. Actual N uptake is limited by the supply of soil mineral N by convective and diffusive transport to the roots and by a maximum uptake rate per unit root length.

The model operates on a daily time step using daily weather data for precipitation, temperature and global radiation. Soil information is required at a vertical resolution of 10 cm for the profile to a depth of 100 cm (optional to 200 cm). The German soil textural classes of AG Bodenkunde (1994) are the most important soil information, but new texture classes and related parameters can be defined by the user. For the plough layer, the organic matter content and its C:N ratio should be given. Additional information like stone content, wetness and groundwater level are needed. Information on wetness can be taken from individual soil profile information or can be derived using the topographic wetness index (Moore et al., 1993) based on terrain analysis of a digital elevation model (Kersebaum et al., 2002). Management information of sowing and harvest dates, and dates and amounts of fertilization and irrigation are also needed to operate the model. Spatial variability and site-specific management can be considered using exported tables from a Geographic Information System (GIS).

Procedure to derive fertilizer recommendations

The basic concept for calculating fertilizer recommendations is described in detail by Kersebaum and Beblik (2001). **Figure 1** demonstrates the principle of the calculation. The simulation of N dynamics in the soil-crop system usually starts from an initial mineral N content in soil, e.g., after harvest of the previous crop using actual weather data from a neighbouring weather station. When a recommendation is required, the model predicts N uptake and soil mineral N changes operating with typical site-specific weather scenarios until the simulation predicts the next relevant development stage for fertilization (e.g., stem elongation for winter wheat (*Triticum aestivum* L.) fertilization).

The model estimates the daily deficiency between N uptake required for N-unlimited growth and available N in soil and accumulates the deficiency over the prediction period. The total deficiency is recommended to be applied in subsequent applications ahead of the critical phases. Between the relevant stages the model should be run after shorter intervals (e.g., 10-15 days) with actualized weather data. If the actual weather deviates strongly from the applied scenario, e.g., N is leached due to high precipitation, the next fertilization has to be given earlier. If N supply is higher than predicted, the next fertilizer recommendation is reduced automatically.

Usually, a medium "representative" weather data set is selected from long term data as shown for the location of our investigation field AUTOBAHN in **Figure 2**. Alternatively, the user can select a typical dry or wet year from the data set to assess the range of uncertainty of the recommendation due to the variability of weather. For our calculations we selected two years with a relative high and low precipitation during the main growing season avoiding years with extreme events within the time courses. As wet, medium and dry the years 1997, 1977 and 1976 were selected, respectively.

Simulation experiment on weather variability impact

We used data from the field "AUTOBAHN" located in Beckum, North-Rhine Westphalia which has been investigated and modeled in the framework

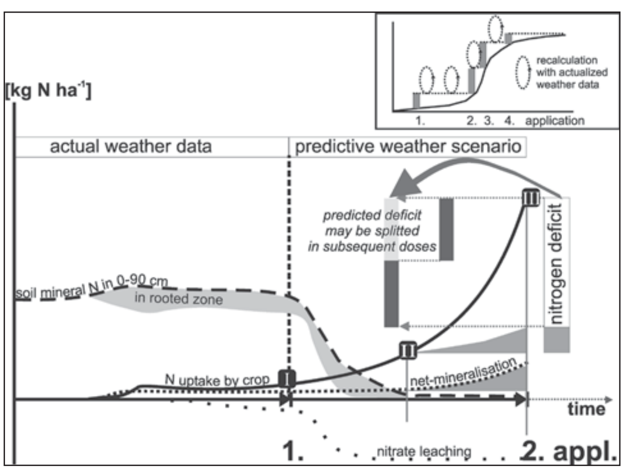

Figure 1. Scheme of model-based fertilizer recommendations with HERMES. (I = day of recommendation, II = calculated date, when N deficit occurs, III = predicted date of predefined development stage for next fertilization) (modified acc. to Kersebaum and Beblik, 2001).

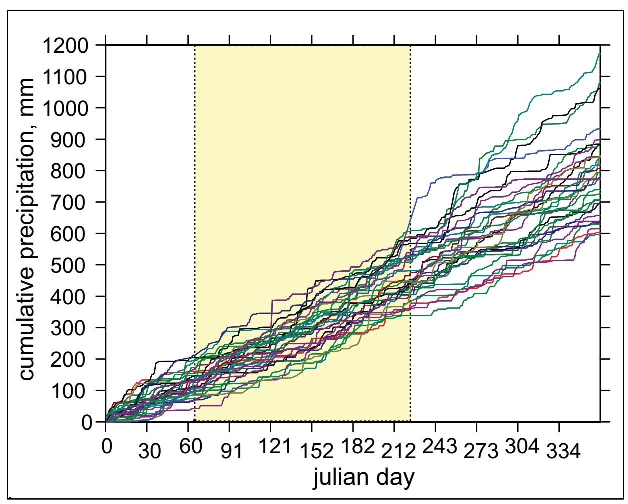

Figure 2. 30 year variability of cumulative precipitation at Beckum, Germany. Black, blue, and red lines mark medium, wet, and dry scenarios during the main growing season of winter wheat (yellow box), respectively.

of Precision Agriculture (e.g., Kersebaum et al., 2003). The field size is 20 ha and is clearly structured in different soil types with high differences in texture ranging from silty sand to clay loam with high stone content from the underlying calcareous marl which limits rooting depth especially in the southern part of the field. The terrain is quite flat with elevations in the range between 96 and 102 m. Soil sampling were taken at 60 locations in a grid of 50 m width, leaving out the forested central area of the field and the headland of the field machinery, to determine the spatial distribution of basic stable soil characteristics required by the model and to observe state variables (soil mineral N, grain yield) to validate the model results. **Figure 3** shows the spatial distribution of selected soil data and the location of the grid points.

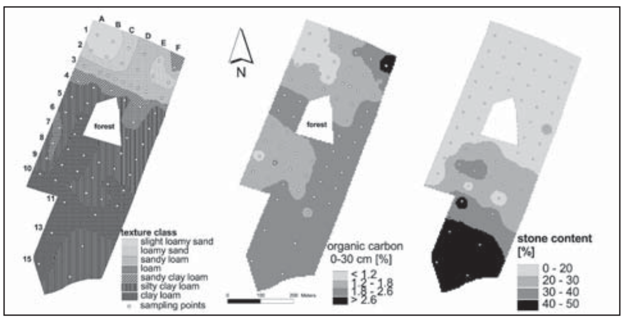

Figure 3. Grid sampling points and spatial variability of A) soil texture, B) organic carbon and C) stone content in 60-90 cm depth on field AUTOBAHN in Beckum, Germany.

Model runs were performed for selected grid points for a defined 2-year winter wheat rotation with a fixed fertilization for the first year and subsequent calculations of the fertilization recommendation at three fixed dates (15 March, 20 April, 10 May) of the second year resulting in a maximum of 4 fertilizer applications. Usually, the model uses the prediction for the estimation of the next fertilization date according to defined crop development stages. In this study the dates were fixed due to technical reasons. Each subsequent calculation uses the actualized weather data up to the new date and the former recommendation as realized fertilizer input. This was done for 29 growing periods using the weather data from 1971 to 2001. Due to the simulation of one previous winter wheat season the first year for the recommendation was therefore 1973. Each assessment of the fertilizer requirement was done with the wet, medium and dry scenario (see **Figures 2** and **5**).

Scenario simulations with different fertilizer levels were also performed to show effects on nitrate concentrations of seepage water.

Real time application for site specific fertilization

The model has been tested in the context of Precision Agriculture to derive spatially variable fertilizer recommendations within fields using site-specific input data from different field locations. A fertilization trial was carried out on a 20-ha field of the Südzucker Company in Saxony, Germany comparing different fertilization methods. The field was located in a hummocky loess region. Therefore, spatial yield variability within the field was mainly determined by its relief (Kersebaum et al., 2002) which led to a spatial variability of weather inputs (e.g., solar radiation, Reuter et al., 2005). Four different fertilizer strategies and a zero fertilization were applied in 2000 and 2002 for winter wheat:

- The "Nmin/sensor" strategy uses the average measured soil mineral N content in early spring to calculate the first N application according to the Nmin-method (Wehrmann and Scharpf, 1986). The next two fertilizer applications were estimated site specifically by an online chlorophyll sensor (Hydro N-sensor) (Leithold, 2000) .
- The "HERMES uni" strategy uses the average of the model based fertilizer recommendation for all grid cells of the field (simulations used only the Nmin observations of August 1999 to 2001).
- For the "HERMES uni ±" strategy, 30% was added to the amount applied in the above-mentioned "HERMES average" recommendation in 2000, and 30% less than in "HERMES average" was applied in 2002.
- The "HERMES ssp" strategy used for each grid cell the site specific model recommendation.

All simulations were based on the Nmin observations after harvest of the previous crop (in August 1999 and August 2001, respectively). During 2001 the field was fertilized for winter rape uniformly except the zero-plots which received no N. The experimental design and results were discussed in detail in Kersebaum et al. (2005).

Results

Weather impact on yields, N recommendations and nitrate leaching

Weather variability has a site-specific impact on yield formation. **Figure 4** shows examples of the temporal yield response of selected grid points representing three field zones. Especially the grid point F1 in the wet northeastern corner of the field showed a different response compared to the other two points. Yields were increasing during dry years, e.g. 1976, while the other two grid points showed yield depressions due to drought effects. The silty

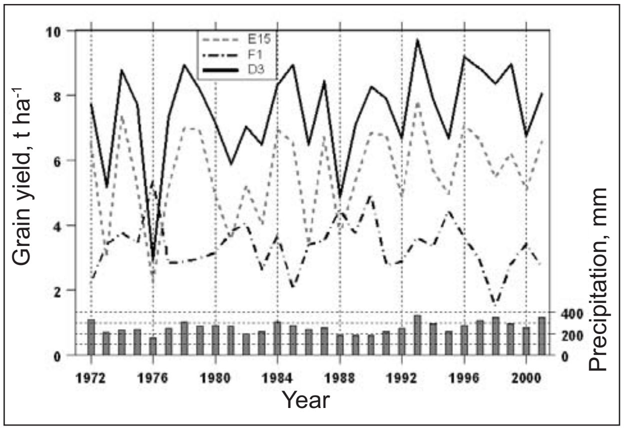

Figure 4. Simulated yield response to annual weather conditions for selected grid points on field AUTOBAHN (precipitation from April to begin of August).

clay loam at E15 showed higher yields mostly in wetter years. However, yields were generally lower than those at D3, a high yield zone, due to oxygen shortage during wet phases. In dry years, yield depression was distinctly pronounced due to root zone limitation by the marl layer compared to the sandy loam at D3 which showed severe yield depressions only in very dry years.

The variability of crop yields has consequences on the model-based recommendations. **Figure 5** shows an example of model recommendations (sum of all applications) from 1973 to 2001 using the dry, medium and wet scenarios for the loamy sand site A1 (see **Figure 3**). The average recommendation using the "normal" weather is at 135 kg N ha^{-1} within a range between 103 and 180 kg N ha^{-1}. Considering the dry and wet scenarios, the range of recommendations was between 82 and 180 kg N ha^{-1}. The largest difference between the scenarios occurred in 1986 with 40 kg N ha^{-1} and indicates a maximum site-specific uncertainty of the predictive assessment caused by the annual variability of the weather.

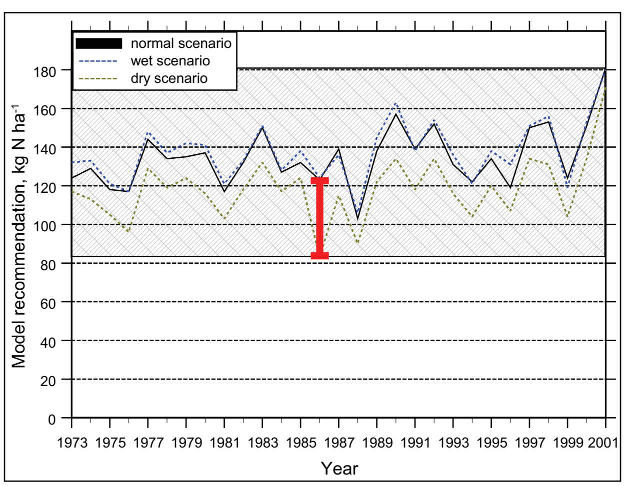

Figure 5. Simulated temporal variability of model-based fertilizer recommendations at grid point A1 on field AUTOBAHN using dry, medium, and wet weather scenarios.

Figure 6 shows the variability of the single applications for the same site. The smaller difference between the scenarios at the first fertilizer applications show that these recommendations were more dependent on the previous weather than on the prediction. During the early growing phase crop demand is not very high. Therefore, the amount of the first application depends more on the availability of mineral N in the root zone in early spring, which is mainly a result of the residual N from the previous crop and leaching losses over winter. Both depend strongly on the weather of the previous year. The second phase is relatively short and the scenarios differ little during this time. On average, the recommendation at this site is rather low. From the point of practicability the combination with the first or the third application seems to be appropriate. The first option would be suitable, if the first application would have a low risk to be leached. Under these site conditions, a combination with the third application would be more recommendable to avoid early leaching. Water availability during the grain building phase seems to have a significant influence on the model recommendation resulting in differences of 20 to 30 kg N ha^{-1} between the scenarios for the 3rd and 4th application.

On the wet location (F1) the recommendations of the model are generally lower (60 kg N ha^{-1} compared to A1; **Figure 7**). Relations between the wet and dry scenario differ depending on the actual weather of the specific year. After a wet spring, like in 1999, the recommendation for the dry scenario remains low because crop growth was suppressed in early phases by lack of aeration in the root zone,

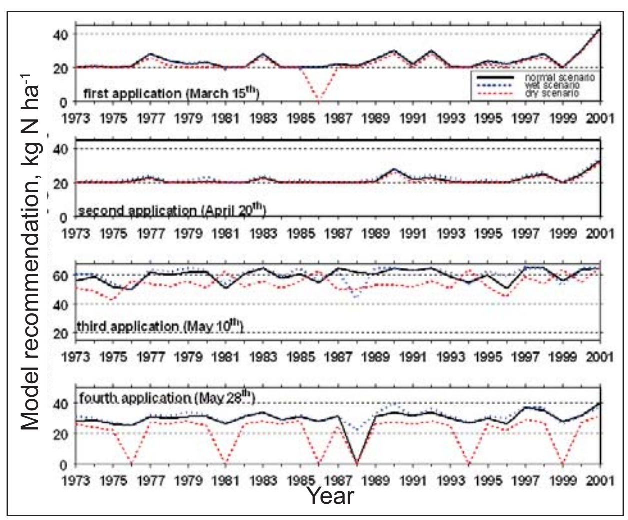

Figure 6. Simulated temporal variability of model-based fertilizer recommendations for single applications at grid point A1 on field AUTOBAHN using dry, medium, and wet weather scenarios.

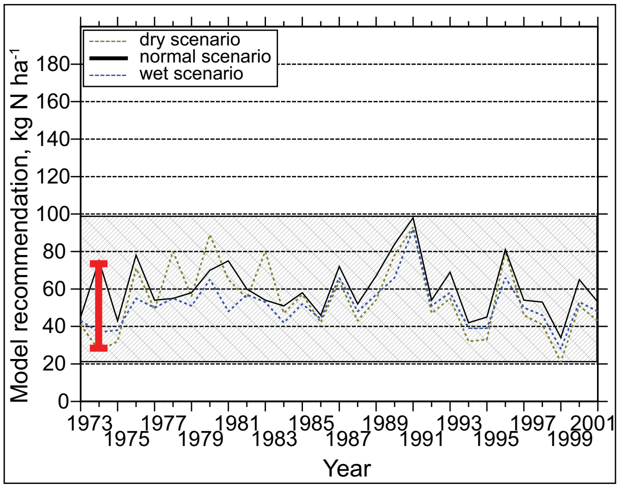

Figure 7. Simulated temporal variability of model-based fertilizer recommendations at grid point F1 on field AUTOBAHN using dry, medium, and wet weather scenarios.

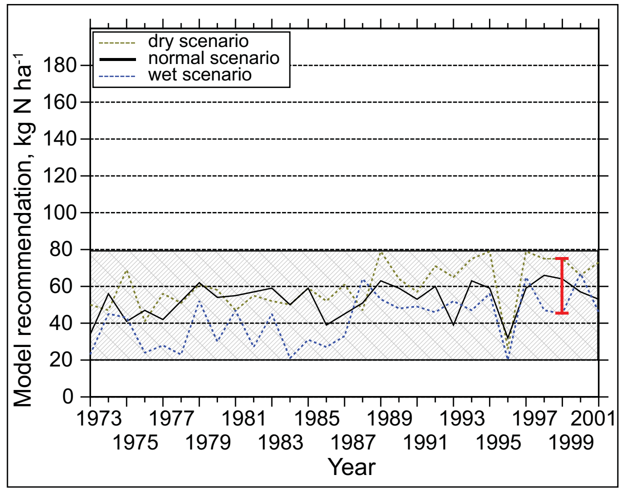

Figure 8. Simulated temporal variability of model-based fertilizer recommendations at grid point E15 on field AUTOBAHN using dry, medium, and wet weather scenarios.

and the assumed dry phase at the end could not compensate the yield depression. On the other hand, N mineralization is enhanced leading to a lower recommendation at the end. If the dry scenario is built on an actual dry spring, like in 1980, the crop growth during the early phase is favoured resulting in a higher demand and recommendation for the last phase. The maximum prediction uncertainty of 48 kg N ha^{-1} is quite high relative to the average recommendation.

Figure 8 shows the recommendation variability on location E15 which is a silty clay loam with a shallow root zone due to the marl layer in the underground. Fertilizer recommendations are low due to a high mineralization potential and a relatively high water holding capacity of the top soil. Yield is depressed in wet years due to temporal lack of aeration in the root zone. Highest recommendations were calculated if the dry scenario was used after an actual wet period like in 1997, 1998, and 1999. During the wet period mineral N was leached out from the shallow root zone while during the dry scenario crop growth conditions were favorable. Another reason for the higher recommendation was caused by the calculation of N uptake by the crop. Usually, the major part of mineral N uptake is calculated as mass flow with the water uptake. However, if soil moisture is depleted in the top soil, water uptake stops and diffusion has to transport N to the root surface. Because the diffusion coefficient decreases with decreasing water contents, the required gradient between soil solution and root surface has to be higher to fulfil the actual demand of the crop. If soil mineral N is available in deeper layers, N uptake is calculated from there. However, if the soil N is depleted in the root zone, the model calculates the required N amount to be applied to the upper layer according to the required gradient. To avoid calculation of unrealistically high fertilizer requirements during drought phases, a maximum N concentration for the upper soil layers of was introduced for the calculation. In these cases an irrigation application would make more sense than a N fertilization because mineral N in the upper layers can be taken up with the water by mass flow again and the required gradient decreases due to a higher diffusion coefficient.

The fertilizer recommendations calculated by the model are oriented to ensure a sufficient supply to the crops. On the other hand, the protection of groundwater resources from pollution might require fertilization limits below the optimum rate for crops depending on the site conditions (soil, climate, crop rotation). The assessment of such a limit requires a simulation with long term weather data, to avoid an overweight of years with unfavourable conditions, when nitrate concentrations might fall beyond the threshold even with low fertilization rates. **Figure 9A** shows, for two grid cells of the field AUTOBAHN, the annual fluctuations of nitrate concentrations in the percolation water. For grid point D3 (sandy loam) the standard application rate of the farmer of 150 kg N ha^{-1} led to concentrations above the drinking water threshold of 50 mg NO_3 L^{-1} only in 2 years, while for the grid point E15, with a shallow root zone and tile drains at the surface of the marl layer, this fertilization rate led to higher concentrations in the drainage and percolation water in most of the years. Performing a virtual fertilizer experiment with HERMES and integration of annual leaching and seepage over 32 years results in the estimation of fertilization limit which ensures against exceedances of the drinking water standard on a long run (**Figure 9B**). However, specific weather conditions might lead in single years to concentrations higher than

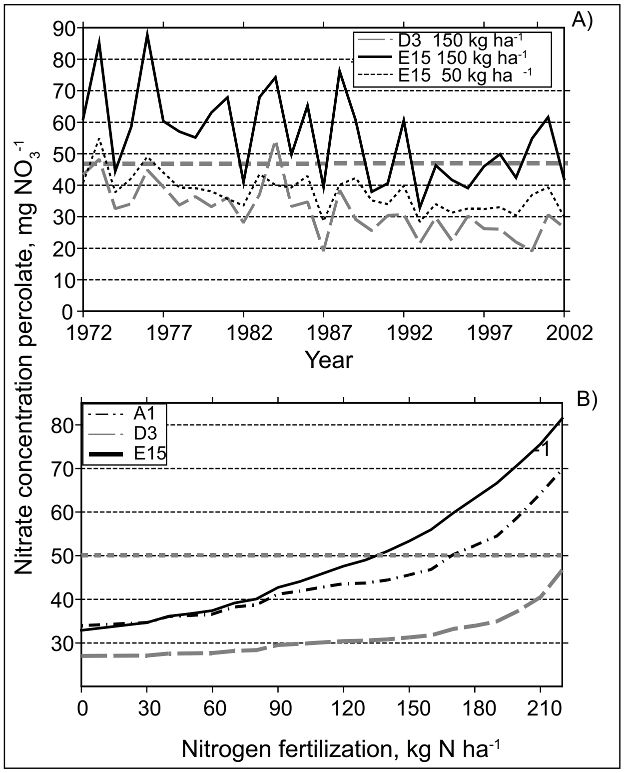

Figure 9. A - annual variability of simulated nitrate concentrations in 1 m depth for 2 grid points on field AUTOBAHN assuming different annual fertilization rates.
B - simulated nitrate concentrations of three grid points integrated over a 30-year period for different fertilizer application rates indicating limits to keep the drinking water standard (grey broken line).

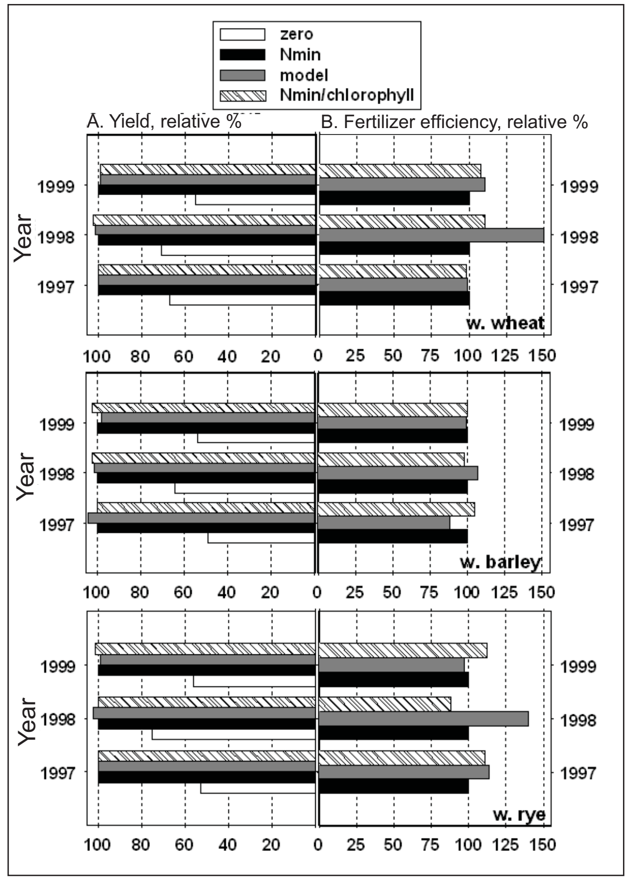

Figure 10. Comparison of different methods for fertilizer recommendations including no fertilization (summary of 41 fertilization plots for three cereal crops performed by the Lower Saxony State Agency for Agriculture in Hanover, Germany) for A) relative crop yields (standard N_{min} method = 100%) and B) relative N efficiency compared to N_{min} method (= 100%).

the threshold even when the fertilization rate is far below the estimated limit. This is demonstrated for a 50 kg N ha^{-1} fertilization rate at grid point E15 in **Figure 9A**.

Real time applications

Up to now, fertilizer recommendations in Germany are usually given for entire fields. The model has been used in field trials comparing yields obtained by different methods of making fertilizer recommendations. **Figure 10** shows a summary of fertilization trials for cereals which was performed over 3 years on different sites in Northern Germany by the Agricultural Advisory Office in Hanover, Germany. The model used in this context was the HERMES descendant MINERVA (Beblik and Kersebaum, 1998; Kersebaum and Beblik, 2001). The comparison comprises the most relevant methods in Germany: a fertilizer recommendation according the N_{min}-method (Wehrmann and Scharpf, 1986), which is based on the measurement of soil mineral N in the root zone (0-90 cm) in early spring, and a combination of soil (N_{min}) and crop N status measurement by an optical chlorophyll detection according to Wollring (1996). In **Figure 10A** the average relative yields (N_{min} standard method = 100) of the three methods plus a non-fertilized plot are shown for winter wheat, winter rye and winter barley. It can be seen that, except for the zero plots, all methods show no significant differences in yields. Under these conditions of equal yields, the N efficiency of the different methods can be calculated relating the yield increase compared to the specific zero plot to the amount of fertilizer applied. **Figure 10B** also shows the relative efficiency (relative yield increase per kg N, N_{min}-plot = 100) averaged over all plots for each crop-year. From this figure it can be seen that, on average, the model recommendations result in a higher N efficiency than the methods based on measurements, for most of the years. Because yields were not significantly different, the higher efficiency was achieved by a lower fertilizer recommendation.

Figure 11A and **B** show a summary of the results of the Precision Agriculture fertilization trial in Saxony regarding the average yields and the corresponding average fertilizer applications of the different treatments. In both years, the model recommendations were about 40 kg N ha^{-1} less than the N_{min}+sensor recommendations without any significant difference in yield. Only the non-fertilized plots differed significantly from the other treatments. The site specific recommendations from the model ranged from 75 to 157 kg N ha^{-1} in 2000 and from 70 to 172 kg N ha^{-1} in 2002, while the N_{min}+sensor recommendation had a range from 154 to 194 kg N ha^{-1} in 2000 and 150 to 202 kg N ha^{-1} in 2002. The main differences between the sensor and the model-based recommendations occurred at the footslope positions of the field with a high topographic wetness index where crop growth is depressed during wet phases. While the sensor responds to the lower biomass with an increased fertilizer recommendation, the model predicts a lower yield and correspondingly a lower fertilizer demand. The different fertilization recommendations on the sensor plots are shown in **Figure 11C**,

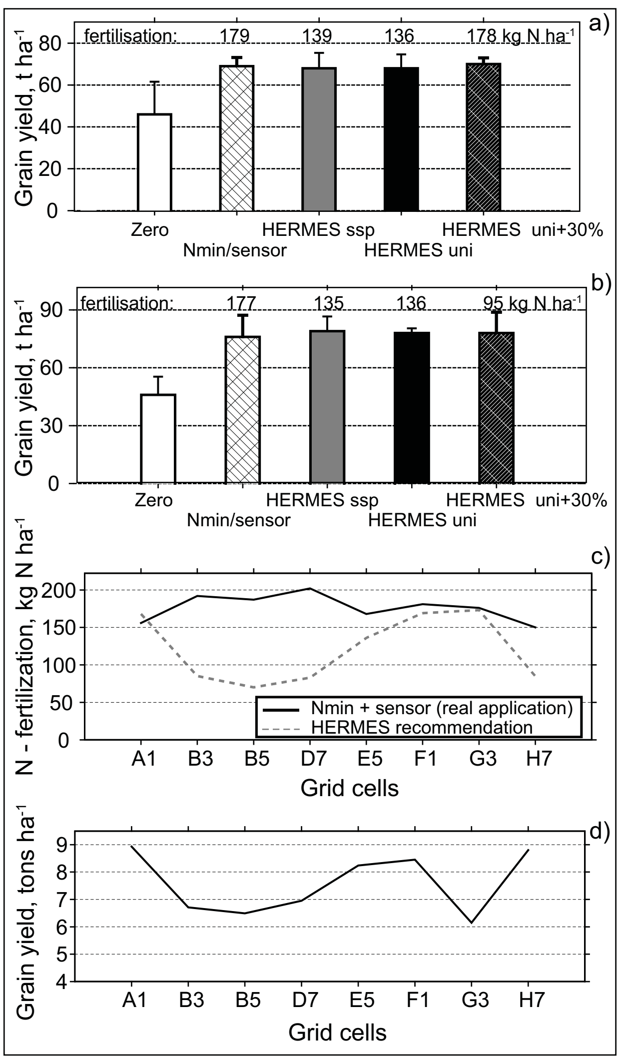

Figure 11. Comparison of different uniform and site specific fertilization recommendations on a 20 ha field in Saxony, Germany (averages of 8 grid cells for each fertilization, except HERMES ssp. (= 32 grid cells) in a) 2000 and b) 2001. c) comparison between real fertilizer applications on Hydro-N-sensor plots and alternative virtual model recommendations and d) corresponding crop yields.

the corresponding yields achieved with the sensor-based fertilization are displayed in **Figure 11D**. It can be seen that at the footslope positions B3, B5 and D7 the yields were lower although higher fertilization doses were applied.

Nevertheless, the results of the HERMES uni-30% variant in 2002 indicate that there is still a potential to reduce fertilization without yield reduction. That is because the model-based recommendations indirectly account for the uncertainty of the prediction keeping a "safety distance" above the critical N content function, which marks the threshold for crop growth reduction in the simulation.

Conclusions

The results show that the model HERMES is able to be used as a tool for fertilizer recommendations using daily weather data and site specific weather scenarios. Spatial distributions of soil and terrain properties can be used to produce site-specific recommendations within the framework of Precision Agriculture. Although the model has demonstrated its capability to save fertilizer compared to other methods, e.g. N_{min}/sensor based recommendations, without significant yield loss, the results of the fertilization experiments show that there is still some potential for reduction of N fertilizer. The uncertainty of input data, the model error itself and the predictive calculation require some security distance to the critical point, where yield might be reduced. The uncertainty caused by the prediction can be assessed using weather scenarios which cover the main range of the weather variability. However, the different response of different sites to weather variability has to be taken into account. Further development of models and of various technical equipment to improve the quality and resolution of site characteristics might partly reduce these uncertainties. Nevertheless, agro-meteorological forecasts over longer periods will remain as a main source of uncertainty for the prediction of crop growth and N dynamics for fertilizer recommendations. On the other hand, long-term time series of weather data can be used to calculate fertilization limits to protect groundwater resources from nitrate pollution.

Acknowledgments

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

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Abstract

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

Introduction

Current environmental and economic concerns demand improved N use efficiency from cropping systems. Concerns exist related to excessive nitrate levels in groundwater and N-induced hypoxia in estuarine areas from agricultural sources (McIsaac et al., 2002), and also with the high energy consumption for N fertilizer manufacturing and greenhouse gas impacts from soil 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 efficiency, or recovery efficiency (RE), which is the proportion of applied fertilizer that is taken up by the plant. Through on-farm experiments in six northcentral U.S.A. states, average RE was determined to be 37% with a standard deviation of 30% (Cassman et al., 2002). This suggests both low nutrient use efficiency and high potential N losses to the environment.

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

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

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

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

Estimating Optimum N Rates

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

Mass-Balance Approach

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

Maximum Return to N Approach

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

Soil Testing

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

The Pre-Plant N Test (PPNT; Bundy et al., 1995) measures soil nitrate or soil nitrate-plus-ammonium in the soil (typically from 0 to 60 cm) early in the season to guide N fertilizer applications at planting. It is generally recommended for cases with either high residual inorganic N from the previous season, or with organic N inputs such as manure, where it provides some guidance for adjusting early N fertilizer application rates. Its accuracy, however, is deemed limited for determining EONR in humid regions where the inorganic N is highly susceptible to losses during the early season.

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

Crop Leaf or Canopy Sensing

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

Temporal Dynamics in Soil N

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

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

N Mineralization and Uptake

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

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

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

The variability in SMN and PAN is a critical aspect of this data set. At pre-sidedress time (late spring), the SMN for plots in maize following barley showed a large range from 25 to 175 kg ha^{-1}, and even 37 to 271 kg ha^{-1} for maize following barley+clover. At maturity, PAN ranged for 63 to 309 kg ha^{-1} for maize after barley and 93 to 333 kg ha^{-1} for maize after barley+clover. Much of the differentiation in available N therefore occurs early in the growing season (Kay et al., 2006).

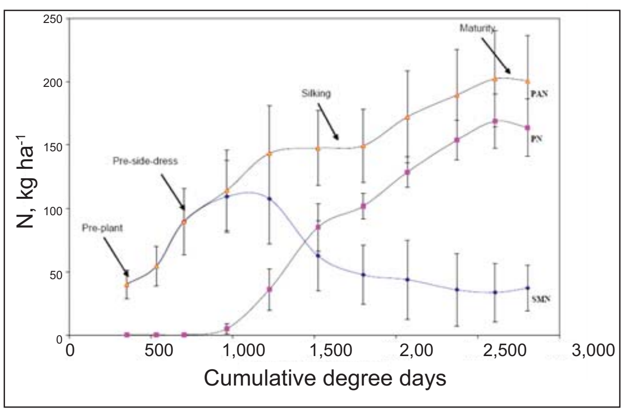

Figure 1. Accumulation of soil mineral N (SMN), total shoot N (PN), and plant available N (PAN) in the 0N plots over the growing season. Bars describe standard deviations among years (from Kay et al., 2006; reprinted with permission).

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

Yearly Optimum N Rate and Rainfall

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

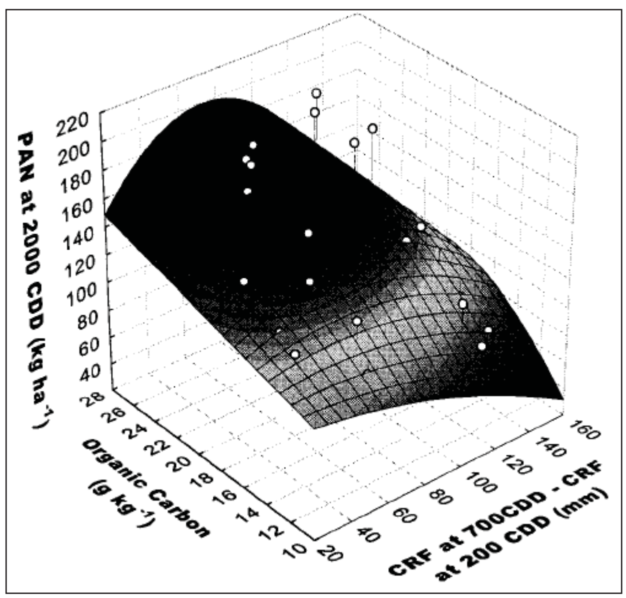

Figure 2. Variation in plant available N at 2000 CDD with organic carbon content and cumulative rainfall in the period 200 to 700 CDD for the barley-NT treatment, based on a regression equation with r2=0.63 (from Kay et al., 2006; reprinted with permission).

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

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

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

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

Generally, the optimum rates were similar for the 1978, 1979, and 1981 years (with dry springs), being 15 to 26 kg N ha^{-1} *below* the grand mean for all drainage classes. In 1980 and 1982 (with wet late springs), optimum N rates were much higher, from 17 to 39 kg N ha^{-1} *above* the grand mean (**Table 1**), indicating that in these years significantly more N was needed to achieve optimum maize yields. For the 5-year period of this study, the field-averaged EONR had a range of 65 kg ha^{-1}. A variance component analysis (**Table 2)** corroborates that annual variability was the dominant source of variation for EONR, that drainage class (soil type) effects were insignificant, and that drainage class by soil type effect was significant in that EONR was higher (about 50 kg N ha^{-1} above the grand mean) on poorly drained soils in years with wet springs (Sogbedji et al., 2001).

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

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

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

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

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

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

Towards Dynamic N Recommendations

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

Losses are also affected by the accumulation of heat units over the first months of a growing season. In the case of a cool spring, N mineralization is slow, and the accumulation and subsequent loss of SMN is smaller when excessive wetness occurs (**Figure 3a**). In all cases, the end result is that the supplemental N fertilizer rate varies greatly depending on water and temperature conditions during the entire early season, including the accumulated heat units, the occurrence and timing of excess wetness, and the soil temperature during those times of saturation (affecting denitrification rates; **Figure 3a**).

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

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

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

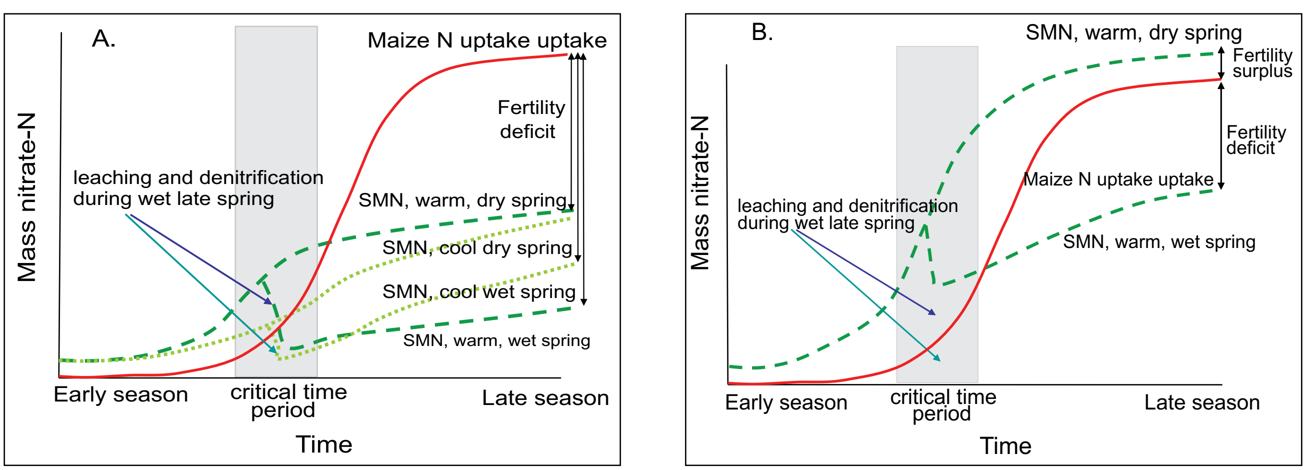

Figure 3. Conceptual gains and losses of soil mineral N and crop N over a growing season for a low soil N system (a), and a high soil N system (e.g., livestock; b). Broken and dotted lines represent SMN accumulations; solid line depicts maize N uptake.

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

Modeling Approach

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

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

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

Conclusion

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

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Application of Dynamic Simulation Modeling for Nitrogen Management in Maize

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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 recoded 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**).

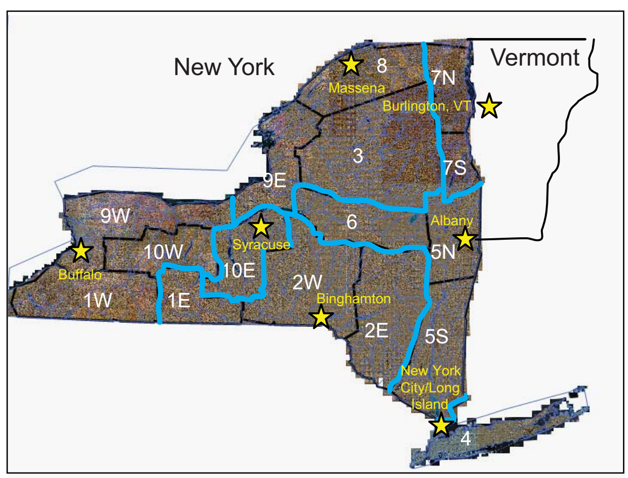

Figure 1. Climate regions of New York state, defined by historical precipitation and temperature averages. The stars (☆) indicate locations where mean Benchmark Net-N (BNN) was calculated from 35 climate year simulations. The climate regions where the BNN for a particular location were applied are outlined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

	Mean BNN by soil texture		
Location	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.

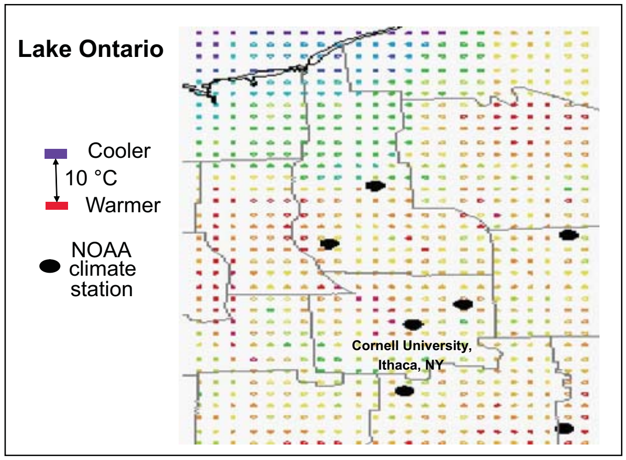

Figure 2. Maximum temperature data at 5-km grid resolution for 1 June 2006 for central New York state. The color code represents a temperature range of 10 ºC. Overlaid on the grid are the NOAA weather stations in that region, represented by the large black ovals.

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

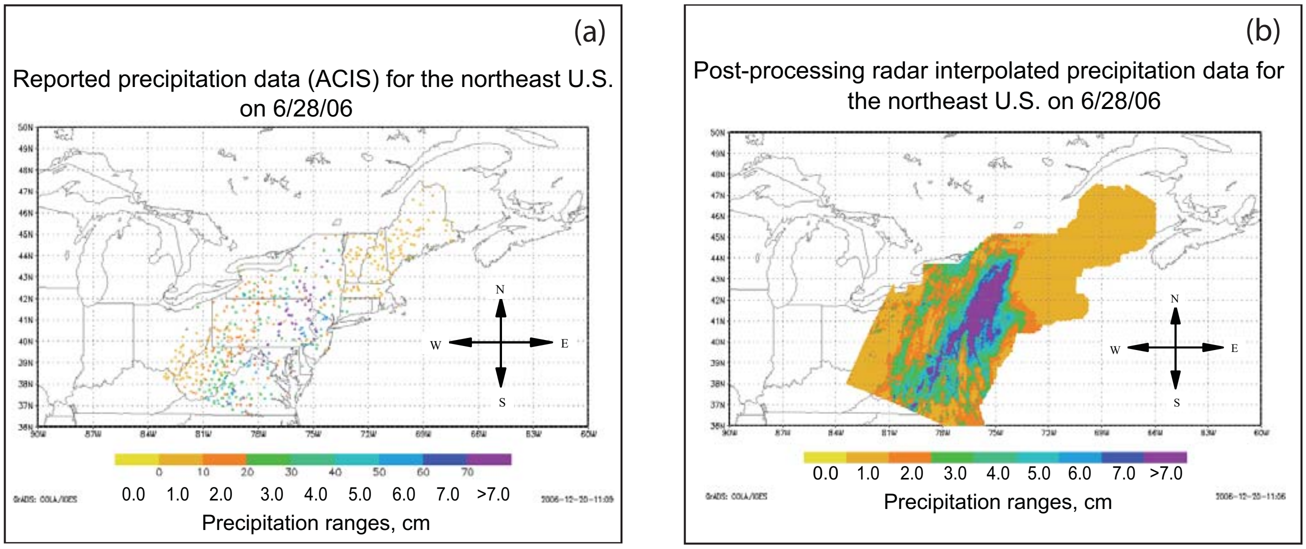

Figure 3. (a) Weather station precipitation totals for 28 June 2006 in the northeast U.S. obtained from an operational real-time climate database maintained by the Regional Climate Center Program using Applied Climate Information System methods, and (b) post-processing interpolated radar-based high resolution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

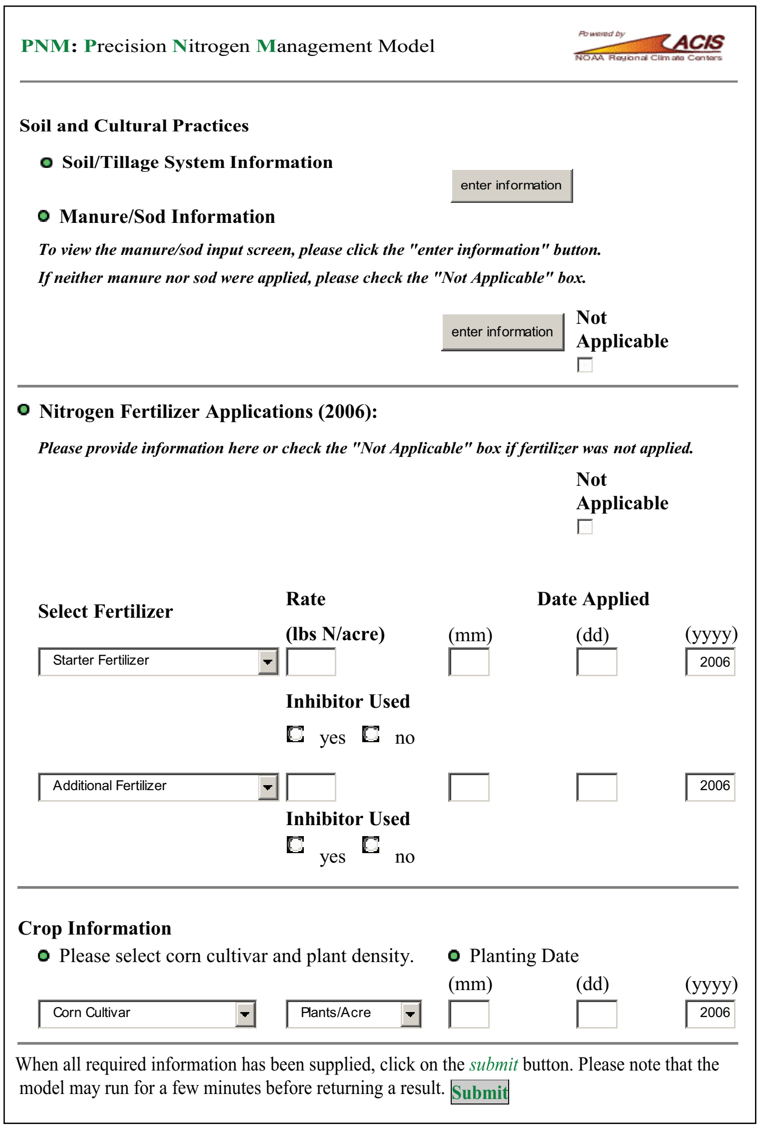

Figure 4. Main page of web interface for providing PNM model-generated field specific in-season N recommendations for maize.

