Nitrogen Losses: A Meta-analysis of 4R Nutrient Management in U.S. Corn-Based Systems

A Proposal to the 4R Research Fund, December 2013

Modern fertilization practices have fed the world, but unfortunately they also contribute to serious environmental consequences – coastal dead zones and fish kills, acid rain, climate change, and stratospheric ozone destruction. These result most notably from nitrate (NO_3) leaching and runoff, and nitrous oxide (N_20) emissions coming from nitrogen (N) not taken up by crops. Improved fertilizer management is vital to efforts that seek to increase cropping efficiency and minimize these nutrient losses. Such improvements can enhance both farm profitability and environmental sustainability. Many studies have evaluated responses of yield to varying fertilization rates, some have measured losses of NO_3 and a few have included N_20 , but rarely have they considered these all together, and not in a way that accounts for multiple aspects of proper nutrient management or how these relationships vary with soil, climate, or crop type. A meta-analysis of existing research would allow evaluation of many of these relationships and significantly enhance our understanding of what is controlling N use efficiency (NUE) and N loss pathways.

Rationale and Objectives

The aim of this project is to determine the impact of 4R nutrient management (Right rate, Right timing, Right placement, and Right source) on total N losses relative to yield from corn-based cropping systems in North America. We propose a meta-analysis that considers multiple factors and their interactions to address the following questions:

1. *How do crop yield, NO_3 leaching, and N_20 emissions respond to N fertilizer application rate, timing, type, and placement?*
2. *How do these effects of fertilization practices depend on climate and soil factors?*

Answering these questions in a comprehensive and integrating manner will provide novel, region-specific information that can be used to 1) estimate the magnitude of reduced fertilizer needs and reduced excess N under different scenarios of 4R management, 2) estimate the magnitude of NO_3 and N_2O losses under different scenarios of 4R management, 3) invest limited research dollars more strategically and 4) implement N management in ways that maintain or improve yields while minimizing environmental costs.

Current state of knowledge on agricultural N losses

Key loss pathways for N include gaseous emissions in the form of ammonia (NH_3) and nitrous oxide (N_2O) and aquatic losses that stem mainly from nitrate (NO_3) leaching. Nitrate in drinking water can have negative health impacts and is responsible for algal blooms and dead zones in impaired waterways and coastal areas. Ammonia contributes to acid rain and can further harm sensitive natural habitats by adding N through deposition after being transported long distances through the air. One of the most significant ozone depleting substances in the stratosphere, N_2O is also a potent greenhouse gas (GHG) with about 300 times more warming potential than carbon dioxide.

Reported recoveries of fertilizer N by corn range from 14 to 65% (Dinnes et al. 2002), and while some of unused fertilizer stays within soil organic matter, significant losses are not uncommon. An improved understanding of the form of these losses can help target management efforts. Much of the N lost tends to be leached as NO_3, although studies on arable systems have found this to be highly variable, with losses of between 3 and 54% of applied N (Di and Cameron 2002). An extensive review by Bouwman et al. (2002) concluded that 7% of N in synthetic fertilizer is lost as NH_3 in industrialized countries. Ammonia losses from manure are three times those from synthetic fertilizer. Grace et al. (2011) estimated that 1.75% of N applied to cereal corn in the North Central Region of the U.S. between 1964 and 2005 was lost as N_2O. Although a smaller proportion of total N losses, the N_2O emissions have significant environmental implications, since agriculture accounts for 75% of total annual N_2O emissions in the U.S. (Cavigelli et al. 2012). These studies provide rough estimates of N loss pathways on a large scale, but do not provide sufficient insight into the impact of alternative management, especially how these impacts may differ across climates and soils.

Given the ability of N to shift form readily in the environment, and that most forms of N can result in environmental impact, a holistic approach to measurement and management is important. For example, if in a given situation, improved timing reduces multiple forms of N loss and enhances NUE, but changing fertilizer source just shifts losses from NO_3 to N_2O, it would be valuable to track both loss pathways to inform management.

While many research studies only quantify a subset of management options and do so in a limited range of natural variability (soils and climate), meta-analysis can serve to bring together information on 4R management, crop yield, climate, soil, and N loss pathway. By ensuring that all effects of management practices are suitably analyzed, this comprehensive approach reduces the risk of unintended negative consequences when recommending management change.

4R nutrient management: crop yield and environmental benefits

The 4R nutrient management approach promoted by the world fertilizer industry and government agencies identifies four key factors of fertilizer management, namely, the right rate, right timing, right placement, and right source (e.g., see USDA NRCS 2013). When applied to N fertilizer, farmers can change one or more of these factors to increase NUE, achieving greater yield per unit of N applied, increasing profitability, and reducing negative environmental consequences. Maintaining or increasing yields along with improved N management is critical to avoid shifting production and the N losses elsewhere. Given that the objective is NUE (i.e., yield per unit of nutrient) rather than yield increases or N loss reduction alone, yield-scaled N losses are becoming more prominent in research reporting (Johnson et al. 2011; van Groenigen et al. 2010; Venterea et al. 2011).