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.

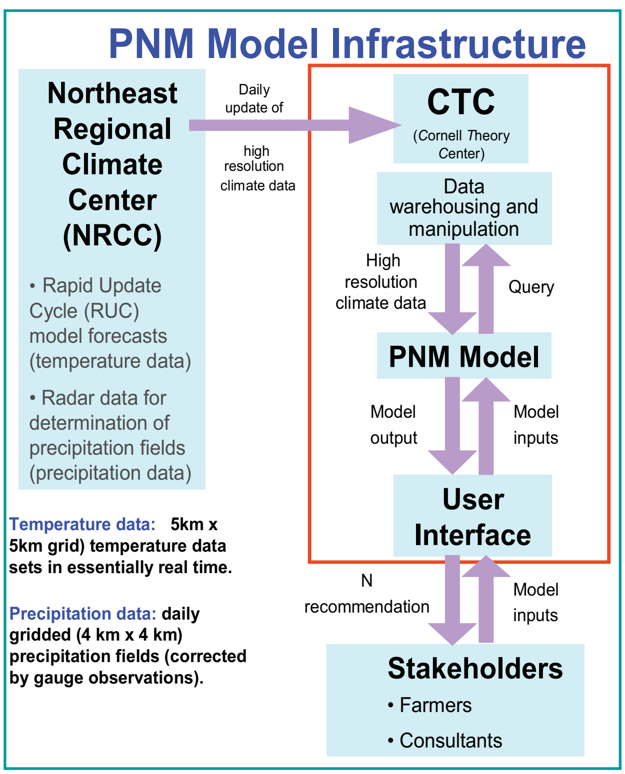

Figure 5. Infrastructure of the PNM model web interface for providing field specific in-season N recommendations for maize, including links to the Northeast Regional Climate Center.

Acknowledgments

This research was supported by the U.S. Department of Agriculture Special Grants Computational Agriculture Initiative and the Agricultural Ecosystems Program. We also gratefully acknowledge the expert assistance of Professor Bev Kay (University of Guelph, Ontario, Canada), Larry Geohring (Dept. of Biological and Environmental Engineering, Cornell University), and Professor Bill Cox (Dept. of Crop and Soil Sciences, Cornell University) in this research.

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Optimum Nitrogen Rate for Corn Increases with Greater Soil Water Availability

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Abstract

Improving site-specific N recommendations for corn (*Zea mays* L.) will depend on an improved understanding of the interactive effects of yield response to N and other independent variables. The objective of this study was to determine in-season soil water content redistribution (ΔW) for 10 locations along a hillslope and to characterize the relationship between ΔW and the economic optimum N rate (EONR) for corn. Ten plot locations were selected in 2005 along a 300 m toposequence of a production field in central Pennsylvania. At each location, two replications of six N treatments (0, 56, 112, 168, 224, and 280 kg N ha^{-1}) were broadcast-applied at planting as NH_4NO_3. Soil water content (0 to 90-cm depth) was recorded approximately weekly at each location between 5 June and 2 September. Grain yield was determined at harvest. A quadratic-plateau grain yield response to N fertilizer was observed at all locations and for the field-mean response. The EONR ranged from 47 to 188 kg N ha^{-1} among locations, while EONR for the mean response was 137 kg N ha^{-1}. The soil profile water content between 30 June and 25 July (ΔW_j) increased from -0.5 to 10.7 cm among these ten locations when rainfall was 12.2 cm. A linearly positive relationship between EONR and ΔW_j (representing the driest and wettest soil conditions early in the growing season) was the defining relationship in this study (r^2=0.83, P>F<0.0002). A "subsurface" wetness index, TWI_{sub}, derived from a "subsurface" digital elevation map (elevation – soil depth), was also positively related to ΔW_j (r^2=0.60, P>F=0.01), suggesting that subsurface water movement was, in part, responsible for the variability in soil profile water content redistribution. Although the causal mechanism responsible for the variability in EONR observed along this hillslope was not identified during this relatively dry growing season, ΔW_j and TWI_{sub} were better indicators of EONR than maximum grain yield. Understanding the relationships between these types of independent variables and the yield response to N fertilizer will be essential to improving site-specific N management.

Trade or manufacturers' names mentioned in the paper are for information only and do not constitute endorsement, recommendation, or exclusion by the USDA-ARS.

The interactive effects of nutrients, available water, and many other independent variables on crop yield have long been recognized (Havlin et al., 1999). However, fertilizer recommendations are generally based on single response variable experiments, with an effort to minimize the spatial variability of every other causal independent variable. This approach was successful in developing widespread and effective soil testing and fertilizer recommendation programs during the middle to latter part of the 1900s. The success of these programs was, in part, dependent upon the concept that all other limiting nutrients were applied to sufficient levels so as not to limit yield or alter the yield response function to the independent variable under consideration. Providing non-limiting amounts of most nutrients is generally practical and a reasonable tack for developing generalized nutrient recommendations. However, many other independent variables that might affect the yield response function, such as available water or physical soil characteristics, are not considered in developing fertilizer recommendations. With the advent of precision agriculture technologies representing the availability of a suite of new tools that rely on a geographic information system (GIS), a global positioning system (GPS), and powerful mobile computers, crop producers now have the opportunity to manage for yield-affecting independent variables that were practically unapproachable prior to 2000.

Increasing global trends in N fertilizer use underscores the importance of minimizing environmental impacts of N fertilizer, and in North America increasing natural gas and fertilizer costs increases the economic incentive to avoid over application of N. Both needs can be addressed by applying spatially and temporally appropriate amounts of N fertilizer. An important question in this context is, "What is the appropriate amount?" From the economic standpoint, the EONR is by definition the appropriate amount, defined as the N rate for

Abbreviations: EONR, economic optimum N rate; DEM, digital elevation map; TDR, time domain reflectometry; ΔW_j, change in soil profile (0to 90 cm) water content between 30 June and 25 July; ΔW_a, change in soil profile (0 to 90 cm) water content between 25 July and 24 August; TWI_{sub}, subsurface wetness index; N, nitrogen; NO_3, nitrate.

which the cost of the last increment of N is recovered by the additional return obtained from the corresponding incremental increase in grain yield. From an environmental standpoint, the EONR is also an appropriate amount of N, because applying the EONR corresponds to the greatest N rate without increasing either post-harvest soil residual NO_3 (Hong et al., In press) or shallow groundwater NO_3 (Hong et al., 2006).

Spatial and temporal variability in EONR for corn has been documented recently among and within fields (Fox and Piekielek, 1983; Scharf et al., 2005) and among years (Fox and Piekielek, 1983; Mamo et al., 2003). For example, field-to-field (within and across years) variability in EONR ranged between 22 and 203 kg N ha^{-1} for continuous corn at 11 site-years in Pennsylvania (Fox and Piekielek, 1983). In this same study, EONR varied from zero to 215 kg N ha^{-1} across all site-years, including various crop rotations and histories of manure application. Fox and Piekielek (1998) noted that maximum grain yield for corn was linearly related (r^2=0.69) to July precipitation for 15 years of results from a study at Rock Springs, Pennsylvania, but that there was no relationship between maximum yield and EONR (r^2=0.08) (Fox and Piekielek 1995). In a later unpublished report, Fox and Piekielek (2001) demonstrated that maximum corn yield was linearly related to July rainfall for rainfall less than 9.4 cm, then reached a maximum yield with a linear-plateau relationship (r^2=0.62) for 20 years of results from the Rock Springs Farm (the latter report presumably includes data from the 1998 publication).

The hillslope is a typical agricultural landscape unit in the Northeast, with variability in soil characteristics, such as soil water content, that could contribute to EONR variability. Variability in soil water content along a hillslope is not simply a function of elevation and rainfall. As Famiglietti et al. (1998) demonstrated for a hillslope near Austin, Texas, surface soil water content (0 to 5 cm) depended on soil porosity and hydraulic conductivity during wet soil conditions and on relative elevation, aspect, and clay content during dry conditions. Ridolfi et al. (2003) underscored the complexity of soil moisture dynamics along a hillslope by identifying 10 different phenomena that contribute to the spatial variability of soil moisture. Pachepsky et al. (2001) used topographical features to explain variability in soil water content, and suggested that topographic variability had a potential use for interpreting field-scale variability in precision agriculture.

The objective of this study was to characterize the soil water content redistribution along a 300 m hillslope, considering implications for the observed spatial variability in EONR for corn and the consequences for developing N fertilizer recommendations for site-specific management in the northeast U.S.A.

Materials and Methods

This experiment was conducted in 2005 at the Russell E. Larson Agronomy Research Farm at Rock Springs in central Pennsylvania. The experimental site was chosen along a 300 m long, westerly aspect hillslope in a rolling agriculture landscape. Total relief along the hillslope was 10 m (**Figure 1**) with slopes ranging from 1.5 to 5.4%. A second order soil survey (USDA-SCS, 1981) together with soil cores (1.1 m depth, 5 cm diameter) at 10 soil water access tube locations (described below) were used to verify that the soils along the hillslope are Hagerstown silt loams (Fine, mixed, semi-active, mesic Typic Hapludalfs). The thickness of the Ap soil horizon was also determined from these cores. This field did not receive any manure applications within the past 20 years, and the previous crop was soybean. Corn (var. Pioneer 34D72) was no-till planted on 3 May 2005. Typical production practices were followed (i.e. herbicides and pesticides to control weeds and pests) except for N fertilizer application. Plant population at harvest was 72,750 ha^{-1}.

Ten evenly spaced locations along the hillslope (**Figure 1**) were selected, each 18.3 m long by 27.5 m wide. Distance between locations was 12.2 m. The yield response to N fertilizer rates was evaluated using a randomized complete block design with two blocks at each location. Plots were six rows wide (4.6 m) and 9.1 m long. Nitrogen fertilizer treatments were 0, 56, 112, 168, 224, and 280 kg N ha^{-1} broadcast applied at planting as granular NH_4NO_3.

Prior to applying N treatments, soil samples were collected for routine soil analyses at Locations 2, 6, and 10, representing the toe slope, mid slope, and head slope positions, respectively (**Figure 1**). Soil samples (0 to 15, 15 to 30, and 30 to 60 cm depths) consisted of three sub-samples collected with an open-faced bucket auger (5 cm diameter) and composited for each depth. Analyses were completed at The Pennsylvania State University Agricultural

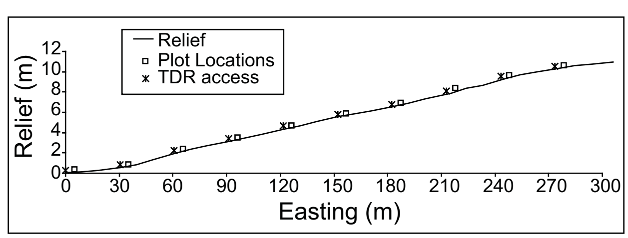

Figure 1. Local relief, plot locations, and TDR access tube locations along a 300-m toposequence.

Table 1. Selected soil (0 to 15 cm depth) characteristics and preplant inorganic N (three depths) for three locations along the toposequence.

Location	pH†	Acidity‡	CEC	SOM††	Mehlich 3§ P	K	Ca	Mg	Zn	S	Total inorganic N¶ 0-15 cm	15-30 cm	30-60 cm
		- - cmolc kg^{-1} - -		g kg^{-1}	- - - - - - - - - - - mg kg^{-1} - - - - - - - - - - -						- - - - - - - - - mg kg^{-1} - - - - - - - -		
2	5.5	4.5	13.6	28.7	46	97	1426	203	2.1	15.0	66.2	13.6	8.3
6	5.3	7.5	12.7	27.1	77	156	836	75	2.5	17.2	14.7	11.0	7.3
10	5.7	3.3	10.8	24.3	24	135	1210	138	1.3	12.5	12.1	9.2	7.5

† 1:1 soil:water pH

‡ Mehlich Buffer pH

§ Mehlich 3 extractant and using an inductively coupled plasma spectrophotometer (Wolf and Beegle, 1995)

¶ NO_3 and NH_4, 2 *M* KCl extract

†† SOM, soil organic matter (Schulte, 1995)

Analytical Service Laboratory, except for inorganic N, which was determined by flow injection analysis of 2 *M* KCl extract (QuikChem® Methods, Lachat Instruments, Loveland, Colorado). General soil nutrient characteristics, except for inorganic N, were similar among soils along this toposequence (**Table 1**) and were typical of agricultural fields in central PA.

Daily rainfall was recorded at a weather station located within 1.2 km of the field. The 30-yr average rainfall was obtained for the State College, Pennsylvania, weather station, which is located within 5 km of the field, and data were retrieved from http://climate.met.psu.edu/data/IA/ [verified on 7 March, 2007].

Corn grain was harvested from three of the four inside rows with a combine modified for plot work. Corn grain yield was adjusted to a moisture content of 155 g kg^{-1}. The EONR at each location was determined for the selected yield response function using a N fertilizer cost of \$0.66 kg^{-1} (\$0.3 lb^{-1}) and a corn price of \$0.078 kg^{-1} (\$2 bu^{-1}), equating the first derivative of the response equation to the fertilizer-to-corn price ratio and solving for X (Cerrato and Blackmer, 1990). Delta yield, the difference between grain yield at EONR and grain yield for the control (zero N), was determined for each location based on the approach of Lory and Scharf (2003).

Volumetric soil water content was determined using a factory-calibrated time domain reflectometry (TDR) moisture meter (TRIME-FM3) with a cylindrical probe (T3 probe) (both from Imko GmbH, Ettlingen, Germany). The TRIME-FM3 provides an effective way to obtain profile soil water content at multiple landscape positions, and the performance of this instrument has been evaluated by Laurent et al. (2005) (root mean squared error = 0.0662 when compared to neutron probe measurements). A TDR access tube was installed at Locations 1 through 10, located in the same row (between the first and second plot along the length of the hillslope) adjacent to and immediately in front (within 5 m on the downhill side) of each location (**Figure 1**). A hydraulic soil probe was used to remove a soil core to 1.1-m depth. One PVC tube (5.0-cm inner diameter) was fitted snugly into each hole. Access tubes were not placed in the plots receiving varying N fertilizer rates, but in "alley" areas that received a uniform 200 kg N ha^{-1} immediately after planting. We sampled soil water content with the TDR at 0 to 20, 10 to 30, 30 to 50, 50 to 70, and 70 to 90 cm depths on approximately weekly intervals between 5 June and 2 September, 2005, and after significant rainfall events. This period corresponded to approximately the 5-leaf growth stage to grain fill. Equivalent depth of soil water, Wp, was calculated for the top 90 cm of the soil profile using Equation (1):

$$W_p = 30\left(\frac{W_{20} + W_{30}}{2}\right) + 20(W_{50} + W_{70} + W_{90}) \quad (1)$$

where W_{20}, W_{30}, W_{50}, W_{70}, and W_{90} are soil water content for the 0 to 20, 10 to 30, 30 to 50, 50 to 70, and 70 to 90 cm depths, respectively. The change in W_p between 30 June and 25 July was defined as:

$$\Delta W_j = W_p \text{ on 25 July} - W_p \text{ on 30 June} \quad (2)$$

The change in W_p between 25 July and 24 August was defined as:

$$\Delta W_a = W_p \text{ on 24 August} - W_p \text{ on 25 July} \quad (3)$$

The first period (ΔW_j) was selected because this represented a period during the early growing season of overall slight water recharge that followed an earlier period of soil drying (**Figure 2**). This first period also coincided with a rapid increase in water demand by the crop. The second period (ΔW_a) represented a period of decreasing soil water content (low rainfall relative to crop demand), ending

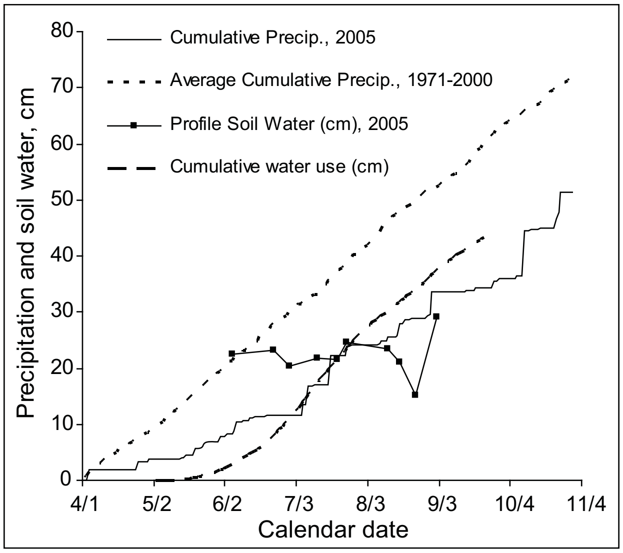

Figure 2. Cumulative daily precipitation (1 April to 31 October) for 2005, the 30-yr average for State College, Pennsylvania, mean profile soil water content (0-90 cm), and hypothetical cumulative water use for corn in central Pennsylvania. Cumulative water use was determined based on a typical year using results from the Integrated Farm System Model (http://www.ars.usda.gov/Main/docs.htm?docid=8519, verified 8 March 2007), which is a whole farm simulation model.

when the soil water content was the lowest during the entire growing season (**Figure 2**).

Elevation and geographic position were obtained at the corner of each plot and for each TDR access tube site using a Sokkia Set 3CII Total Station (Sokkia Co. LTD, Tokyo, Japan). Additional elevation and position measurements, outside the plot area, were obtained to ensure sufficient positions to determine catchment area for any position within the plot area. A 5-m digital elevation map (DEM) was derived from the survey data using the kriging gridding routine of the Surfer 8.0 software package (Golden Software, Golden, Colorado). Topographic analyses of the DEM were performed using ESRI ArcMap 8.3 (Environmental Systems Research Institute, Redlands, California). Slope was determined as the average slope across each location's plot area. Local relief and curvature were determined at the position corresponding to the TDR access tube. Curvature was determined based on the 5-m DEM, using the pixel corresponding to the TDR access tube position and eight adjacent pixels.

A topographic wetness index (TWI), which is an index of hydrological similarity based on topography and is related to the Horton model and Darcy's Law (Kirkby, 1975; Burt and Butcher, 1985), was determined using Equation (4).

$$TWI = \ln(\alpha / \tan\beta) \quad (4)$$

where α is the area draining through a point from upslope and β is the local slope angle. The TWI for each location was determined as the mean TWI for the nine pixels corresponding to the TDR access tube and adjacent pixels. A modified TWI, TWI_{sub}, was determined using Eq. 4 and a modified DEM derived by subtracting soil depth from the digital elevation map. Soil depth across the hillslope was determined using electromagnetic resonance measurements (EM31h) that were collected on approximately 30 m intervals. Soil depth was verified at selected locations, correlated to EM31h, and a surface map of soil depth developed using kriging. Soil depth at each location was determined based on the mean soil depth of the 5 m pixels corresponding to the TDR access tube and eight adjacent pixels.

Nitrogen treatment effect on grain yield was determined with PROC GLM (SAS® Institute, 1999). Regression analyses were completed using PROC REG (SAS® Institute, 1999) for linear or quadratic functions and PROC NLIN (SAS® Institute, 1999) for exponential, linear-plateau or quadratic-plateau functions. The quadratic-plateau model was constrained so that X0, where the quadratic function meets the plateau, was constrained to be less than or equal to Xm, where the slope of the quadratic function = 0. Regression analysis (PROC REG, SAS® Institute, 1999) was used to evaluate the relationships between EONR and numerous topographic and agronomic characteristics at each location.

Results and Discussion

Indicators of Economic Optimum Nitrogen Rate

Four different response functions were considered in evaluating the grain yield response to N at each of the 10 locations and for the mean yield response of the whole field site. These included the quadratic, linear-plateau, quadratic-plateau, and exponential models. Because the quadratic-plateau model most often provided the smallest residual sum of squares (SS) across all locations, provided the smallest residual SS for the mean grain yield response for the field (Schmidt et al., 2007), and is consistent with examples cited from the literature (Cerrato and Blackmer, 1990; Fox and Piekielek, 1995; Derby et al., 2005; Scharf et al., 2005), this model was selected as the best model to describe the yield responses to N fertilizer observed in this study (**Figure 3**).

Grain yield response to N was significant ($P>F<0.05$) at all ten locations. Based on results using the quadratic-plateau response (Schmidt et al., 2007), EONR ranged from 47 to 188 kg N ha^{-1} (**Table 2**). The EONR for the mean yield response (across all ten locations) was 137 kg N ha^{-1}. Yield at EONR ranged from 11.1 to 13.5 Mg ha^{-1} and the corresponding mean yield at EONR, based on the mean yield response, was 12.3 Mg ha^{-1}. The range

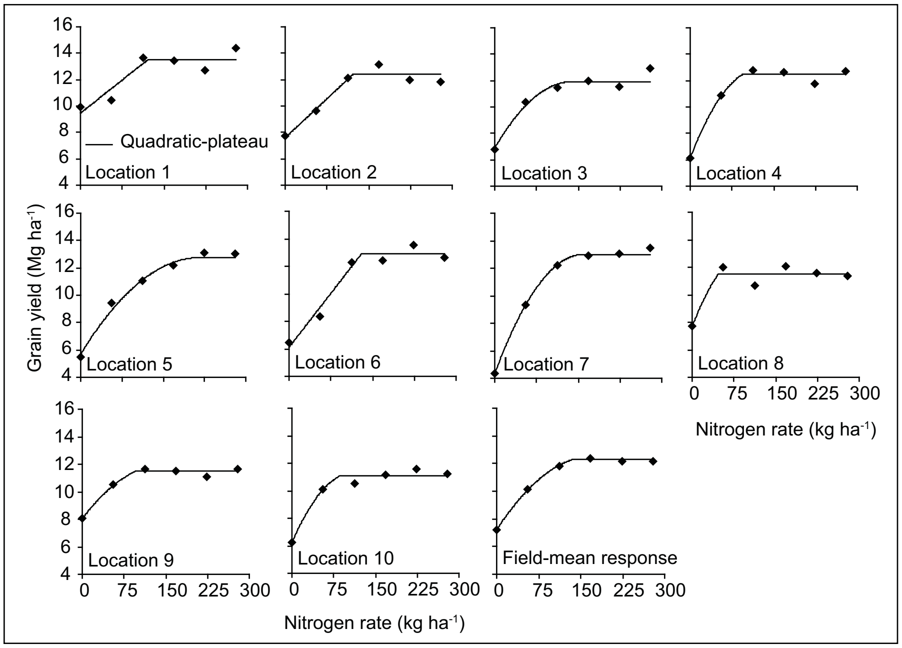

Figure 3. Grain yield response to N fertilizer for all ten within-field locations and the field-mean yield response for the entire study area (including Location 3). Parameter estimates for regression equations are provided by Schmidt et al. (2007).

the same research farm. Fox and Piekielek (unpublished report, 2001) later demonstrated with the continuation of the same study, that maximum corn yield increased linearly as July rainfall increased to 9.4 cm. Then, with additional rainfall in excess of 9.4 cm, yield remained constant in a linear-plateau type relationship. Fox and Piekielek's results also indicated that there was a linear relationship between July rainfall and EONR (r^2=0.5, P>F=0.001), which can be considered a convenient measure of water availability to the growing crop.

of EONR (67 to 212 kg N ha-1) observed by Fox and Piekielek (1995) from field studies representing 57 site-years, 43 of which were conducted at the same research farm as the current study, was similar to the range in EONR observed for the current study.

The change in soil profile (0-90 cm) water content between 30 June and 25 July, ΔW_j, was the best indicator of EONR (**Table 3**). Rainfall at the study site was 20 cm below the 30-yr normal rainfall between 1 April and 30 June 2005 (**Figure 2**), and the lowest mean soil water content (ten locations) during the growing season prior to 24 August was observed on 30 June. Rainfall during early July (12.2 cm) replenished the mean soil profile (0 to 90 cm) water content along this hillslope (**Figure 2**), unevenly changing ΔW_j from -0.5 cm at Location 8 to +10.7 cm at Location 5 (**Table 2**). The EONR observed at each location was strongly and positively related to the change in soil profile water content during this period of rapid vegetative growth (r^2 = 0.83; P> F<0.0002; **Table 3**).

Grain yield at EONR was marginally related to ΔW_j (r^2 = 0.48; P>F=0.10), and not as strongly related as the relationship between EONR and ΔW_j. The positive impact of water availability during the growing season on grain yield, and in this study particularly during July, is not unusual because the impact of soil moisture deficit stress on plant growth is considered self-evident. Fox and Piekielek (1998) observed a linear relationship between July precipitation and maximum corn grain yield (r^2=0.69) from 15 years of N fertilizer studies at

Economic optimum N rate was not significantly related to grain yield observed at EONR (**Table 3**), which suggests that maximum yield, or yield goal, may not be appropriate as a criterion from which to develop site-specific N recommendations. Using yield goal to develop site-specific N recommendations is probably an over-simplification of a relationship that has been effective for developing N recommendations at larger spatial scales than the field (Mortvedt et al., 1996; Shapiro et al., 2003). The range in yield observed for this study was 11.1 to 13.5 Mg ha^{-1}, representing variability that did not correspond to variability in N demand. This supports conclusions by Katsvairo et al. (2003) who suggested that more information would be required for successful site-specific N management than provided by a late spring soil NO_3-N test and a yield map. However, delta yield, representing the yield difference between yield observed at EONR and yield for the control treatment, was linearly related to EONR (P>F=0.05; **Table 3**), supporting the approach by Lory and Scharf (2003) who used delta yield as an indicator from which to develop N recommendations.

Various other agronomic, topographic, and soil indicators that could potentially impact EONR were evaluated (**Table 2**), but none of these indicators provided as strong a correlative relationship with EONR as ΔW_j (**Table 3**). One other independent variable that was significantly correlated to EONR was TWI_{sub} (r^2 = 0.43, P>F=0.04; **Table 3**), which is a modification of the wetness index based on the subsurface topography (i.e., local relief minus soil depth). This result suggests that subsurface water movement could be responsible for the uneven redis-

Table 2. Topographic and agronomic characteristics of the ten experimental locations along a hillslope in Pennsylvania.

Location	Position	EONR†	Yield at EONR	Rel. elev.‡	Slope	Slope curvature	Depth to bedrock	TWI§	TWI(sub)	Ap thickness¶	ΔW_j††	ΔW_a
		(kg N ha^{-1})	(Mg ha^{-1})	(m)	(%)		(m)			(cm)	----- (cm)	-----
1	toe slope	121	13.5	0.00	1.5	-0.0028	2.28	11.09	6.28	25	6.30	-6.10
2	toe slope	123	12.4	0.30	3.6	-0.0023	2.12	10.33	4.57	25	6.48	-8.14
3	mid-slope	123	11.8	1.37	5.2	-0.0048	1.62	9.48	5.00	13	9.01	-15.54
4	mid-slope	94	12.5	2.81	4.5	-0.0048	1.41	10.69	4.75	15	3.33	-10.56
5	mid-slope	188	12.6	3.95	5.1	-0.0053	1.46	10.69	4.53	15	11.71	-13.53
6	mid-slope	129	12.9	5.24	4.0	-0.0016	1.78	10.61	4.27	20	4.23	-8.22
7	mid-slope	147	13.0	6.23	5.1	-0.0036	1.82	9.96	3.59	13	7.76	-8.49
8	mid-slope	47	11.5	7.52	5.4	-0.0045	1.31	9.88	3.97	13	0.46	-7.56
9	head slope	96	11.5	8.89	4.6	-0.0015	1.20	9.14	4.32	14	2.30	-8.40
10	head slope	88	11.1	10.11	3.1	-0.0006	1.41	9.16	4.03	11	2.18	-8.36

† Economic Optimum Nitrogen Rate (Schmidt et al., 2007)

‡ Relative elevation with the location 1 as a reference with an elevation of 371.9 m.

§ Topographic wetness index that is defined in Eq. [2].

¶ The Ap horizon thickness.

†† ΔW_j and ΔW_a represent the change in soil profile water content between 30 June and 25 July, and 25 July and 24 August, respectively.

tribution of soil water content (0 to 90 cm) observed between 30 June and 25 July, ΔW_j (**Table 3**). Greater soil water content observed between 30 June and 25 July, ΔW_j, corresponded to greater decreases in soil water content between 25 July and 24 August, as mean soil water content among all locations decreased (**Figure 2**). A linear relationship ($r^2 = 0.38$, P>F=0.06) between ΔW_j and ΔW_a suggests that soil conditions at some locations were conducive to providing more water to the growing crop during this relatively drier year (**Figure 2**). This is supported by the additional observation that those locations with greater soil water content on 25 July also had the greatest decrease in soil water content between 25 July and 24 August (ΔW_a = -66.5 + 5.44W_p, 25 July - 0.12 W_p, 25 July 2; $r^2 = 0.93$, P>F<0.0001). Similar to results observed by Fox and Piekielek (unpublished report, 2001), EONR increased with increasing rainfall, or as in the current study, with additional soil water content during a relatively dry growing season.

While a mechanistic explanation for the strong positive relationship between EONR and ΔW_j is beyond the scope of the current study, the variability in soil water content during the growing season can be explored in more detail.

Indicators of In-season Soil Water Content Re-distribution

Soil water availability can vary quite significantly along a hillslope (Famiglietti et al., 1998; Ridolfi et al., 2003), and year-to-year variability in July rainfall was an indicator of corn grain yield and EONR variability for previous studies at the current research farm. July rainfall in 2005 (12.4 cm) exceeded the yield-limiting July rainfall (9.4 cm) determined by Fox and Piekielek (unpublished report, 2001), and grain yield observed in 2005 exceeded maximum grain yield (10.4 Mg ha^{-1}) observed by Fox and Piekielek. However, the amount of water available to the growing crop was not simply a function of rainfall, as demonstrated by the variability observed in ΔW_j (**Table 2**) and as was suggested and illustrated by the 10 processes affecting hillslope hydrology identified by Ridolfi et al. (2003). Observed differences in ΔW_j (-0.54 to 10.7 cm of water; **Table 2**) reflect differences

Table 3. Performance of various agronomic-, topographic-, and soil-dependent variables as indicators of the economically optimal N rate (EONR).

Independent variable	EONR (Mg ha^{-1})	r^2	P > F
ΔW_j (cm; 7/25 - 6/30)†	y = 9.8x + 72.5	0.83	0.0002
TWI_{sub}	y = 29.7x - 35.7	0.43	0.04
Grain yield at EONR (Mg ha^{-1})	y = -19.4x2+ 505x – 3146	0.42	0.15
Delta yield (Mg ha^{-1}) ‡	y = 13.9x + 40.6	0.39	0.05
TWI	y = 22.3x - 110.2	0.17	0.24
Control yield (Mg ha^{-1})	y = -9.76x + 182.6	0.16	0.25
Local relief (m)	y = -4.1x + 134.5	0.15	0.27
Depth to bedrock (m)	y = 38.6x + 52.1	0.13	0.30
Ap thickness (cm)	y = 1.7x + 88.3	0.05	0.53
Slope curvature	y = -5175x + 99.0	0.05	0.53
Slope (%)	y = 0.9x + 111.7	0.00	0.94

†Change in soil profile water content in the top 90 cm between the specified dates.

‡Delta yield = Grain yield at EONR - Grain yield with zero N.

Table 4. Performance of various topographic- and soil-dependent variables as indicators of the change in soil profile (0-90 cm) water content between 30 June and 25 July, ΔW_j.

Independent variable	ΔW_j (cm)	r^2	P > F
TWI sub	y = 3.4x - 13.9	0.60	0.01
ΔW_a (cm; 8/24 - 7/25)†	y = -0.74x - 2.63	0.38	0.06
TWI	y = 2.64x - 22.9	0.28	0.14
Local relief (m)	y = -0.49x + 6.42	0.26	0.17
Slope curvature	y = -826x + 1.49	0.15	0.30
Ap thickness (cm)	y = 0.19x + 0.80	0.08	0.45
Depth to bedrock (m)	y = 3.92x -2.47	0.02	0.25
Slope (%)	y = 0.03x + 3.86	0.001	0.98

†Change in soil profile water content in the top 90 cm between the specified dates.

in soil and landscape characteristics that affect water redistribution within this landscape. Perhaps less than 100% of rainfall in early July infiltrated at Location 8, while infiltration may have equaled rainfall at Location 5 and / or Location 5 was the beneficiary of subsurface redistribution of rainfall, resulting in a change in soil profile water content at Location 5 almost equal to rainfall despite evapotranspiration by a growing corn crop.

Various hillslope- and soil-dependent characteristics were evaluated in an attempt to better understand the variability in soil profile water redistribution observed at this study site between 30 June and 25 July (ΔW_j). As already described, ΔW_a was linearly and inversely related to ΔW_j (**Table 4**). Other characteristics that were considered as potential explanatory variables for ΔWj included: local relief, TWI, TWI_{sub}, slope, slope curvature, depth to bedrock, and Ap thickness. The only other variable that was significantly related to ΔW_j was TWI_{sub}. As TWI_{sub} increased by one unit, ΔW_j increased by 3.4 cm (**Table 4**). This index was also related to EONR (**Table 3**). If growing season rainfall had been above average, this result suggests that TWI_{sub}, as an indicator of wetness, might be providing some measure of denitrification. However, this explanation seems incongruent with the dry growing conditions observed during 2005. A probable alternative explanation depends on a synergistic effect between additional water availability and increasing N demand during a dry growing season. With the additional water available at some locations, the growing corn crop could take advantage of greater N rates, so EONR was greater at those locations. Given this latter explanation, then a practical question is, "What is responsible for the differences in soil profile water redistribution at each location?" Can we identify landscape characteristics that can be used in developing *a priori* site-specific N fertilizer recommendations?

The soil profile water content distribution on 30 June, 25 July, and 24 August for each location is depicted in **Figure 4**. Those locations with greater ΔW_j corresponded to greater EONR, and the redistribution of water in the soil profile was not the same among these ten locations.

At Location 5, where the EONR and ΔW_j were the greatest among the 10 locations, the increase in soil water content between 30 June and 25 July (+10.7 cm) was evident throughout the 90-cm profile (**Figure 4**), and particularly pronounced at 0 to 30 cm and 50 to 90 cm. The only other location with a similar increase in ΔW_j (+8.0 cm) was Location 3, where the change in water content distribution with depth was relatively uniform (**Figure 4**). The EONR at Location 3 was 123 kg N ha^{-1}, which was less than EONR observed at Location 5; however, the difference in EONR between these two locations could be attributed to the greater initial soil NO_3 levels (**Table 2**) observed for the toe slope positions of this hillslope. Locations 3 and 5 were the only locations that were beneficiaries of an increase in water content lower in the soil profile between 30 June and 25 July (**Figure 4**), corresponding to a period when 12.2 cm of rainfall was recorded;

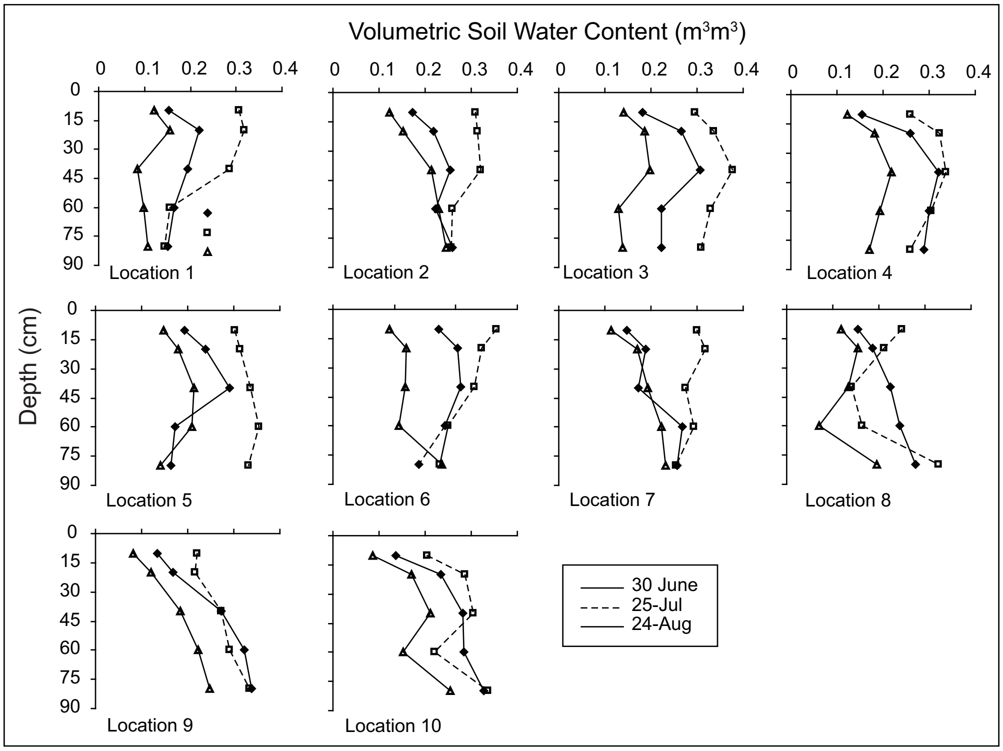

Figure 4. Volumetric soil water content in the 90 cm profile on 30 June, 25 July, and 24 August for each location along the hillslope.

and these were locations where N requirements to obtain maximum corn yield were high.

The EONR at Locations 1, 2, 6, and 7 was between 100 and 150 kg N ha^{-1} and the ΔW_j at these locations was between 3.2 and 6.8 cm (**Table 2**). Water recharge within the soil profile between 30 June and 25 July was more consistent with typical expectations of infiltration without subsurface redistribution, where there was a greater increase in water content observed in the surface soil than compared to the subsurface (**Figure 4**). For example, soil water content in the top 20 cm at these locations was between 0.14 and 0.17 m3 m-3 on 30 June, and on 25 July, soil water content was between 0.26 and 0.31 m^3m^{-3}. By contrast, soil water content below 50 cm at these locations was similar on 30 June and 25 July. These locations may represent the typical soil conditions (i.e. recharge from the surface) that correspond to typical N requirements for this field and geographic region, consistent with the average N requirement for this type of field and growing conditions (Beegle, 2004).

Three locations (4, 9, and 10) corresponded to slightly smaller EONR (88 to 96 kg N ha^{-1}) and slightly smaller ΔW_j (1.1 to 2.3 m^3m^{-3}) than observed at Locations 1, 2, 6, and 7, suggesting that with less water available for crop growth less N was required to reach maximum yield. Grain yield at EONR was marginally related to ΔW_j (**Table 3**), and maximum yield at Locations 9 and 10 were only 11.5 and 11.1 Mg ha^{-1}, respectively (**Table 2**). The changes in soil profile water contents between 30 June and 25 July at Locations 4, 9, and 10 were similar in one respect to ΔW_j observed at Locations 1, 2, 6, and 7 – subsurface recharge was negligible. The primary difference between the former and latter locations was that surface recharge of the soil water content was much smaller for Locations 4, 9, and 10 (**Figure 4**). These results suggest that N was not the most yield-limiting factor at these locations, and perhaps the less than average water recharge between 30 June and 25 July during a relatively dry growing season was restricting crop growth.

The location (8) for which the smallest EONR (47 kg N ha^{-1}) was observed also corresponded with the smallest ΔW_j (-0.5 cm; **Table 2**). At this location, the change in soil profile water content was quite distinct from the change in soil profile water content observed for any other location (**Figure 4**). On 30 June the soil water content increased from 0.15 m^3m^{-3} to almost 0.3 m^3m^{-3} with increasing depth and was similar to the distribution observed for some of the other locations; however on 25 July, the soil water content was > 0.2 m^3m^{-3} in the soil surface, but less than 0.18 m^3m^{-3} at the 30- to 70-cm depths. Although there was an increase in soil water content in the top 30 cm of soil, there was a large decrease in water content below 30 cm. The very low EONR observed at Location 8 appears to be related to the net negative change in soil water content in the lower profile.

Economic optimum N rate varied between 47 and 188 kg N ha^{-1} along this central PA hillslope, and EONR was strongly related to ΔW_j, representing the change in soil profile (0-90 cm) water content during a period of slight water recharge in a relatively low-rainfall growing season. At locations along this hillslope where more soil water recharge had occurred, EONR was greater (**Table 3**). The uneven redistribution of soil profile water (**Figure 4**) was most closely related to TWI_{sub} (**Table 4**), indicating that subsurface water movement likely contributed to the water redistribution. Surface features: TWI, local relief, slope, slope curvature, were not related to ΔW_j (**Table 4**), suggesting that surface distribution of water was not likely responsible for the uneven changes in soil profile water content. After 25 July, when soil water content was decreasing at all locations (**Figure 4**), those locations with greater soil water content on 25 July had the greatest decrease in soil water content. During a relatively low-rainfall growing season when rainfall was probably limiting plant growth, any additional water availability corresponded to increased N demand and a greater EONR.

Implications for Nitrogen Fertilizer Recommendations

General N fertilizer recommendations that have been developed with the intent to be implemented on large geographic regions (e.g. an entire U.S. state) are commonly a linear function of yield goal. These include N recommendations from Pennsylvania (Beegle, 2004), Colorado (Mortvedt et al., 1996), and Nebraska (Shapiro et al. 2003), as well as other states. While there was some evidence from the current study to support this concept for site-specific N management (grain yield at EONR was marginally related to EONR, $r^2 = 0.42$, P>F=0.15), the results here suggest that other underlying hillslope or soil characteristics need to be identified and the causal relationship with EONR better understood to take advantage of site-specific technologies. Kastens et al. (2003) presented an approach with which this type of information could be integrated with traditional fertilizer recommendations in developing site-specific fertilizer recommendations for an individual producer or group of producers. Computer modeling that incorporates current soil water conditions, hillslope water redistribution, and short-term weather forecasting could be used to adjust N recommendations for in-season applications, similar to the approach described by Melkonian et al. (in this volume) and being implemented in New York. Many practitioners and researchers continue to approach site-specific N management by not adequately accounting for the interactions of yield-affecting independent variables; consequently, these technologies remain largely unexploited for the purpose of developing improved N recommendations.

Recent research focusing on the variability in corn yield response to N fertilizer has indicated that N requirement for corn varies among fields (e.g., Schmitt and Randall, 1994; Scharf et al., 2005) and within fields (Blackmer and White, 1998; Scharf et al., 2005). Scharf et al. (2005) indicated that the field-median economical optimum N rate (EONR) among eight site-years ranged from 63 to 208 kg N ha^{-1}, indicating that field-to-field N management was important to improving overall N management. In the current study, EONR for 10 locations along a central Pennsylvania hillslope was strongly related to the change in soil profile water content (0 to 90 cm) between 30 June and 25 July ($r^2 = 0.83$; P>F<0.0002). The change in soil profile water content between those two dates, ΔW_j, was strongly related to a topographic wetness index that was modified to represent the hillslope topography below the soil (TWI_{sub}). Differences among locations in the vertical distribution of the profile water content observed between 30 June and 25 July corroborate the possibility of subsurface water flow (**Figure 4**).

Below average rainfall early during the growing season in 2005 (**Figure 2**) resulted in yield-limiting conditions that were mostly alleviated with July rainfall. Those locations where soil recharge was greater corresponded to greater EONR, as indicated by the strong relationship between EONR and ΔW_j (**Table 3**). Although weather conditions are difficult to forecast for any one growing season, the physical soil and hillslope features affecting water redistribution are relatively static and are relatively easy to characterize with site-specific technologies. In this study, TWI_{sub} was indicative of ΔW_j and EONR. In identifying these important relationships, subsequent studies should be designed and implemented to better understand the causal mechanisms affecting corn yield response to N. While yield variability within and among fields is generally recognized, the relationship between yield variability and optimum N rate is not often completely understood, or perhaps, does not receive adequate consideration.

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Spring Rainfall Dictates Success of Nitrogen Applied to Corn in Fall or Winter

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Abstract

Nitrogen fertilizer applied to corn (*Zea mays* L.) well before plant uptake is susceptible to losses from certain weather conditions, especially spring rainfall. Our objectives were to determine how spring rainfall and the N application time interact to result in grain yield loss, and to develop functions to predict and correct these yield losses with supplemental N. Variable application times were achieved by fertilizing at monthly intervals with a constant N rate (134 kg N ha^{-1}), and then determining grain yield loss from a fall (Oct/Nov) or winter (Dec/Jan/Feb) application compared to the spring (Mar/Apr). The same N treatments were applied at 10 site-years in central and northern Illinois between 1997 and 1999 and weather data were collected at each site. The responsiveness to N was assessed by including an unfertilized treatment at all sites, and seven sites had an N titration (five rates from 67 to 201 kg ha^{-1} in 34 kg increments) applied in April. All but one site exhibited yield increases from N application, and only three sites did not have a fall or winter application that yielded less than spring. Plateau-linear functions best described the relationship between spring (Mar, April, and May) rainfall and yield reductions from fall or winter applied N, and indicated the precipitation threshold above which these yield losses accentuated (270 mm and 325 mm for fall and winter applied N, respectively). We used these relationships and historic rainfall data to predict the probability for a given yield loss from fall or winter applied N, and we developed equations to determine the amount of supplemental N needed to correct for this loss.

Introduction

The best time for N application to corn must balance a number of contentious issues including: the propensity for N to be lost, the biology of the crop in using N, the unpredictability of the weather, the availability of equipment and manpower, and the economics of fertilizer cost and grain value. A number of N fertilizer recommendation systems have been developed for different geographic regions that attempt to accommodate these variables, but in many cases the success of N fertilization is largely dependent on the weather. This is obviously because of the major impacts that temperature and precipitation have on the microbial and physical processes associated with N loss. Clearly, from the standpoints of N loss and crop biology, the best time to apply N should be just prior to the period of rapid crop uptake. The risk of adverse weather, however, plays a large role in the reluctance of growers to widely adapt this practice and necessitates other times for N application. These times are also dictated by the impact that weather has on soil moisture, which determines when equipment for N application can be used. Despite its major impact on N fertilization, weather considerations are generally secondary to economic ones, especially since fertilizer cost and grain prices both exhibit large and independent fluctuations.

The major distinction in timing of N application is between fall and spring, and an abundance of research shows that applying N in the spring is usually superior to the fall (Bundy, 1986; Miller et al., 1975; Randall et al., 2003; Randall and Vetsch, 2005; Stevenson and Baldwin, 1969). The degree of yield reduction from fall fertilization is often associated with spring rainfall (Malzer and Randall, 1985; Randall and Vetsch, 2005; Vetsch and Randall, 2004). Guidelines for fall N fertilization, however, do not include any means of predicting the degree to which spring rainfall causes yield loss, or any recourse for supplemental N application if yield loss has occurred. Our objectives were to address this issue by: (i) determining the degree of yield loss associated with spring rainfall and N application time, and (ii) developing functions to predict when yield loss has occurred and the amount of supplemental N needed to correct this loss.

Materials and Methods

Nitrogen was applied at monthly intervals from October through April at 10 site-years in Central and Northern Illinois, and grain yield was measured along with weather data. Field and cultural characteristics at each site are given in **Table 1**. There were three sites in 1997 and 1998, and four in 1999. Each site-year is abbreviated by three letters, followed by two numbers representing the

Abbreviations: N = nitrogen;

Table 1. Characteristics of the 10 Illinois site-years where fertilizer N was applied from October through April.

Site-year	Nearest town	Site-year Characteristics: Soil Bray P1	Soil Exch. K	O.M., %	pH	Soil series, Texture	Slope, %	Prev. Crop	Tillage
		- - - - - mg/kg - - - - -							
Gif 98	Gifford	13	190	3.7	7.3	Swygert, SiCl	2-5	Corn	Plow
Man 99	Manlius	19	108	3.5	6.9	Joy, Sil	0-2	Corn	Strip
Ran 98	Rantoul	47	207	5.2	4.7	Raub, Sil	0-2	Soybean	Mulch
Mor 98	Morris	30	163	3.4	5.5	Darroch, Sil	2-5	Soybean	Zero
Dek 99	Shabbona	37	175	4.1	6.0	Elpaso, SiCl	0-2	Soybean	Mulch
Lex 97	Lexington	50	192	2.9	6.2	Elpaso, SiCl	2-5	Soybean	Strip
Urb 97	Urbana	63	202	2.5	4.7	Drummer, SiCl	0-2	Corn	Zero
Tow 97	Towanda	52	209	3.8	6.2	Sabina, Sil	0-2	Corn	Strip
Ran 99	Rantoul	26	174	2.5	5.5	Dana, Sil	2-5	Soybean	Mulch
Fla 99	Flanagan	40	292	3.4	5.9	Chenoa, SiCl	2-5	Soybean	Strip

year in which the experiment was conducted. None of the sites were repeated and eight were conducted on-farm. Soil fertility levels were generally within accepted levels, and except for the N treatments other management practices were in accordance with the grower's standard practices that used local recommendations for high yield. Corn was planted between April 15th and May 11th, at seeding rates that ranged from 67 to 82 thousand seeds per hectare.

Nitrogen was applied between the 8th and 20th of each month at a rate of 135 kg ha^{-1}. This rate was selected based on preliminary trials conducted at four of the sites (Lexington, Morris, Towanda, Urbana) in 1996, and on the advice of the farmers and farm managers at each site. To assess the responsiveness to N, all sites had an unfertilized control. Seven sites (1998 and 1999) had a N titration of five rates ranging from 67 to 201 kg N ha^{-1} in 34 kg increments applied in April. The N source at all sites was granular ammonium sulfate which was broadcast on the soil surface. At all sites, N treatments were arranged in a randomized complete block design with four replications, with plot dimensions of 6.1 m wide and 30.5 m long.

Precipitation data were collected on-site using a tipping bucket and self-emptying style rain gauge with a 200 mm collection opening. Air temperature was measured 1.5 m above the soil surface and all data logged with WatchDog™ data loggers (Spectrum Technologies, Inc. 23839 W. Andrew Rd., Plainfield, IL 60544). Corn grain yield was measured by harvesting the center two rows of an experimental unit with plot combines or by hand harvest. When machine harvested, the entire 30.5 m length of plots was used, while 5.3 m in a row was used for hand harvested plots. Grain moisture was determined, and grain dry matter yields were adjusted to zero moisture.

Statistics were performed by ANOVA using the GLM procedures of SAS (SAS Institute, 2003). A LSD at α=0.10 was used for means separations. Corn yield loss for fall (October through November) and winter (December through February) N fertilization was calculated as the difference between corn yield for spring (March through April) fertilization and fall and winter applied N at each location, respectively.

Mean monthly temperature and total monthly precipitation, as well as cumulative precipitation and mean temperature for the periods fall, winter, and March through May were evaluated as independent variables to estimate yield loss. The effect of spring rainfall on fall and winter yield loss and on supplemental N needed was modeled with a plateau-linear function using the NLIN procedure of SAS (SAS Institute, 2003). Corn yield response to N fertilizer across all sites was modeled with the same procedure. Linear-plateau and quadratic-plateau models were tested and the linear-plateau model was chosen because it provided the best fit to the data. All parameters for yield loss, supplemental N, and yield response models were tested at α=0.1.

The cumulative probability of yield loss from fall and winter applications was calculated for Urbana (40°6'N, 88°12'W), Bloomington (40°28'N, 88°59'W), Paw Paw (41°41'N, 88°58'W), and Monmouth (40°54'N, 90°38'W), Illinois, based on the yield loss functions. These locations were selected to provide a range of environmental conditions within Northern and Central Illinois, the inference space for this research. Total spring (March through May) precipitation was calculated based on weather data obtained from the Illinois State Climatologist Office (http://www.sws.uiuc.edu/data/climatedb/). The weather data encompassed 106 records for Urbana and Monmouth, 86 for Paw Paw, and 56 for Bloomington.

Results

There was considerable variation among the sites in their responsiveness to N, and in the degree of yield loss from a fall or winter N application compared to spring (**Table 2**). At all sites, spring-applied N produced yields that were higher or similar to N applied in the fall or in the winter. The biggest difference was between fall and spring applications, with 5 of the 10 sites producing lower yield with fall applications ($p \leq 0.10$), and two sites producing lower yield with winter N applications, compared to spring application. At all but three sites there was at least one monthly N application that produced a grain yield less than spring.

While no, or a small, yield response to N lessened the likelihood of an N-timing effect, a large N-induced yield increase did not always equate to a large difference in yield from fall or winter application. This occurred at Urb97 and Mor98, which exhibited large yield responses to N (193 and 116%), but negligible differences due to N timing (**Table 2**). Other sites (Gif98 and Man99) exhibited large differences due to the time of N application, but smaller magnitudes of yield response to N application (75 and 85%). The yield response to N for the seven sites where an N titration was conducted is shown in **Figure 1**. A greater range was observed among the sites for the yield of unfertilized plots, which narrowed with any rate of applied N. A linear-plateau function best fit the data ($R^2 = 0.42$), and indicated an average maximal yield of 8.81 Mg ha^{-1} with 126 kg ha^{-1} of N. The N rate that maximized yield turned out to be fairly similar to the N rate used to compare N application times (135 kg ha^{-1} N).

The magnitude of grain dry matter yield loss (in Mg ha^{-1}) from a fall or winter N application was calculated for each site by subtracting the season average yield from the yield obtained in the spring. This resulted in a range of yield losses of from 0 to 3.3 Mg ha^{-1} for fall N applications and from 0 to 1.8 Mg ha^{-1} for winter N applications. The only weather parameter related to the degree of this yield loss was spring rainfall (cumulative total for

Table 2. Influence of ammonium sulfate (AMS) application time on the grain dry matter yield of corn grown at 10 Illinois site-years (1997-1999). Ammonium sulfate was broadcast on the soil surface at the same rate (135 kg ha-1) for each application time.

Time of N application		Site-year										
Season	Month	Gif98	Man99	Ran98	Mor98	Dek99	Lex97[1]	Urb97	Tow97	Ran99	Fla99	Avg.
		Mg per ha										
No fertilizer N		4.91	3.71	7.04	3.82	6.55	8.13	4.36	6.27	8.95	5.35	5.91
Fall	Oct	5.24	4.69	8.78	7.47	8.95	8.67	——	——	8.95	7.97	7.59
	Nov	5.40	6.11	9.27	7.77	8.73	9.24	8.13	7.15	9.55	7.97	7.93
	Avg.	5.36	5.40	9.03	7.62	8.84	8.96	8.13	7.15	9.25	7.97	7.76
Winter	Dec	6.49	6.87	9.93	8.07	8.51	9.06	8.18	7.20	9.77	7.26	8.13
	Jan	6.55	6.38	9.71	7.97	9.06	9.11	8.18	6.22	9.33	7.42	7.99
	Feb	7.47	6.82	9.27	7.97	9.71	9.11	8.29	6.66	9.66	7.64	8.26
	Avg.	6.84	6.69	9.64	8.00	9.09	9.09	8.22	6.69	9.58	7.44	8.13
Spring	Mar	7.80	7.04	9.93	7.91	9.27	9.55	8.35	7.53	9.93	8.18	8.55
	Apr	9.44	6.66	10.04	8.57	9.44	9.55	8.57	7.58	9.27	7.31	8.64
	Avg.	8.62	6.85	9.98	8.24	9.36	9.55	8.46	7.56	9.60	7.75	8.60
LSD(0.10)[2]		1.10	0.68	0.65	0.54	0.52	0.54	0.77	0.73	ns	0.74	0.44

[1]20 kg N ha^{-1} was applied to the No-N control. [2]The LSD applies to the means of No fertilizer N and to the means of each season.

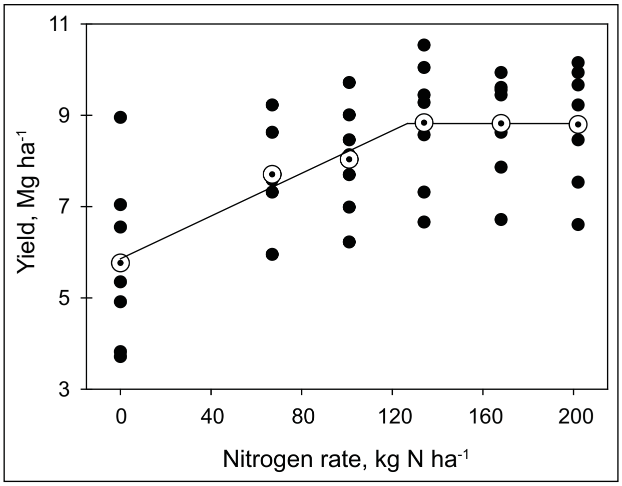

Figure 1. The grain dry matter yield response of corn to varying amounts of spring applied N for the seven sites where a complete N-rate titration was conducted. A linear-plateau function best fit the data ($R^2 = 0.42$) with model parameters $y = 5.86 + 0.0234x$ if $x < 126$, or $y = 8.81$ if $x > 126$.

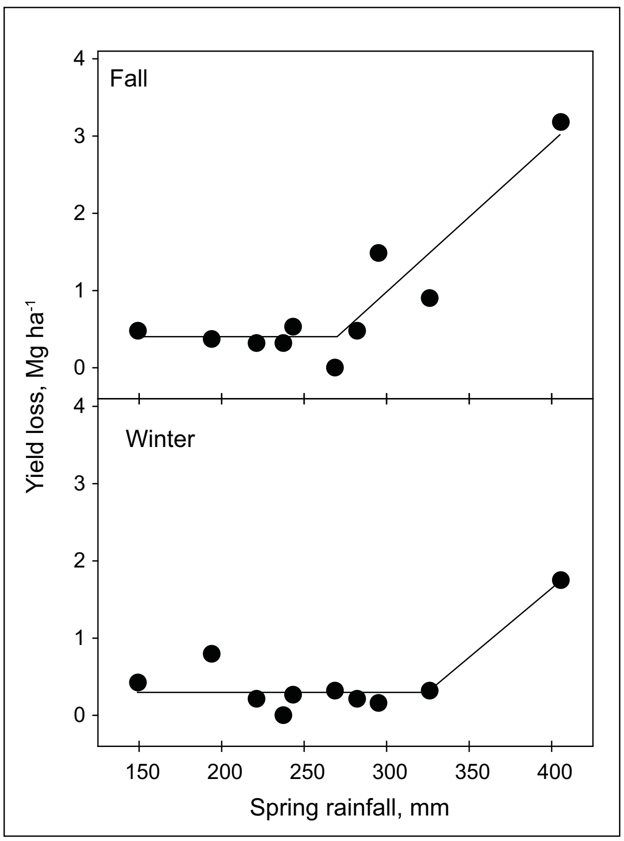

Figure 2. The relationship between cumulative spring rainfall (March, April, May) and the amount of grain dry matter yield loss associated with a fall (top) or a winter (bottom) application of N compared to spring. Data are from 10 sites in central and northern Illinois over a 3-year period. The degree of yield loss associated with spring rainfall can be explained by the models: $y = 0.40 + (\text{rain} – 270) \times 0.01936$, if $x > 270$ ($R^2 = 0.82$) for fall, and $y = 0.30 + (\text{rain} – 325) \times 0.01788$, if $x > 325$ (R2 = 0.83) for winter.

March, April, and May). These relationships were best described by plateau-linear models, which also indicated the precipitation threshold above which yield loss occurred (**Figure 2**). For fall applications, yield losses greater than 0.40 Mg ha^{-1} occurred when spring rainfall was more than 270 mm, while winter N application required more than 325 mm of spring rain for yield losses greater than 0.30 Mg ha^{-1}. The rate of yield loss (Mg ha^{-1} mm^{-1}) above the critical level was similar between both application times.

These functions along with historic spring rainfall data from four regions in Central and Northern Illinois were used to predict the cumulative probability for a given yield loss (**Figure 3**). This analysis indicated a higher probability of yield loss for fall than winter N applications in all regions, and a region specific difference in the likelihood of these yield losses to occur. For example, yield losses from fall applications will be greater than 1.25 Mg ha^{-1} in 40% of years in Urbana, while this level of yield loss is expected to occur only 20% of the years in Paw Paw (**Figure 3**). Alternatively, in one out of five years a yield loss greater than 2.5 Mg ha^{-1} is expected to occur in Urbana when N

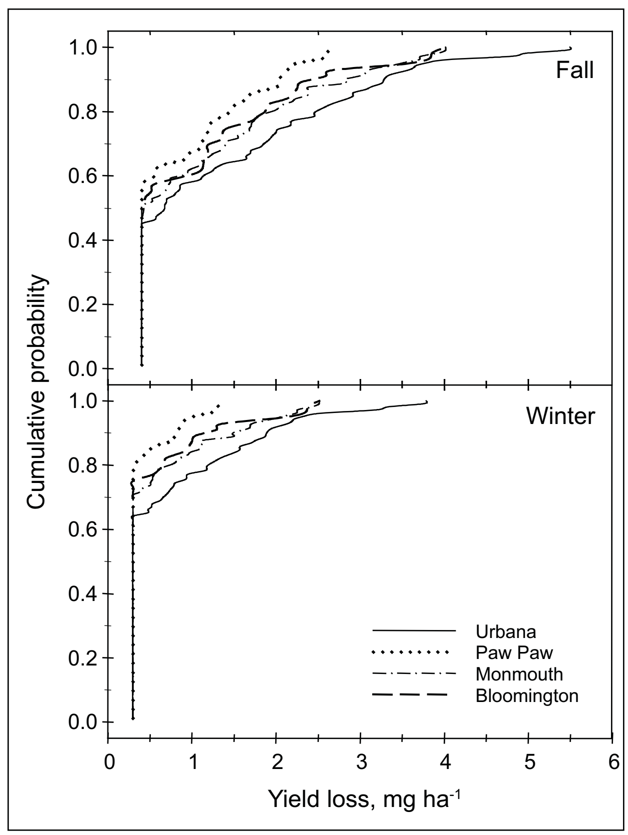

Figure 3. The cumulative probability of predicted corn grain dry matter yield loss for fall (top) or winter (bottom) applications of fertilizer N compared to spring for four locations in central and northern Illinois. Locations include Urbana (40º6'N, 88º12'W), Bloomington (40º28'N, 88º59'W), Monmouth (40º54'N, 90º38'W), and Paw Paw (41º41'N, 88º58'W).

is applied in the fall compared to 1.4 Mg ha^{-1} yield loss in Paw Paw.

Based on the yield loss functions from fall or winter N and spring rainfall (**Figure 2**), and the overall yield response function to N (**Figure 1**), we predicted the amount of supplemental N needed to produce yields like spring applied-N, based on the time of N application and the spring rainfall (**Figure 4**). These plateau-linear functions indicate that fall and winter applied fertilizer rates should be increased by 20 kg N ha^{-1} and 13 kg N ha^{-1} with respect to spring application even when spring precipitation is low. For fall applications, the supplemental N required increases linearly when spring rainfall exceeds 267 mm, whereas for winter N application this threshold was 320 mm. For both application times, the supplemental N required per mm of spring rainfall in excess of the threshold was very similar.

Discussion

Weather and the availability of N are usually the two factors exerting the greatest impact on corn yields. They can act independently, or be closely linked, and their effects can be to either increase or decrease crop growth and yields. Considerable variation in yield at the same site is generally attributed to weather, usually the amount and distribution of preseason and seasonal precipitation (Anderson et al., 2001; Magrin et al., 2005; Thompson, 1986). Nitrogen supply is also of major importance in crop productivity because it impacts all phases of plant growth and yield determination (Below, 2002).

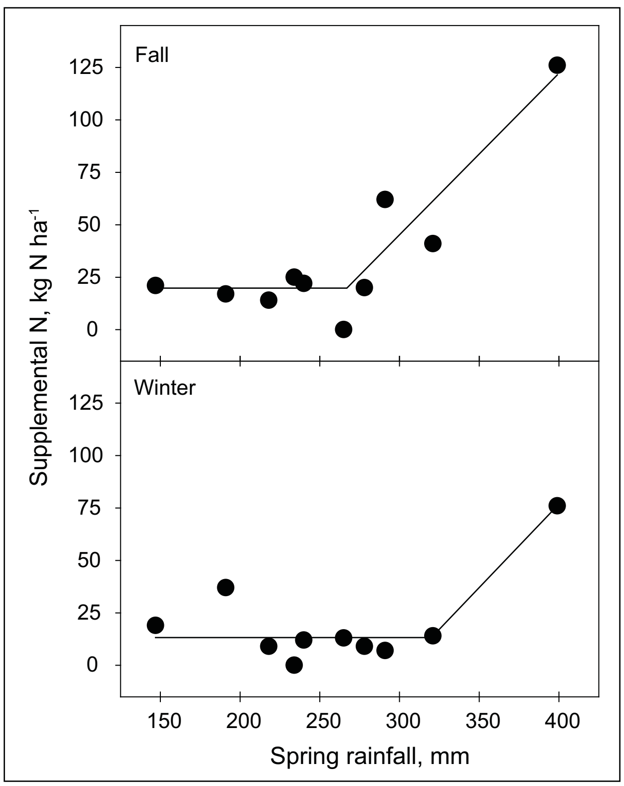

Figure 4. The predicted supplemental N needed to obtain yields similar to spring-applied N as a function of spring rainfall (March, April, May) when N is applied in the fall (top) or in the winter (bottom). Data are from 10 sites in central and northern Illinois over a 3-year period. The supplemental N needed can be explained by the models: y = 20 + (rain – 267) x 0.77, if x > 267 (R^2 = 0.88) for fall, and y = 13 + (rain – 320) x 0.79, if x > 320 (R^2 = 0.81) for winter.

Understanding how to best manage N fertilization to account for potential weather influence is clearly an important consideration in corn production, and has been the subject of numerous scientific studies and extension recommendations (Bundy, 1986; Hoeft and Peck, 2000; Malzer and Randall, 1985; Rehm et al., 1994). Obviously, when N is applied many months prior to crop uptake, it is even more subject to the vagaries of the weather, which is clearly demonstrated from our data. Similar to other published reports (Malzer and Randall, 1985; Randall and Vetsch, 2005; Vetsch and Randall, 2004), we noted a clear relationship between spring rainfall and yield when N was applied in the fall, and also showed a similar, although more tempered, relationship for N applied in the winter. Spring rainfall was the only weather parameter related to these application-induced losses in yield. Multiple regression models that included temperature, winter precipitation, and the responsiveness to N did not improve the relationship (data not shown).

Although considerable variation existed between sites, and for application times within sites, as a general rule the closer the N was applied to spring the better (**Table 2**). We also noted a fairly distinct difference in corn yield between fall and winter N applications, compared to spring applications, so we developed our predictive functions accordingly. These functions predicted a certain degree of yield loss from fall (0.40 Mg ha^{-1}) and winter N applications (0.30 Mg ha^{-1}) over a fairly wide range of spring precipitation, and the rainfall threshold at which these losses accentuated. This threshold was obviously lower for fall than winter applications (270 and 325 mm, respectively). These results indicate that irrespective of spring rainfall, a certain amount of N will become unavailable between N fertilization and corn uptake, resulting in corn yield loss. Sanchez and Blackmer (1988) found that 50 to 65% of fall applied N was not taken up by the plant and/or was lost from the soil, and our results suggest this effect is more pronounced for fall than winter applied N.

The potential loss of N increases with the length of time between N application and crop uptake

(Dinnes et al., 2002; Karlen et al., 1998). The higher temperatures prevalent in Northern and Central Illinois during fall compared to winter probably caused more nitrification of the fertilizer ammonium the earlier it was applied. Consequently, the higher concentration and the longer residence time of fertilizer-derived nitrate-N in the soil increases the likelihood of fall applied N to become unavailable for corn roots compared to winter and spring applied N, and explains the higher yield losses found with the earliest application time.

The relatively similar slopes of the yield losses and supplemental N requirements for fall and winter applied N indicate that the loss mechanisms driven by spring rainfall are similar for both application times, and consequently both application times would require the same management to minimize these losses.

Knowing the expected yield loss of a fall or winter N application in advance, and the precipitation threshold to exceed these losses gives growers a tool to help manage the interaction between the weather and N supply. In order to make informed management decisions, it is important to have an estimate of the likelihood of yield loss, which will depend on the frequency of spring rainfall exceeding the precipitation threshold for each application time at each location. This likelihood of a given yield loss for fall and winter applied N can be easily quantified with **Figure 3**. We selected four representative locations in north central Illinois that encompass a N-S transect (Urbana, Bloomington, and Paw Paw), and an E-W transect (Paw Paw and Monmouth). These figures indicate that the highest likelihood of yield loss is expected at the southernmost location (Urbana), and the lowest at the northernmost location (Paw Paw). In the latter location, the likelihood of a yield loss exceeding 0.3 Mg ha^{-1} is 1 in 5 years (20%) with winter fertilization, and 3 in 5 years (60%) for a yield loss higher than 0.4 Mg ha^{-1} for fall fertilization. At Urbana, these yield losses are expected to occur in slightly more than 5 out of 10 years (50%) and 3 out of 5 years, for fall and winter N applications, respectively. Clearly, fall N application has an extremely high risk of producing a yield loss in Urbana, but not so high a risk in Paw Paw.

Producers and nutrient management specialists could use these yield loss probability curves to assess the likelihood of a given yield loss from fall- or winter-applied N and evaluate if spring fertilization is required to eliminate or reduce it; or to decide if fall fertilizer application should be avoided in the first place. Alternatively, these figures could also be used as a management tool to evaluate if sidedress application of N is required to compensate fall or winter applied fertilizer N loss. At the sidedress time, in early to mid June, the total spring rainfall (March through May) is already known, allowing the estimation of the expected yield loss and the rate of N fertilizer that would be required to eliminate or reduce it, based on the yield loss and supplemental N functions.

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Dynamic Site-Specific Fertilizer Management Triggered by Real-Time Simulations and Weather Conditions

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Abstract

Typically, the guiding principle for fertilizer management is a rather fixed cropping calendar in which fertilizer is applied at fixed moments in time or at specific crop development stages. Recommendations are based on average weather conditions, soil properties and/or crop development. However, the 'average' year and 'representative' soil profile are rare. Weather conditions differ between years and soil properties vary within fields. It is therefore a logical option to adapt management during the growing season according to specific soil conditions and changing weather and crop development. Apart from experimental knowledge of farmers, different techniques are available to support fertilization more dynamically including simulation models, decision support systems and real-time weather records. We present three very different case studies in which these tools have been used. The first case refers to an arable farm in the southwest of the Netherlands where actual N stocks and N uptake by wheat (*Triticum aestivum* L.) are simulated for different parts of the field using dynamic real-time simulation modeling. A second case refers to a Costa Rican program on precision agriculture in banana (*Musa* sp.) plantations. No simulation models are available in this case and a field trial yielded information on nutrient use efficiencies as the basis for fertilizer recommendations. Finally, we looked at dairy farming and the effect of different feeding strategies on manure composition and subsequent nutrient use efficiencies for various farms in the northern part of the Netherlands. The three case studies illustrate the potential for more dynamic cropping calendars, but at the same time show some of the practical operational problems. This includes the need to look into the environmental aspects, but also the management goals of the farmer.

Introduction

In many agricultural systems, crop production depends on the supply of nutrients through fertilization. Agricultural science has traditionally been focusing on a key question: how much nutrient to apply in order to reach economically optimal yields? However, the fertilization question exceeds the problem of the quantity of nutrients. We also have to deal with the timing of the fertilizer applications, the form of the nutrients (organic or mineral fertilizer but also the formulation of the mineral fertilizers), and how to adapt management according to weather conditions and crop development. The latter is in contrast to the rather static cropping calendar that is often used in fertilizer recommendations (Ministry of Agriculture, 1987; Van Dijk, 2003). Finally, there is increasing political pressure through various regulations to deal with the environmental aspects: control nutrient emissions from agricultural systems, and maintain or improve soil and water quality (Sonneveld and Bouma, 2003; Stoorvogel and Bouma, 2006).

When discussing farm management, it is important to distinguish between the strategic, tactical, and operational decisions. The strategic management decisions deal with the long-term choices of farmers involving key investment problems (*e.g.* machinery). Tactical decisions deal with the yearly decisions, *e.g.,* in terms of crop choice. In this context, the decision on a particular cropping calendar would fit this picture. Finally, there are the operational day-to-day decisions of the farmer, *e.g.*, When do we go out to seed or harvest? The guiding principle (or tactic) for a long time has been the fertilizer use recommendation programs, although it should be noted that many farmers deviated from these programs in their operational decisions. We can list a large number of reasons why farmers did deviate from these recommendations. One important reason was that they were not suited for the

Abbreviations: EU, European Union; N, nitrogen; NO_3^-, nitrate;

specific conditions on a farm in a particular year (including the economic conditions!).

In many cases, there has been a call for new approaches to fertilization. There is a strong call from society for higher nutrient use efficiencies to reduce the emissions to the environment. This is certainly the case in Europe with the new EU regulations (Sonneveld and Bouma, 2003). In other cases the markets demand "best practices" in crop management. At the same time we also see that new tools have become available that allow for site-specific crop management (precision agriculture) through the introduction of geographical information systems (GIS), global positioning systems (GPS), proximal sensing for easy detection, and operational simulation models. In general, we can discuss the new guiding principles behind fertilizer use:

- Soil variation (spatial variation): Where in the past fertilizer recommendations were based on a single representative site, we increasingly see that if we want to refine fertilizer management we will have to differentiate between soils. This can take place to distinguish between major soil units; *i.e.,* different fields will be managed differently but also at more detailed scale levels, *i.e.,* manage the soil variation within a field. The latter is considered site-specific farming (Robert et al., 2000).
- Weather variation (temporal variation): In contrast to the fixed cropping calendar weather conditions are highly variable resulting in changing growth rates and nutrient requirements over time.
- On-farm environmental quality: Sustainability of agricultural systems has been a key word for a long time. Maintenance of soil quality has been the responsibility of the farmer. Today's cropping activities should not negatively impact future productivity and soil quality should be maintained. Increasingly, sustaining soil quality is included in the policy debate. Examples are the regulations for cross compliance within the EU, but also the call for best management practices from consumers.
- Off-farm environmental quality: Excessive fertilization in which fertilization levels are higher than crop requirements will inevitably result in losses of nutrients to the environment. High fertilization rates may lead to the contamination of groundwater and surface water.

In this paper we discuss elements of fertilizer management on the basis of three very different case studies. We will start with a case to show the potential of new technology in which we present almost perfect N management. However, the case is almost ideal with crop development relying entirely on N fertilization for a single crop. In addition, we will look at two other cases with a very different focus: a tropical plantation crop for which no simulation model is available and in which problems of pest and disease prevail, and finally, a case that deals with organic rather than mineral fertilizer. Manure quality is determined by livestock management and it shows how in some cases we have to deal with the entire (integrated) farming system. Finally, we discuss the options and potential of the new developments for the future of improved fertilizer management.

Case 1: Wheat Cultivation in the Netherlands

Study area and standard N management

Some of the prime agricultural soils in the Netherlands can be found on the former island of Voorne-Putten in the central-western part of the Netherlands. Research was conducted on a commercial farm of approximately 100 ha (51°48' N and 4°16' E). The soils consist of calcareous marine deposits with a fine loam to heavy clay loam texture. The soils are classified as Typic Fluvaquents (Soil Survey Staff, 2006) with an average summer temperature of 17.3°C and an average annual rainfall of 760 mm. Many of the farmers apply a crop rotation of potato, sugar beet, and winter wheat. In this case we will discuss the fertilization of winter wheat on a 10-ha field with excellent drainage conditions controlled by a dense system of pipe-drains.

Conventional N management for winter wheat is based on fertilizer recommendations provided by the Dutch extension service. The basis for these recommendations was established some 25 years ago through extensive field experiments. Fertilizer rates have been adapted to the introduction of more productive varieties. Current fertilizer recommendations for winter wheat aim at production levels of 12 t ha^{-1}, assuming 25 kg of mineral N is required for each ton of wheat. Recommendations are provided for individual fields and incorporate average soil mineral N levels measured in the root zone at the start of the growing season. In the experimental field this amounted to 60 kg N ha^{-1}. In addition, a top-dressing of 40 kg N ha^{-1}, which is applied just before flowering, is recommended. The corresponding fertilizer recommendation was calculated as 12 t wheat x 25 kg N – 60 kg available N + 40 kg N topdressing = 280 kg N ha^{-1}. Mineral fertilizer was applied using a split fertilization strategy, which has become common practice in the Netherlands. Four applications were scheduled: a base application in February or March as soon as machinery could enter the field, two applications during April and May using development stage and coloring as triggers, and a top-dressing before flowering in June. With the top-dressing fixed at 40 kg N ha^{-1}, remaining fertilizer was distributed evenly over applications one to three of 80 kg N ha^{-1} each.

The 1998 growing season started with two relatively warm months. Crop development progressed rapidly and the base fertilization was applied early on February 21st. A wet period followed throughout March, allowing the second fertilizer dosage to be applied no earlier than April 23rd. This meant a delay of two weeks compared to the desired schedule: development had progressed beyond the recommended stage and crop color had become paler than desired. Wet conditions prevailed throughout the remainder of the growing season, resulting in a third and final application on May 20th. By then fungus infestations were detected on leaves and emerging ears. To avoid further deterioration of crop condition the scheduled top dressing was cancelled. The total amount of fertilizer was thereby reduced to 240 kg N ha^{-1}.

Improved N management

Van Alphen and Stoorvogel (2000b) developed a new methodology for high precision N fertilization on the farm. Various approaches exist for high precision fertilization (Robert et al., 2000). The basis for many of them is a detailed description of prevailing soil conditions (*e.g.,* Vrindts et al., 2003). The farm was surveyed in detail with 612 observations to describe soil variability. All soils were chemically and physically characterized to 1 meter in depth. Soil variability is mainly present through differences in texture (clay content varies from 14% to 50%), soil organic matter (varying from 5% to 5.8%), and subsoil composition (peat or mineral matter). Instead of following standard soil survey procedures or using yield patterns, it was decided to establish functional management units (Van Alphen and Stoorvogel, 2000a). At all observation points, soils were characterized according to simulated water stress in a dry year, N-stress in a wet year, N-leaching from the root zone in a wet year, and residual-N content at harvest in a wet year through simulations with the mechanistic-deterministic simulation model 'WAVE' (Water and Agrochemicals in soil and Vadose Environment; Vanclooster et al., 1994). Subsequently four management units were identified through a fuzzy classification of the various points and a boundary detection algorithm. These units have unique functional properties relevant to N dynamics.

The management units form the basis for management recommendations. After the initial sampling of N contents in early spring, soil N contents and crop N uptake are simulated in real time for each of the management units using weather observations from a nearby weather station. As soon as the weekly N uptake rate exceeded half the amount of remaining available N in the soil in one of the management units, N fertilization was planned for all the management units. Quantities were estimated using the crop growth simulation model and equaled expected uptake in the next weeks minus available N in the soil.

Results and discussion

Figure 1 presents the results for the main management unit. After an initial application of 80 kg N ha^{-1} on February 21st (day 52; app. 1), the threshold level for N depletion was first reached on April 20th (day 110; app 2.). Soil available N levels had dropped to 26 kg N ha^{-1} and crop uptake had reached 6 kg N ha^{-1} week^{-1}. If decision rules had been applied strictly, the threshold level would have been set at 12 kg N ha^{-1} (twice the uptake rate), indicating no action was required. However, uptake had been extremely low in that particular week caused by unfavorable weather conditions (low radiation and temperature). Two weeks earlier, uptake rates had been up to 14 kg N ha^{-1} week^{-1}, indicating action was required (threshold at 28 kg N ha^{-1}) under normal conditions. Taking this into consideration, it was decided to apply a second fertilizer dose on April 23rd (day 113). The fact that this coincided with standard fertilization was purely coincidental and was caused by weather conditions. The standard application had been planned two weeks earlier, but heavy rainfall had kept machinery from entering the field. The fertilizer rate for the second application in the 'precise' system was established at 60 kg N ha^{-1}. This quantity was derived through an exploratory or 'forward-looking' simulation. Starting with the situation on April 20th, the simulation covered a period of four weeks, corresponding to the estimated interval between applications two and three (the latter was scheduled for the second half of May). The calculated rate proved accurate, as threshold levels were reached for the second time on May 18th (day 138). By then soil available N concentrations had dropped to 24 kg N ha^{-1} and crop uptake had

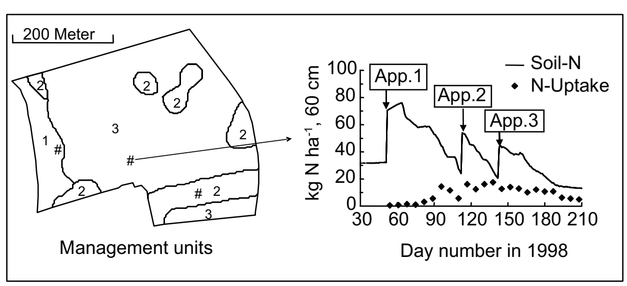

Figure 1. Management units for a Dutch arable farm with real time simulations for soil available N contents (line; kg nitrate-N ha^{-1} in the top 60 cm) and crop N uptake rate (dots; kg N ha^{-1} week^{-1}).

reached 17 kg N ha^{-1} $week^{-1}$. The third application occurred soon after on May 20th (day 140). Again traditional and 'precise' fertilization coincided, only this time both were applied according to schedule. A second exploratory simulation was conducted, resulting in a recommended fertilizer rate of 45 kg N ha^{-1} for application three. The scheduled fourth and final application is traditionally applied just before anthesis. This was expected to occur in the second week of June, rendering an estimated time interval of three weeks between applications three and four. When flowering was witnessed on June 6^{th}, a fungus infestation was found throughout the field and additional fertilizer was expected to only deteriorate crop condition. Therefore, the fourth application was canceled. Precision management resulted in a total fertilizer dosage of 185 kg N ha^{-1}; a reduction of 55 kg N ha^{-1} or 23% compared to traditional management.

Important to realize is that although fixed cropping calendars do exist for general recommendations, farmers may have to deviate from them for practical reasons. In this particular case study, the farmer was not able to enter the field due to weather conditions and in a later stage excluded the top-dressing due to fungus problems. At the same time, different management units reach the threshold for fertilization at different moments of time. For practical reasons it was decided that as soon as a single management unit reaches the threshold value, explorative simulations will be carried out for all management units, and all units will be fertilized at the same time but, if necessary, with different fertilization levels. The case highlights the value of recommendation systems based on in-season adjustments and multiple applications in matching nutrient supply to crop demand. Precise N management resulted in different N management in each of the management units and specific to the weather conditions during the growing season.

Case 2: Banana Production In Costa Rica

Study area and standard N management

Banana plantations cover almost 10% of the tropical lowlands of the Atlantic Zone in Costa Rica (Stoorvogel and Eppink, 1995). Research focused on the La Rebusca plantation in the perhumid lowlands in the northeast of Costa Rica (10°28' N, 84°00'W). The plantation measures approximately 124 ha of which 111 ha is used for the cultivation of banana. Soils are classified as Typic Udivitrands. Andic Eutrudepts, and Typic Dystrudepts (Soil Survey Staff, 2006). Weather conditions on the plantation are perhumid with an annual rainfall of 3760 mm and an average temperature of 26.2°C. Agricultural management is highly intensive in terms of drainage, fertilization, pest and disease control, and crop management. Banana yields average 68, 000 kg of export bananas ha^{-1} yr^{-1}. With such an export of fruit, fertilizer management becomes important to replenish soil nutrients. In general, an annual total of 2600 kg mineral fertilizer is applied in two-weekly applications of 100 kg corresponding to a total application of 600 kg N, 200 kg P, and 600 kg K. Two fertilizer recommendations exist for banana applications in the Atlantic Zone in Costa Rica. One is specific for the volcanic ash soils in the western part of the banana producing area in which the Rebusca plantation is located, another is specific for the eastern part with the non-volcanic ash soils. In practice, these fertilizer use recommendations are adapted on the basis of soil fertility samples.

Improved N Management

An integrated system for precision agriculture (PA) was developed for the Rebusca plantation. A detailed description of the system and the process of implementation is presented in Stoorvogel et al. (2004). In contrast to common practices in PA we could not make use of standard yield mapping techniques. In addition, the technological focus of PA was not easily adoptable in a continuous cropping system with almost no mechanization and managed by manual labor. Banana plantations in Costa Rica are frequently (2 to 3 times per week) screened for bunches ready for export. Bunches are harvested and transported by a dense cable system (every 100 m) to the packing plant. For the yield monitoring, groups of bunches are coded based on their origin (cable number and the location along the cable). A weighing balance is installed in the main cable just before the packing plant. Codes are registered at the balance and bunches are weighed. A software package denominated BanMan was developed for data processing and to create and analyze the yield maps. An example is presented in **Figure 2**. In addition to the yield maps a detailed soil survey was carried out for the Rebusca plantation (Kooistra et al., 1997). Key element in an effective system for precision agriculture is the translation of site-specific soil and production data into management recommendations. There is an increasing call for the use of crop growth simulation models. However, for many tropical crops these simulation models do not exist. In this case we analyze the yield maps in relation to the soil conditions and determine the location of so-called problem areas. These areas are characterized by relatively low production compared to the average for areas with similar soil conditions (**Figure 2c**). This is an important signaling function after which more detailed studies have to pinpoint to the exact causes of the low

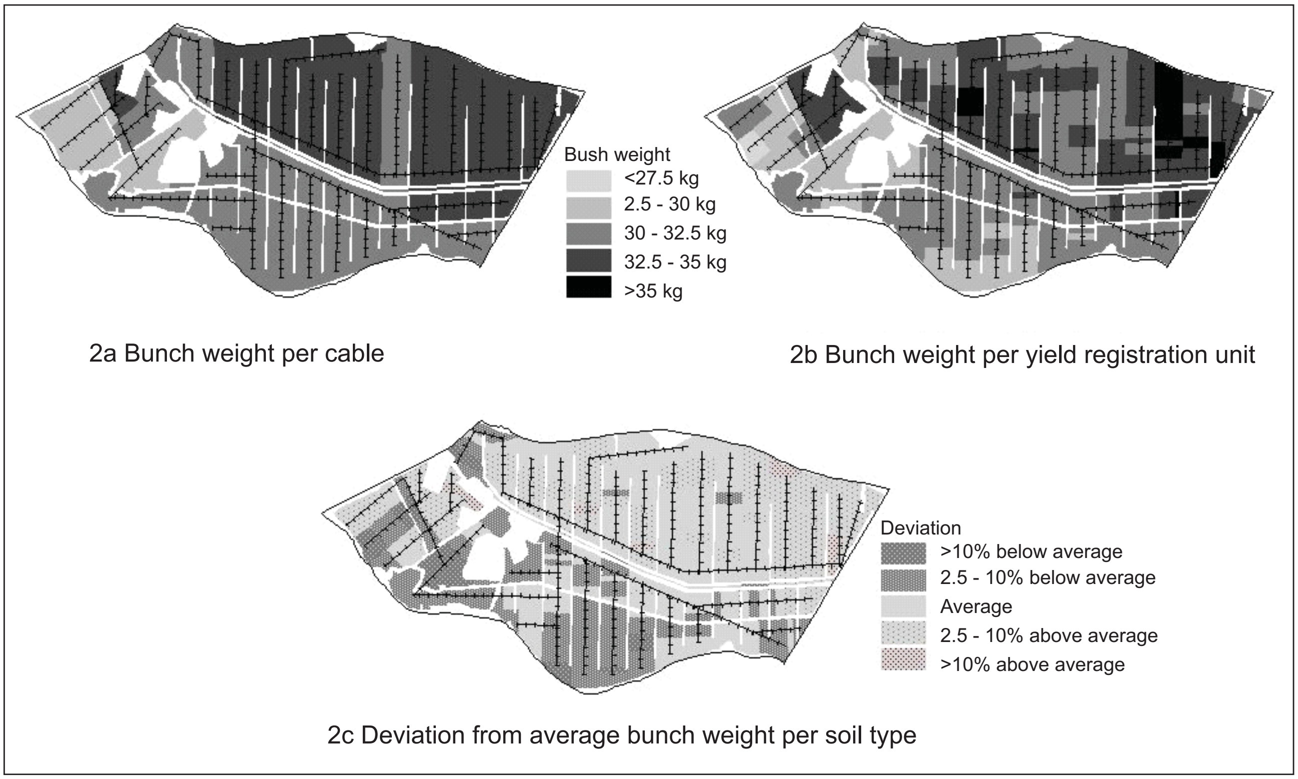

Figure 2. Yield maps and problem areas for a Costa Rican banana plantation.

production, and management can intervene. In addition, fertilizer experiments were carried out on the three main soil types in the plantation, where, during a period of a year, 1-ha blocks received 75%, 100%, and 150% of conventional fertilization. In these blocks crop performance as well as nutrient leaching was monitored.

Results and discussion

Depending on the soil, changes in fertilization resulted in changes in production and/or nutrient leaching. Results for the three main soils are presented in **Table 1**. In soil 1 and 2, almost all additional N is taken up by the plant, moving from 75 to 100% fertilization rate. However, further increasing fertilization resulted in increased leaching. In soil 3, however, leaching already increased – moving from 75 to 100% (with a stable bunch size) indicating that fertilization could be reduced. The low production was caused by the heavy soil textures, poor internal drainage, and low pH. These results formed the basis for site-specific fertilizer recommendations. The recommendations resulted in a decrease in fertilizer use of 12%. An important new development in banana management has been the renovation of areas that experience a decline in production and for which no clear cause can be identified. Often, the deterioration of the plants has been given as the main cause. Due to the site-specific yield monitoring, we can accurately identify the areas that may improve through renovation.

Table 1. Production and nitrate concentrations in the vadose zone under three fertilization levels in a Costa Rican banana plantation.

		Treatment		
Soil	Variable	75%	100%	150%
1	Fruit weight (kg/bunch)	32.8	33.0	33.3
	Hands (nr)	8.3	8.3	8.3
	NO_3^- (mg l^{-1})	3.61	3.81	4.96
2	Fruit weight (kg/bunch)	34.3	33.5	32.9
	Hands (nr)	8.3	8.0	7.9
	NO_3^- (mg l^{-1})	4.02	4.08	6.36
3	Fruit weight (kg/bunch)	32.8	35.0	36.1
	Hands (nr)	8.2	8.6	8.7
	NO_3^- (mg l^{-1})	1.91	3.04	3.29

Case 3: Animal Production In The Netherlands

Study area and standard N management

The region of the Frisian Woodlands is situated on the northern edge of a till plateau and mostly consists of sandy soils classified as Plagganthreptic Alorthod (Soil Survey Staff, 2006) with some peaty and clayey soils in the northern part. This sandy soil series with its characteristic anthropogenic topsoil is generally regarded as an excellent soil for agricultural purposes. The study focuses on various commercial dairy farms on the sandy soils (53°10' N; 6°04' E). The animal production systems contrast with the previous agricultural systems. In specialized dairy farming systems, such as those in the Netherlands, expert systems for fertilization have long focused on the pastures rather than on the whole farm. This resulted in specialization and emphasis on improving the output of the soil subsystem without considering impacts on the animal sub-system, leading to low efficiencies at farm level (Van Bruchem et al., 1999). Sonneveld and Bouma (2003) studied 3 farms in the area in 2000. These farms applied on average 187 kg N ha^{-1} as mineral fertilizer and 208 kg N ha^{-1} as slurry.

Improved N Management

A group of dairy farmers in the North of the Netherlands developed a new trajectory to decrease external fertilizer N inputs while increasing the overall efficiency of the farming system. An important element in their strategy was the increased emphasis on fine-tuning management to actual soil and weather conditions. Although the research encompassed many different elements of N management, here we will focus on one particular element: livestock feeding strategies to create a slurry that can be applied with higher efficiencies, *i.e.,* with reduced losses through N leaching and ammonia volatilization. Bussink and Oenema (1998) indicated that N in slurry is especially susceptible to ammonia volatilization. Volatilization can be reduced by improved storage facilities and application techniques, and also by a reduction of the protein content of dairy cow diets (Külling et al., 2001)

For the production of different types of slurry, a feeding experiment was carried out by Reijs et al. (2007) in a tie-stall from 21 January until 11 March 2003. The slurry pit was divided into eight compartments by means of wooden partitions. Above every compartment two non-pregnant, non-lactating Holstein Friesian cows were placed. Main differences in the feeding treatments are the relative levels of forage and the type of concentrates. Two main groups of feeding can be distinguished: high-protein diets with highly digestible grass silage and/or soya versus low-protein diets with less digestible grass silage and straw. The feeding experiment resulted in 8 different slurries with different chemical compositions. The experiment was complemented with 4 commercial slurries to obtain a total of 12 different slurries. The NH_4-N ranged in the slurries from 13 to 48 g kg^{-1} dry matter. The slurries were applied on an old sward that was at least 38 years under permanent unploughed grassland and a young sward that had been used for 5 years as grassland. The different types of slurry have been applied on small plots of 3.2 by 10 m. For every treatment there were three replications in each field. Separate treatments with four levels of mineral fertilizer N (calcium ammonium nitrate) were included in the experiment. On the basis of observed grass production, Reijs et al. (2007) calculated mineral fertilizer equivalents for each of the different slurries.

Table 2. Ammonium contents of three different slurries and the mineral fertilizer equivalent values determined on young (MFE-young) and old (MFE-old) grasslands (Reijs et al., 2007).

	NH4-N content, g kg^{-1} DM	MFE-Young, %	MFE-Old, %	MFE-average, %
High protein diet slurry	45	65	56	61
Low protein diet slurry	25	53	43	48
Commercial slurry	23	50	42	46

Results and discussion

Table 2 summarizes the results of the experiment. First of all the experiment shows that ammonium contents in the slurries with high-protein diets is almost double the ammonium content in the slurries derived from low-protein diets. The commercial slurry has similar ammonium content as the slurry derived from the low-protein diet. This is also reflected in the mineral fertilizer equivalent which is 13% higher for the slurry derived from the high protein diet. Not only do we see major differences in composition of the slurry and their mineral fertilizer equivalent, at the same time there are significant differences in the mineral fertilizer equivalents measured at the young and old grassland. The old grassland—with higher organic matter contents, a lower bulk density, and higher water holding capacity—had mineral fertilizer equivalents that were approximately 10% less than the young grassland.

The strong interactions between animal feeding, slurry composition and fertilizing efficiency indicate the need for whole farm approaches when we deal with animal production systems. The case study is particularly interesting when we consider Dutch legislation to meet European standards for groundwater quality. Sonneveld and Bouma (2003) evaluated the Dutch policies for the study area. Interestingly enough, the policies put thresholds on the quantities of N applied as mineral and organic fertilizer. However, almost no attention is being paid to the type of organic fertilizer and the farming system.

Discussion And Conclusions

Case studies like the ones presented in the paper can only illustrate the complexity of N management. The diversity of farming systems makes it practically impossible to provide generic tools or expert systems. Nevertheless, there are some lessons to be learned in an era where still too many expert systems rely on fixed cropping calendars and standard recommendations. Spatial variation in growing conditions and temporal variation in weather conditions require more dynamic approaches. In a research environment, crop growth simulation models have proven to be excellent tools to deal with the spatial and temporal variability. The first case in this paper confirms this. However, we have to keep in mind that these simulation models are not available for every farming system. This is illustrated with the second case where other experimental approaches were required to deal with the spatial variation. Modeling the dairy farms including the use of organic manure and the animal systems becomes even more complex although attempts are being made (Wolf et al., 2005). In addition, we have to remember that in many cases the calibration of the simulation models for the specific conditions on a farm is a cumbersome process. It can be done for specific cases, but the simulation models, although often with a mechanistic character, are not generic enough. Part of the problem is that we lack in many cases at least part of the input data and we have to fall back on default estimates. Finally, even if calibrated simulation models are available, experts are required to operate them. In other words, although research is making significant progress we do not have operational expert systems based on crop growth simulation models available. However, simulation models are constantly improving and various cases have demonstrated their use (David et al., 2004; Hanson et al., 2006; Lewis et al., 2003; Rinaldi, 2004; Sonneveld and Bouma, 2002; Van Alphen and Stoorvogel, 2000[b]; Van Delden et al., 2003; Wolf et al.., 2005). The question that remains is when and where we need the complex methods and when we can get by with more simple approaches. At the simple level, expert systems use simple leaf color charts to determine whether nutrient limitations do occur (Murshedul Alam et al., 2006). The limitation of such a method is that it is reactive rather than pro-active and identifies the need for fertilization after nutrients are limited. More advanced methods using chlorophyll meters (Arregui et al., 2006) or hyperspectral reflectance measurements (Pattey et al., 2001) probably work better as the stress is determined at an earlier stage. Ideally, simulation models are used as presented in the first case study to detect whether nutrients are becoming limiting, to be able to intervene before the actual limitation arrives. Interestingly enough, hybrid methods are being developed that make use of high-tech simulation models to set up a low-tech approach. A good example is provided by Pampolino et al. (2006) who carried out an analysis using simulation models and developed a method based on leaf color charts. The discussion can be approached on the basis of the various decisions taken on the farm: the operational decisions discussed above and the tactical and strategic decisions. For tactical decisions, research focuses on medium-term weather forecasts (Dailey et al., 2006; Lobell et al., 2004) but also on fertilization strategies with simulation models (Rinaldi, 2004; Rathke et al., 2006). Finally there are the main strategic decisions to enter; *e.g.,* organic farming (David et al., 2004; Lewis et al., 2003; Van Delden et al., 2003) or precision agriculture (Thorp et al., 2006; Smit et al., 2000).

The potential efficiency of N fertilization strongly determines some tactical and strategic decisions. In the first case study there is a significant cost of going out to fertilize. Therefore, only a limited number of N applications are made and if one management unit reaches the threshold, fertilizer is applied to all management units. In the Costa Rica case, fertilizer is applied manually on a two-weekly basis allowing for significant variation. On the other extreme, fertigation allows for continuous adaptation of fertilization rates according to the circumstances (see for example Hanson et al., 2006). In the Costa Rica case, fertilizer formulation is adapted according to the weather conditions although hard data to back up these decisions are lacking. Karaivazoglou et al. (2007) present an example in which they show the importance of the proper formulation on a tobacco crop in Virginia, U.S.A.

At the end of the day we cannot deal with N by itself. Many studies showed the interaction with, e.g., tillage and residue management (Dolan et al., 2006), variety choice (Jiang et al., 2004), catch crops, and green manures (Thorup-Kristensen et al., 2003). At the same time we have to bear in mind that for many crops fertilization is not only related to the physical crop production but can also be related to pest and disease management (as mentioned in the first case study) and the quality of the produce. The latter is typically the case for potatoes, barley, and oil crops like oilseed rape (Rathke et al., 2006). At the same time we have to keep the economic objectives in mind (*e.g.*, Rejesus and Hornbacker, 1999).

Especially in western agriculture, high fertilization has resulted in contamination of surface water and groundwater. Increased environmental concern has led to the development of agricultural policies to control NO_3^- concentrations in the environment. A proper evaluation of policies at the regional scale is only possible with the proper model-based approaches. Illustrations are given by Zebarth et al. (1999) and Wolf et al. (2005).

The three case studies and the final discussion show the complexity of nitrogen management. This clearly provides us with a major challenge for the future. Progress is being made to deal with the spatial variation through site-specific management and the temporal dynamics through the use of real time simulation. The main problem remains the complexity of the farming systems with many different interacting factors that finally determine crop performance.

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Optimizing Nitrogen Management for Rainfed Wheat and Maize in Africa

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Abstract

The constraints faced by farmers in rainfed agriculture are far more complex than those faced by their counterparts using irrigation. Rainfed agriculture is characterized by high production risks associated with rainfall amount and distribution. Fluctuations in costs of inputs and prices of produce further enhance their risks. These biophysical and socioeconomic factors are responsible to a large extent for their low agricultural productivity — less than 20% compared to irrigated agriculture. Nitrogen management under such conditions is dependent on rainfall, soil water-holding capacity, organic matter content, N loss processes, and cost of N fertilizers. Taking into account all of the above factors, N management needs a truly dynamic and site-specific decision support tool. The decision support toolbox (DST) presented in this chapter captures the biophysical processes and multitude of factors associated with the past and current management and production objectives of a farmer.

The crop simulation models in the DST — particularly the wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) models — were validated through field trials conducted in Morocco (for wheat), and Benin, Nigeria, and Togo (for maize). There was a very good agreement between observed and simulated grain yields and phenological events with R^2 ranging from 0.86 to 0.97. The validated models, using geo-referenced soils and long-term weather data and linked with GIS capability, were used to generate N management recommendations. The management options available to farmers to reduce risks and improve productivity are presented for Morocco and Togo. These include a choice of crops, varieties, optimum planting windows, crop rotation, and integrated N management with options to choose different sources (mineral fertilizers, organic material, or the combination of both).

Introduction

Drought and low soil fertility are among the most important biophysical factors threatening agricultural production, food security, and economic growth in many developing countries, particularly in Sub-Saharan Africa. The unprecedented combination of climatic risks (rainfall and temperature), expansion into marginal lands due to increasing food demand, high input costs, noncompetitive product prices compared to input costs, extreme poverty, and unavailability of credit systems have resulted in farmers opting for low-input, low risk, non-sustainable agriculture (Keatinge et al., 2001; Smaling et al., 1997). These factors are responsible to a large extent for the low agricultural productivity under rainfed conditions—less than 20% compared to irrigated agriculture.

Nitrogen is the key nutrient behind the green revolution and human nutrition. While farmers are aware of the N needs of crops, they are often unable to supply N for sustainable and productive agriculture. This is due to lack of crop response when other factors are limiting and high N losses associated with leaching, denitrification, and volatilization. Other factors include poor residual value of applied N fertilizers, the cost of N fertilizers, and limited availability of organic N sources, particularly under unfavorable rainfall conditions. Reducing risks associated with N fertilizer use and improving N use efficiency in rainfed systems will increase yields, profitability, and farmers' confidence in inputs' use while reducing N losses.

The current research paradigm demands that sustainable agricultural development under rainfed agriculture not only address the production goals of farmers but ensure ecological sustainability of agroecosystems and the natural resource base. Methodologies and tools are needed that prescribe a truly dynamic and site-specific N management (Singh, et al., 2002). In this chapter we will give a brief overview of a decision support toolbox (DST) that allows for site-specific crop management. The main component of the DST, the Decision Support System for Agrotechnology Transfer (DSSAT) has

Abbreviations: DST, decision support toolbox; DSSAT, Decision Support System for Agrotechnology Transfer; GIS, geographic information systems; N, nitrogen; P, phosphorus.

been described elsewhere (Jones, et al., 2003; Gijsman et al., 2002).

This chapter presents systems-based methodologies that have been implemented to promote dynamic N management under rainfed conditions. The soil and plant N dynamics model used in DSSAT simulates soil N transformation, N losses due to leaching, volatilization and denitrification, and plant N uptake and N stress effects on crop growth and development (Godwin and Singh, 1998). Examples have been chosen to illustrate the wide diversity of crops, cropping systems, and management affecting N management under rainfed agriculture.

Decision Support Toolbox

A DST comprised of crop simulation models including DSSAT (Tsuji, et al., 1994) and spatial data handling and display capabilities of a GIS integrates knowledge about soil, climate, crops, and management. Options are offered for making site- and season-specific management recommendations. The DST links together the soil and weather databases as polygon layers with a simulation model designed to mimic crop growth. The toolbox provides an interactive evaluation simulator with dynamic graphics that assesses the feasibility of land units for crop production. It also encourages exploratory analysis with farmers, extensionists, and policymakers by providing rapid feedback on crop management.

When the DST application is combined with real time, historical, and forecast weather data, then time-dependent strategic decisions can be made. Such decisions include the determination of: crops/varieties to grow, planting date, planting density, timing and rate of N application, and crop rotation alternatives. An analysis of alternatives offers opportunities to benefit from good seasons and to reduce risks and associated economic losses during poor rainfall years. In addition, it offers planning and tactical resources to policymakers.

N Management for Rainfed Wheat

Much of the wheat in Morocco is grown under rainfed condition with N being the major crop nutrient limiting yields. Settat Province, in the northwest region of Morocco, typifies rainfed agriculture with mean rainfall ranging from 200 to 450 mm during the wheat growing season (**Figure 1**). Field trials conducted during 2004-2006 were used to validate the DSSAT wheat model (**Figure 2**). In general the model captured the range of yields and duration of wheat cultivars grown in Settat Province. The model's inability to capture yield reduction due to pests and diseases and nutrients other than N and P is reflected in over-prediction

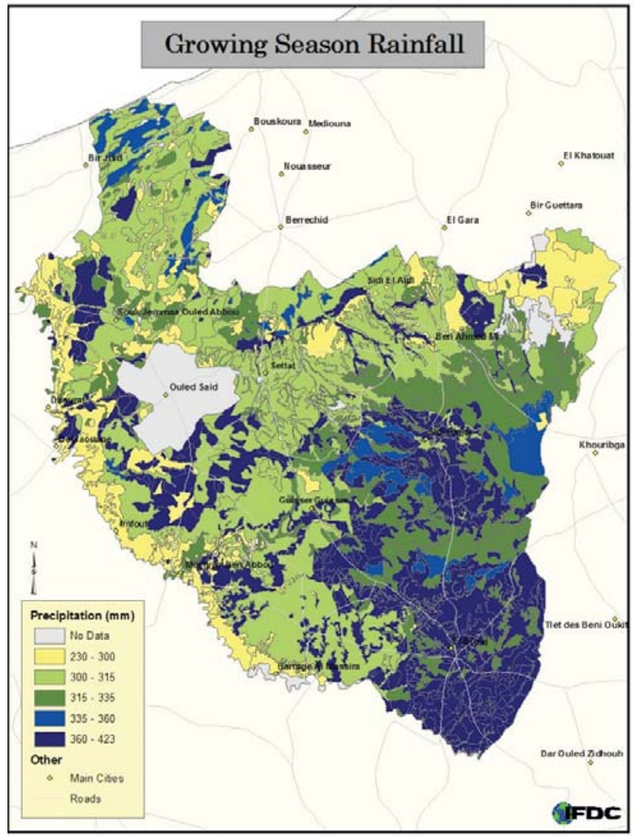

Figure 1. Mean growing season (November – April) rainfall (mm) for Settat Province, Morocco, based on 20 years of long-term generated weather data.

of yields for some of the trials (points above the 1:1 line in **Figure 2**).

Within the province there is marked difference in amount and distribution of rainfall and soil properties, hence it is not surprising that the N recommendations have to be site-specific (**Figures 3 and 4**). Also at a given location there is a wide variation in rainfall amounts, for example, 250 to 700 mm at El Brouj (**Figure 3**) and 100 to 450 mm at Sidi El Aidi (**Figure 4**). The economic returns as presented in Figures 3 and 4 were based on actual wheat production costs in Settat Province (**Table 1**). At El Brouj farmers will lose money growing durum

Table 1. Wheat production cost for Settat Province, Morocco.

Wheat grain price (mean)	$250 t^{-1}
Wheat grain price (standard deviation)	$ 16 t^{-1}
Harvest byproduct	$ 25 t^{-1}
Base production cost – including cost of fertilizers other than N	$100 ha^{-1}
N fertilizer cost	$0.55 kg^{-1}
N cost per application	$5.00
Irrigation cost	$0.50 mm^{-1}
Irrigation cost per application	$12.50
Seed cost	$0.50 kg^{-1}

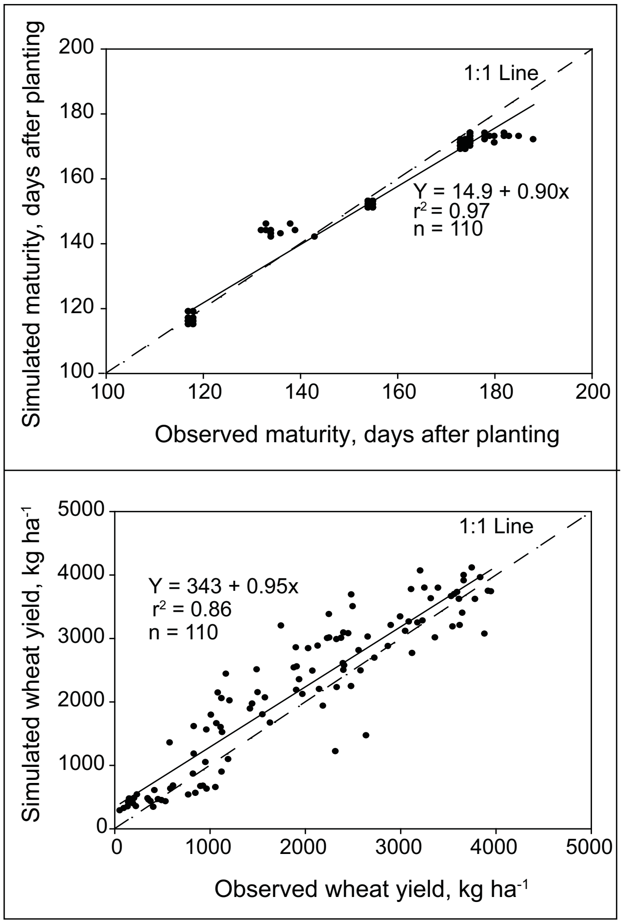

Figure 2. Comparison of observed and simulated days to maturity and grain yield for commonly grown wheat varieties in Settat Province, Morocco for 2004-2006 seasons using DSSAT's CERES Wheat Model.

wheat (cv. Karim), particularly when they do not apply any N fertilizer. The economic returns are higher with N fertilization; however, farmers will still lose money more than 75% of the time (**Figure 3**). If farmers continue to grow wheat at El Brouj, it is recommended to keep the N rates low. Nevertheless, the recommended N rates are 100 to 140 kg N ha^{-1} at Sidi El Aidi and farmers are expected to make profits each year (**Figure 4**). The economic gains from N applications at El Brouj are very poor in spite of good rainfall. This is due to shallow soils, poor rooting depth, and soils with low water-holding capacity. In contrast, the deep soil with high water-holding capacity at Sidi El Aidi resulted in higher wheat yields and higher profits even with lower rainfall. The model predicted higher N leaching losses at El Brouj with increasing N fertilizer application, with N leaching losses as high as 80% of applied N. This further justifies not applying any N in El Brouj or keeping the N rate to less than 30 kg N ha^{-1}.

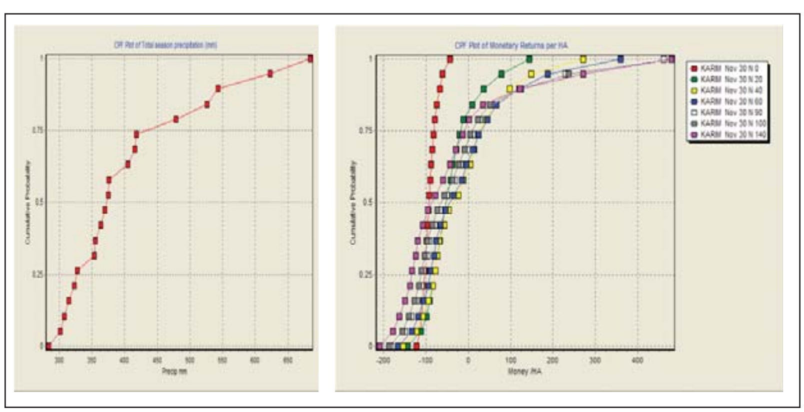

Figure 3. Cumulative Probability Distribution of rainfall (mm) and net monetary returns (\$ ha^{-1}) over 20 years for durum wheat (cv. Karim) planted on November 30 with applied rates of 0 to 140 kg N ha^{-1} at El Brouj, Settat Province, Morocco.

When the DST is used across all soils and weather stations in Settat Province, yield prediction and N recommendation maps can be generated (**Figure 5 and 6**). These maps clearly show areas with: high yield potential, high N response, and high N leaching loss. The N recommendation given in **Figure 6** is based on maximum economic returns. The economic return is computed from simulated yield response of bread wheat (*cv Achtar*) to N rates, long-term weather data (20 years), and soils in Settat Province. Other factors are costs and prices of inputs (seed, fertilizer, and labor), outputs (grains, stover), and fixed costs as shown in **Table 1**. If the cost of N fertilizer came down and/or the wheat grain price increased, then recommended optimum N rates might increase. In contrast, higher input costs and lower grain prices will definitely result in lower N recommendation rates. As evident from the comparison of the rainfall map (**Figure 1**) and yield map (**Figure 5**), rainfall itself is not a reliable indicator of yield for many areas. For example, some of the high rainfall areas (such as El Brouj) have lower wheat grain yields. For such conditions the DST may recommend low or even no N fertilizer application (**Figure 6**).

The N recommendation based on economics, long-term weather variability, and soil types provides opportunities to maximize profit, and reduce farmers' economic risks, and reduce environmental pollution such as high N leaching loss (**Figure 6**). The figure shows N leaching losses associated with the given N recommendation. If groundwater contamination is a major concern in certain areas then different N management strategies may be selected based on targeted (lower) N losses.

N Recommendation for Single and Double Maize Cropping

Crop simulation studies using the long-term

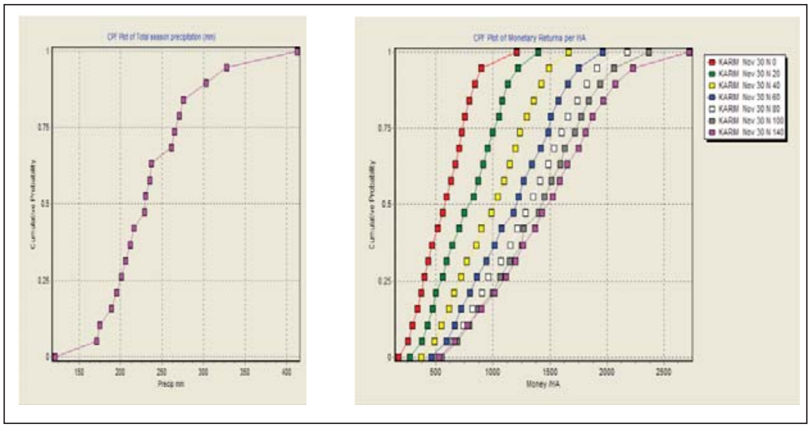

Figure 4. Cumulative Probability Distribution of rainfall (mm) and net monetary returns ($ ha^{-1}) over 20 years for durum wheat (cv. Karim) planted on November 30 with applied rates of 0 to 140 kg N ha^{-1} at Sidi El Aidi, Settat Province, Morocco.

historical data for the last 20 years were undertaken for Davié in southern Togo, which has a bimodal rainfall distribution (**Figure 7**). Maize is the staple crop widely grown throughout the region with typical farmer yields ranging from 1 to 2.5 t ha^{-1}. The DSSAT maize model was used for the studies because it allowed evaluation using field observations. It has been widely used in the region and has the capability to simulate and analyze long-term seasonal experiments and cropping sequences.

Model validation

A comparison of observed and simulated maize grain yields for the experiments conducted in Benin, Nigeria, and Togo is shown in **Figure 8**. Only those treatments with high P rates were used because the P sub model has yet to be tested in the region. If the model were a perfect predictor and if there were no experimental errors, all data points would lie on the 1:1 line. The overestimation (above the 1:1 line) arose due to the presence of uncontrollable factors in some plots such as weeds and termites, which resulted in lower observed yields. The model is also not sensitive to nutrients other than N and P.

Production determinants

Simulations estimated maize grain yields for cv. Ikene (EV-8449) at potential production level—that is with only temperature and solar radiation influencing yield potential—for monthly plantings in Davié, Togo. These potential yields were used as the

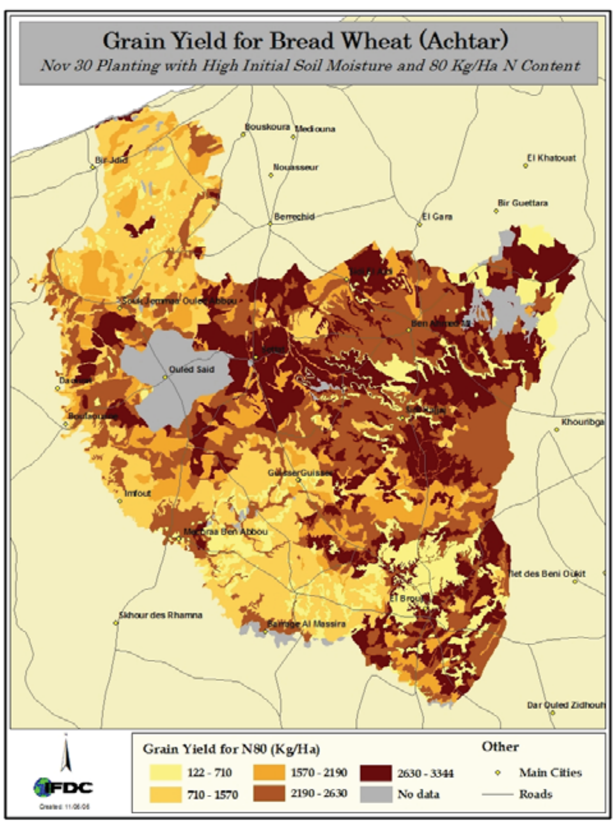

Figure 5. Grain yield map for bread wheat (cv. Achtar) for November 30 planting with high initial soil moisture content and fertilizer application rate of 80 kg N ha^{-1}, Settat Province, Morocco.

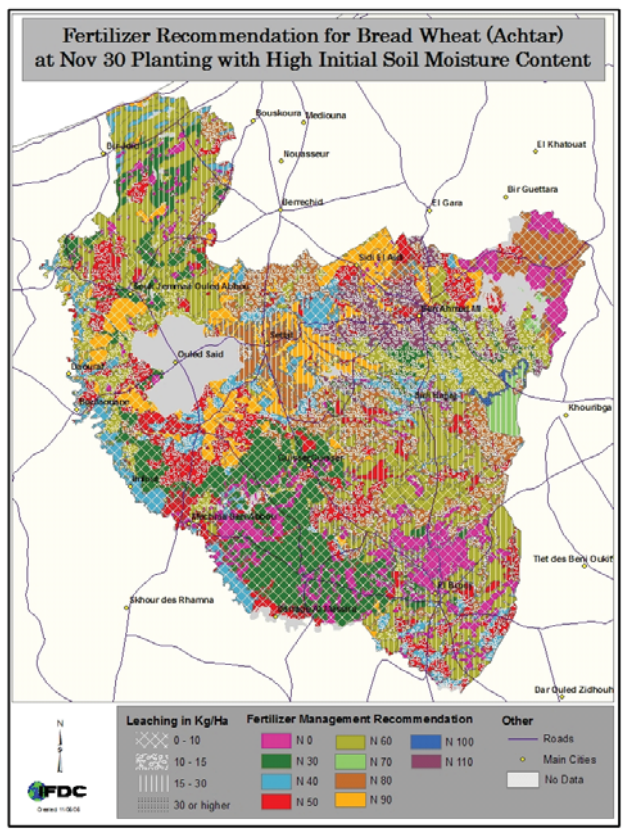

Figure 6. Map of N fertilizer recommendation (in color) and N leaching loss (in hatch) expressed as kg N ha^{-1}, Settat Province, Morocco.

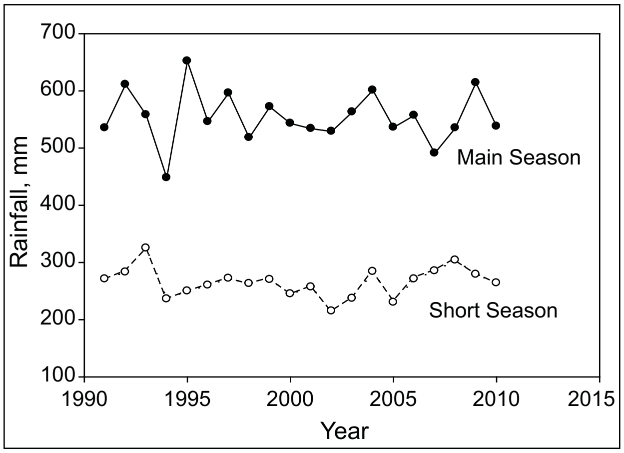

Figure 7. Rainfall amount and variation during the main- and short-season at Davié, Togo.

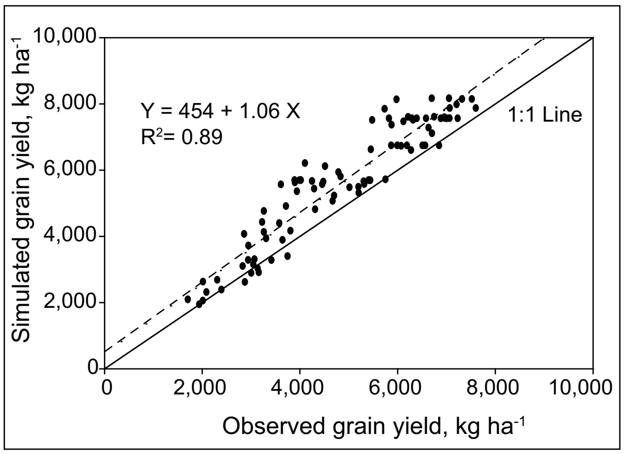

Figure 8. Comparison of observed and simulated grain yields using the DSSAT maize model for field trials conducted in Benin, Nigeria, and Togo during 1998-2002.

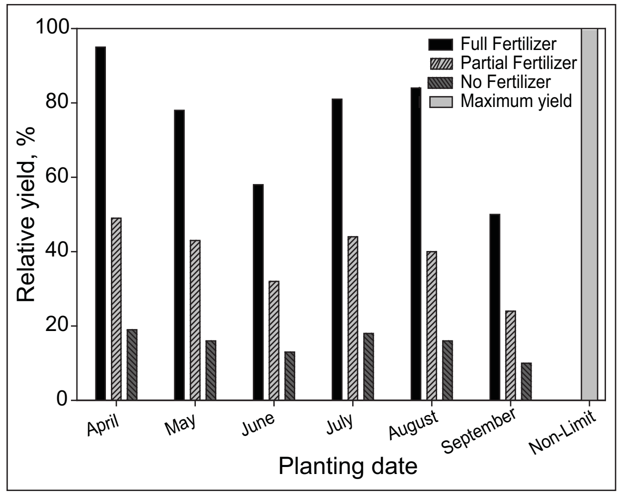

Figure 9. Simulated relative maize grain yield (%) at different planting dates at Davié, Togo, for rainfed conditions: (1) not limited by N (full fertilizer), (2) with 45 kg N ha^{-1} (partial fertilizer), and (3) with no fertilizer applied. Maximum yields are defined as those with no limitations from rainfall or nutrients.

basis for expressing simulated relative yields for (1) rainfed full fertilizer conditions—with rainfall and soil water-holding characteristics also influencing the yield but not limited by nutrients—and (2 and 3) rainfed conditions with partial or no fertilizer (**Figure 9**).

During the April to September planting window, 50% to 95% of the potential yield is reached under rainfed conditions ("full fertilizer" in **Figure 9**). However, planting in the first season (May-June) is associated with much lower variance. The few farmers who do plant maize early in Davié and southern Togo, in general, attain higher grain yields.

A more typical farmer condition was simulated using Davié soil with available N at 53 kg N ha^{-1}, plant extractable soil water at 22 mm, and no fertilizer. We assumed, however, all other nutrients, weeds, termites, and other pest and diseases were fully controlled so as not to influence the yield. Simulated mean yields amounted to less than 20% of the potential grain yield for each of the planting dates (**Figure 9**). The simulated results show that in contrast to what is often assumed, N may be more limiting than water in sub-Saharan Africa. With external N application of only 45 kg N ha^{-1} (partial fertilizer), yields at the optimum planting dates were doubled (**Figure 9**). With nutrient input, appropriate planting date, and responsive maize genotypes, grain yields could potentially be increased by 2 to 4 times the current farmers' yields. The range of N rates and planting simulated here were validated with on-farm field trials in southern Togo (**Figure 8**) and is also described by Dzotsi and coworkers (2003).

Cropping Sequence

From the above analyses, it is very clear that external nutrient input is essential for profitable and stable maize grain yields. Scientists have sought to answer the question, "Could a green-manure crop, such as mucuna (*Mucuna pruriens*), meet the N requirement for sustainable maize production?" It was determined that mucuna would be best suited for the second season in bi-modal rainfall regions because the principal crop maize would be planted during the more favorable and stable first season and the more drought-tolerant mucuna would fare better than maize during the risky second season.

The simulation of maize cropping sequence as presented in this paper involved setting the initial conditions at the start of the run. Then crop growth was simulated during a number of successive growing seasons interspersed with mucuna cover crop or maize in the second season. The soil water, nutrient, and organic matter status at harvesting of maize became the input status for the next crop in the sequence, whether it was maize or mucuna. The results from sequential runs allow quantification of

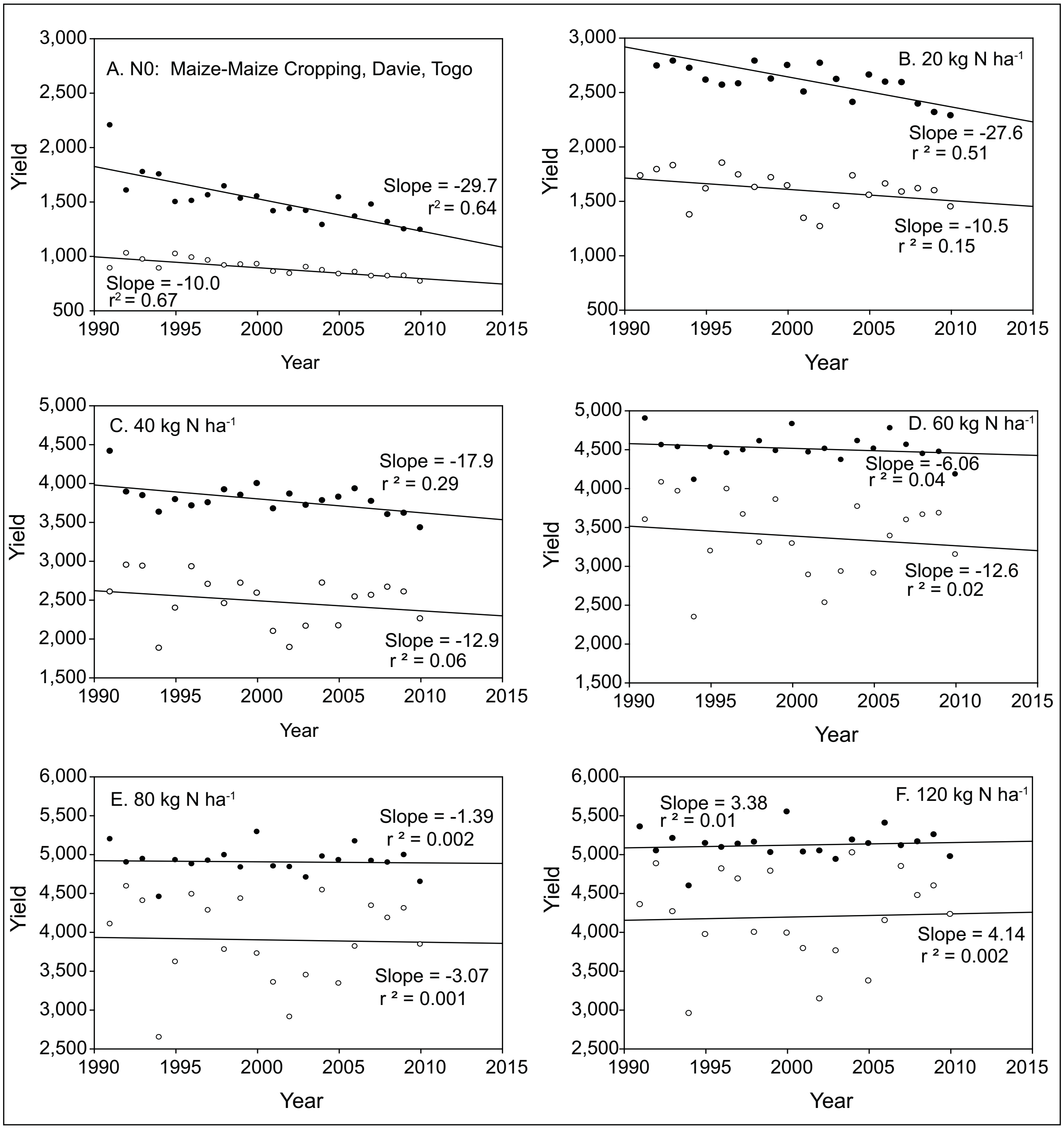

Figure 10. Yield and yield trends of maize grown during short- (open circle) and main- (closed circle) season at Davié, Togo. Amounts of N applied were the same for each season, for example, 20 kg N ha^{-1} for each season in (B).

long-term production and sustainability (Thornton et al., 1995). The sequence analysis program can also be used to investigate, validate, and summarize the primary results from long-term field trials (Timsina et al., 1997).

To compare maize-maize and maize-mucuna cropping sequences, the simulation experiment, run as a 20-year sequence, was replicated 5 times; simulated weather records for the Davié site were obtained by using WGEN, a statistical weather generator (Richardson, 1985). In the maize-maize sequence, the first-season maize planting occurred during May as dictated by soil moisture status (40% to 100% of field capacity). The second season planting occurred soon after the harvest of the first-season maize, provided the moisture requirement for sowing was met. The cumulative annual N fertilizer application rates for the double maize-cropping ranged from 0 to 240 kg N ha^{-1} $year^{-1}$. Cumulative P rates were 75 kg P_2O_5 ha^{-1} $year^{-1}$, and all other nutrients were assumed non-limiting. The short-duration maize genotype Ikene, with mean growth duration of 85 to 90 days at Davié, was used.

In the maize-mucuna sequence, maize was planted during the first season in May followed by mucuna in the second season. Prior to the next maize planting, approximately 1 to 8 t ha^{-1} of mucuna was incorporated as input to the model. The amount of

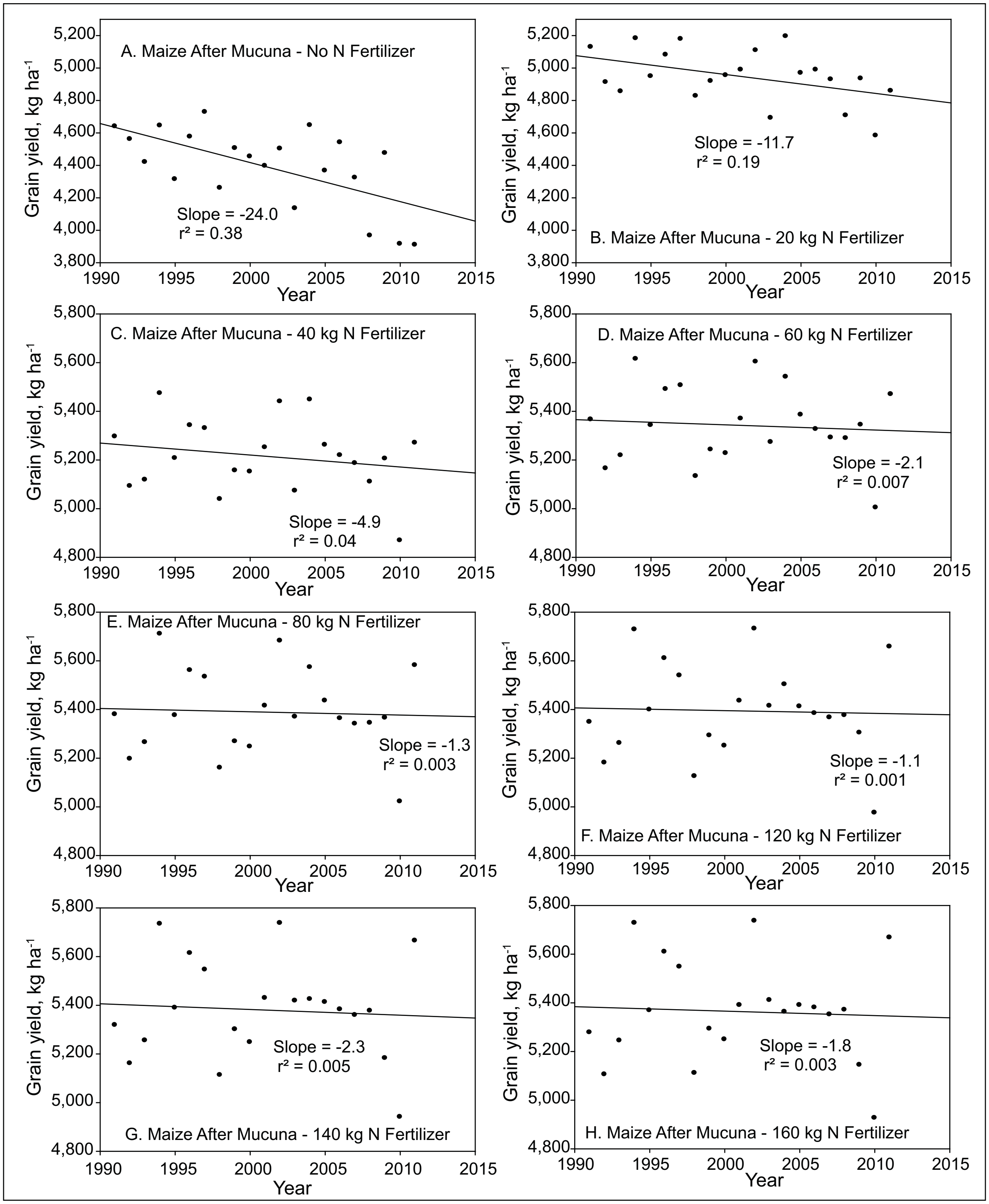

Figure 11. Yield and yield trends of maize grown during the main rainy season and Mucuna grown as green manure during the short season at Davié, Togo.

N supplied to the maize crop by mucuna tops and roots ranged from 10 to 110 kg N ha^{-1}. The P rate for maize was 45 kg P_2O_5 ha^{-1} and for mucuna 30 kg P_2O_5 ha^{-1}. In the above simulation experiments, it was assumed that all other nutrient elements were available in non-limiting quantities over the 20-year period and soil acidity and pests and diseases did not reduce maize or mucuna growth.

The mean cumulative yield in the maize-maize sequence ranged from 2.0 to 2.8 t ha^{-1} without N application (**Figure 10A**). The cumulative yield increased to 5.5 to 6.5 t ha^{-1} at 80 kg cumulative N ha^{-1} rate (**Figure 10C**) and to 7.4 to 10.1 t ha^{-1} at 240 kg cumulative N ha^{-1} (**Figure 10F**). At lower

N rates (0 to 80 kg cumulative N ha^{-1}), maize yield over time declined; however, at higher N rates stable production trends were observed with slopes approaching zero or even becoming positive. The low N rates, while economical for now, tended to have negative impact with depletion of nutrients and organic matter in the long-term and yield decline (negative slopes). With the low N application rates, crops are removing more nutrients than being added as fertilizers or through recycling of root and straw biomass.

During the maize-mucuna sequence, even without any fertilizer addition, N contribution from mucuna resulted in a single-season maize yield of 3.9 to 4.7 t ha^{-1} (**Figure 11A**). The mucuna N contribution is equivalent to the yield obtained in maize-maize sequence (4.2 t ha^{-1}) with cumulative N of 40 kg N ha^{-1}. Optimum maize yield of 5.2 to 5.8 t ha^{-1} was obtained when 60 kg N ha^{-1} was combined with mucuna residue in the maize-mucuna sequence (**Figure 11D**). While mucuna alone resulted in maize yields of more than 4.5 t ha^{-1}, the yields were not stable over time and tended to decline. Thus, mere incorporation of a green manure crop into a cropping system does not assure sustainable production, but its integration with nutrient management practice can ensure improved yields, increased nutrient and water use efficiencies, and increased soil organic matter content. The plant-available N and plant-extractable water content increased from 1.2 to 2.2 times the initial condition values for the Davié soil.

Summarizing the results from the maize-mucuna and maize-maize simulations, it is evident that under a low input system (external N inputs of less than 60 kg N ha^{-1}) maize-mucuna cropping is preferred (**Figure 12**). As the farmers' economic condition improves and intensified cropping (double maize) is preferred, a shift towards higher N inputs is predicted.

Conclusions and Recommendations

Nitrogen management under rainfed agriculture is highly dependent on amount and distribution of rainfall, soil types, and choice of crops, varieties, and planting dates. Apart from weather and soil variability, optimum N rates are driven by the price of grains and costs of inputs. In many parts of Africa, farmers pay twice the price for N fertilizers compared to their counterparts in the developed world. There is also a large fluctuation in the prices of grains, with prices plummeting with surplus cereal production due to poorly developed markets. Given this grim reality, site-specific fertilizer recommendations become an integral component of rainfed agriculture.

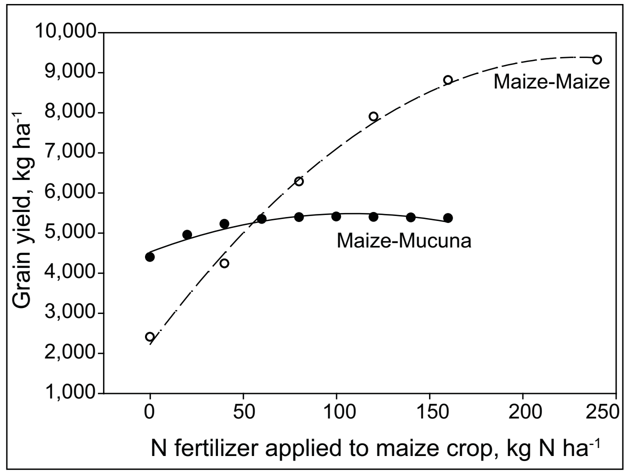

Figure 12. Comparison of mean maize grain yields for the maize-maize and maize-mucuna system, Davié, Togo. The maize grain yields and N rates are cumulative for the two crops for the maize-maize cropping system.

The decision support toolbox used in our studies successfully generated site-specific N recommendation for wheat. Biophysical and economic constraints faced by the wheat farmers in Settat Province, Morocco, were considered. The DST was also successfully used in Davié, Togo, to optimize planting windows for maize and thus take advantage of rainfall to secure high returns from applied fertilizers. In the low input system, Togolese farmers could use mucuna as a green manure crop during the second (short) rainy season. The adoption of mucuna is also dependent on land tenure and weed infestation (Galiba et al., 1998). Long-term tenure and high weed infestation favor mucuna as a green manure/land reclamation crop. With increasing crop intensification, double-maize cropping is recommended. The yield trends from the long-term cropping sequence simulations show that N recommendations must consider sustainability and be revised to avoid soil nutrient mining and yield decline. The decision support toolbox, albeit with its limitations, provides useful information on yield potential, on possible reasons for the existing yield gaps, and on possible N management options.

Acknowledgments

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Growing Season and Soil Factors Related to Predicting Corn Nitrogen Fertilization in Quebec

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Abstract

The effect of season on N fertilizer requirements of corn (*Zea mays* L.) in Quebec is not different than in other areas with temperate humid climate. Both the requirements and the supply of N vary among soils and across the landscape within a field. They are also expected to vary within and between seasons due to variable weather conditions. This paper proceeds from three databases to study the influence of N fertilization management, previous crops, and soil types on the yield response of corn among seasons. It also examines opportunities to mitigate seasonal effects on potential response to N by postponing fertilizer application until the crop is in a position to take up the N at its disposal. Early spring N application results in nitrate release in advance of crop N uptake, and may also result in losses arising from leaching and denitrification. Late spring precipitation and temperature are critical controls of this release and loss. The assessment of N sufficiency is intended to predict potential response of the crop to N. In-crop assessment of N sufficiency based on chlorophyll saturation index can be helpful.

Introduction

Grain corn is the most important feed for animals in eastern Canada. In Quebec, grain corn is produced on 385 thousand ha for a total annual yield of 2.8 million tonnes (Fédération des producteurs de cultures commerciales du Québec, 2006). Its N requirements are relatively high. Over the last 40 years in Quebec, sales of N fertilizers have gone from 12 to 100 thousand tonnes (Développement durable, environnement et parcs Québec, 2000; CRAAQ, 2003).

Nitrogen lost to denitrification, leaching, volatilization or surface erosion is harmful to the environment. Intensive agricultural practices in the south-western part of Quebec contribute to the degradation of surface and subsurface water quality. Nitrous oxide (N_2O) and ammonia (NH_3) produced by denitrification and volatilization, respectively, are the most important gaseous emissions increased by N fertilization and contribute to atmospheric pollution. Nitrous oxide is 300 times as effective as CO_2 as a greenhouse gas. Production of N_2O is estimated by IPCC Tier 1 methodology to increase by 1% of N applied, but reported emission factors vary widely. Nitrous oxide emissions in Quebec were reported as unaffected by N rate (Elmi et al., 2002), though work in the Canadian prairies suggests small increases in emissions with N applied.

Nitrogen uptake of corn approximates a sigmoid pattern. N uptake is very slow until the V6 stage. Its rate increases until the V12 stage and decreases after silking (Karlen et al., 1988; Magdoff, 1991; Dharmakeerthi et al., 2006). Toward physiological maturity, N uptake virtually stops. Although the pattern of N uptake is consistent among seasons, uptake rates vary (Dharmakeerthi et al., 2006). Under conditions of high N supply, total corn biomass is increased but partitioning to grain yield may be negatively affected (Ma et al., 2005b). Ma et al. (2005a) report that even though grain yields varied among hybrids and N rates from year to year, there was no N x hybrid interaction on yield.

The official fertilizer recommendation guide in Quebec recommends a total of 120 to 170 kg N ha^{-1} depending on region and soil textures, with 20 to 50 kg ha^{-1} of this amount applied in a starter band at planting (CRAAQ, 2003). Ma et al. (2003) report for three consecutive seasons in Ontario that N fertilization at 60 (or 80 in 1999) or 180 kg ha^{-1} resulted in better yields than without fertilization, but did not differ significantly between each other. Ma et al. (2005b) reported that in the Ottawa, Ontario Central Experimental Farm environment, N appli-

Abbreviations: CDD, cumulative degree days; N, nitrogen; NO_3, nitrate; N_2O, nitrous oxide; NH_3, ammonia; MERN, maximum economic rate of N; OC, organic carbon; PAN, plant-available N; PSNT, presidedress soil nitrate test; NTOT, sum of N applied by starter and sidedressing.

cations exceeding 120 kg N ha^{-1} were not efficient. Elmi et al. (2002) reported that N fertilization at 200 kg ha^{-1} does not always result in higher yields than 120 kg ha^{-1} in Quebec, depending on season.

Responsible fertilization of agricultural fields will often increase crop production, improve quality (e.g., protein), increase net incomes, reduce the risk of monetary loss, improve soil quality and reduce N loss in the environment, but weather and edaphic factors affect N use efficiency and raise the level of uncertainty for making field management decisions (Pattey et al., 2001).

Soil and crop factors can be involved in this effect of weather. Organic carbon (OC) content, soil water content and plant available N (PAN) were found highly variable in space and strongly correlated (Dharmakeerthi et al., 2005). The relation between PAN and OC changed from linear in the early part of the growing season to parabolic later in the season. However, the degree of significance as well as the magnitude of the PAN-OC correlation varied between growing seasons, with the lowest significance level obtained in dry growing seasons (Dharmakeerthi et al., 2004). However, even in landscapes where the textural variation is marginal, the amount of PAN at a given growth stage and the N accumulation rate was found to be heavily dependent on weather (Dharmakeerthi et al., 2005).

Dharmakeerthi et al. (2005) report that at physiological maturity of corn, the differences in mean PAN among landscape positions varied in their study from 57 kg N ha^{-1} in 2000 to 123 kg N ha^{-1} in 1999. The year 2000 was very wet, especially during the early periods of the season (214 mm of rainfall was received between the first and the second sampling), and a considerable proportion of PAN was lost.

In non-irrigated regions, water availability usually plays a major role in crop production. In the eastern Ontario–western Quebec region, water deficits in July are common (about -44 mm in the Ottawa area). This deficit is more severe in eastern Ontario than in western Quebec (Pattey et al., 2001). During a drought, a decrease in Ni/Nc is observed (Ni, N concentration in the aerial dry matter at a given time; Nc, critical N concentration in the aerial dry matter) (Dharmakeerthi et al., 2006). On the other hand, in parts of Quebec where corn production on poorly drained clay soils is common, N uptake may be more frequently limited by water saturation (Dam et al., 2005). Corn roots are sensitive to even short periods of restricted aeration (Elmi et al., 2002).

There are conditions under which the corn crop does not respond to N fertilizer applications in Quebec. These conditions are related to weather, soil, site history and crop factors. The objectives of this paper are: 1) to review the scientific literature on the topic with an emphasis on studies conducted in Canada; 2) to analyze the relationship between N rate and the yield response of corn; 3) to identify potential factors involved in the modulation of this relationship; and 4) to propose strategies of corn N fertilization taking into account the constraints imposed by seasonal weather changes.

Materials and Methods

Databases

Three databases (experimental farm, local, and provincial) were used to achieve the different goals of the study.

The experimental farm database comprised 7 years (1999 to 2005, inclusive) of corn N response trials conducted on soils of loamy to clay-loam, and occasionally of the sandy loam type from the L'Acadie experimental research station of Agriculture and Agri-Food Canada in the Montérégie region of Quebec. The previous crop was generally either corn or soybean.

The local database was courtesy of Éric Thibault (Club Techno-Champ 2000, located in the Napierville area of the Montérégie region of Quebec). It regrouped information from 5 corn growers over the years 2003, 2004 and 2005.

We were granted access to a provincial database (Gilles Tremblay, CEROM) consisting of 164 trials over the years 1995 to 2005 for a total of 3977 plots in the grain corn growing area of the Quebec province. The trials consisted generally of five to seven rates of side-dress N (40 to 240 kg ha^{-1} in addition to starter N) in a completely randomized block design with four replications. Regions were selected whenever they were subjected to trials for a minimum of three years which left a database containing 683 observations in 19 regions. Each observation is the mean of 4 replications. This data bank presented a diversity of soils, manure history, and former crops.

Seasonal characteristics (based on L'Acadie experimental farm data)

The 1995 growing season was marked by a period of severe drought in May and June. Although rainfall recorded in the following months was within the normal range for the season, it was not sufficient to meet crop water needs. The growing season was also characterized by mean temperature higher than usual. June and August were particularly warm, with temperatures above 30°C and very high humidity.

Weather conditions prevailing in 1996 during the planting period were adequate. Following planting, cool temperatures were recorded so that degree-days accumulation was very low as compared to normal. June was characterized by high rainfall. July was also quite rainy but not more than average. In August and September, temperatures were relatively warm while the first month was relatively dry and the second presented precipitation comparable to normal.

The 1997 growing season was characterized by a cool spring followed by a dry spell and from July to September, a return to normal climatic conditions. However, July and August precipitation was slightly greater than normal.

Large temperature ranges prevailed during the 1998 season. Indeed, from May through September, maximal and minimal temperatures were respectively higher and lower than the average of 16 years. Monthly maximal temperatures from June through September were higher than normal. However, average temperatures during these months were similar to normal since relatively cool minimal temperatures were recorded. Spring was relatively dry. In July and August, total monthly rainfalls were similar to normal. In July and August, total monthly rainfalls were similar to normal, but were lower in September.

Warm and dry conditions prevailed during the whole 1999 season. Monthly maximal, minimal and average temperatures were higher than normal from May through September. Monthly average temperatures were higher than normal, ranging from 2.4 to 7.1°C. This season, cumulative degree-days in base 5°C and 10°C were also higher than normal. May, June, and August were quite dry with rainfalls of 50 mm, 62 mm, and 57 mm of water respectively (normal in May: 83 mm; June 88 mm; August: 97 mm). Rainfalls were more abundant in July and September, respectively, with 141 mm and 182 mm of water (normal in July is 95 mm; in September, 92 mm).

The 2000 season was characterized by cooler conditions than those of 1998, 1999, and normal. The accumulation of degree-days was less than normal, and less than the accumulation in 1998 and 1999. The month of May was wetter than usual, with 121 mm of precipitation, while the months of June and July had lower than normal levels of precipitation. Despite frequent rains, July was particularly dry; only 59 mm of precipitation fell, compared with the average 101 mm. Finally, during the months of August and September, precipitation exceeded the normal levels.

Weather in 2001 was warmer than 2000, but cooler than 1999 for the months of May, June, and September. Mean temperatures were higher than normal, except in July. The months of June and August were wetter than normal. May, July, and September, however, had less precipitation than normal. Early July was rainy, but there was a drought from July 12 to August 16, during which time only 7.4 mm of rain fell.

The 2002 growing season was characterized by cooler conditions in May, June, and August than in 2001. Conversely, temperatures were generally warmer in 2002 than in 2000, except for May, when they were cooler. May was not only cool, but also very wet, with twice the precipitation normally received during the month. However, July, August, and September were above normal in mean maximum, minimum, and monthly temperatures. The months of May, June, and September were wetter than normal. In July and August, however, precipitations were below normal. Only 34 mm of rain fell between August 3 and September 10.

In 2003, cooler conditions than in 2002 prevailed in July and September and by fairly similar conditions to 2002 in August. In addition, temperatures were cooler in 2003 than in 2001 for May, June, and August. The 2003 temperatures were above normal for the entire season, and this was true for the mean maximum, minimum, and monthly temperatures. May was wetter than normal, while July was close to normal. In contrast, June, August, and September saw less precipitation than normal. Only 32 mm of rain fell between June 21 and July 20.

The 2004 season was marked by cooler conditions than in 2003 in June, July, August, and September; only May was warmer. In comparison with 2002, temperatures in 2004 were cooler in July, August, and September, similar in June, and higher in May. Average maximum, minimum, and mean temperatures in 2004 were above normal in May and September, but below normal in June and August. Only July was more humid than normal.

The 2005 season was marked by warmer conditions than in 2003 and 2004; only May was cooler. Average maximum, minimum, and mean temperatures in 2005 were above normal in June, July, August, and September, but below normal in May. July, August, and September were more humid than normal. By contrast, May and June had somewhat less than normal precipitation. The 2005 season had low precipitation periods at the beginning and end of June, but in mid-June, rain fell for four consecutive days for a total of 62.4 mm.

Attribution of classes to regions

The provincial database without restriction was used for the attribution of classes to regions (years 1995 to 2005). Regions in the province were attributed to one of two classes for the magnitude [high (H) and low (L)] and stability [stable (S) or variable (V)] of the yield response of corn to total N rate (starter N + sidedress N) among years (**Table 1**). The threshold for the attribution of either the H-L or V-S status was defined by the significance of the F test ($p \leq 0.05$) for sources of variation due to N and its interaction with years, respectively. The F-test criterion may be slightly biased toward classifying sites as stable, since the F test for the interaction pools a large number of degrees of freedom. However, this test effectively identified the regions of greatest variability in response.

Of the 19 regions, 8 were therefore categorized in the HS class which is characterized by a high and stable response of corn grain yield to N rates from year to year. Five regions were members of the LS class that consistently did not respond to N rate. The two remaining classes presented variable behaviors to N rates among years. Those of the HV class (4 members) were strongly affected by N rates. For the LV class (1 member) the effects of N rates were not significant. Characteristics of fertilizer use and yield of the corn-growing regions and their respective classifications are shown in **Table 2**.

Table 1. Attribution to regions in Quebec of classes based on the responsivity and stability of corn yield response to N fertilization rates (NTOT) among years.

	F ratio			Classes
Region	NTOT	Year	NTOT* Year	Responsivity & stability
L'Acadie	15.1	5.2	1.2	HS
L'Ange-Gardien	0.2	0.1	0.1	LS
Laplaine	6.4	4.5	1.1	HS
Marieville	6.7	4.9	1.6	HS
Monteregie Ouest	7.6	16.6	0.4	HS
Napierville	4.2	7.3	1.6	HS
Ormstown	1.5	10.5	0.4	LS
St-Anicet	2.8	8.1	2.8	LV
St-Antoine	0.7	0.8	0.9	LS
St-Bartholome	24.0	55.6	6.5	HV
St-Blaise	48.3	9.9	4.7	HV
St-Bruno	2.6	37.0	0.9	LS
St-Césaire	2.5	0.6	0.6	LS
Ste-Barbe	60.5	4.3	4.0	HV
Ste-Marie-Salome	19.1	3.2	2.2	HS
Ste-Martine	5.4	3.4	0.8	HS
St-Hyacinthe	3.8	1.5	0.8	LS
St-Philippe	35.1	0.4	0.7	HS
Varennes	27.2	28.9	4.4	HV

N response classes: HS = high and stable; HV = high but variable; LS = low and stable; LV = low but variable. High is distinguished from low as a response to N significant at $p \leq 0.05$. Variable is distinguished from stable as a year x N interaction significant at $p \leq 0.05$

Results and Discussion

Influence of season

This paper proceeds from databases in which a wide range of N rates (from none to excessive) were tested for their effects on corn yields. In this rather artificial context, the proportion of yield variance explained by the season is generally inferior to the one explained by N rates (median of F ratio "variance due to season/variance due to N rate" = 0.7 in the provincial study and 0.03 in the local study). In the local study, the year * N rate interaction was found significant (data not shown). It follows that despite the determinant effect of season on yield, the leverage offered by N fertilization is likely of greater importance.

At the L'Acadie farm (data not shown) there was a range of 98 kg N ha^{-1} (min. 86, max 184) in the rates necessary for economically optimal yield. The plots were located on soils of slightly different types and following different crops, but most of the variation in optimal rates is assumed to come from the effect of seasons. Average rate for optimal yield was 139 kg N ha^{-1} and the rate of 177 kg N ha^{-1} secured optimal yield in 85 % of the years. Ball-Coelho et al. (2005) reported a range of 170 kg ha^{-1} (min 100, max 270) in the N rate necessary for obtaining 95% of maximal yield under conventional tillage. Their study was performed on one site over 9 years. According to our own estimation from their data, the average N rate required for 95 % maximal yield was 140 kg ha^{-1} while the rate of 175 kg ha^{-1} was enough in 85 % of the years. Kahabka et al. (2004) found that optimal N rate varied from 110 kg ha^{-1} for dry years to 220 kg ha^{-1} for those with a warm wet spring. They also state that annual variations in optimum N rate are not related to annual yield differences and yield potential itself did not appear to be a good predictor of N needs. It is obvious that the inclusion of a weather component in N recommendations would be beneficial (Pattey et al., 2001).

At the provincial level, the

Table 2. Characteristics of fertilizer use and yield of corn growing regions used in the provincial database.						
					Yield	
Regions	Classes	Number of observations	Mean N from manure	Mean N from starter fertilizer	Mean	Standard Deviation
			- - - - - - - - - - kg ha^{-1}	- - - - - - - - - -		
L'Acadie	HS	34	0	51	6903	2198
L'Ange-Gardien	LS	18	43	30	11771	1136
LaPlaine	HS	20	0	87	7254	1847
Marieville	HS	84	54	49	10576	1458
Montérégie Ouest	HS	36	28	45	10301	1473
Napierville	HS	54	3	48	10697	2425
Ormstown	LS	29	0	48	7822	2227
St-Anicet	LV	49	6	48	9237	1890
St-Antoine	LS	36	23	56	9859	924
St-Bartholome	HV	31	47	36	9262	2172
St-Blaise	HV	42	0	54	10933	1654
St-Bruno	LS	23	0	37	8621	1545
St-Césaire	LS	40	70	65	11369	795
Ste-Barbe	HV	46	0	43	8178	1461
Ste-Marie-Salomé	HS	22	0	63	10286	1381
Ste-Martine	HS	24	25	49	9864	1108
St-Hyacinthe	LS	34	0	47	9281	1504
St-Philippe	HS	23	0	64	10390	828
Varennes	HV	38	0	47	10636	1466
Province		683	16	51	9644	1552

years 1997 to 2005 presented important variations in optimal N rates, both within and among years (**Figure 1**). The median optimal rate was normally within the range of 100 to 150 kg N ha^{-1}. It was lowest in 2002 and highest in 2005. To a certain extent, these yearly differences may also be related to variations in regions, soil types or other factors in the sample considered.

Relationships among yield and N fertilization components

Each of the four classes previously defined were submitted to a principal component analysis (PCA) and a varimax rotation (**Table 3**). The parameters considered in the PCA were grain yield, N in manure, N in starter fertilizer and N in sidedressing. The HV class shows a strong positive "yield – N in sidedressing" relationship (**Figure 2**) in the second component (**Table 3**). The database does not allow for a clear understanding of manure or starter N effects in this class. Yield in the LV class as well is apparently subjected to a complex structure of influence and it contains too few observations to make interpretations. This may only be an artefact, however, since the database is not sufficiently rich in this particular case to be positive about the nature of the relationships.

Yield in both the HS and LS classes is characterized by a positive relationship with N contained in manure (**Table 3**; **Figure 2**). McGonigle et al. (2004) reported that similar values for soil mineral N on June 10 in plots given manure at planting had yields typically 0.5 to 1.0 t ha^{-1} greater than those in plots given urea at planting. Gradual release

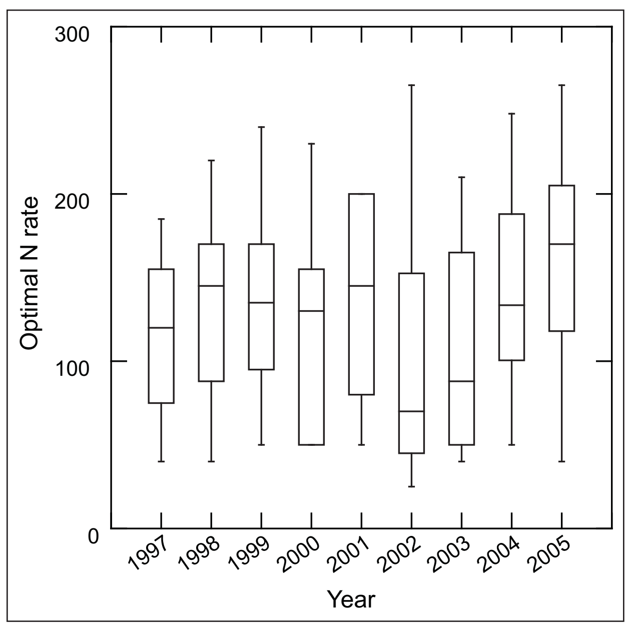

Figure 1. Box plots of economically optimal N rates for corn among years in the province of Quebec. Optimal N rates (kg ha^{-1}) calculated by Gilles Tremblay. (Provincial database).

Table 3. Principal components analysis of the relationships among corn yield and N fertilization variables within regional groups.

	HS		HV		LS		LV	
Variables, kg ha^{-1}	PC1	PC2	PC1	PC2	PC1	PC2	PC1	PC2
Yield	**0.78**[1]	0.33	-0.12	**0.80**	0.86	0.12	0.57	**0.63**
N in manure	**0.77**	-0.17	-0.95	-0.02	**0.88**	0.02	0.84	-0.12
N in starter fertilizer	-0.46	0.58	0.96	0.02	0.17	0.68	-0.93	-0.20
N in side-dressing	0.18	0.84	0.16	**0.78**	-0.05	0.81	-0.08	**0.89**
Variance explained (%)	36	29	46	31	39	28	48	31

Regions with high (H) or low (L) response to N. Regions with stability (L) or variability (V) or response to N among years. PC = principal component from a varimax rotation.
[1]Bold type indicates a loading with an eigenvalue greater than 1 and an association with yield.

of immobilized N from manure after the time of sidedress N and undetected as soil mineral N on June 10 can contribute to yield increases of corn. Our study indicates that the use of manure can also contribute to reduce the impact of season on response of corn to N fertilization.

The years 1998, 2000, and 2001 were characterized by a negative relationship of yield with starter N, while the relationship was positive in 1997, 1999, and 2003 (data not shown). The application of N in sidedressing was positively correlated to yield in all years, but much less so in 2000 and 2003. The spread of starter N applications was much more limited in the database than the one of N in sidedressing which reduces the value of the interpretation that can be drawn from the analysis for the former parameter. According to Kay et al. (2006), spring N applications (such as starter N) are susceptible to be released in advance of crop uptake, and therefore are more susceptible to leaching losses. Scharf et al. (2002) suggested postemergence application of N as a way to reducing early-season N losses in wet years. Sidedressing at V6 was reported by Ma et al. (2005b) as being rapidly taken up by the crop, resulting in minimal N loss and improving N use efficiency, reducing the risk of leaching or gaseous N emission.

The 1948-2006 national weather data shows a trend for warming summer temperatures in recent years (Environment Canada, data not shown). It is possible that global climate change will lead to a higher frequency of extreme weather events. The year 2006 was the most recent example of how much in practice weather events can impact N fertilization in Quebec. Between May 1st and June 20th, 2006, a total precipitation of 277 mm was recorded at the L'Acadie experimental farm. Most of the corn planting in producers' fields was done during this period. Growers who had put on all their N dressing at planting time were concerned as to how much of it was leached, denitrified, or otherwise lost. On the other hand, growers using sidedressing were in a position to make in-season adjustments. They were applying the premise that it is more logical to preserve N from losses early in the season and to better match crop demand by an in-season N application.

The corn crop is responsive to N applications until silking but full yield may then not be achieved (Scharf et al., 2002). Dharmakeerthi et al. (2006) report that under southern Ontario conditions, the surface soils (0 to 0.30 m) are normally driest during silking to the R3 stage and transpiration requirements are then met primarily from water taken up from deeper in the profile. Nitrogen concentrations at greater depth are smaller than those of the surface soils so that N taken up by the plants during this period could be low. Plants that had excess N accumulated would have an advantage during this period because stored N could be remobilized to the sink (ear) without deleteriously affecting the N concentration in the source (leaves).

Former crop

When the previous crop is corn, soybeans (*Glycine max* L.), other beans (*Phaseolus sp.*), or sorghum, corn is about 75% likely to be highly responsive to N rate (**Table 4**). The opposite was true (80% unresponsive) when the former crop is a cereal. Other crops, including alfalfa, peas, grazing lands, or sorghum were associated exclusively with stable behaviour with respect to N response. Obviously, former crops can greatly influence the amount of mineral N made available to the following corn crop. Yield response to applied N and crop N uptake were strongly affected by soil residual nitrate (Rashid and Voroney, 2005). Dharmakeerthi et al. (2006) found that the effect of fertilizer N on corn was reduced when a legume was a cover crop prior to corn. Dharmakeerthi et al. (2005) reported that plant available N (PAN) at maturity at the average value of organic carbon (OC) across the site

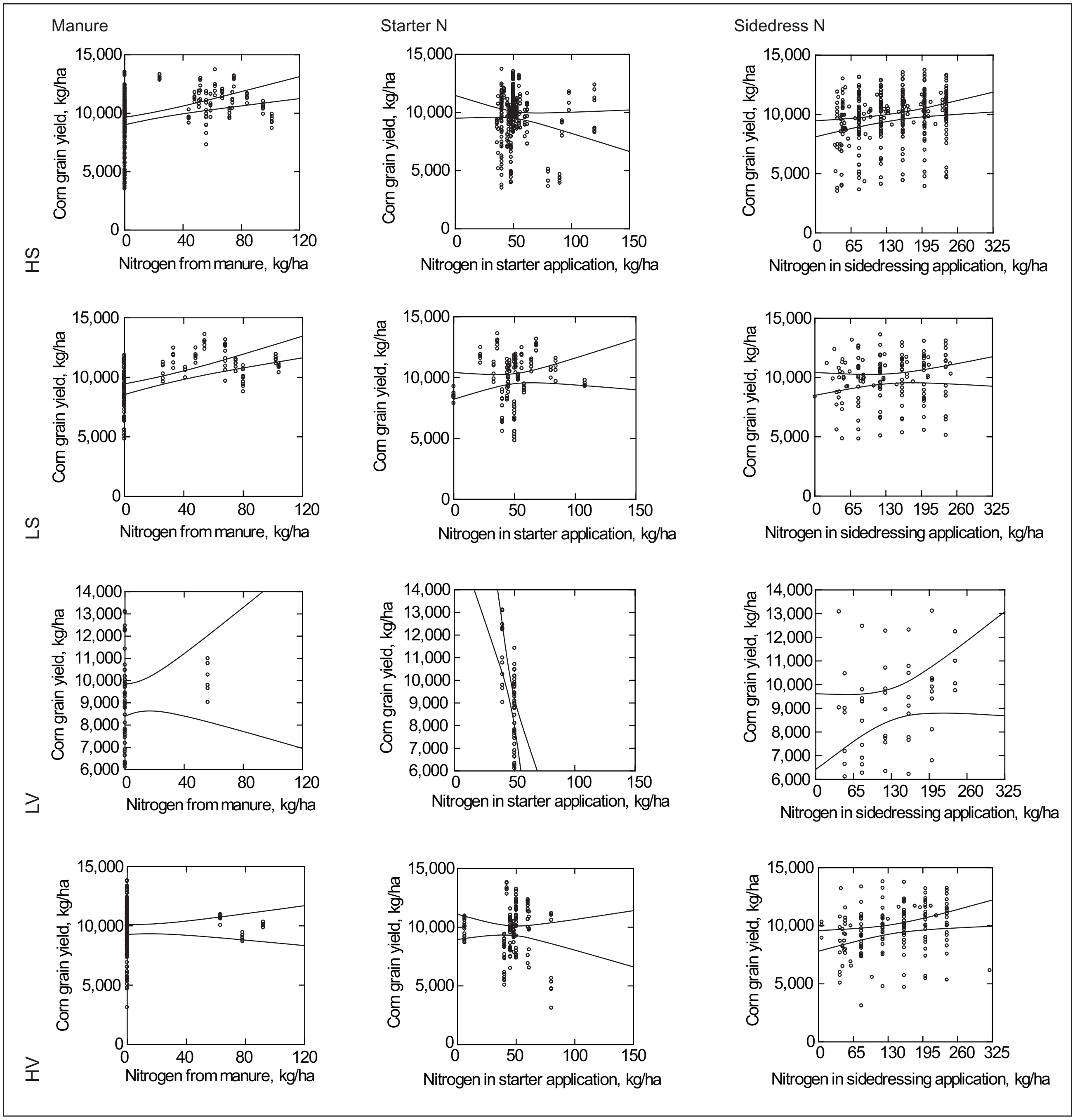

Figure 2. Scatterplots showing the relationships between corn grain yield and N rate from different sources of fertilization. Provincial database. Each line of figures correspond to a region either with high (H) or low (L) response to N and with stability (L) or variability (V) of response to N among years.

(19.5 g OC kg^{-1} soil) was at a mean of 58.9 kg N ha^{-1} per 1% OC, which is comparable with the rule of thumb that 58.6 kg N ha^{-1} would mineralize in a 5-month growing season in Colorado for every 1% OC [Soltanpour (1979), as cited by Vigil et al. (2002)]. Potentially mineralizable N content increases as the organic matter content increases across the landscape (Dharmakeerthi et al., 2005). Corn N uptake increased with organic carbon content in a quadratic manner (Dharmakeerthi et al., 2006).

Soil textures

Soils of coarse textures are likely almost 70% of the time to have observations classified as highly and regularly responsive to N (HS class; **Table 5**). This is also true for 40% of soils of medium textures. Actually, the HS class is generally (77%) found on soils of medium or coarse textures. However, the HV class is very seldom (4%) found on soils of coarse textures. Soils of fine textures are almost equally likely to result in observations in the HS, HV, or LS

Table 4. Frequencies of regional classes as related to the type of crop grown prior to corn.

Regions	Corn	Soybean or bean	Cereals	Peas, forage, or sorghum	Others	Total
HS	0.50	0.44	0.10	0.75	0.83	0.48
HV	0.23	0.33	0.10	0.00	0.00	0.23
LS	0.18	0.15	0.70	0.25	0.17	0.22
LV	0.09	0.08	0.10	0.00	0.00	0.08
Total	1.00	1.00	1.00	1.00	1.00	1.00

The numbers in columns represent the proportion of the corn land area, following different crops, in each of four response classes:
HS = high and stable
HV = high but variable
LS = low and stable
LV = low but variable
High is distinguished from low as a response to N significant at $p \leq 0.05$
Variable is distinguished from stable as a year x N interaction significant at $p \leq 0.05$

classes. The HV (62%) and the LV class (100%) are highly represented in the "medium" textures. The local database was submitted to an ANOVA with years (2003, 2004, 2005), soil texture classes, and the sum of starter and sidedressed N (NTOT) as sources of variation. Yields were found significantly different among years. The year 2005 (10 753 kg ha^{-1}) was slightly more productive than 2003 (10 449 kg ha^{-1}) or 2004 (10 361 kg ha^{-1}). There was a trend for lower N rates to generate more yield variability than higher rates (**Figure 3**). Spatial yield variability is affected by weather and tends to decrease with higher N application rates (Pattey et al., 2001). Yields were on average equivalent between loam and sandy loam soils on one hand, and between clay loam and silt loam soils, on the other hand. The latter group generally yielded significantly higher than the former. Yearly conditions brought about differences in the way corn yield responded to N rates (**Figure 4**). Loams were apparently most responsive to N rate in 2003 while this was the case for clay loams in 2004. This may be partly due to the fact that May 2003 was wetter than normal and that leaching may have occurred in loams. The cool conditions of the summer 2004 (June to August) may have reduced mineralization particularly in the clay loams and hence favoured the effect of N applications.

Both the requirements and the supply of N vary among soils and across the landscape within a field. They are expected to vary within and between seasons due to variable weather conditions. Variations in soil texture and excess winter rainfall (rain that falls after soils have fully rewetted in the autumn) are the main factors that influence N losses from soil. Sands are much more easily leached than silt or clay soils, but denitrification losses tend to be greater on clays (Rothamsted Research, 2007). The values of potentially mineralizable N content and the mineralization rate constant for years when rainfall is much greater than the average in May, June, and July may reflect large losses in N due to leaching or denitrification (Dharmakeerthi et al., 2005). Further information on the spatial variability in these losses is required, especially in the early part of the growing season in cool humid temperate environments where such losses may have the greatest impact on fertilizer requirements (Dharmakeerthi et al., 2005). Indeed, early season

Table 5. Number of observations per corn regional class in the different soil textural classes (Provincial database).

		Soil textural class									
		Fine		Medium				Coarse			
Regional class	unknown	clay	silty clay	loam	clay loam	silt loam	silty clay loam	sandy loam	sandy	loamy sand	Total
HS	126	42	21	77	14	21	21	35	21	21	399
HV	7	63	0	56	0	35	21	7	0	0	189
LS	21	56	14	14	7	21	21	14	0	14	182
LV	35	0	0	0	0	28	0	0	0	0	63
Total	189	161	35	147	21	105	63	56	21	35	833[†]

Regions with high (H) or low (L) response to N. Regions with stability (L) or variability (V) of response to N among years.
[†]Additional sites from other years were added to the 683 observations used in Tables 1 and 2.

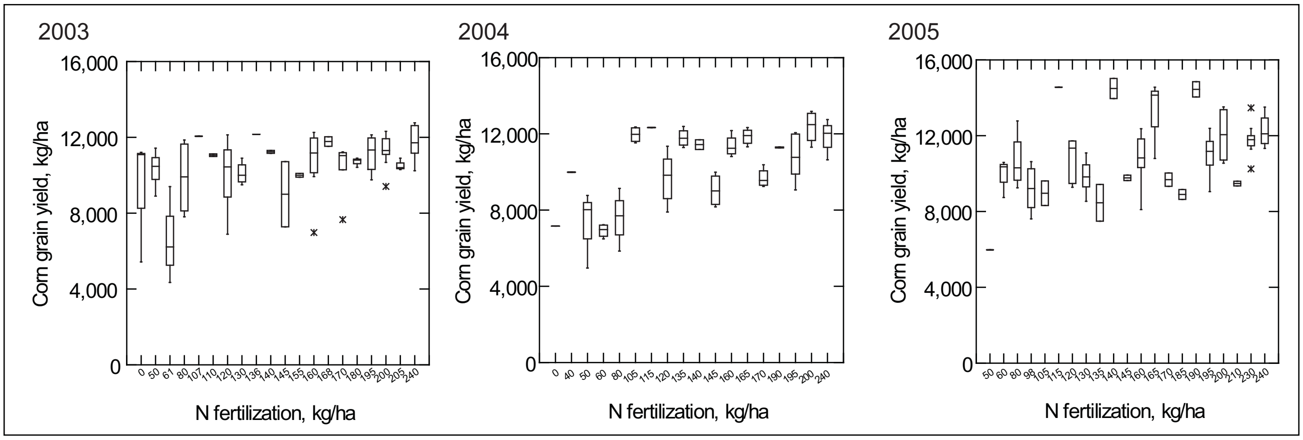

Figure 3. Box plots of the relationships between corn grain yield and total N fertilization for the years 2003 to 2005, inclusive. Local database.

precipitation interacts with soil drainage classes to determine the yearly variation in yield response of maize to fertilizer N (Sogbedji et al., 2001). The absence of response to N application rates may also be affected by soil physical factors such as compaction (Turpin et al., 2005).

Strategies to account for the effect of weather

Soil tests of NO_3-N allow for the tuning of N fertilization at planting or sidedressing time. Early in-season soil mineral N samples were better predictors than pre-planting ones in Ontario (McGonigle et al., 2004; Rashid and Voroney, 2005). Depending on season, the concentrations of NO_3-N present in the soil are at their maximum 10 to 35 days after sowing (McGonigle et al., 2004), a period at which the uptake by the crop is extremely small (McGonigle et al., 2004; Kay et al., 2006).

The presidedress soil nitrate test (PSNT) is considered the most reliable soil test (Rashid and Voroney, 2005) since it represents the net balance between production and loss of mineral N from the soil system. Indeed, at the stage of the PSNT, crop uptake is insignificant. The inverse relationship ($r = -0.88$) of the PSNT with maximum economic rate of N (MERN) is higher than at preplant (Rashid and Voroney, 2005).

The PSNT was developed in New York (Magdoff et al., 1984) and found valuable in Wisconsin (Andraski and Bundy 2002) and in Spain (Ferrer et al. 2003). However, Ma et al. (2005b) found the response of corn yield to N fertilization to be little correlated with soil mineral N at preplant or presidedress in humid environments such as Ontario and Quebec.

For similar corn yields, soil mineral N content measured 3 to 4 wk after planting was generally 10 to 20 kg N ha^{-1} lower with preplant manure applications than with urea applied at planting because of a more gradual release of mineral N from manure than from urea (McGonigle et al., 2004). These authors stated that recent manure history should be considered when using soil tests for mineral N that are taken 3 to 4 weeks after planting to calculate sidedress N fertilization. The prediction of N availability to crops from manures with variable ammoniacal and organic N contents has known little success and is somewhat related to growing degree days. Hence, manure management recommendations to ensure the release of mineral N in synchrony with crop requirements remain difficult to formulate (McGonigle et al., 2004).

Large numbers of samples are required to obtain representative results (Ma et al., 2005b). Spatial variations in soil N test levels, crop yields, and crop response to applied fertilizer N were not strongly related to one another (Kahabka et al., 2004), so either soil N test levels or yields may not adequately delineate farm-scale management zones for the variable application of N fertilizer (Turpin et al., 2005).

The greatest source of variability in N requirements was observed with the annual effects of weather, and presents a greater potential for precise N application than site-specific application (Kahabka et al., 2004). Actually, the potential benefits of site-specific management would only be fully captured if N management could be adjusted annually in response to changing weather conditions, especially those early in the growing season (Kay et al., 2006). Spatial yield response analysis showed limited field-scale regionalization of both yield and profit response to N, suggesting that site-specific application of N based on PSNT is impractical (Kahabka et al., 2004).

In-season crop assessment constitutes an alternative to soil tests for establishing sidedressing rates (Tremblay, 2004). Leaf chlorophyll and canopy reflectance measured at V6 responded linearly and

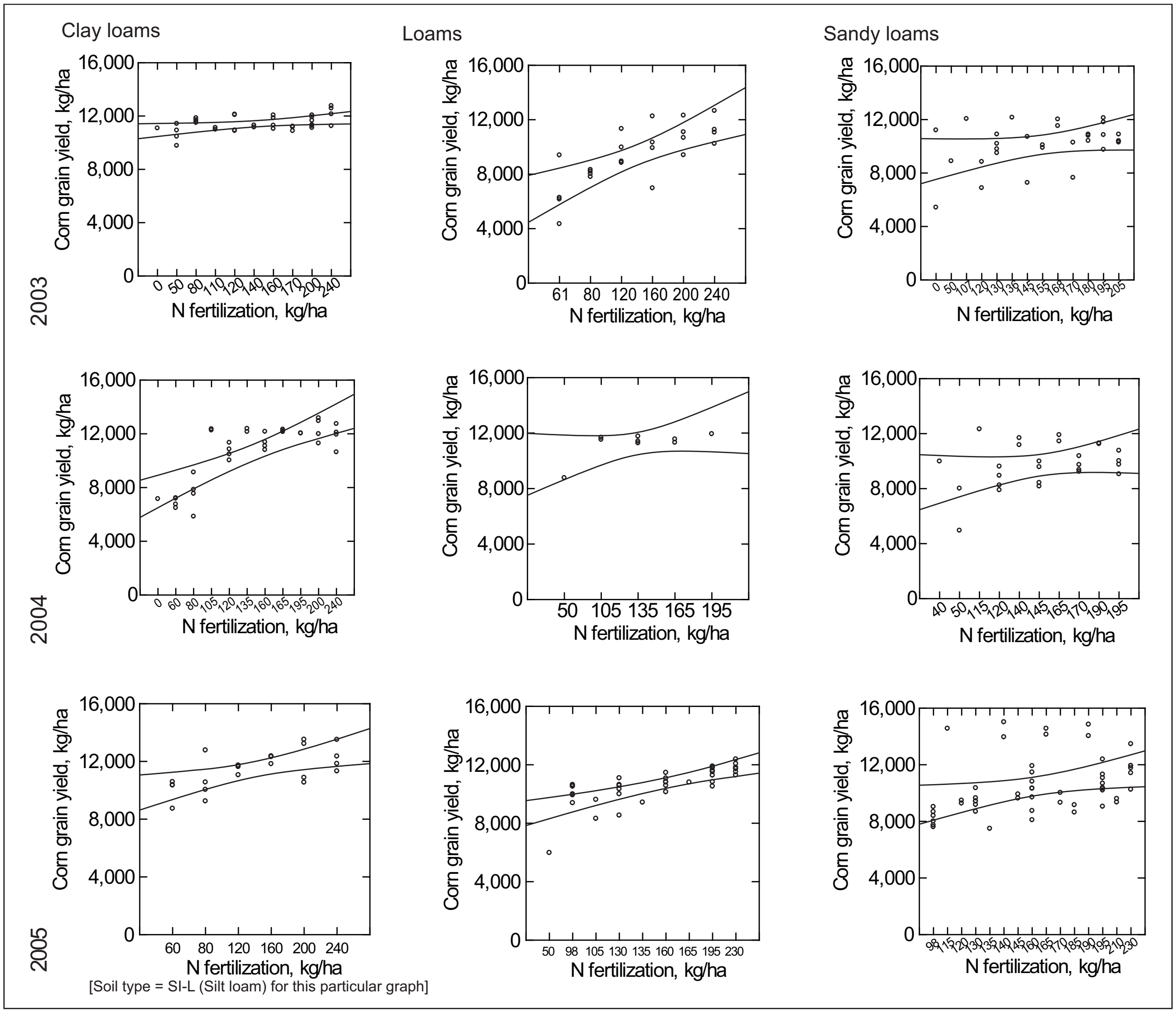

Figure 4. Scatterplots showing the fitted linear relationships between corn grain yield and N fertilization for different soil types and years. The lines show the confidence intervals limits (p ≤ 0.05). Local database.

consistently among years to fertilizer N up to 120 kg N ha^{-1} and can be used as crop-based indicators for early-season N amendment (Ma et al., 2005b). Applying N at sidedress (V6 to V8) should be one of the best ways of supplying N to meet the higher demand since grain yield is likely affected to a larger extent by the conditions after sidedressing. In addition, the decision on the quantity to apply should be made late enough to reflect the effects of spring weather conditions (Rashid and Voroney, 2005). Ma et al. (2005b) stated that chlorophyll meter readings are more strongly correlated with whole-plant N concentrations than with soil nitrate, and that crop-based optical indicators would be the parameters of choice to determine early N requirements of corn. Sensor-based systems usually require a non-N-limiting test strip (Schlegel et al., 2005). When expressed as a N sufficiency index, this comparison constitutes a reasonable outlook into N response potential for that given year (Schepers et al. 1992; Peterson et al. 1993; Minotti et al. 1994). Schroder et al. (2000), however, question whether a young crop properly predicts the status of that crop over the entire season. Also, at an early growth (15 to 30 cm) stage the starter N may be having more influence on leaf greenness than the bulk soil N availability. This may limit the accuracy of using chlorophyll readings to make predictions for corn need for N.

Conclusion

The potential for N adjustments according to year is of great significance. On some occasions, there is no response of corn yield to fertilizer N. The challenge is to properly identify the circumstances under which reductions of N doses are warranted and to quantify them as accurately as possible. This study found that fine- and medium-textured soils need more N adjustments. N fertilization can benefit coarse-textured soils the most, but high rates have to be managed with caution because of higher risks of losses to the environment. Cereals as previous crops were mostly found in regions with low N response potential. With other former crops, chances of response are about 75%. On top of these considerations, strategies and tools are available to mitigate the effect of season on corn N fertilizer requirements. First of all, limiting the amount of N provided before the crop is ready to take it up constitutes the best way to prevent N losses due to excessive rain during the period from planting to growth stage V6 to V8. In-season N application can be made at this growth stage, when crop demand is high. At this point in time, both soil N supply and crop demand can be assessed by quick methods. Given the limitations of soil nitrate assessments for the determination of in-season N requirements, field chlorophyll or vegetation index measurements, compared to those of a well-fertilized reference plot in the form of a N sufficiency index, appear promising (Tremblay and Belec, 2006). This potential response should then be adjusted based on the yield potential of the soil as well as the risk of N losses with the help of easy-to-map terrain features (soil electrical conductivity and topography). The above strategy will likely allow for a reduction in average fertilizer N use, and make the use of "insurance" rates less necessary. Lower rates would likely be recommended for normal and dry years, and higher N rates when wet late spring conditions cause a loss of mineralized soil nitrate.

Acknowledgments

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In-Season Real-Time Plant Analysis for a more Flexible Nitrogen Recommendation System

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Abstract

European cereal producers are finding advantages to applying N in multiple small doses through the growing season. The advantages include increased yields as well as enhanced N use efficiency. In-season applications need to be adjusted to suit the needs of the crop, which are best determined by analysis of crop N status. Such analysis can be done by analysis of plant tissue, tissue sap, or measures of leaf or canopy reflectance related to chlorophyll content. The key advantage of multiple applications is that more knowledge of the weather and its impact on crop nutritional need is obtained before the last decision on the final total N dose.

Introduction

Efficient crop production needs appropriate plant nutrition strategies that take into account the type of crop as well as soil and climatic conditions. Nitrogen is the plant nutrient that most frequently limits crop production. It is needed by most crops at higher quantities than other plant nutrients. In principle, the optimum N fertilizer rate depends on the N requirement of the plant minus soil N supply. Plant N uptake depends on yield and N content. If the final yield and N content could be accurately predicted before fertilizer application, a good estimation of the necessary N supply would be possible. This is the reason why many N recommendation systems are based on predefined average crop yields (= “expected yield”) and N contents (MacKenzie and Taureau, 1997; Havlin, 2004).

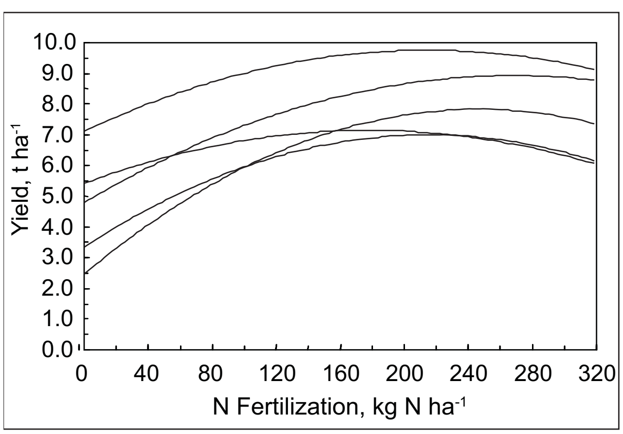

Figure 1. Typical N response curves for winter wheat.

Optimum N fertilizer use means, from an economic perspective, to apply just that amount of N that will give the maximum financial return considering crop and fertilizer prices. This amount of N fertilizer is called the *economic optimum N rate* (N_{opt}); less or more N would reduce the farmer’s profit. From typical N response curves for winter wheat (*Triticum aestivum* L.) for example, it can be seen, even at the same yield level, that N_{opt} varies considerably among fields and years (**Figure 1**). Based on studies conducted by Lory and Scharf [2003; data from 298 field experiments with corn (*Zea mays* L.)] as well as Brentrup and Link (2004; data from 79 field trials with winter wheat) it can be concluded that any general relation between grain yield and N_{opt} is obscured by the many additional factors affecting N_{opt}.

This conclusion is related to the fact that neither plant N uptake nor soil N supply is constant from year to year because both are dependent on the climatic conditions during the individual growing season. Climatic variations like precipitation cause a significant deviation of the observed crop growth from the average. Therefore it is difficult to accurately predict yield level. Long-term field trials confirm that even on one field with the same yield potential the grain yield of winter wheat varied considerably over time. For example in Rothamsted between 1990 and 2001 yields varied from 6.14 to 9.74 t ha^{-1} (Barraclough, 2002), and in Bad Lauchstädt between 1983 and 1992, from 4.6 to 9.5 t ha^{-1} (Körschens, 1994).

Studies that investigate the actual N supply from soil in a specific growth period show that N mineralization from soil organic matter is also largely dependent upon climatic conditions prior to and during the growing season. Therefore it is difficult to predict actual N supply from soil in a given year.

The N_{opt} is not constant for a specific crop or field, but can vary substantially from site to site and year to year (MacKenzie and Taureau, 1997). Even for the same crop grown on the same field, N_{opt} is not the same each year. This is confirmed by the data from the long-term trial in Rothamsted, where at the same site the same crop rotation is grown each

Abbreviations: N, nitrogen; N_{opt}, economic optimum N rate; S, sulfur.

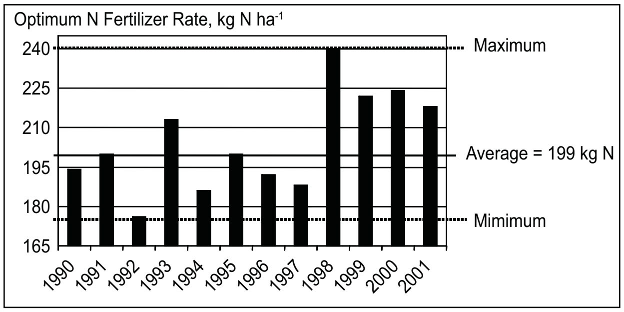

Figure 2. Optimum N fertilizer rate for winter wheat (Broadbalk Experiment, Rothamsted, UK; adapted from Brentrup and Link, 2004).

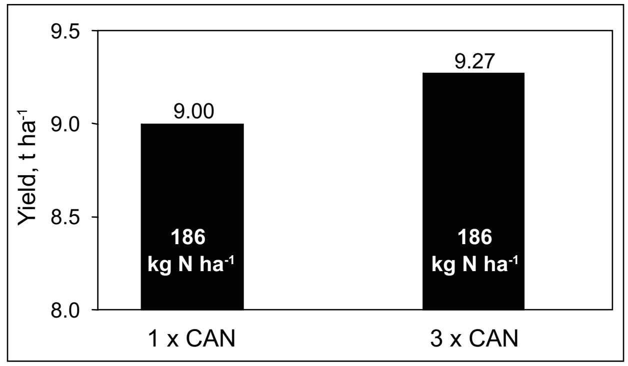

Figure 3. Average yield of 38 field trials with winter wheat with one dressing (1x CAN) or three dressings (3x CAN) supplying N at a total rate of 186 kg ha^{-1}.

year. During the period from 1990 to 2001, N_{opt} for winter wheat varied between 176 N ha^{-1} in 1992 and 240 kg N ha^{-1} in 1998, while the average was 199 kg N ha^{-1} (**Figure 2**).

The main explanation for the variability among years is the changing weather conditions, while differences among fields can mainly be correlated to soil conditions. Climatic factors and soil conditions particularly influence water and nutrient availability for crops. For instance, drought periods can substantially reduce biomass yields and consequently plant N uptake. Furthermore, the interaction of soil properties (e.g. water-holding capacity) and weather conditions significantly affect the magnitude of in-field variability. Hence, fertilizer recommendations solely based on yield expectations do not take into account the annual variability in growing conditions, and as a consequence can lead to incorrect N application (Lobell et al., 2004; Lory and Scharf, 2003).

Split Application Strategy

It is difficult to determine the required N fertilizer rate at the beginning of the growing season. Any fertilizer strategy with a single N application or the main N application at the beginning of the growing season has to manage a risk of uncertainty because over-estimation of N_{opt} reduces the N use efficiency, while under-estimation reduces profitability. Thus, defining the optimum N fertilizing strategy is a recurrent challenge for the farmer before and during each growing season.

A solution could be multiple applications of N fertilizer. To split the N fertilizer rate in several dressings reduces the time span between application and uptake by the crop, reduces the amount of applied N at risk of loss at any given time, and delays the final decision about the total N amount applied to the crop to later growth stages. For high yielding crops the shorter time span between N fertilizer application and crop nutrient uptake increases N fertilizer use efficiency. **Figure 3** illustrates the impact of different fertilizer strategies on the yield of winter wheat. As an example, it shows the average yield data of 38 field trials with winter wheat. Calcium ammonium nitrate (CAN) was applied in one single application (1xCAN) at tillering, or split applied at tillering, stem elongation and head emergence (3xCAN). With the single application of N a grain yield of 9.0 t ha^{-1} was obtained. Split application of the same amount of N gave a yield of 9.27 t ha^{-1}. The yield increase of 0.27 t ha^{-1} was a result of the split application of the N fertilizer.

A split application of N shortens the time span between fertilizer application and nutrient uptake and therefore reduces the risk of N losses during the growing period. In addition, a split application strategy enables the farmer to adjust the N fertilizer rate according to the specific weather conditions during the growing season. Yield data of three field trials with winter wheat show the result of a flexible fertilizer strategy based on split application. In the flexible N management strategy the total amount of N fertilizer applied is the result of individual decisions during the growing season, based on the nutritional status of the crop. After a moderate 1st application at tillering, the applied N fertilizer rates for the 2nd dressing at stem elongation and for the 3rd dressing at ear emergence are calculated from actual plant analysis data. The data in **Figure 4** give an example. Plant analysis recommended the application of 194 kg N ha^{-1} instead of 172 kg N ha^{-1} and the yield was increased to 11.75 t ha^{-1} instead of 11.35 t ha^{-1}. The rate of 172 kg N ha^{-1} in the treatment with three fixed applications has been based on one decision at the beginning of the growing period, based on soil mineral N content and yield expectation. In the flexible application strategy a new decision at each dressing has been made about the actual N requirement. The flexible strategy has additional cost to acquire the necessary information on how much fertilizer should be top-dressed. Methods of plant or canopy analysis have proven to be suitable tools to support in-season decisions.

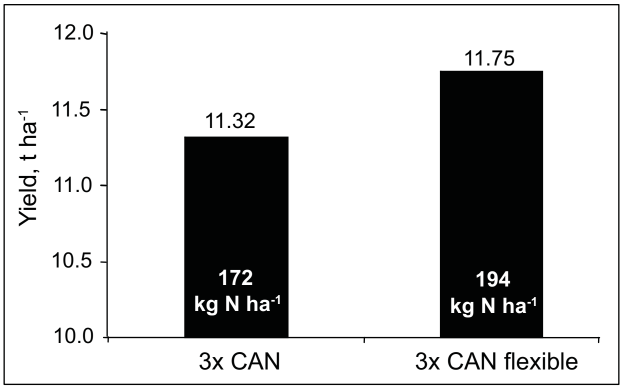

Figure 4. Average yield of 3 field trials with winter wheat for a static (3x CAN) and a flexible (3x CAN flexible) N recommendation system.

Plant Analysis

The use of plant analysis is based on the concept of plant nutrition. As long as the plant is not short of N no additional N fertilizer shall be applied. In addition, the plant itself is the best indicator of N supply from the soil during the growing season. The level of N in the plant is the result of the interaction between N from soil N mineralization, from previous crop residues, water supply, root growth, losses from soil, and N uptake efficiency (Rice et al., 1995). The correct use of plant analysis requires an accurate definition of the plant part to be measured (or sampled) and the correct growth stage, because critical N concentration changes as the plant matures. Furthermore calibration work under field conditions is a necessity.

The simplest (and oldest) method of using the plant itself as an indicator for the assessment of the N requirement is a visual judgment based upon crop color and density. Most growers still use visual judgment for N application decisions. Currently there are several tools available for using plant analysis for calculation of N fertilizer recommendations in arable crops (Wollring et al., 1998). These tools differ considerably in which plant parameter is to be measured and in the way the obtained information is used for a recommendation. The following plant indicators are most commonly used as a base for a N fertilizer recommendation:

- total N concentration or its ratio to a critical N concentration
- plant sap or petiole nitrate N concentration,
- relative chlorophyll content of leaves.

Total N Concentration

The chemical determination of the total N concentration is an accurate and reliable method, but requires an expensive analysis in the laboratory. Since leaf N concentration changes within the growing period, these measurements should be done at clearly defined growth stages to aid in interpretation. Furthermore, distinct plant parts have to be sampled, as the optimal concentration of N varies between different plant organs. For most crops, critical values for different plant organs and growing stages have been determined under field conditions. In the transitional zone between optimal and critical concentration, N recommendation might be based on the so-called “sufficient range”.

The use of the N nutrition index (NNI) is based on the theory that a certain N concentration in the dry matter is needed to enable maximum crop growth. The NNI describes the ratio between the actual and the critical plant N concentration at a particular biomass. NNI values above 1 indicate well-supplied crops, whereas NNI values below 1 indicate N deficiency. As the critical plant N concentration decreases with increasing biomass, NNI can be calculated at any time during crop growth. The NNI provides a diagnosis of the existence and intensity of N deficiency (Lemaire and Meynard, 1997), but does not result in a specific fertilizer recommendation.

Measurement of total N concentration and the calculation of NNI are mainly used for scientific purposes, to check fundamental relations between tissue N concentration, plant dry matter, and the required N fertilizer demand. Because these tests can be costly and time consuming, their use is most common in high value crops. They are less appropriate for use in standard cereal crop production.

Plant Sap (or Petiole) Nitrate-N Concentration

Simple, non-laboratory and semi-quantitative nitrate sap tests have been developed to replace total N concentration measurement. These tests enable farmers to get information about the current N status of the crop and to determine optimum N rate and timing directly in the field. Generally, nitrate sap tests are more sensitive for measuring the N status of a crop compared to total N tissue analysis. This is because the nitrate concentration reacts more rapidly to changes in the N supply than the total N concentration (Huett and White, 1992). Thus, the nitrate sap test is often used to decide the right timing of a fertilizer application. If calibrated correctly, it is also possible to determine the amount of N required. The interpretation of nitrate in plant sap is subject to many complications, including environmental factors that can cause rapid changes. The review of these is beyond the scope of this paper.

Wehrmann et al. (1982) developed a nitrate sap test to give a quantitative N recommendation for the second and third N dressing in cereals. The method is based on the determination of the nitrate concentration in the stem base of cereals using a mixture of diphenylamine and sulfuric acid reacting with nitrate in the plant sap to form a violet color complex. A color card was used to transfer the color intensity into four units. Based on extensive field calibration work, these units were translated into fertilizer recommendations (Wollring and Wehrmann, 1981). Some years later, the procedure was further improved and simplified by using a handheld reflectometer to quantify the color intensity on the test strips (Jemison and Fox, 1988). The development of portable electrodes for rapid direct determination of the nitrate concentration in the sap can be regarded as the latest development of methods based on plant sap nitrate measurements.

Especially in potato (*Solanum tuberosum* L.), and cotton (*Gossypium hirsutum* L.) and other vegetable crops, the petiole test is a widely accepted procedure to enable a quick assessment of the crop N status and to derive N fertilizer recommendations. Errebhi et al. (1998) revealed in a 4-year field study with irrigated potato that results from lab nitrate analysis and portable nitrate meters were linearly correlated during the whole growing season. They established nitrate sufficiency ranges for several potato growth stages including tuber initiation, tuber bulking and maturity.

Chlorophyll Content

The chlorophyll content of a plant is a good quantitative indicator for leaf N concentration. It has been demonstrated for several crops that leaf N and chlorophyll concentration are strongly correlated. Since N fertilizer recommendations based on leaf N concentrations have been established years ago for many crops, efforts have been made to use chlorophyll measurements to derive information on the N status of plants instead of lab N analyses (Wood et al., 1992).

Although leaf N concentration has the strongest effect on chlorophyll meter readings, other factors may also impact the measurement. Besides N, S deficiency shows the clearest influence on leaf chlorophyll concentration. Thus, to derive a reliable N fertilizer recommendation from chlorophyll measurement, it is important to ensure sufficient S supply. Under drought stress, plants suffer from water deficiency and chlorophyll concentration tends to increase (Ommen et al., 1999) without representing a better nutritional status. Crop varieties differ in their genetically determined chlorophyll content, which should be taken into account if chlorophyll measurements are used for nutrient management decisions. Also the growth stage of the crop, the age of the leaf to be measured and the point of measurement on the leaf itself (Neukirchen and Lammel, 2002) impact the chlorophyll reading, and thus have to be clearly defined. Taking into account these possible sources of variation, the use of chlorophyll measurement for N fertilizer management requires, like any crop analysis, "a strict sampling protocol."

Nitrogen fertilizer recommendations can either be based on a relative approach, e.g., on the ratio of chlorophyll readings in an over-fertilized reference plot compared to the rest of the field (e.g. Denuit et al., 2002), or as an absolute recommendation scheme, using variety-specific correction factors for the readings (Neukirchen and Lammel, 2002). For instance, in Germany more than 100 field trials with winter cereals have been conducted since 1992 in order to establish recommendations for N application at stem elongation (GS 30-32) and ear emergence (GS 37-51) based on chlorophyll measurements. In France, chlorophyll measurements are used in winter wheat to decide about the necessity and the optimum rate of a 3rd N application between stem elongation (GS 32) and late booting (GS 45). In field trials, the flexible N strategy based on in-season chlorophyll measurements was compared to the traditional N recommendation method named "Balance Sheet". The latter one is an almost static N recommendation method based on estimated yield and estimated N supply from the soil. The average yield, protein content and N fertilizer rate of 23 trials with both N recommendation strategies were tested (**Table 1**). In-season fertilizer management based on chlorophyll measurements increased yield by 0.26 t ha^{-1} and grain protein content by 0.4 % with just a minor increase in the applied N fertilizer rate by 7 kg N ha^{-1}.

Table 1. Yield and protein content of winter wheat at different N fertilizer strategies

Average of 23 trials, winter wheat, 1999	Average yield, t ha^{-1}	Average protein content, %	Average N rate, kg ha^{-1}
Balance sheet (static)	9.44	10.8	195
Chlorophyll meter (flexible)	9.70	11.2	202

These data show that a split application strategy is more suitable to address the nutrient requirements of a crop during the growing season. A shorter time span between fertilizer application and nutrient uptake reduces the risk of nutrient losses. It is not necessary to make an early decision about the right N fertilizer rate for the whole cropping season. A split N application strategy allows farmers to make several corrective decisions on the optimum N fertilizer rate during the growing season. Each time the decision is made, the N_{opt} can be adjusted to the actual growing conditions and the N status of the crop, which is a result of preceding and current weather conditions.

Plant Analysis for Variable Rate Application Within Fields

The introduction of yield monitoring systems has confirmed a large variation of crop yields within large fields. It is a logical question to ask how to address these yield differences with an appropriate approach to fertilizer management. If N fertilizer application rates could take into account the significant in-field variability of crop growth, it would reduce over- and under-fertilization, and as a consequence improve crop production and economic results, and reduce environmental impacts.

To address the in-field variability of N fertilizer demand, in principle the same methodology can be employed as that used to optimize N fertilizer application to entire fields. A flexible in-season adjustment of the N fertilizer is an effective way to address the variation in N fertilizer demand caused by varying climatic conditions. Therefore the concept of plant analysis has been adapted to variable N application within large fields. Variable rate N application requires information on N fertilizer demand with high spatial resolution. Compared to traditional methods of soil and tissue analysis, non-destructive methods of plant analysis are capable of delivering these data quickly, efficiently and at affordable costs (Lammel et al., 2001).

As already mentioned, leaf chlorophyll content is mainly determined by N availability. This leads to a strong relationship between optical reflection of a green crop canopy and the N content (Wollring et al., 1998). Most promising approaches to site-specific N application are based on optical measurements of crop canopy light reflectance (remote sensing). This method provides a rapid estimate of the crop N status with high spatial resolution.

Reflectance spectra of plant canopies are characterized by low light reflectance data in the visible domain (400-700 nm), due to absorption of the incoming radiation by leaf chlorophylls. In the near-infrared domain (700-1300 nm) the light reflectance is high because the absorption of leaf pigments and cell walls in this wavelength range is low and incoming radiation is either reflected or transmitted (Guyot, 1990). Vegetation indices, i.e., particular combinations of reflectance generally observed in two wavebands, are derived from the spectra and used to set up empirical relationships to detect variations of crop reflectance. Several spectral indices have been successfully related to crop biomass as well as to chlorophyll content and N uptake (Gilabert et al., 1996; Schmidhalter et al., 2003).

Commonly used vegetation indices are:

- Infrared-to-Red-Ratio (IR/R)
- Normalized Difference Vegetation Index (NDVI)
- Soil-Adjusted Vegetation Index (SAVI)
- Red-Edge-Inflection-Point (REIP)

Spectral radiometers and spectral cameras for optical remote sensing may be mounted on satellites, or on airborne or ground-based equipment. The suitability of satellite- and aircraft-mounted systems to support time-sensitive agricultural applications is sometimes limited, because of their dependence on suitable weather, the necessity to correct the data for atmospheric noise and the need for ground-truth measurements to determine quantitative causes for the qualitative variations detected (Bennedsen and Guiot, 2001).

Tractor-mounted systems are designed to be conveniently used on-farm. Similar to other agricultural machinery, they can be used regardless of cloud cover and allow real-time plant analysis when applying fertilizer. The first operational system for on-line variable rate N fertilizer application has been the N-Sensor™, commercially available for practical farming since 2000 (Lammel et al., 2001). The N-Sensor™ is a tractor-mounted multispectral real-time scanner, designed to determine the crop N status by measuring the reflectance properties of crop canopies, to calculate optimum N rates and to apply appropriate amounts of N fertilizer on-the-go (Link et al., 2002). The N-Sensor™ is a passive system measuring reflectance of ambient light (Reusch et al., 2002). Since 2005 the N-Sensor™ ALS (Active Light Source) is available which makes use of an artificial light source. These sensors enable real-time plant analysis and variable rate N application on-the-go irrespective of ambient light conditions. Also other concepts for tractor-mounted remote sensing make use of artificial light sources, emitting light at specific wavelengths and measuring either optical reflectance at the appropriate wavelengths or electromagnetic emission at wavelengths that indicate chlorophyll fluorescence induced by the illumination (Solie et al., 2002; Schächtl et al., 2003).

Field-scale trials, comparing variable with uniform N fertilizer application, confirm increased N use efficiency, higher yields, better and more uniform crop quality, more even ripening and drying as well as positive effects on combine harvest (Feiffer, 2004; Link et al., 2004). As an example, winter wheat was grown in a field in which a variable N fertilizer application was tested against a uniform N application (**Table 2**). Real-time plant analysis with the N-Sensor™ and variable N application increased yield by 0.3 t ha^{-1} and grain protein content by 0.7 % with just a minor increase in the applied N fertilizer rate by 7 kg N ha^{-1} (Maidl, 2005).

Table 2. Effect of variable N fertilizer application on yield and protein content of winter wheat (Maidl, 2005).

Winter wheat trial, 2001	Average N rate, kg ha^{-1}	Average yield, t ha^{-1}	Average protein content, %
Uniform N application	180	9.1	10.8
Variable N application (YARA N-Sensor)	187	9.4	11.5

Conclusions

During the last decades, strategies to decide on the economic optimum N fertilizer rate have been under continuous reconsideration in order to improve N use efficiency. An increased N use efficiency would reduce environmental impact and improve economic return to farmers, who need to achieve high yields without over- or under-supplying N. At first glance, application strategies with reduced numbers of N dressings are appealing to farmers, as application costs and labor can be saved. However, under farming conditions with high yields and high N fertilizer rates, a single N application strategy may not be the right choice for most arable crops, because the decision on the total amount of N to be applied has to be taken too early in the season. Furthermore, N recommendation schemes based mainly on yield expectation and average figures for estimated N supply from the soil have to be regarded as inferior, as reliable long-term weather forecasts are not available. As a consequence, all the relevant interactions between crop growth, N turnover processes in the soil, and losses from the soil-plant system are not known at the beginning of the growing season. Best management practices with regard to N fertilizer application need to consider the N status of the crop during the vegetative growth period to adjust the N application rate accordingly.

A multiple N application strategy allows farmers to decide on the required amount of N before each N application and to adopt the N application rate to the actual growing conditions. Especially for cereal crops, which might reach yield levels of more than 12 t ha^{-1} in several North-European regions, it is potentially beneficial to both crop yields and environmental impact to split the total N rate into 3 or more dressings. Methods of real-time plant analysis can support the decision of the grower on the timing and the application rate for a given field during the vegetation period. In-field methods like plant sap/petiole nitrate test, chlorophyll-meter measurements, and optical sensors provide such information at a very reasonable cost and time involved for growers.

Matching N supply with variations in crop N demand both spatially (i.e., between and within fields) and temporally (i.e. within and between seasons) will be an important component for maintaining optimum yields while improving the environmental performance of agricultural systems.

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Fifty Years of Predicting Wheat Nitrogen Requirements in the Pacific Northwest U.S.A.

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Abstract

During the early 1950s, synthetic N fertilizers were gaining widespread adoption in the dryland wheat growing region of the inland northwestern U.S.A. Agronomists quickly recognized water and N as the two principal determinants of grain yield and quality. Numerous N fertility trials across a range of climatic environments, soils and cropping systems provided the initial data for estimating wheat yield potentials based on predicted precipitation and root zone soil moisture. Nitrogen fertilizer recommendations were made from yield-based crop N requirements, estimates of soil N supplies and N use efficiencies. Leggett's N recommendation model, based on the regional variations in yield-water relationships and crop-soil N budgets, has stood the test of time for nearly 50 years, as confirmed by recent N fertility and agronomic trials. A recent data analysis of yield-water relationships reveals a remarkably similar slope but different x-intercept defining the lowest available water levels at which grain yields are obtainable. Spring soil moisture remains a reasonable yield predictor in this Mediterranean climate, but variable in-season rainfall is still a major source of error. Adjustments in the N recommendation model have been made to accommodate differences in wheat class, soil characteristics, management practices and climatic factors that affect water and N use efficiencies. However, our ability to extrapolate the regional model to site-specific applications has been restricted by the inability to predict landscape-scale processes that control water redistribution, water-yield, and yield-N use relationships that define the unit N requirement. The generalized 50% single season N uptake efficiency used in the model is not likely to occur consistently within a given field or from year to year and is currently under increased scrutiny in order to realize improvements in field-scale N management and N uptake efficiencies.

Introduction

Relationships among rainfall, soils, fertilizers and wheat yields have been integral to N recommendations since the early adoption of synthetic N fertilizer in the 1950s. This is no more apparent than in the progressive development of N recommendation models for dryland wheat production in the inland northwestern U.S.A. The purposes of this paper are to: (1) review how our evolving understanding of these interrelationships has provided the foundation of past and current N recommendation models; and (2) assess prospects for extending this regionally-based model into the future.

Historical Perspective

By the turn of the 20th century, the bunch-grass prairie and sheep-grazing rangeland of the Columbia Plateau in the inland northwestern U.S.A. was almost entirely converted to an important wheat-producing region (McGregor, 1982). The deep, loess-derived soils stored 60 to 75% of overwinter precipitation and supplied essential plant nutrients, thereby contributing to successful and profitable wheat farming on silt loam soils with limited rainfall. Soil organic matter oxidation was by far the major source of N for the wheat crop during the first half of the century. As soil organic matter was depleted, legumes such as peas (*Pisum sativa*), sweet clover (*Melilotus alba*) and alfalfa (*Medicago sativa*) were introduced to build soil and supply N. While the introduction of synthetic N fertilizers was recognized for its ability to increase straw production (Horner, 1950) and maintain organic matter, it was also noted that these materials were not as effective as manure, which was not widely available (Baker, 1950). Furthermore, adoption of legumes as green manures was limited by outbreaks of aphids and weevils, and legumes also competed for yield-limiting water (McGregor, 1982). Thus, water-N interactions were recognized as key production factors in the early history of wheat farming in this region.

As synthetic N fertilizer became widely available in the 1940s and ´50s, N fertilizer experiments on grower fields further defined the water-N interac-

Abbreviations: N, nitrogen; UNR, unit N requirements; NUE, N use efficiency.

tions that would lead towards weather-driven N recommendations for dryland wheat production. The predictable rainfall gradient in the Columbia Plateau that resides in the rain shadow of the Cascade mountains of Washington state (Douglas et al., 1990) provided a unique setting for examining water-N-wheat yield relationships. Nitrogen response trials conducted between 1944 and 1948 revealed that "variation in precipitation was the principal factor that caused differences in N fertilizer effectiveness" (Horner and Vandecaveye, 1950). This variation in precipitation was manifested in two ways: across precipitation zones of the region, and as a result of annual precipitation fluctuations. Reduced rates of N were prescribed in water deficit years to avoid "drought injury to the crop and a decrease in returns obtained from the fertilizer" (Horner and Vandecaveye, 1950; Hunter et al., 1957). It was also recognized at this time that adequate rainfall was required to transport N into the root zone within a 5 to 6 ft soil depth for efficient utilization (Smith, 1950; Horner and Vandecaveye, 1952; Jackson et al., 1952a). Adjustments in N fertilizer recommendations accounted for previous crop residues (legume vs. cereal), summer fallow, differential yield goals for spring wheat vs. winter wheat, and market class driven protein goals (Jackson et al., 1952a; 1952b).

Quantitative empirical relationships among water, N, and wheat yields were subsequently determined through extensive field experimentation. Jacquot (1953) was the first to publish temperature and precipitation data and relate it to wheat growth, yields, soil N mineralization, and N fertilizer responses for the region. He estimated that an inch of available soil water would produce 3.5 bu/A of winter wheat, which, in turn, would require 7 lb/A available N from residual soil nitrate or mineralized organic matter. This low water use efficiency was likely to be attributable to his experimentation with annual cropping in an area normally more suited to crop-fallow rotations. Nevertheless, the actual concept was first published for relating wheat yields to total N supply, both of which were recognized as being affected by water availability. Cropping sequence was also noted to affect not only N supply, but also soil water carryover. Impressively, the essential parameters for today's regionally-based N recommendation system (Koenig, 2005) were recognized within this first decade of synthetic fertilizer adoption. Jacquot later resigned from Washington State College to work for an emerging agrichemical company in the region, the MacGregor Company, where he continued to conduct fertilizer experiments and promote the use of fertilizer N (McGregor, 1982).

Leggett (1959) took these basic concepts and conducted an additional 90 replicated treatments in field trials between 1953 and 1957 on winter wheat and spring wheat across a similar range of eastern Washington precipitation zones. In these trials he collected soil samples for water and nitrate analyses around April 1st, figuring that typical N topdressing would need to occur during that period of the growing season, and this would be the appropriate time to soil test and adjust N availability according to yield potential. The relationship between available water and wheat yields defined by these trials has been used ever since to estimate regional wheat yield potentials (**Figure 1**). Winter wheat yield estimates (bu/A) were based on multiplying the available soil water (spring sampled soil water [4 to 6 feet deep] + rainfall during the remainder of the growing season in in./acre) by water use efficiency, 5.6 bu/A/in. Separate multipliers were also determined for the spring soil water (5.4 bu/A/in.) vs. the remaining growing season rainfall (7 bu/A/in.). In addition, a baseline 4 in. of water was a defined requirement for growing the vegetative tissue, as indicated by the x-intercept (**Figure 1**). Leggett further estimated the amount of available N required to produce an additional wheat bushel (currently referred to as the unit N requirement, UNR), which he determined to be in the range of 2.7 to 3 lb N/bu (**Figure 2**) for soft white winter wheat.

The concepts and quantitative relationships established by the aforementioned soil fertility pioneers were updated and organized twenty years later into a comprehensive N recommendation guideline by Engle et al. (1975). The worksheet in this fertilizer guide is an early forerunner of the typical N budget-based fertilizer calculation model used today. The basic components of the calculation are:

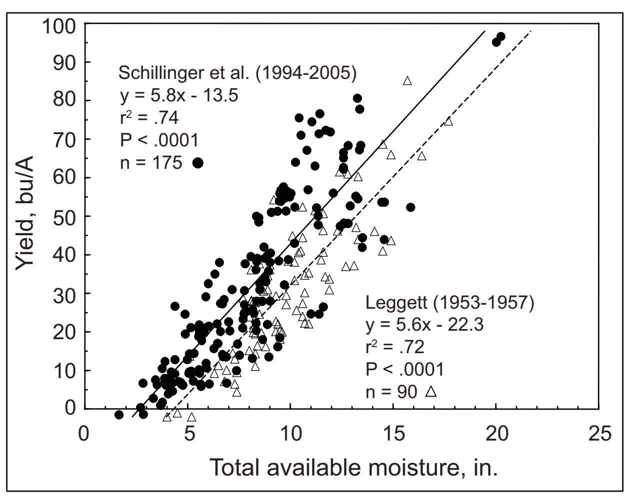

Figure 1. The relationship between available soil water and grain yield of dryland wheat in eastern Washington. Data were collected by G.E. Leggett (open triangles, dotted line) from 1953 to 1957 and by W.F. Schillinger et al. (filled circles, solid line) from 1993 to 2005.

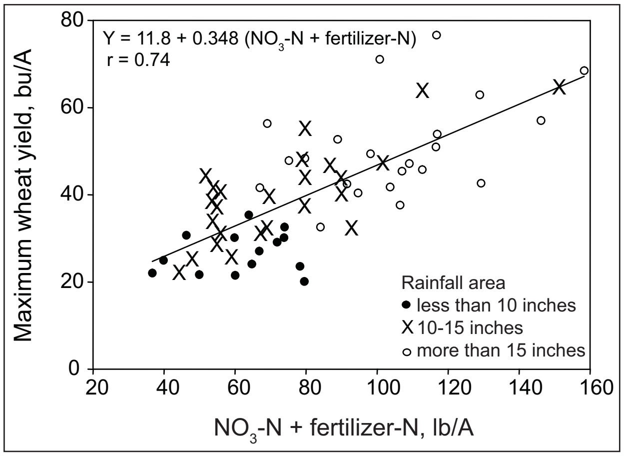

Figure 2. Wheat yield vs. available N in dryland areas of the Pacific Northwest (taken from Leggett, 1959). Available N is defined as soil NO_3-N in the top four feet + fertilizer-N.

(1) the yield potential as determined by available water and water use efficiency, defined as 7 bu/A/in. for soft white winter wheat and 6 bu/A/in. for hard red winter wheat; (2) the total N supply needs based on yield potential and the unit N requirement, defined as 2.7 lb N/bu for soft white winter wheat, and 3.0 lb N/bu for hard red winter wheat; and (3) the soil N inventory of contributions from soil nitrate and organic matter mineralization/immobilization balance as determined by degree of erosion, soil organic matter and previous crop history. Current nutrient management guidelines (Koenig, 2005) utilize the same N budgeting approach with more recognition that unit N requirements (UNR in lb/bu) will vary from 2.7±0.2 for soft white winter wheat and 3.0±0.2 for hard red winter wheat) with changes in N use efficiency (NUE; the inverse of UNR) as affected by N management practices and landscape variations (Fiez et al., 1994, 1995). These updated guidelines also encourage growers to conduct a post-harvest assessment of crop performance in relation to N supply to facilitate identification of site-specific UNRs and improve NUE. In addition, N requirements for protein enhancement in the hard wheat grown in the inland northwestern U.S. have also been based on NUE (Pan, 1987; Brown et al., 2005), which can be partitioned into soil and plant processes governing N uptake efficiency and N utilization efficiency (Huggins and Pan, 1993).

Available Water and Wheat Grain Yield

Great advances in agronomic management and wheat genetics have occurred since Leggett (1959) established the regional-based relationship between available water and dryland wheat yields. Semi-dwarf wheat germplasm that ignited the green revolution was developed at Washington State University by USDA-ARS scientist Orville Vogel and released to the world by Norman Borlaug. The fundamental shift from tall- to short-stemmed wheat increased carbon partitioning to the grain and immediately improved yield potentials and water use efficiency. Subsequently, wheat varieties were developed with improved resistance to fungal pathogens and insects which further increased their yield potential. Schillinger et al. (2006) recently re-evaluated the relationship between available water and grain yield with wheat yield data collected between 1993 and 2005 (**Figure 1**). Data from 174 replicated treatments showed that wheat requires 2.5 in. of available water just for vegetative growth. For every inch of available soil water above the 2.5-in. baseline, one inch of stored soil water provided 5.4 bu/A of grain and one inch of spring rainfall provided 6.9 bu/A. When the effectiveness of rainfall in the individual months of April, May, and June (i.e., growing season) was compared, they found that rain in May and June is much more beneficial than rain in April for both winter wheat and spring wheat grain yield. However, the contribution of May and June rain is 50% more effective in boosting winter wheat grain yield compared to spring wheat. These recent data on dryland wheat yield-water relationships revealed a remarkably similar slope but different x-intercept defining the lowest available water levels at which grain yields are obtainable compared to Leggett (1959).

Both Leggett (1959) and Schillinger et al. (2006) found that spring rainfall was more effective than stored soil water for increasing wheat yield. Predicted grain yield differences between the two models may likely be due to the ability of modern wheat varieties to begin grain production with less available water compared to wheat varieties in the 1950s, possibly reflecting the shift from tall- to short-stemmed wheat cultivars, and the lower water required to produce the smaller proportion of wheat straw in the modern semi-dwarf wheat. Additional factors that could account for the improvement include improved weed and disease control. If the upper boundaries of the water-yield data are used to define the yield potentials at given available water levels, water use efficiencies of 7 bu/A/in. of available water are obtained, which is the WUE used in the current N fertilizer guide for soft white winter wheat (Engle et al., 1975; Koenig, 2005). Similar correlations between available water and wheat grain yield have been used to estimate yield potential in dryland wheat systems (Mahler, 2004; Robertson et al., 2004).

Spring precipitation occurs after the final time window for effective N topdressing, and represents the major uncertainty in yield predictions that affect estimates of total N supply requirements. On average there is 2.5 in. of precipitation during April, May and June in the region, which translates to 17.2 bu requiring 46 lb available N. It appears that rainfall during May and June has the largest impact on yield potential on a unit basis Schillinger et al. (2006). Since this rainfall is difficult to predict at the time when topdressing needs to be done, there will always be a degree of uncertainty around recommendations for optimum rates of N application. Accurate weather forecasts will improve the recommendations for N topdressing applications..

A 60-year summary of spring precipitation demonstrates the average regional variation across an eastern Washington transect and the range of annual variation within each site (**Figure 3**). Long-term weather data over 1944 through 2003 indicates that spring precipitation (April, May and June) averages 2.5 in. higher in Pullman, Washington, compared to Lind, Washington, but that within a location there is year-to-year variation with a standard deviation of 1.2 to 1.5 in., and maximum recorded spring precipitations (excluding extreme outliers in 1948) were roughly 170% of the average. These historical weather records can be used to predict yield potential and N supply needs according to previously described relationships. Depending on grower optimism, the cost of N fertilizer, and assessment of risk to benefits, the grower may want to target yields based on average rainfall, one standard deviation above average or higher.

Regional Variation in NUE and UNR

Water-N interactions produce predictable regional and annual variation in NUE and UNR that have been recognized for over 50 years. Horner and Vandecaveye (1950) noted higher NUE in years with higher than average precipitation compared to drought years. Leggett (1959) observed average NUE of 0.348 bu/lb N supply over a regional range in precipitation from 4 to 18 in. available moisture (**Figure 2**). However, closer examination of his results reveals that the low rainfall sites mostly fell below the regression, suggesting lower NUEs (and therefore higher UNRs) are apparent in the low rainfall zone than predicted for the entire region. Lack of sufficient spring rainfall results in rapid drying of the surface soil, decreased surface soil root activity which results in unused ("stranded") shallow topdressed N (Pan et al., 2001). Mahler (2004) also points out that lower NUEs and higher UNRs are apparent at greater than 24 in. annual precipitation in northern Idaho, where nitrate leaching lowers NUE and increases UNR for soft white winter wheat from 2.7 intermediate rainfall zone to 2.9 lb N/bu in the high rainfall zone, unless improved N management practices such as split N applications are utilized to attain lower UNRs. Any weather-driven fertility models should account for these shifts in NUE that occur across rainfall gradients as in the Columbia Plateau (**Figure 4**). Ideally, adjustments in N management practices can be recommended to overcome these inefficiencies.

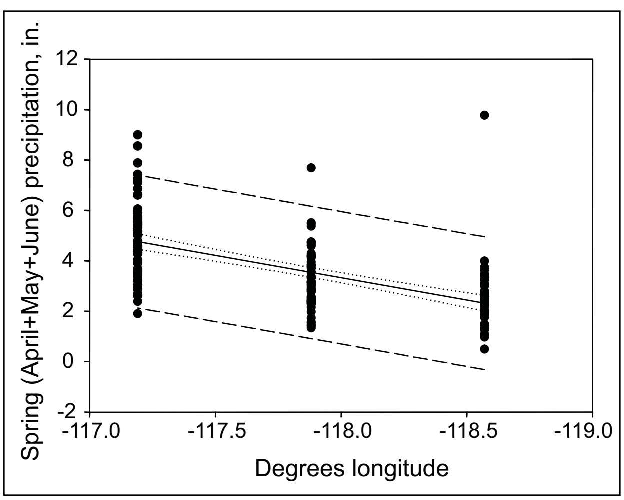

Figure 3. Spring precipitation (April+May+June) over 1944 to 2003 for three locations (Pullman, Lacrosse and Lind, WA) across an eastern Washington transect. Dotted lines represent the 95% confidence interval defining the mean values, and the dashed lines represent the 95% prediction interval.

Adaptability of Regional N Models to Site-Specific N Management

Since N fertility models are generally derived from regional databases, it can be questioned whether these models are adaptable to modeling site-specific N needs on a landscape scale (Pan et al., 1997). Applicability of the current model requires that meaningful differences in water availability occur across the landscape that, in turn, can be used to predict site-specific yield potentials and formulate corresponding N recommendations. In much of the dryland cropping region of the inland Pacific Northwest, landscape and soil attributes contribute to complex spatial variations in available

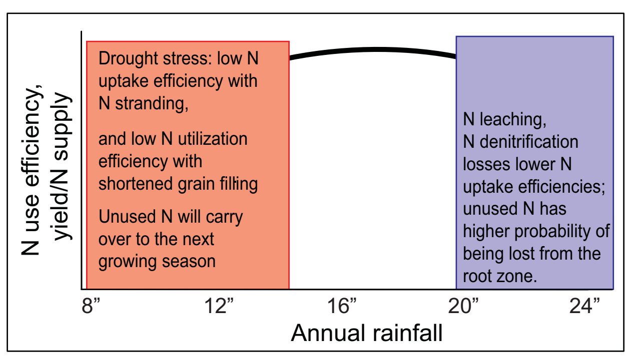

Figure 4. Conceptual relationship between N use efficiency and rainfall zones.

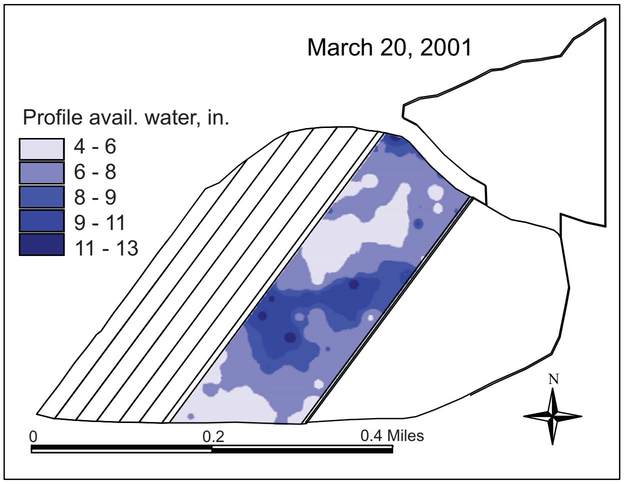

Figure 5. Crop available water in the soil profile (0 to 5 feet) based on 124 geo-referenced grid points sampled on 20 March 2001. Samples are from a 30-acre area on the Washington State University Cook Agronomy Farm near Pullman, WA, just prior to planting spring wheat.

water, organic matter and rooting depth (Busacca and Montgomery, 1992). For example, available soil water ranged from 2.4 to 16.4 in. and averaged 7.5 in. in 5-foot soil profile samples collected across a 30-acre grid (130 geo-referenced points) of the Cook Agronomy Farm near Pullman in late March, 2001 (**Figure 5**). This uneven distribution in stored soil water across the landscape arises from several different processes including: (1) uneven snow accumulation due to over-winter drifting and subsequent melting; (2) preferential pathways of water flow both vertically and horizontally that direct water toward lower landscape positions; (3) soil layers that restrict vertical movement of water and promote subsurface lateral flow to down-slope landscape positions; (4) surface runoff often in conjunction with soil freezing near the surface that impedes water infiltration; and (5) differences in water evaporation due to slope and aspect characteristics. These water redistribution processes likely result in differences not only in the amount of water that is available to the crop, but also in the timing of water availability as redistribution across the landscape occurs throughout the year. Presuming that the field distribution of soil water represented in **Figure 5** is the majority of available moisture for each site-specific location and that the subsequent precipitation would be more uniformly distributed as spring and summer rainfall, then a correlation between stored available water and wheat yield would be anticipated. The poor correlation between available water and wheat yield (**Figure 6**) suggests that water redistribution and timing of availability during the spring and summer months may also be important yield determinants or that other factors are limiting yield across the

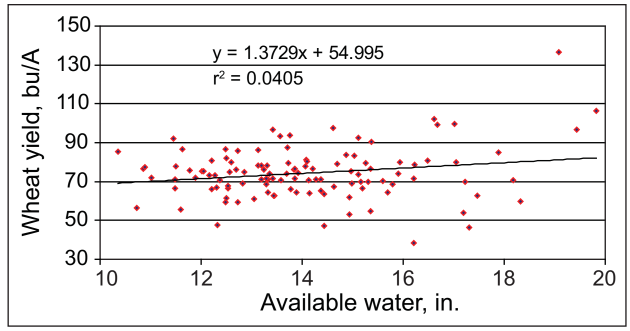

Figure 6. Grain yield of wheat in the 2001 season at the Cook Agronomy Farm (Pullman, Washington) plotted against estimated available water (available soil water on 20 March 2001, to a depth of 5 feet, plus subsequent growing season precipitation).

landscape. These factors will need to be elucidated if the traditional relationships between available water and grain yield are to be applied to a landscape scale in predicting N needs. Landscape level hydrology also influences N movement, loss and availability, thereby contributing to variations in landscape level NUE and UNR that would further complicate site-specific recommendations. Future strategies for site-specific N management are likely to integrate precision agricultural technologies to enable: (1) site-specific diagnosis of factors influencing grain yield and quality; (2) site-specific N applications at key times during the year; and (3) site-specific evaluation of N management strategies including measures of NUE. These strategies will need to be integrated with weather-based crop modeling to generate meaningful prediction models on a field scale.

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A Water Use Based System for Deriving Nitrogen Recommendations in the Canadian Prairies

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Abstract

The maximum genetic potential yield of any given crop under any given set of climatic conditions and with no nutritional restrictions is determined by solar energy. The main modifier to this potential in the Canadian prairies is water use. A series of experiments on summer-fallow land under weed-free conditions were utilized to derive water use efficiency of crops by agro-ecological zone. A system to predict target yield and subsequently derive N recommendations was thus developed and was originally put in place in 1991. Target yields are derived based on available water during the growing season and water use efficiency by a crop. Available water during the growing season in the system is defined as the sum of soil water in a given year as of May 1 and precipitation in May, June, and July. The system is equipped with default soil water and precipitation data (30-year averages organized as 25, 50, and 75% probabilities) and a threshold value of water that is required before a base yield for a crop is established. Actual data can be entered at any given time to allow for refinement of target yield predictions. Water use efficiency for each crop is defined as the seed yield per unit of water and is a function of precipitation. Once a target yield is established, the N recommendation is derived based on a balance between major inputs—fertilizer, fixation (where applicable), plant residues, and soil N mineralization—and major outputs—crop uptake, leaching loss, denitrification loss and immobilization. Mathematical functions directly relating an input or output to water use have been developed for mineralization, leaching, denitrification and immobilization. The original system was "truthed" using a series of independent experiments that included both soil water and precipitation data. The system is updated constantly as relevant research is being generated.

Introduction

The importance of water use in the semi-arid environment of the western Canadian prairies has been contemplated as well as investigated by many (Staple and Lehane, 1954a,b; deJong and Rennie, 1969; Campbell et al., 1977; Hoyt and Rice, 1977; Steppuhn et al., 1984; Henry et al., 1986; Steppuhn and Zentner, 1986; Campbell et al. 1987). A relationship between the grain yield of Canada west red spring (CWRS) and durum wheat for the period of 1983 to 1986, and the amount of water used by the crop was established by deJong and Halstead (1986) (**Figure 1**). The authors utilized data from over 130 field-scale experiments that were part of the Innovative Acres program in the early 1980's in the province of Saskatchewan and contrasted the results to earlier studies, noting that yield potential

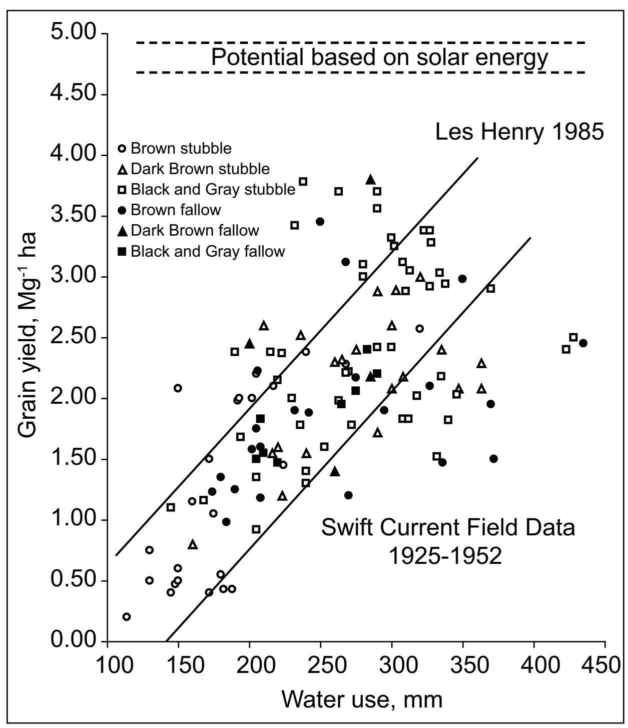

Figure 1. Relationship between grain yield of CWRS and durum wheat and water use in Saskatchewan (reproduced from deJong and Halstead 1986).

Abbreviations: AGW, available growth water; CI, Climate Index; CWRS wheat, Canada west red spring wheat; FNUE, fertilizer N use efficiency; GSCI, Growing Season Climatic Index; MNUE, mineralizable N use efficiency; N, nitrogen; NFRZ, Nitrogen Fertilizer Recommendation Zone; SCZ, soil climatic zone; SNUE, soil N use efficiency; SZ, Soil Zone; WUE, water use efficiency.

at the time exceeded that obtained in those earlier studies. The authors concluded that a minimum of 125 mm of water was required overall before any crop was produced, and that above that minimum every 10 mm increment contributed to an average 0.2 Mg ha^{-1} grain yield increase up to 300 mm, beyond which yields dropped off. The authors also concluded that the cultivars of the time could potentially produce 4.5 Mg grain yield ha^{-1}. In contrast, Henry et al. (1986) reviewed a number of studies in western Canada and concluded that the minimum water use was 50 mm for CWRS and durum wheat and each additional 10 mm should produce 0.10 Mg ha^{-1} of grain; the corresponding values for soft white wheat were 75 mm and 0.15 Mg ha^{-1} of grain. Further, Henry (1989) conducted a similar review of western Canadian data for barley and concluded that water use efficiency values for barley ranged from 0.01 to 0.016 Mg grain ha^{-1} mm^{-1}. The differences may reflect the higher evaporative demands in the drier parts of Saskatchewan compared to other regions in western Canada.

Utilization of water use and water use efficiency to derive target yields in order to be used in conjunction with soil test N to derive N recommendations was first proposed in western Canada by Henry (1990). Although the existing systems of the time that had primarily been developed in the late sixties and early seventies were making provision for recommendations under "wet", "normal", and "dry" moisture conditions, the distinction between those conditions was only qualitative. Key to the development of the new system was the derivation of a map of seven Soil Climatic Zones (SCZ) of Southern Saskatchewan by Henry and Harder (1991). A SCZ is an agroecological zone, which is identified based on a climate index (CI) derived from annual precipitation and temperature. The first attempt of establishing a relationship between climate and crop production in western Canada and specifically in the province of Saskatchewan was made by Mitchell et al. (1944). They developed a climate index (CI) based on mean annual precipitation and mean annual temperature as follows:

$$\mathrm{CI} = 1895 \times \frac{\text{Precipitation}}{\text{Temperature} \times (1.38 \times \text{Temperature} - 27.4)}$$

The mean annual precipitation was expressed in inches and the mean annual temperature in °F. The CI is meant to provide a relative value of the sufficiency of water supply for crop production, with precipitation being an indicator of supply and temperature of demand. It resulted in numerical values ranging from 20 to 130. The Soil Climatic Zones (SCZ) developed by Henry and Harder (1991) were defined by dividing the CI into classes, e.g. Moist Dark Brown soils were defined as those for which CI ranged from 36 to 41.4. Meyers and Karamanos (1997) later expanded the concept to the derivation of 30 SCZ for the whole of Canadian Prairies.

One of the important assets of this index was that weather data were available from a sufficient number of weather stations on the Prairies – more than 300 – so that geographical boundaries of the classes could be defined with confidence. The major disadvantage of the CI was that it utilized mean annual climate characteristics. Thus, it did not necessarily represent growing season conditions; rather, it reflected long-term climatic conditions. Growing season for cereals and oilseeds is generally recognized as only slightly exceeding three months (May, June, and July) (Shaykewich et al., 2000).

Crop yield potentials and, hence, fertilizer recommendations are determined by the balance between crop water demand and soil water at seeding time and growing season precipitation. Crop water demand depends upon a number of factors, e.g., solar radiation, temperature, relative humidity, wind, as well as the degree to which the crop covers the ground. The only one of these variables for which data is available for a significant number of weather stations on the Prairies is temperature. Shaykewich et al. (2000) assumed that crop water demand was proportional to the average temperature during the months of May, June and July and derived a Growing Season Climatic Index (GSCI) that is designed to be an indicator of the degree to which crop water demand is met. It was calculated by dividing the estimate of supply (mm) by the estimate of demand, as follows:

$$\mathrm{GSCI} = \frac{\text{May precipitation} + 2 \times \text{June precipitation} + 4 \times \text{July precipitation}}{\text{Average May, June, July temperature (°C)}}$$

The index was calculated for 373 weather stations in the Prairies. Numerical values of the index

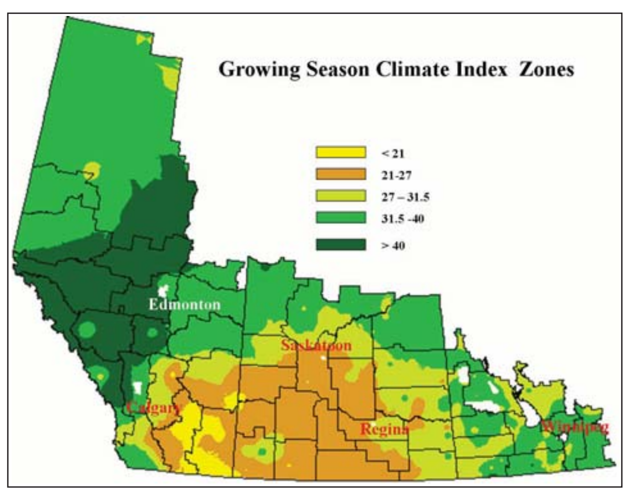

Figure 2. Growing season climatic index (GSCI) zones of the western Canadian prairies.

Table 1. Major soil zones in western Canada.

Soil Zone
Brown
Dark Brown
Thin Black
Thick Black
Gray Black
Gray
Dark Gray

Table 2. Nitrogen Fertilizer Recommendation Zones (NFRZ) of the western Canadian prairies.

N Zone	N Zone Description†	Sub-group‡	GSCI Index§
1	Palliser Dry Plain	—	< 21
2	Palliser Plain	—	21 – 27
3	Parkland	—	27.1 – 31.5
4	Moist Parkland	Transitional Wooded	31.6 – 39.9
5	Humid Parkland		27.1–31.5
6	Alberta Highlands	West	> 40
7	Dry Peace Country		< 33
8	Peace Country		33.1 – 40
9	Moist Peace Country		> 40

† Originally proposed by Shaykewich et al. (2000).
‡ Added subsequently.
§ Growing season climatic index.

ranged from <20 to >40 (**Figure 2**).

Derivation of GSCI led to the development of Nitrogen Fertilizer Recommendation Zones (NFRZ) as a substitute for the SCZ (Karamanos et al. 2001). These zones are a function of Soil Zones (SZ), which are groups of soils with similar genetic characteristics (**Table 1**) and a GSCI that reflects growing season environmental conditions. Nine main NFRZ plus three subgroups within two of the main ones are recognized in the prairies (**Table 2**).

Development of the System

Derivation of Crop Grain Yield Equations

Henry (1990) originally developed yield equations for CWRS wheat, barley, oats, canola and flax; the system was adopted in 1991 by the Saskatchewan Soil Testing Laboratory (now ALS Laboratories). A second version of this system adopted in 1996 by Western Cooperative Fertilizers Limited resides in the AgroManager software and in its present form contains 43 field crops and 46 forage seed and hay crops. The system operates in imperial units, but conversion to SI units has been made for this manuscript. The grain yield equations are based on long-term cereal variety trials that were carried out on fallowed soils under generally weed-free conditions. These data provided a basis to compare grain yields of one crop to those of another and allow filling voids for areas where the database for a crop was weak. For example, data from trials carried out over a 20-year period

Table 3. Derived water use efficiency (WUE) values for barley on the Canadian Prairies (Henry 1989).

Zone as mapped by Dumanski and Kirkwood (1988)	Approximate Soil Zone	Annual rainfall	Seasonal potential evapotranspiration	Ratio of P.E.T.‡ to Dark Brown Soil Zone	Actual WUE Source	Derived WUE
		- - - mm - - -			- - - kg ha^{-1} mm^{-1} - - -	
H7	Dry Brown†	220	650	1.18		10
H6	Brown	225	600	1.09	Bole and Pittman (1978)	11
H5	Dark Brown	250	550	1.00	Henry (unpublished data)	12
H4	Thin Black	275	500	0.91		13
H3	Thick and Gray Black	300	450	0.82		15
H2	Gray	325	400	0.73	Hoyt and Rice (1977)	16

†Subsequently introduced by Henry (1990).
‡ P.E.T. = potential evapotranspiration.

(1950-1969) established that the barley:wheat yield ratio varied between 1.03 and 1.35 with an average of 1.21, thus demonstrating that a factor of 1.2 is suitable when barley grain yields are compared to those of wheat (Henry, 1990). Hence data derived for water use efficiency values for barley (**Table 3**) were used to derive those of wheat (**Table 4**). The yield equations are of the type:

$$\text{Yield} = (\text{AGW} - \text{TH}) \times \text{WUE}$$

where, AGW = Available growth water that includes soil water plus precipitation during May, June and July (in inches), TH = threshold value to establish yield of a crop (in inches), and, WUE = water use efficiency (in inches per bushel/A). Soil water is determined as the total of soil available water (defaulted to May 1). Default values for soil water were established in the original system based on SCZ, soil texture and previous crop/practice (fallow, stubble, and established forage). Actual available soil water values from measurements taken in the spring can substitute for default values. Available soil water can either be entered as inches of actual water or as inches of depth of moist soil determined with a Brown soil moisture probe (Brown, 1959; Brown and Carlson, 1990) and then converted by the system into available soil water. The system utilizes default May, June, and July precipitation based on 75, 50, and 25% probability of precipitation in a given SCZ over a period of 30 years (1968-1998)[1] or can be individualized based on farm records.

Table 4. Development of water use efficiency (WUE) coefficients for barley and wheat (Henry 1989).

Soil Zone	WUE barley		WUE wheat
	- - - - - - kg ha^{-1} mm^{-1} - - - - - -		
Dry Brown	10	÷ 1.2 = 8.3	8
Brown	11	÷ 1.2 = 9.17	9
Dark Brown	12	÷ 1.2 = 10	10
Thin Black	13	÷ 1.2 = 10.83	11
Thick/Gray Black	15	÷ 1.2 = 12.5	12
Gray	16	÷ 1.2 = 13.3	13

Note that the term "probability of precipitation" is used differently here than in common daily weather forecasts. In this paper, it refers to the probability of precipitation exceeding a specified amount over a given time period, and thus decreases as the amount increases. In weather forecasting, it refers to the probability of any precipitation event occurring on a given day, which is a completely different concept.

[1] Environment Canada http://www.climate.weatheroffice.ec.gc.ca/climate_normals/index_e.html

Threshold values in the current system are based on NFRZ and vary from 31.8 to 63.5 mm for grain and forage seed crops and 12.7 to 19.1 mm for hay and forage crops based on evapotraspiration averages for each NFRZ (**Table 5**). This distinction was introduced to accommodate differences in the units used to express yields, i.e., bushels/acre for grain crops and hundred weights (cwt) for hay and forage crops.

Table 5. General threshold values (TH) for grain and forage seed crops and forages.

NFRZ	Grain crops	Hay and forages
	- - - - - - - - mm - - - - - - - -	
Palliser Dry Plain	63.5	16.5
Palliser Plain	57.2	17.8
Parkland	44.5	16.5
Moist Parkland	38.1	15.2
Moist Parkland Transition	38.1	15.2
Moist Parkland Wooded	38.1	15.2
Humid Parkland	31.8	12.7
Alberta Highlands	31.8	12.7
Alberta Highlands West	38.1	15.2
Dry Peace Country	38.1	16.5
Peace Country	31.8	12.7
Moist Peace Country	31.8	12.7

Water use efficiency of crops in the original system (Henry 1990) was unique for each crop and SCZ. Since the introduction of NFRZ, WUE values became a function of probability of precipitation (Karamanos et al. 2001) with boundary values set at 25 and 75% probability of precipitation. Water use efficiency values for CWRS wheat, barley and canola are presented in **Table 6**. Recently, Karamanos and Selles (2006) compared WUE values obtained in a series of experiments that assessed responses to N fertilization by crops grown on fallow fields and found those in the Karamanos et al. (2001) version to be significantly better than the ones originally proposed by Henry (1990) (**Table 7**). The authors also found a closer relationship between observed and predicted WUE values for wheat when May, June and July precipitation was used, whereas for canola a closer relationship was obtained when May, June, July and August precipitation was used. This point merits further investigation.

Table 6. Water use efficiency values for CWRS wheat, barley and canola.

	CWRS wheat			Barley			Canola		
	Probability of precipitation, %			Probability of precipitation, %			Probability of precipitation, %		
	75	50	25	75	50	25	75	50	25
	kg ha^{-1} mm^{-1}								
Palliser Dry Plain	3.2	3.7	4.3	4.3	4.5	4.7	1.8	2.0	2.2
Palliser Plain	3.7	4.3	4.8	4.7	5.1	5.6	2.0	2.2	2.5
Parkland	4.0	4.6	5.1	5.4	5.8	6.2	2.5	2.7	2.9
Moist Parkland	4.3	4.8	5.4	5.8	6.2	6.6	2.9	3.1	3.3
Moist Parkland Transition	4.6	5.1	5.1	6.0	6.4	6.9	3.1	3.3	3.3
Moist Parkland Wooded	4.6	5.1	5.1	5.8	6.2	6.6	2.9	3.1	3.1
Humid Parkland	4.0	4.6	5.1	5.1	5.6	6.0	2.6	2.9	3.1
Alberta Highlands	4.3	4.8	5.4	5.6	6.0	6.4	2.9	3.1	3.3
Alberta Highlands West	4.3	4.8	5.4	5.6	6.0	6.6	2.9	3.1	3.3
Dry Peace Country	4.3	4.8	5.4	5.8	6.2	6.6	2.9	3.1	3.3
Peace Country	4.3	4.8	5.4	5.8	6.2	6.6	2.9	3.1	3.3
Moist Peace Country	4.3	4.8	5.4	5.8	6.2	6.6	2.9	3.1	3.3

Combination of general TH values (**Table 5**) and WUE (**Table 6**) with default soil water and data for 25, 50 and 75% probability of precipitation generated the examples of target grain yields for dryland CWRS wheat in **Table 8**.

Intervention in Generating Target Yield as a Result of Changing Water Conditions

One of the key components in the system is the ability to influence N fertilization decisions by estimating soil available water with a very simple tool (Brown probe) and thus the ability to modify the default grain yield targets. Henry (2003) best described this as "water in the ground is like money in the bank." This is unlike growing season precipitation, which can only be considered when fertilization decisions are made based on probability of precipitation that has been derived from long-term precipitation records. Although real-time modifications to the precipitation forecast can be made during the growing season, those would be of value only when fertilizer application is split (a rare practice in western Canadian prairies) or when rainfall earlier on in the growing season exceeds the long-term average, thus creating an opportunity for application of additional N through topdressing. The value of being able to estimate spring soil available water and consequently assess the probability of obtaining a target yield is illustrated in **Figure 3**. The majority of farmers on the Canadian prairies choose to fertilize based on long-term (50%) precipitation, hence, knowledge of soil water can contribute to almost 1 Mg ha^{-1} opportunity between drier and wetter conditions (**Figure 3**) under average precipitation.

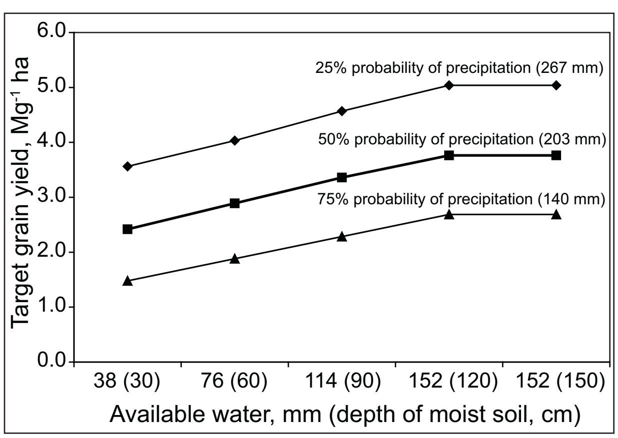

Figure 3. Impact of changing depth of moist soil/soil available water on the target grain yields of CWRS wheat to be grown on a loam soil in the Thick Black Soil Zone, Moist Black Soil Climatic Zone and Moist Parkland Nitrogen Fertilizer Recommendation Zone combination under default rainfall conditions.

Other Parameters Influenced by Changes in Water Regime

In addition to target yields, a number of other parameters, such as mineralization, immobilization, leaching, denitrification as well as soil residual N, mineralizable N, fertilizer N use efficiency, and N content in plants vary with water regime.

Mineralization: Mineralization of N is also a function of environmental conditions (water) and can be effectively reduced to 0 under drought conditions or become as much as 1/3 higher under favorable (moist) conditions compared to "normal" conditions. Mineralization values in the original version of the system (Henry 1991) were fixed for SCZ at 0.6 to 0.8, 0.7 to 1.0, and 0.8 to 1.2 for the

Table 7. Relationship between measured and theoretical water use efficiency (WUE) values as a function of soil available water plus precipitation (AGW) (Karamanos and Selles, 2006).

Period	Equation	R^2
	Wheat	
May-July	$WUE_{1991}{}^{\dagger} = 3.06 + 0.2707AGW - 0.0205AGW2$	0.20
	$WUE_{2001} = 3.46 - 0.208AGW + 0.0608\ AGW2$	0.46
May-August	$WUE_{1991} = 3.32 + 0.169AGW - 0.0068AGW2$	0.26
	$WUE_{2001} = 4.08 - 0.4486AGW + 0.1001AGW2$	0.27
	Canola	
May-July	$WUE_{1991} = 2.88 + 0.020AGW - 0.0002AGW2$	0.09
	$WUE_{2001} = 2.64 + 0.0276AGW + 0.0073AGW2$	0.60
May-August	$WUE_{1991} = 3.01 - 0.0821AGW + 0.0176AGW2$	0.30
	$WUE_{2001} = 2.29 + 0.296AGW - 0.0229AGW2$	0.78

†1990 and 2001 refer to the original (Henry, 1990) and the subsequent modification with the introduction of NFRZ (Karamanos et al., 2001).

75%, 50%, and 25% probabilities of precipitation, respectively, and there was a linear slide between these three boundaries. Karamanos and Cannon (2002) utilized a limited amount of data from the work of Myers et al. (1982) and Campbell et al. (1984) to derive a relationship between the mineralization rate constant (k35C) and organic carbon content as follows:

$$k_{35C} = 0.0722 + 0.03083 \times \%\text{Organic Carbon } (r=0.803^{***})$$

with maximum k35C value attained at 2.6% organic carbon.

The values for k_{35C} thus derived were used to estimate potential mineralizable N under "normal" conditions from the equation:

$$N_t = N_o\,[1 - e^{-kt}] \times F$$

where N_o was considered equal to 2.6% of organic N (Campbell et al. 1994; Zhang et al., 2002) for t=16 to 20 weeks and F=0.2 to 0.6 (**Table 9**). Mineralizable N is adjusted based on probability of precipitation as follows:

$N_a = N_t \times F_a$, where N_a is adjusted mineralization, F_a adjustment factor that slides between 0.56 and 1.2 for 75% and 25% probability of precipitation, respectively and is set at 1.33 for irrigated soils.

Mineralizable N use efficiency (MNUE) is assumed to be 100% for organic carbon levels less than 2.3% and 50% above organic carbon levels greater than 8.7%; it slides between these two boundary values based on the following equation that was derived from limited data:

$$MNUE = [139 - ((18.824 \times \text{Organic Carbon}) - (0.982 \times \text{Organic Carbon}^2))] / 100$$

Mineralized N (N_m) is then calculated from:

$$N_m = N_a \times MNUE$$

Estimated mineralized N values for 50% probability of precipitation over the most common organic carbon range in each of the NFRZ (excluding Peace River Country) are shown in **Figure 4**. An example of estimating N mineralization is offered below:

1. As the system accepts organic matter levels only, organic matter is converted to organic carbon by dividing by 1.724 (e.g., organic matter of 1.8 % = organic carbon of 1.044 %).

Table 8. Examples of target grain yield derived using the default parameters for a number of Soil Zone (SZ), Soil Climatic Zone (SCZ) and Nitrogen Fertilizer Recommendation Zones (NFRZ) combinations.

			Probability of precipitation, %					
			25		50		75	
Soil Zone	SCZ	NFRZ	Precipitation, mm	Yield, $Mg\ ha^{-1}$	Precipitation, mm	Yield, $Mg\ ha^{-1}$	Precipitation, mm	Yield, $Mg\ ha^{-1}$
Brown	Brown	Palliser Dry Plains	201	1.88	145	1.08	86.4	0.47
Dark Brown	Dark Brown	Palliser Plains	221	2.49	163	1.61	99.1	0.81
Thin Black	Black	Parkland	241	3.36	191	2.42	122	1.48
Thick Black	Moist Black	Moist Parkland	267	4.03	203	2.89	140	1.88
Thick Black	Moist Black	Humid Parkland	267	4.8	203	3.8	140	2.6
Gray Black	Gray	Moist Parkland	254	3.90	196	2.75	119	1.68
Gray	Gray	Moist Parkland	254	3.90	196	2.75	119	1.68
Dark Gray	Dark Gray	Alberta Highlands	221	3.83	165	2.96	96.5	1.88

Table 9. Values for F factor in the N mineralization equation.

NFRZ	F factor
Palliser Dry Plain	0.3
Palliser Plain	0.3
Parkland	0.4
Moist Parkland	0.4
Moist Parkland Transition	0.5
Moist Parkland Wooded	0.5
Humid Parkland	0.5
Alberta Highlands	0.4
Alberta Highlands West	0.6
Dry Peace Country	0.5
Peace Country	0.5
Moist Peace Country	0.5

2. Organic N is estimated from the C:N ratio that is assumed at 10:1 (e.g., organic N = 0.1044 % or 1044 mg kg^{-1}).
3. The total mineralizable N pool, No, is estimated at 2.6% of organic N (e.g., No = 27 mg kg^{-1} or approximately 60 kg N ha^{-1}).
4. The mineralization constant that is needed to calculate how much N can be potentially mineralized is estimated from the equation:
5. k_{35C} = 0.0722 + 0.03083 x %Organic Carbon
   (e.g., k_{35C} is estimated at 0.0722 + 0.30838 x 1.044 = 0.10439).
6. Mineralized N under "normal" conditions is estimated from the equation:
7. $N_t = N_o\,[1 - e^{-kt}] \times F$ for t = 20 weeks and F = 0.4
   $N_t = 60 \times (1-e^{-0.10439*20}) \times 0.4 = 21$ kg N ha^{-1}.

The impact of precipitation on mineralized N for the most common organic carbon ranges in the Alberta Highlands, Humid Parkland and Palliser Plains NFRZ that represent high, medium and low mineralized N conditions on the Canadian prairies is illustrated in **Figure 5**. The impact of the water regime on mineralization at this time is a function of precipitation only; i.e., it is independent of starting soil water.

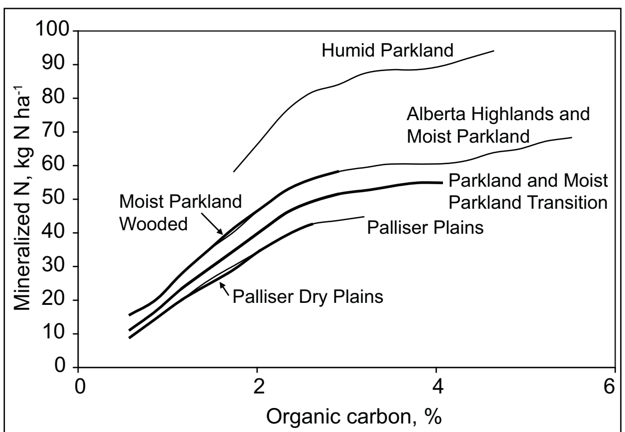

Figure 4. Estimated mineralized N values for 50% probability of precipitation over the most common organic carbon range in each of the NFRZ of southern Canadian prairies.

Immobilization: Immobilization in the original system proposed by Henry (1991) was based on typical straw yields and total soil N values (**Table 10**). Henry (1991) made a simple assumption that since straw contains on average 0.5% N and the N requirement for immobilization is 1.5%, the difference (1.5 – 0.5) of 1% of the straw weight represented the amount of N in the soil that will be immobilized. Straw loadings in the updated version of the system are a function of previous practice, e.g., conventional fallow, chemical fallow, stubble spread, baled or burnt (non-continuous cropping), stubble spread, baled or burnt (continuous cropping) and forage. Immobilized N is now a function of the probability of precipitation, sliding between 1% and 0.3% of straw loading, the higher value used for average and above average and the lower value for dry conditions; for drought immobilization is set at 0.

Grain protein content: The system allows sliding protein content between dry and wet conditions based on long-term protein trends in western Canada[2]. Boundary values were established for average (50%) as well as 25 and 75% probability of precipitation. Alternatively, there is a provision for "locking in" a target protein value, which then leads to adjusting the N recommendation to fit the conditions that correspond to a selected crop and protein target.

Deriving N Recommendations

Nitrogen recommendations are generated as a result of drawing a N balance by accounting for inputs and outputs in the soil-plant system. Therefore, understanding how the system works requires

[2]Canadian Wheat Board, http://www.cwb.ca/en/

Table 10. Typical straw yields and total soil N values (Henry 1990).

Soil Climatic Zone (SCZ)	Typical straw yields	Total soil N
	- - - - - - - - - - Mg ha^{-1}	- - - - - - - - - -
Dry Brown	2.24	2.24
Brown	2.80	2.80
Dark Brown	3.36	3.36
Moist Dark Brown	3.58	3.92
Black	3.92	4.48
Moist Black	3.92	6.72
Gray	3.92	2.24

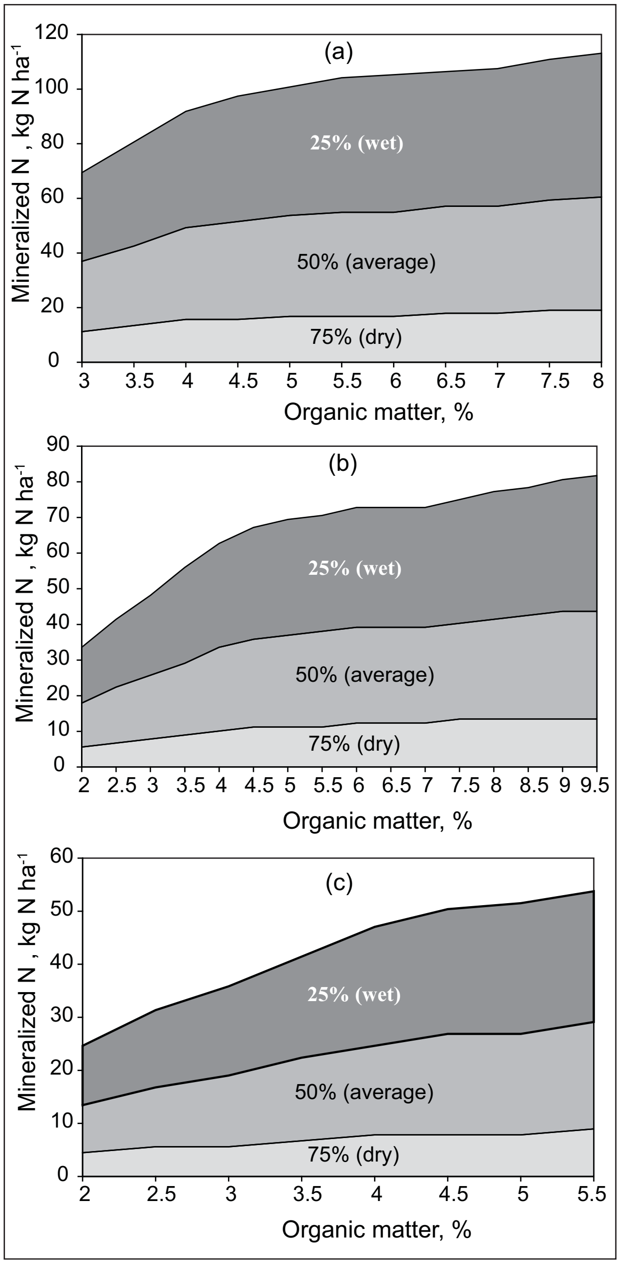

Figure 5. Mineralized N under 25, 50 and 75 % probability of precipitation (wet, average and dry conditions, respectively) for (a) Humid Parkland, Alberta Highlands (b) and Palliser Plains (c) NFRZ, which represent high, medium and low mineralized N conditions.

an understanding of how inputs and outputs of N both from the soil and the available pool (**Table 11**) are being utilized.

Inputs

Estimation of soil "available" N that contributes to plant uptake: Nitrate-N content in the 0 to 60 cm depth is required. Any other depth is converted to 60 cm depth through a series of conversion factors developed from historical data (Karamanos and Henry, 1991; Karamanos, 2004). The efficiency of soil N uptake depends on weather

Table 11. Inputs and outputs of N from the soil.

Inputs	Outputs
Soil	
Fertilizer	Crop Uptake
N Fixation	Leaching Loss
Plant & Animal Residues	Denitrification
(Precipitation[1])	(Volatilization[1])
Available pool	
Mineralization	Immobilization

[1]Not directly accounted for in the system.

conditions. Under "average" conditions it is 50% but can be as low as 30% under below normal and as high as 60% under above normal precipitation conditions. Nitrogen that is not utilized by the crop remains in the soil as "residual" N, however, it is subject to a number of loss mechanisms (outputs).

Estimation of mineralization: Discussed above.

Estimation of fertilizer N contribution: Fertilizer use efficiency is defaulted to banded N and under "normal" conditions is assumed to be 50%; it can be as low as 30% under dry and as high as 60% under above average (but not wet) conditions.

Estimation of N fixation: Pulse crops fix 50 to 80% of their N. The system assumes that on "average" pulses fix 70% of their N and that the remaining N comes from other sources (e.g., soil "available", mineralizable and fertilizer N).

Outputs

Estimation of immobilized N: Discussed above.

Estimation of crop uptake: Nutrient uptake depends on the type of crop and the protein level in the grain. It is estimated by multiplying yield by N uptake per tonne of grain.

Estimation of denitrification: Denitrification primarily occurs during snowmelt and during and after precipitation events, however, the system only calculates the latter. It is estimated as a portion (0 under drought, 15% under 75 to 50%, 25% under 50 to 25%, and 50% under 10% or less probability of precipitation, respectively) of the unutilized "available" N; the latter is assumed to be that portion of the N available pool (available plus mineralized N plus fertilizer N) that is neither immobilized nor taken up by the crop during the growing season.

Estimation of leaching: Leaching occurs primarily under irrigation and during "wet" growing seasons, since in the majority of cases crops in western Canada are grown under a water deficit (Shields et al. 1968). Soil test N along with fertilizer

N and N released from organic matter (mineralized N) are subject to leaching under irrigation or excessive soil water. Losses are estimated as 10% of potentially available N from the three sources (fertilizer, available, and mineralized N) described above when the probability of precipitation is less than 10% or fields are under irrigation.

Estimation of N credits from fixation by the preceding crop: Depending on the crop these can be between 4 and 8 kg N Mg^{-1} of legume grain. Credits for breaking forage stand can be between 35 and 70 kg N ha^{-1} depending on the crop and SZ.

Application of the System

Process

The stepwise process to deriving a N recommendation is as follows:

Step 1. Define assumptions from assumptions table in the system, which includes: Soil N Use Efficiency (SNUE) = 50%; Fertilizer N Use Efficiency (FNUE): Wet (25% probability): 60%, Average (50% probability): 50%, Dry (75% probability): 30%, >75% probability: 20%; Irrigation: 90%

Step 2. Obtain Plan information: NFRZ, SZ, SCZ, previous crop, previous crop yield, crop rotation, crop residue management, dryland or irrigation, soil test details, soil texture, and organic matter.

Step 3. Get nutrient groups from NFRZ table: Mineralization Group; NFRZ are divided into two groups based on the weeks that mineralization is calculated over, namely, Group 1, t = 20 weeks, and Group 2 t = 16 weeks; the latter group includes all Northern (Peace River) NFRZ as well Alberta Highlands West.

Step 4. Get N Credit Group; NFRZ are also divided into two groups based on value of N credits attributed when the previous crop is a legume or pulse; credits in Group 1 (southern NFRZ) are assigned at face value, whereas those of Group 2 (northern NFRZ) are increased by 20% to reflect overall higher moisture conditions.

Step 5. Assign soil water conditions (default or actual) and target yield or target precipitation over the growing season. Assign protein level (if applicable and/or desirable) or let predictions be derived using default values.

Example with CWRS Wheat

The five steps described above are applied here to demonstrate the application of the system for CWRS wheat (**Table 12**). The TH for this NFRZ was 38.1 mm and WUE of 4.7, 4.2, and 3.7 mm kg^{-1} of grain for 25, 50 and 75% probability of precipitation, respectively. Hence, target yields derived for the three default conditions were 4.03, 2.89, and 1.88 Mg ha^{-1}. Organic carbon level in the soil was calculated by dividing organic matter level by 1.724, i.e., 2.32%. The calculated value for the mineralization constant k35C was of 0.1437. Potential mineralization (Nt) was estimated to be 50 kg ha^{-1}; adjusted mineralization for 25, 50, and 75 % probability of precipitation was 63, 50 and 29 kg N ha^{-1}, respectively, with F value of 0.412 and MNUE of 1 (100%). Corresponding immobilized N values were 33.6, 33.6, and 11.2 kg ha^{-1}. At protein target of 13.5 % (0.0303 kg N uptake kg^{-1} grain), total N required will be:

25% probability: {N Uptake (122.3 kg ha^{-1}) – N credit (0) – N mineralized (63 kg N ha^{-1}) – N immobilized (33.6 kg ha^{-1}) + N denitrified (0) + N leached (0)} / FNUE (0.6) = N requirement (155 kg

Table 12. Values for parameters used to derived N recommendations in an example.

Parameter	Value
Soil Zone (SZ)	Thick Black
Soil Climatic Zone (SCZ)	Moist Black
Nitrogen Fertilizer Recommendation Zone (NFRZ)	Moist Parkland
Previous crop	Canola
Previous crop yield	2.69 Mg ha^{-1}
Crop rotation	Continuous cropping
Crop residue management	Spread
Dryland or irrigation	Dryland
Soil depth	0-15 cm
Soil texture	Loam
pH	7.6
EC	0.7 mS cm^{-1}
Organic carbon	2.3 %
Soil N (NO_3-N)	22.4 kg ha^{-1}
Mineralization Group	1 = 20 weeks of mineralization
Get Nitrogen Credit Group	1 = legume or pulse credits at face value
Soil water	Default at 914 mm
Precipitation	Default values: 25% = 267 mm 50% = 203 mm 75% = 140 mm

ha^{-1}). Hence, N recommendation will be: N requirement (155 kg ha^{-1}) – Soil N converted to 60 cm depth (47 kg N ha^{-1}) x SNUE (0.5) / FNUE (0.6) = 116 kg N ha^{-1}.

50% probability: {N Uptake (87.7 kg ha^{-1}) – N credit (0) – N mineralized (50 kg N ha^{-1}) – N immobilized (33.6 kg ha^{-1}) + N denitrified (0) + N leached (0)}/ FNUE (0.5) = N requirement (137 kg ha^{-1}). Hence, N recommendation will be: N requirement (137 kg ha^{-1}) – Soil N converted to 60 cm depth (47 kg N ha^{-1}) x SNUE (0.5) / FNUE (0.5) = 91 kg N ha^{-1}.

75% probability: {N Uptake (57 kg ha^{-1}) – N credit (0) – N mineralized (29 kg N ha^{-1}) – N immobilized (11.2 kg ha^{-1}) + N denitrified (0) + N leached (0)} / FNUE (0.3) = N requirement (130 kg ha^{-1}). Hence, N recommendation will be: N requirement (130 kg ha^{-1}) – Soil N converted to 60 cm depth (47 kg N ha^{-1}) x SNUE (0.5) / FNUE (0.3) = 52 kg N ha^{-1}.

The results of this analysis are summarized in **Figure 6**. The impact of rainfall in May, June and July on the grain yield of CWRS wheat assuming that protein content remains at 13.5% is illustrated in **Figure 7**; however, change in precipitation given a constant N fertilization rate most likely will result in greater yield and correspondingly lower protein (**Figure 7**). This relationship is very difficult to predict; however, this tool may be used to a producer's advantage when soil water is estimated prior to seeding (**Figure 8**).

Validation of the System

Published reports in the literature of fertility work for which spring soil water has been recorded are scarce. Three sets of experiments were utilized to verify the basic model in this system (Karamanos and Henry, 1991). Validation was focused on the ability of the system to correctly predict target yields based on moisture conditions and crop moisture use efficiency. These experiments were not ideal in all aspects, since in some cases precipitation was the average of many sites and N fertilization rates were limited. Predicted yields for the corresponding soil moisture and precipitation conditions were between -5% and +28% different from those actually obtained (average 7%). The N rate structure in those experiment did not always allow for a direct comparison to the recommendation that the system generated. The results were re-calculated based on subsequent modification in the system and are presented in **Tables 13** and **14**.

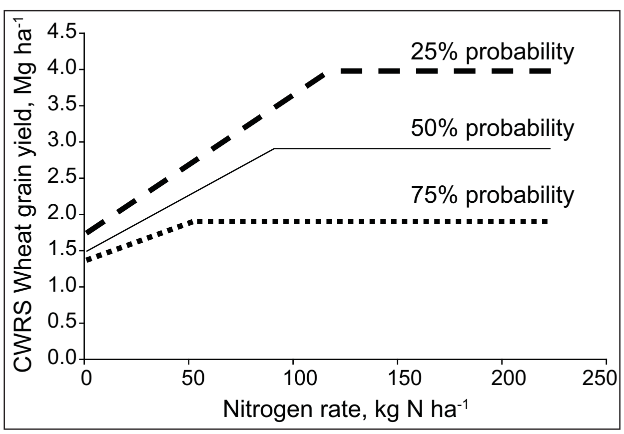

Figure 6. Output from the system illustrating the relationship between CWRS wheat grain yield and fertilizer N rate using the values of the parameters in Table 12.

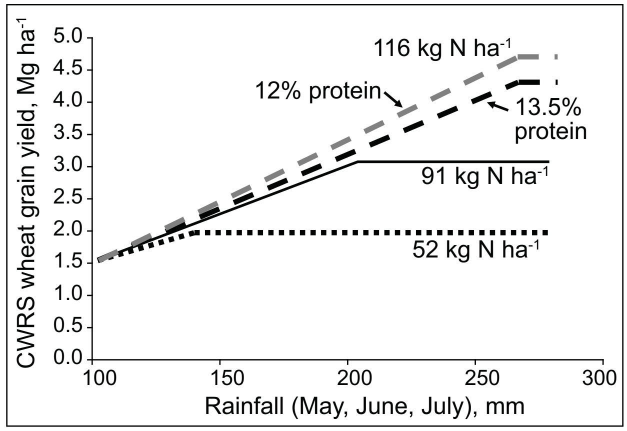

Figure 7. Output from the system illustrating the relationship between CWRS wheat grain yield and growing season precipitation using the values of the parameters in Table 12.

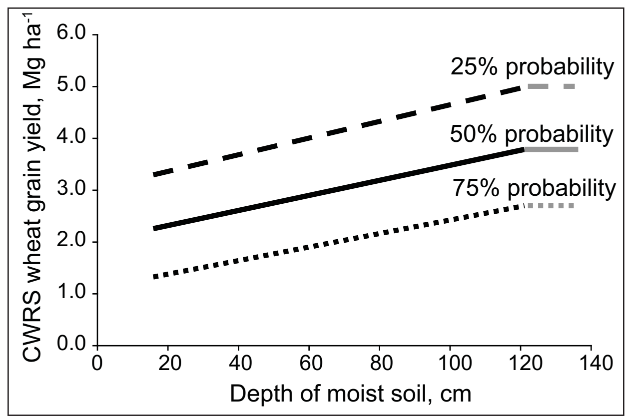

Figure 8. Output from the system illustrating the relationship between CWRS wheat grain yield and depth of moist soil using the values of the parameters in Table 12.

Concluding Remarks

A water based system for deriving N recommendations in the Canadian prairies that was developed in 1990-91 was first utilized by the Saskatchewan Soil Testing Laboratory to serve farmers in that province. A large proportion of the soil tests carried out in western Canada are being interpreted using this system. Although the system itself remains in

Table 13. Comparison of model estimated CWRS wheat grain yields to those actually observed in two sets of experiments and corresponding N fertilizer rates using parameter.

Year	Spring soil water	May, June, July precipitation	CWRS grain yield estimated	CWRS grain yield observed	Nitrogen recommendation	Rate for observed yield
	mm	mm	- - - - - Mg ha^{-1} - - - - -		kg ha^{-1}	kg ha^{-1}
Selles et al. (1988)						
1982	46	244	3.1	3.0	129	115
1983	71	188	2.6	2.1	106	110
1984	30	99	0.9	0.7	0	0
1985	0	74	0.5	0.5	0	0
1986	10	206	2.2	2.0	67	131
van Kessel and Livingston (1989)						
Dryland	38	132	1.1	1.1	15	131
Irrigation	38	279	2.6	2.6	47	131

the public domain, different versions of software for this system are proprietary to ALS Laboratories and Western Cooperative Fertilizer Limited. This system allows for on-time adjustment in water conditions (soil water and precipitation), thus leading to refinement and customization of default recommendations generated if actual water conditions are not known. The system is an empirical model based on long-term grain yield and water data and is continuously involving. It is not a predictive tool, rather a planning tool, which in addition to N contains databases for phosphorus, potassium, sulphur and all micronutrients. Reversal in the process followed in this system has allowed the introduction of Virtual Soil Testing (VST) as a soil macronutrient level predictive tool (Karamanos and Cannon, 2002; Karamanos, 2003).

Table 14. Comparison of targeted and actually observed yields of CWRS wheat by Entz and Fowler (1989).

Year	Spring soil water	May, June, July precipitation	CWRS grain yield estimated	CWRS grain yield observed
	mm	mm	- - - - Mg ha^{-1} - - - -	
Clair				
1986	30	218	2.3	2.2
1987	25	173	1.7	1.7
1988	18	127	1.1	1.1
Outlook				
1986	23	198	1.6	1.4
Watrous				
1986	25	191	1.7	1.4
Hagen				
1987	20	163	1.7	1.8
Paddockwood				
1987	38	198	2.2	2.3

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Exploring the Effect of Weather Forecast Accuracy within a Nitrogen Fertilizer Recommendation System.

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Abstract

Model systems such as SUNDIAL provide advice for N fertilizer use on arable crops by modeling the N supply from soil. However, poor knowledge of coming weather reduces accuracy. We attempt to quantify the degree that the accuracy of such advice is reduced by poor knowledge of coming weather, and the potential for medium term forecasts to improve this advice.

We used a weather generator to produce sets of simulated weather forecasts, of a range of accuracies and durations, for 10 regions representing England and Wales. In a series of simulations, SUNDIAL was used to test the benefit of prior knowledge of weather following the date of N fertilizer application, in terms of improved crop performance and reduced N losses to the environment. The changes in crop N offtake, N leaching and denitrification due to the forecast quality were calculated. Yield and gross profit changes as a result of this simulated foreknowledge were estimated from N offtake.

Accurate forecasts reduce the risk of under-application of N. Three-week forecasts of perfect accuracy increase crop offtake by an average of 2 kg N ha^{-1}, and farm profit in England and Wales by £23M per annum. The decrease in losses is small, however. Similar improvements may be expected for other dynamic recommendation systems that exploit post-application weather.

Introduction

Farming in England and Wales, as elsewhere, is under conflicting pressures: on the one hand there are environmental norms to be met (Pretty et al., 2001), on the other hand profitability has declined (Defra, 2006). Nitrogen fertilizer use is an issue that farmers must balance between these two pressures. Within the EU, water quality legislation (Anon, 2000) requires practices that limit nitrate leaching into ground and surface water below tight thresholds; in the UK this legislation is enforced through restrictions to fertilizer use on land situated in Nitrate Vulnerable Zones (Defra, 2002b), as well as through requirements to comply with good practice which are linked to farm subsidy payments (Defra 2005, p. 37). Furthermore, denitrification may produce nitrous oxide (N_2O), which is an important greenhouse gas (IPCC, 2001).

However, in the UK, despite recent rises in fertilizer prices, for most crops N is a cheap input relative to the value of the yield response. Thus it remains economic for farmers to fertilize crops at rates close to those that can attain maximum yields. Losses of N to the environment increase rapidly with applications of N beyond the optimum for crop yield, but as this optimum cannot be predicted precisely, farmers may tend to over-apply N (e.g. Sylvester-Bradley et al., 1987; Whitmore and Van Noordwijk, 1995) because under-application would result in a large loss of farm yield and income, whereas the diffuse pollution caused by over-application has little direct cost to the farmer. Systems such as SUNDIAL (Bradbury et al., 1993; Smith et al., 2001) are intended to optimize N fertilizer advice for farmers by taking account of the N that will be supplied from soil, thereby maximizing yields and minimizing N pollution. SUNDIAL models crop growth as affected by soil N supply, but it does not take account of all factors that influence growth and N use (for instance drought and disease), so under-utilization and losses of N may occur as a result of processes not considered in this study.

In general, SUNDIAL has been shown to agree well with RB209 (MAFF, 2000, ADAS 2005), the recommendation system for N that is currently sponsored by Defra (the UK Government Department for the Environment, Food and Rural Affairs). Predictions from SUNDIAL, however, are dependent on estimates of the weather post-application which generally differ from actual weather. Thus the fertilizer advice may turn out to be non- optimal, resulting in either increased losses to the environment or a decrease in yield and profit. There is potential for medium-term weather forecasts to be made available to the farming community; this raises the question of how much these forecasts would

Abbreviations: N, nitrogen;

improve the accuracy with which farmers can obtain site and season-specific fertilizer advice using fertilizer recommendation systems such as SUNDIAL. In the UK, an exercise known as Foresight (Anon, 2001)— which examines how future science might benefit the economy—assessed the potential value to the food supply chain of medium-term weather forecasts of two or three months.

In this work we quantify the potential for medium-term forecasts to improve the accuracy of N fertilizer recommendations, using the recommendation system SUNDIAL as an example. We relate the avoided loss of yield and the reduction in loss of N (denitrification or leaching) reported by SUNDIAL to increased prior knowledge of weather. In this way we examine the potential of medium-term weather forecasts to reduce N pollution and to contribute to the farming economy in England and Wales.

Method

A weekly time-step weather generator (Dailey et al., 2005) was developed for use with the SUNDIAL N dynamics model for arable crops (Smith et al., 1996). Modifications were made to the weather generator so that it can produce sequences of weather data that emulate medium term weather forecasts of different accuracies. Weather data was generated for sites representative of England and Wales.

The generated weather was used in a study (Dailey et al., 2006) to quantify the effect that forecasts of different accuracies and durations would have on the efficient use of N fertilizer, when using SUNDIAL to determine fertilizer applications.

The weather generator

The weather generator provides weather data for SUNDIAL: rain, air temperature and evapotranspiration on a weekly basis. The generator is parameterized using 20-year runs of observed weather, and then generates sets of weather data that are statistically similar to, but independent of, the observed weather. This approach is similar to that of Richardson (1981).

Generation of rain, evapotranspiration and temperature

The weather generator is described in full in Dailey et al., 2005, and is briefly summarised here. The distribution of weekly rainfall for weeks belonging to each four-week period is parameterised as an empirical cumulative distribution curve (Racsko et al., 1991). Generated rainfall amounts correspond to randomly generated probabilities transformed by the cumulative distribution curve. A further modification allows the persistence of rain amount from one week to the next to be reproduced.

Evapotranspiration (ET) and average temperature (T) are each modeled as a Fourier series. One Fourier series relates the seasonal mean of the weather variable to the week of the year, and a further Fourier series describes the seasonal standard deviation of ET or T. The method is extended to take account of the wet or dry state of the week. Residual variation of ET and T, not explained by the season or the wet or dry state, is determined by a method suggested by Matalas (1967), in which the series of residual components is generated using a series of random values. Values of ET or T for the current week are obtained by adding to the seasonal mean the product of the residual component and the seasonal standard deviation.

Generation of weather for forecasts

The generation of weather forecasts is described more fully in Dailey et al., 2006, and is summarised here. In order to examine the effect of forecast accuracy, two sets of weather data are generated. The first series represents weather expected according to the forecast at the time that the fertilizer application decision is needed, and this is the weather used by SUNDIAL to find the optimal fertilizer application; the second series, which deviates from the first, represents the realized weather - the historic weather known at the time the crop is harvested.

We specify the extent by which the realized series deviates from the expected by the forecast accuracy parameter, φ. This has a value of 1 when there is no deviation of the realized weather from the expected; in other words a “perfect” forecast. A lower value of φ signifies that the expected weather forecasts the realized weather with correspondingly lower accuracy. By decreasing φ to zero, we decrease the accuracy of prior knowledge of the weather to zero.

As well as reliability, we must also consider the duration of this prior knowledge. We examined the effect of having forecasts with durations of up to 27 weeks.

Modifications to generator for forecast work

The series of expected rain amounts is generated from a series of random numbers as described above. To produce the corresponding series of realized rain, the random series is modified by a further, independent random series which has been scaled according to $(1 - \varphi)$. Thus as the forecast accuracy decreases, the realized rain becomes increasingly independent of the expected rain.

Likewise the series of residuals of expected ET and T is generated from a random series as described above. To generate the corresponding residuals for realized ET and T, a new series of

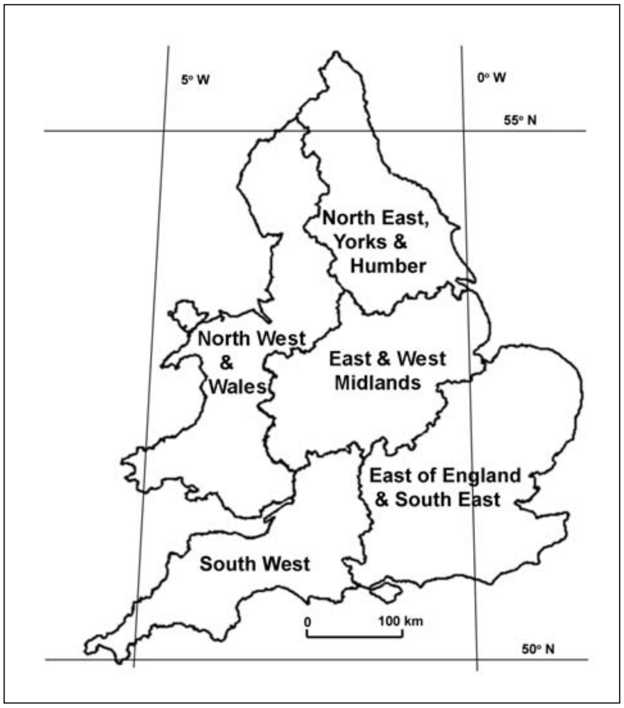

Figure 1. England and Wales, showing areas for which results are presented.

the random variables is generated that tracks the original series, but deviates from it by a random amount with an average magnitude dependent on φ. Thus the realized series of ET and T will have residuals that vary independently of those of the original expected series, to a degree controlled by the forecast accuracy parameter.

The SUNDIAL model

The SUNDIAL model simulates N dynamics in arable land. It takes account of soil N supply as affected by weather and other factors, and reports N removal in harvested yield (N offtake), as well as losses of N from the soil by leaching and denitrification (described in Bradbury et al., 1993; verified using farm trials in Smith et al., 2001). SUNDIAL will optimize fertilizer N application to satisfy, but not to exceed, the crop's requirement of N for yield and vegetative growth. Alternatively SUNDIAL will model the outcome of specified fertilizer applications.

The simulations

To coincide with officially reported cropping data, we collected data from the ten Government Office Regions of England (e.g. Defra, 2002a), and Wales, but combined into five regions according to climatic differences (**Figure 1**).

Results were weighted by the extent of cropping in each of the regions (**Table 1**).

Ten weather stations, two per region, having at least 20 years of records were chosen for the simulations to represent wet, moderate and dry regions, and warm, moderate or cool conditions.

Three soil types, the default soils in the SUNDIAL model, were used: sand, loam and clay.

Four crops were investigated that represent major classes of arable crops grown in England and Wales: winter wheat, an autumn drilled cereal; spring barley, a spring drilled cereal; winter oilseed rape, a crop leaving large N residues; and potatoes, a shallow-rooting spring planted crop. In all cases the simulated crop was preceded by winter wheat. Dates of establishment and harvest, and potential yield (**Table 1**) were according to normal practice and published average yields for the UK (MAFF, 2000, Nix, 2001).

Sets of weather were created having forecast accuracies of 0, 30, 50, 70, 90 and 100%, and durations of 1, 3, 5, 7, 9 and 27 weeks. For each combination of forecast accuracy and duration and agronomic conditions, 80 independent simulations were performed using unique sets of generated weather data, in order to span the range of possible outcomes.

For this work, SUNDIAL uses average yields for the UK (Nix, 2001) and weather data for each location to simulate up to the date at which fertilizer is to be applied. Then using the expected weather for the period up to harvest, the system optimizes the amount of fertilizer that should be applied for the expected conditions. A second series of simulations is then performed using this same fertilizer recommendation. This time, however, realized weather for the period following fertilizer application is used, having different degrees of prior knowledge, and different durations of that prior knowledge. For the remainder of each simulation until harvest, realized weather data that represents no prior knowledge is used (**Figure 2**). For each simulation, results for nitrate leaching, denitrification and crop offtake (N in the harvested yield) are obtained. Table 2 gives these results from the simulations using the expected weather.

Table 1. Potential yields and dates used in the simulations; areas grown in England and Wales in 2002.

	Potential yield		Date		
Crop	Sand	Loam or clay	Establish	Harvest	Area grown
	- - - t ha^{-1} - - -				ha
Winter wheat	8.0	9.0	8 Aug	12 Aug	1,886,800
Spring barley	5.5	6.0	18 Feb	12 Aug	870,200
Winter Oilseed Rape	3.5	3.5	3 Sep	5 Aug	325,900
Potatoes	45.2	45.2	1 April	30 Sep	122,300

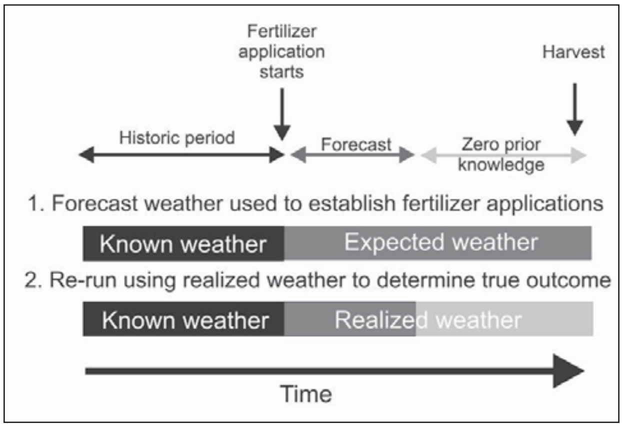

Figure 2. Diagram to show how generated data is used to represent the expected weather which must be used for deciding the fertilizer requirement, and the realized weather known after harvest, in which the crop actually grows.

Table 2. Nitrogen lost during the growing season by denitrification and by leaching, and taken up by the crop. Mean for all soils and climatic regions.

Crop	Denitrification	Leaching	Crop offtake
	kg N ha^{-1}		
Winter Wheat	8	17	200
Spring barley	7	19	133
Winter Oilseed Rape	6	8	197
Potatoes	8	19	178

We then calculated the change in these values due to using a forecast, and found the increase in crop offtake, and the avoided leaching and denitrification.

SUNDIAL does not predict yield explicitly, but models the uptake of N by the crop for yield (N offtake) and vegetative growth, and assumes that the N content of the yield is constant. If the N offtake achieved is less than the potential N offtake, yield is reduced proportionately. We assessed the value of access to medium-term weather forecasts in terms of changes in yield and in losses to the environment by leaching and denitrification.

Estimation of economic benefits

The benefits to the farmer in terms of avoided loss of yield were calculated using published or officially collected N contents, crop areas and prices for 2002. Product prices for April 2002 were obtained from Farmers Weekly (5 April 2002); N and dry matter content for oilseed rape from A.J. Macdonald (Rothamsted Research, personal communication); crude protein and dry matter contents for other crops from Agro Business Consultants (1998); crop areas for England from Defra (2002a); crop areas for Wales, year 2001 from John Bleasdale, Agricultural Statistics, Welsh Assembly Government (personal communication).

We expressed results as the benefit, in terms of avoided loss of crop N offtake and reduced N losses to the environment, from having the given accuracy of prior knowledge of the weather relative to having no prior knowledge. We also expressed this as the increase in gross profit to the arable industry of England and Wales due to avoided loss of yield.

Results and discussion

Losses of N

Increased prior knowledge decreased the amount of N leached and denitrified before harvest, but these changes were small. The average reduction in these losses due to perfect knowledge of the weather was 1.28 and 0.1 kg N ha^{-1} respectively, over all sites, soils and crops. Decrease in such losses prior to harvest was not expected to be large, as only a small proportion of these losses generally occurs during the summer. Moreover, the amount of nitrate N remaining in the soil profile at harvest was reduced by only 2.2 kg N ha^{-1} averaged over all sites, soils and crops, when using a perfect forecast, from an average of 53 kg N ha^{-1} with no forecast. There was as a result only a small effect on the following season, in which leaching losses were reduced by an average of 0.7 kg N ha^{-1}.

Crop N offtake

The benefit of prior knowledge was greatest on crop N offtake, and was larger than on either denitrification or leaching. Crop N offtake increased with forecast quality (**Figure 3**). A forecast of 3 weeks that is 60% accurate gave an increase of 1 kg N ha^{-1} in average crop offtake. For a 3-week forecast that is 100% accurate, the increase would be 2 kg

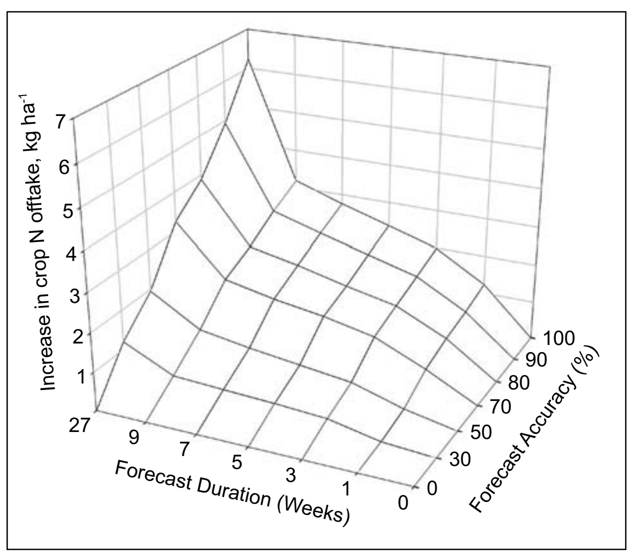

Figure 3. Change in crop N (kg N ha^{-1}) offtake due to weather forecasts of the specified duration and accuracy (φ), relative to offtake with no forecast. Averaged over all crops.

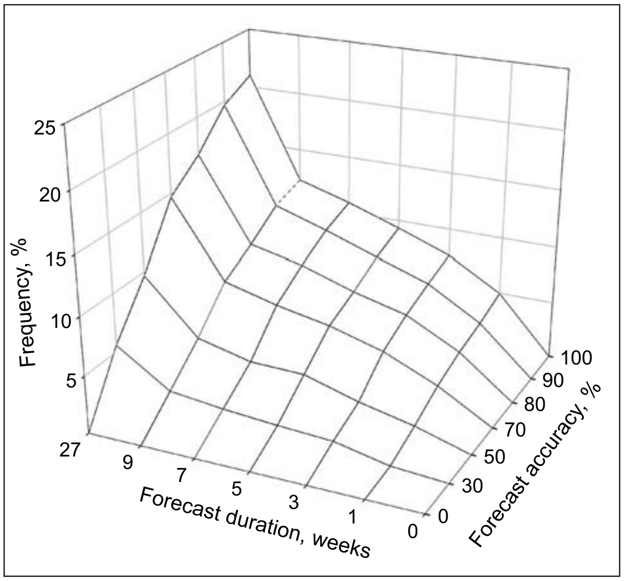

Figure 4. Frequency with which weather forecasts for the specified duration and accuracy (φ) would increase crop N offtake by 12.5 kg N ha^{-1} (for cereals, this would be equivalent to 0.5 tonne yield) relative to offtake with no prior knowledge of the weather (φ=0). Averaged over all crops and weather stations.

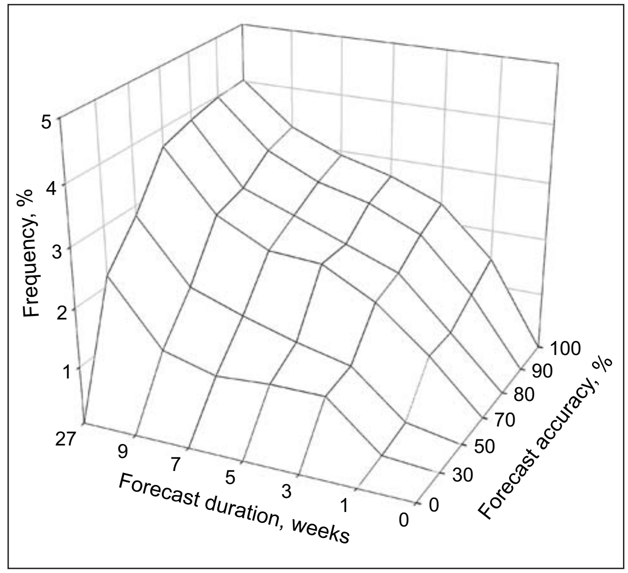

Figure 5. Frequency with which forecasts of weather for the specified duration and accuracy (φ) would increase crop N offtake by 25 kg N ha^{-1} (for cereals, this would be equivalent to 1 tonne yield) relative to offtake with no prior knowledge of the weather (φ=0). Averaged over all crops and weather stations.

N ha^{-1}. A 7-week forecast that is 70 or 80% reliable would increase N offtake by 2 kg N ha^{-1}. Winter wheat showed the largest increase, and spring barley the smallest. These amounts are not large but are averaged effects over the 80 simulation years and represent a consistent benefit to the farmer.

Variability between years

The loss of crop N offtake varies within the 80 years simulated due to occasions where the crop to fails to achieve its potential N offtake. However, the distribution of these offtakes was somewhat skewed. To illustrate this we have plotted the frequency with which crop N offtake was reduced by more than 12.5 or 25 kg N ha^{-1} (**Figures 4 and 5**). A reduction in offtake of 25 kg N ha^{-1} corresponds to a yield loss of approximately one tonne ha^{-1} for cereals, 0.5 tonnes ha^{-1} for oilseed rape, or six tonnes ha^{-1} for potatoes. The larger number and magnitude of shortfalls in N offtake rather than gains in the results (**Figure 6**) arises from the fact that SUNDIAL attempts to supply the minimum fertilizer N required by the expected yield, in order to minimize the losses to the environment that come about with over-fertilization.

The main benefit of prior knowledge of weather is to reduce the number of occasions when N fertilizer requirement is under-estimated and hence yield is depressed, even though the risk of leaching or denitrification turns out to be small. Although the extra amounts of N acquired by a crop are relatively small in comparison to the amount of fertilizer applied (**Figures 4 and 5**), the corresponding yield increases in these crops (one tonne ha^{-1} in the case of cereals) is a significant contribution to farm yield, and also to profit.

Taken over the whole of England and Wales, these benefits would be considerable. A forecast of about 4 weeks of 50% reliability could be worth £9-11M (**Figure 7**). A study by the UK Department of Trade and Industry (Anon., 2001) attempted to quantify the usefulness of forecasts of 2-3 months duration to the food supply chain. We suggest that with an accuracy of 70%, such forecasts would be worth over £23M per year to arable crop farmers in England and Wales in avoided loss of yield.

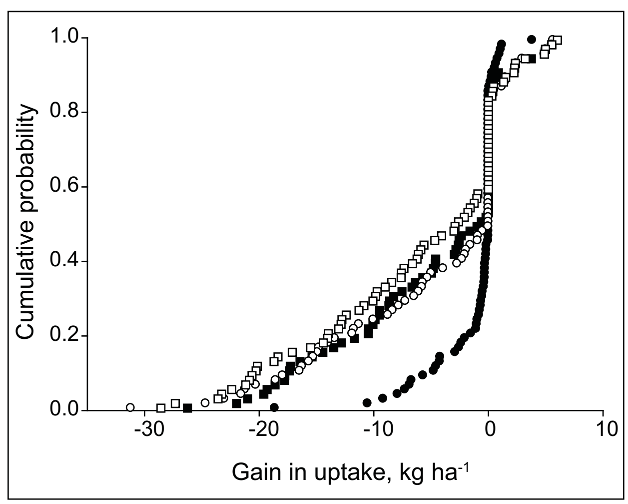

Figure 6. Shortfall or gain in N offtake by a crop of winter wheat in 80 separate realisations of weather, forecast with the specified accuracy and duration; ■, φ =1, duration 1 week; ●, φ=0.9, duration 27 weeks; ○, φ =0.5, duration 5 weeks; □, zero accuracy.

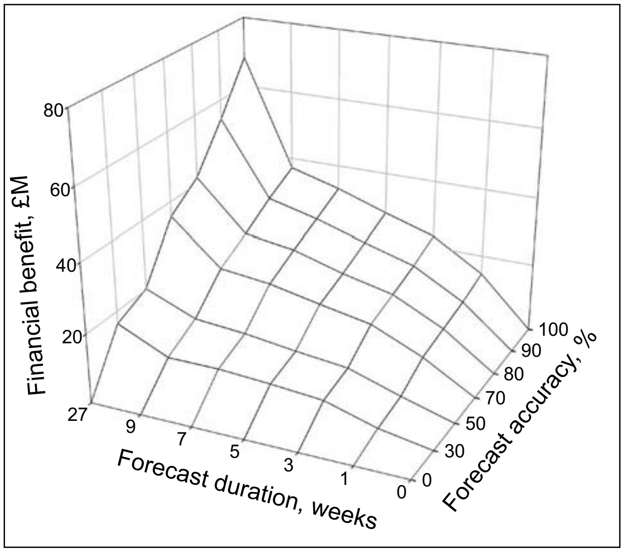

Figure 7. Gross value of avoided loss of yield (£M) due to weather forecasts of the specified duration and accuracy (φ).

We have considered potential benefits in terms of N and its effects only. In reality improved forecasts would have many impacts outside the scope of this study, such as disease, pests and weed control, cultivation, irrigation and market prediction. The financial gains referred to should be seen as potential benefits when using N fertilizer under strict constraints of good environmental practice. In England, such constraints are now imposed on approximately 60% of the land area through the designation of nitrate vulnerable zones (Defra, 2002b).

Conclusions

The benefit of reliable medium term weather forecasts following fertilizer application, to improved water quality through avoided nitrate leaching or to greenhouse gas emissions of nitrous oxide from denitrification is unlikely to be great. Nor, at first sight, do the benefits to crop N offtake appear to be large. However, the distribution of crop responses found here is heavily skewed towards the risk of yield loss through failure to take up sufficient N. In an industry that adheres strictly to a N prediction system to minimize losses of N, the benefit to arable farming in England and Wales of even a limited weather forecast of three-week forecast that is 70% accurate, could be £15M per year. Future increases in fertilizer prices and environmental constraints may cause the value of these benefits to increase.

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The Challenge: a Research Agenda for Managing Crop Nitrogen for Weather

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Farming has always depended on the weather. Since the dawn of agriculture, producers have had to adapt to it. While today's technologies allow a single producer to control a larger area of cropland than ever before, adapting to weather is just as important as it ever was. Weather impacts N dynamics at least as much as crop performance; arguably more, since it additionally influences processes of N supply and loss from soils as well.

Decades of research into improved N management for crops have proven that there is no simple soil test that—on its own—can predict an optimum rate of N. Nevertheless, producers have improved their management of the nutrient. Between 1964 and 2006, partial factor productivity for N use in corn production in North America has increased from 42 to over 60 kg of corn per kg of N fertilizer applied (calculated using the method of Fixen and West, 2002). However, the current partial nutrient balance indicates an average recovery efficiency of less than 80%—that is, the N in the grain harvested from the field amounts to 80% of the N in the applied fertilizers and manures—indicating considerable room for further improvement.

The reason many efforts to improve prediction of optimum rates have failed is that they have focused only on one specific tool at a time, be it a soil test, a plant indicator, or a weather-based predictor. The research effort that is needed must integrate these tools. Single-factor approaches do not lead to improved recommendations, because the factors determining N requirement are multiple.

Any approach that aims to come closer to optimum than current systems must account in a robust manner for the multiple factors affecting the demand for and supply of N (Stanford, 1973). Crop yield potential and its N demand is one of the three main components. The second is the supply function, most of which is directly influenced by management (applications of manure or fertilizer), but a substantial part is governed by biological mineralization and immobilization from native soil organic matter, and biological N fixation. The third component is the loss function, governed by weather processes that control water accumulating in and moving through soil, and the specific timing of these events interacting with the amount in the mobile nitrate form on any given day.

Few studies systematically partition variability in crop N response into the three components described above: crop N demand, soil N supply, and soil N losses. Each of these three has both spatial and temporal components. Spatially, variability both within and among fields may be important. Temporally, the main variation of interest is year-to-year or interannual. The two may interact with each other and thus be difficult to partition.

Process-based models that estimate mineralization, leaching, volatilization and denitrification along with crop growth and development could contribute enormously to the rate decision at the critical point just prior to when crop N uptake begins. Agrometeorological information needs to be integrated into the decision-making process. The uptake of N for most crops, including corn, does not become rapid until several weeks after planting. By that time, probabilistic scenarios for that season's yield prospect can be better defined than they could have been prior to planting. A focused effort is required to develop prediction tools operating from process-based models that incorporate both past data and future probability scenarios.

Delaying applications until the last possible moment helps adapt N management to weather by reducing the time between application and crop uptake. Effectively, it transforms weather forecast probabilities into realities. Both probabilities and current realities need to be dealt with in adapting N management to weather.

However, another consideration with the "just-in-time" approach to N management is the probability of inclement field conditions preventing the timely application of a side-dress dose. Certain soil textures, particularly poorly-drained clay soils, may be most susceptible. The choice then becomes pre-plant with a controlled-release source (or an inhibitor to control transformation to nitrate), versus side-dress or split application, and that choice may be governed by soil texture. Sandier soils are accessible quite rapidly after wetting, so are more amenable to multiple applications, while the slower-drying clay soils are more likely to be better served

Abbreviations: N, nitrogen.

with a controlled-release strategy. Decision support systems must consider not only the physiological needs of the crop, but also the practical realities of possibilities for management operations, including soil conditions supporting application equipment.

The question of whether optimal N rates are related to yield potential arises often and is still controversial. The discussion needs to go deeper (Fixen, 2006). There are many sources of variation in crop yields and yield potentials. Some sources may be more correlated to optimal rates than others. In addition, when the variation in crop yields is accompanied by variations in supply and loss of soil N, the correlation may be obscured. For example, variation in optimal N rate among years at a single site may not correlate to achieved yields, if warm weather causes the variation and increases both soil N mineralization and crop yield. However, in semi-arid areas, where year-to-year variation in crop yield depends on soil water and rainfall, the correlation to optimal N rates can be quite high, particularly if soil N supply varies little, and because soil N losses are small. In some areas, where soils vary greatly in their potential to support high yields, there is more likely to be a correlation between yield and optimal N rate. Therefore it is important to avoid generalizing findings of correlation, or the lack thereof, of crop yield to optimal rate.

Positive aspects of involving yield potential as a factor in crop N recommendations include the recognition of the law of conservation of mass, and the fact that it directs the highest rates to the fields producing the highest yields, which has logical field-level nutrient balance benefits. A negative aspect is that it may convey misperceptions among growers, creating the impression that a fixed quantity of applied N is required to achieve a given yield, and leading to a tendency to overestimate attainable yield potentials. This negative aspect can be overcome by education and by clear guidelines for estimating yield potentials from past attained yields.

Current recommendation systems for N application to corn are based mainly on factors that do not reflect weather. Several states and provinces have made recent advances in developing recommendation systems based on identified databases of crop response trials. The regional N rate guidelines for midwestern states including Illinois, Indiana, Iowa, Michigan, Minnesota, Ohio and Wisconsin are based on factors including the price ratio between harvested corn and N fertilizer, previous crop, and to some extent the productivity of the soil, and are specific to each state. The Maximum Return to N (MRTN) is determined from quadratic-plateau response curves fitted to recent state-specific crop response data (Sawyer *et al*., 2006). In Ontario, a large database comprising over 600 site-years of corn N response trials was used in a similar manner to develop a set of recommendations comprising six factors: price ratio, yield goal, soil texture, previous crop, site heat unit rating, and application timing (www.gocorn.net). It is difficult, however, to adapt current local weather information to make further adjustments to these recommendations. For example, the pre-sidedress soil nitrate test (a soil test with some weather dependence) is advocated in some of these regions, but the producer is left with little guidance as to how to interpret the nitrate result in the context of the full set of other factors.

Computer models of crop growth predict growth and development of crops as a function of their soil and air environment. The primary driving variables are solar radiation, temperature, and water. The function of a model is to predict the outcome of numerous complex processes underlying a main process of interest. In the case of agronomy, the main interest is often the yield outcome. When variables under management control are included, the model can also serve to predict optimum input levels of such variables.

Moving the recommendation approach from single to multiple factors is likely to require some form of computer model to assist with the integration. **Table 1** lists some of the crop models that have been referred to in this publication, and briefly describes the methods used for modeling each of the three components. There are many more models that could be implemented. Supplying accurate input data is a constant challenge with a modeling approach. When models are applied, it is important to critically evaluate each component to ensure a balanced representation of the important processes, and rigorously validate with data from on-farm research.

A research agenda to further the development of integrated model-based N recommendations should include:

- Participatory research with producers and advisers to test feasibility of integrated N management tools, using on-farm weather monitoring;
- Development of models that address the weather's impact on crop growth, soil N supply, and soil N losses;
- Further exploration of datasets of past response research, assembling the necessary soil and weather data to run models to estimate the movement and transformation of soil N;
- Increased use of real-time remote sensed data to detect N status of plants and gauge need for additional N application;

Example	Crop N demand	Soil N supply	Soil N loss
HERMES (Kersebaum)	SUCROS (daily timestep; van Keulen et al., 1982)	Two-pool first order soil N mineralization	Soil water capacity model; Denitrification; Leaching
PMN (Melkonian)	Maize N model (daily timestep; Sinclair and Muchow, 1995)	Two-coefficient model of soil N mineralization	Soil water capacity model; Denitrification; Leaching
LEACHM-N (Hutson and Wagenet, 1992)	Non-interactive with weather	Single-coefficient model of soil N mineralization	Richards soil water flux + convection-dispersion for solute transport
DSSAT-CERES (Singh)	Crop growth and N uptake (maize and wheat; daily timestep)	Godwin & Singh, 1998	Leaching; Denitrification; Ammonia volatilization
SUNDIAL (Dailey)	Crop N uptake, soil N mineralization and losses (weekly timestep)	Soil N mineralization; Crop residue N	Leaching; Denitrification
Dryland wheat (Pan; Karamanos)	Growth based on soil water and anticipated rainfall (seasonal timestep)	Mineralization; Immobilization; Residual	Leaching; Denitrification

Table 1. Examples of crop and soil water models with potential application to weather-based N recommendation, listing the methods used to model the three essential components.

- Development of simplified means to characterize soil physical properties that impact water and nutrient movement in soil for practical management, using principles from the sciences of soil physics and agro-meteorology;
- Spatial analysis and description of nitrate transport and transformation within agricultural fields;
- Identifying genetic traits influencing the physiology of crop growth, to select genotypes that capture more of the nutrients made available through the season by mineralization.
- Field validation of soil-crop-water-nutrient models.
- Increased accessibility of real-time weather data.

Spatial and temporal variation need to be addressed together. The complex interactions that stand out in several of the foregoing studies included in this publication often show that spatial variations in soil properties affect optimal N rates in a complex manner. It can be postulated that a highly site-specific approach to managing N will not be effective without an eye to the weather, and that attempts to make weather-specific recommendations will also fail if there is no eye to the soil and its spatial variability.

An issue raised in discussion during this symposium was whether the trend toward increased regulation of nutrient management would help or hinder the more efficient management of N and the control of its losses and their impacts on the environment. Managing crop N for weather requires site-specific approaches and flexible decision-making. These aspects are difficult to accommodate in regulatory approaches to nutrient management, and indeed are a limitation in nutrient management plans established on cycles of several years. While nutrient management plans have value in tactical planning, it is important that they allow flexibility in day-to-day implementation to suit changing weather conditions. Nutrient management must adapt more closely to changeable weather. Systems allowing producers to make data-driven decisions more rapidly may have advantages over regulatory approaches in improving the efficient use of N.

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Science and Education Needs to Reconcile National Environmental and Energy Goals with Current Nitrogen Recommendations

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Agricultural production has benefited tremendously in the last 50 years from the application of N fertilizer to increase crop yields. Over this same time-frame, natural resource impairment has occurred from increases in reactive N pools in the environment. Research and education have been very instrumental in improving production and growing the agricultural economy. National and global environmental interests now look to research and education to provide solutions to protect the environment and provide new directions in the agricultural economy such as bioenergy. We offer a conceptual approach to research and education interventions aimed at reducing the reactive N pool that will put agriculture on the correct path for reaching their environmental and energy goals. Agriculture needs to go beyond its traditional science and technology thrust and focus on social and economic barriers preventing adoption of improved management practices. We believe a multimedia and multidisciplinary approach is needed to find solutions to environmental problems, while continuing to meet the production demands of feed, fiber and fuel.

Crop Simulation Models and Decision Support Systems

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The first computer simulation models for agricultural systems were developed in the 1970s. These early models simulated potential production for major crops as a function of weather conditions, especially temperature and solar radiation. At a later stage, the water component was added to be able to simulate the soil and plant water balance and the impact of drought stress on growth, development, and yield. This required adding a detailed description of the physical characteristics of the soil surface and individual soil horizons as input to the models, as well as rainfall and irrigation. Further complexity was added by including the dynamic simulation of the soil and plant N balance. This, again, required additional soil inputs as well as a detailed description of the composition of the various plant components. The main soil processes that are simulated include mineralization and immobilization of crop residue and soil organic matter, nitrification and denitrification, and nitrate and urea movement. The plant processes include N fixation for grain legumes and N uptake, N mobilization, and senescence. Many crop simulation models also include genetic parameters and coefficients that correspond to the unique characteristics of each crop and cultivar. All processes are simulated at a daily time step and provide a true integration of the effect of weather and soil conditions and crop management on plant genetics, expressed through plant growth and development. Many models have slowly moved from research applications to decision support tools that can be used for seasonal and tactical decision-making, including the timing and amount of various management strategies, such as irrigation and fertilizer management. With the advancement in automated weather recording and communication and information technologies, these models will be new tools that can be used by decision makers, including growers and producers, to improve and increase crop yield and crop quality.

In-Season Prediction of Yield Potential for Nitrogen Management in Irrigated Corn

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Hybrid-Maize (www.hybridmaize.unl.edu) is a computer program that simulates the growth and yield of a corn crop under non-limiting or water-limited (rainfed or irrigated) conditions. Although the model has no nitrogen (N) component yet, it can contribute important information for fine-tuning N management decisions: (i) quantifying yield potential as the basis for setting realistic yield goals to be used in prescribing total N rates and (ii) in-season prediction of growth and yield potential to down- or upward adjust late-season N applications. In the current season prediction mode, the software allows real-time assessment of corn growth up to the current date based on actual weather data, followed by prediction of growth and final yield thereafter based on historical weather data for the remainder of the growing season. Model validation using data from different sites in Nebraska indicates that final yield predictions became accurate shortly after silking, but relative deviations from normal growth were detected earlier in both irrigated and rainfed environments.

Linking In-Season Fertilizer Decisions to Weather-Based Yield Predictions.

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A linear statistical model was used to evaluate the interactions of nitrogen (N) fertility, weather, soil, and irrigation on corn (*Zea mays* L.) yield from 1990 to 1995 in southeastern North Dakota. The fertility treatments were 0, 45, 90, 135, 180, and 225 kg N ha^{-1}, and 4 irrigation scheduling methods were applied. Also, there were a wide range of cumulative growing degree days (GDD) and evapotranspiration (ET) during this study period. It was found that the amount of GDD was a significant factor contributing to poor yields in 1992 and 1993. The optimum yield was defined as the yield at an optimum level of combined soil and fertilizer N, specific to cumulative ET or GDD from 1 May to 10 July for each site-year. The multivariate model indicated that optimum rates of N increased with increasing yield. Weather induced variations in yield potential should enter into the decision-making process when making fertilizer recommendations.

A regression model was developed that was used to predict the end-of-season corn grain yields on 10 July. This least-squares regression model was based on cumulative ET or GDD from 1 May to10 July and N fertility and corn grain yield. The 10 July prediction of this model corresponded well to individually observed end-of-season yields (r^2 = 0.80), and the predicted optimum yield (Y_{OPT}) was highly correlated to observed end-of-season Y_{OPT} (r^2 = 0.885). This model could provide a season-specific yield potential used to modify N application during the growing season, which could result in fertilizer savings in cool years or fertilizer increases to take advantage of optimum growing conditions and increase yields.