In general, crop yields are expected to increase with fertilizer input up to the point of saturation, beyond which excess N is particularly susceptible to losses (Millar et al. 2010). The right rate of fertilizer application is the one that maximizes yield while minimizing economic and environmental costs (Kyveryga et al. 2007). However, the rate of application that achieves these ends depends strongly on soil fertility and crop type, as well as the type, timing, and location of fertilizer application and other management strategies. Climate and soil characteristics play very important roles, especially as they affect crop yield potential (and thus N uptake), as well as the hydrological and microbiological factors that govern NO_3 leaching and N_2O emissions.

The right timing of fertilizer application can similarly increase N use efficiency. In many regions, fall fertilizer applications have been common practice, allowing for fewer spring field operations and thus earlier planting. However, application rate recommendations are higher to account for the anticipated losses (Shapiro et al. 2008). Shifting application from fall to spring can improve NUE by more than to 20% (Dinnes et al. 2002) and significantly reduce both N_2O and NO_3 losses (Di and Cameron 2002; Hao et al. 2001). Split applications, in which growing season fertilizer is applied at multiple times, can also reduce losses, although additional labor, fuel, and equipment costs may make such practice unattractive in practice. Timing of fertilizer application can have differential effects by climate and soil type as well. For example, losses from fall N fertilizer application may be more pronounced in regions where the spring thaw generates a strong denitrification pulse (Johnson et al. 2011).

Fertilizer placement variations include broadcast versus banding as well as different depths of application. In irrigated systems, fertilizer can also be applied directly within the irrigation water (i.e., fertigation). Placement affects N availability to the plant, as well as availability for loss pathways. Soil and climate factors can also affect loss and yield responses to placement. For example, soils with stratified organic matter (i.e., significantly greater amounts near the surface) may lose less N to denitrification if fertilizer is placed at greater depth (Khalil et al. 2009). Lower temperatures may reduce the otherwise high NH_3 losses from broadcast fertilizer as compared with banded applications. Similarly, precipitation likely reduces NH_3 losses from broadcast fertilizer, but increases denitrification and leaching (N_2O and NO_3 losses).

The type or source of fertilizer influences the timing of availability and susceptibility to loss. For example, different N fertilizer sources perform better in terms of NUE in different locations. For example, ammonium-type fertilizer exhibits different N loss characteristics than urea fertilizer in different soils (Stehfest and Bouwman 2006; Venterea et al. 2010). Controlled- or slow-release fertilizers can also improve NUE and reduce losses (Snyder et al. 2009). Manure is an important nutrient source for many cropping systems, globally accounting for around 30% of N applied to crops (Bouwman et al. 2002), but because of highly variable N availability and significant losses, tends to achieve lower NUE rates.

Numerous studies address one or a few of these factors and their impact on crop yield, N use efficiency (NUE), and N losses. Others have reviewed the field-research to provide comprehensive pictures of the NUE and N loss implications of 4R management (for an example, see Dinnes et al. 2002). However, quantitative summaries of these field studies are limited, with a couple of the existing examples documenting GHG implications. Linquist et al. (2012) used meta-analysis to determine the GHG emission response (including N_2O) to fertilizer management in rice systems. Also, Eagle and Olander (2012) examined the GHG mitigation potential (including N_2O) of a range of agricultural practices, including the 4Rs of fertilizer management.

Any assessment of NUE and N loss must consider climate and soil characteristics in addition to management choices. Climate and soil affect not only yields but also other relevant management practices, such as irrigation, crop variety, and crop rotation, all of which have N use implications. Climate factors (including humidity, rainfall, and temperature) affect growing season length, frost patterns, and an associated spring thaw, with subsequent impact on N cycling dynamics.

Research Approach

A significant proportion of all field crop area in U.S. is in some corn rotation. Of the major field crops, corn uses the most fertilizer (in contrast with wheat or others), and much of the existing field research pertains to rotations dominated by corn. We therefore propose a focus on corn systems, understanding that there is significant potential for insights to be further applied to other cropping systems

The specific goals of this analysis are to determine the fertilizer management strategies that maximize yields while minimizing excess; to determine the factors that cause excess N to be lost via hydrologic and gaseous pathways; and to identify the regions and practices with the greatest potential for increased N use efficiency and reduced N loss. Given the extensive data available to address specific aspects of these relationships, **a meta-analysis will allow us to synthesize these relationships despite the fact that they are typically studied in isolation**.

Previous work by this research team compiled all known field research (as of 2011) in the U.S. and Canada regarding N_2O emissions and 4R Nutrient Management (Eagle and Olander 2012). This research project will use the literature database and expand that work to examine variability in climate and soils alongside other information on N loss and management. Specifically, we will develop a database of studies relating N fertilizer rate to corn yield, N_20 flux, and/or NO_3 leaching/runoff. The data base will include all other N management treatments (timing, placement, and source) as well as critical information on soils and climate. We will use this data base to assess the following:

1) The relationships between fertilizer application rate and corn yield across all soil types, climates, and fertilizer application practices.
2) Assess the rate of NO_3 runoff (or leaching) and N_20 emissions as a function of fertilizer application rate and as a proportion of excess N.
3) Test the hypothesis that the relationships for 1 and 2 above differ depending on fertilizer management practices (timing, placement, and source) and their interactions with soil type and climate. Figure 1 depicts what might be expected when comparing two different soil types.

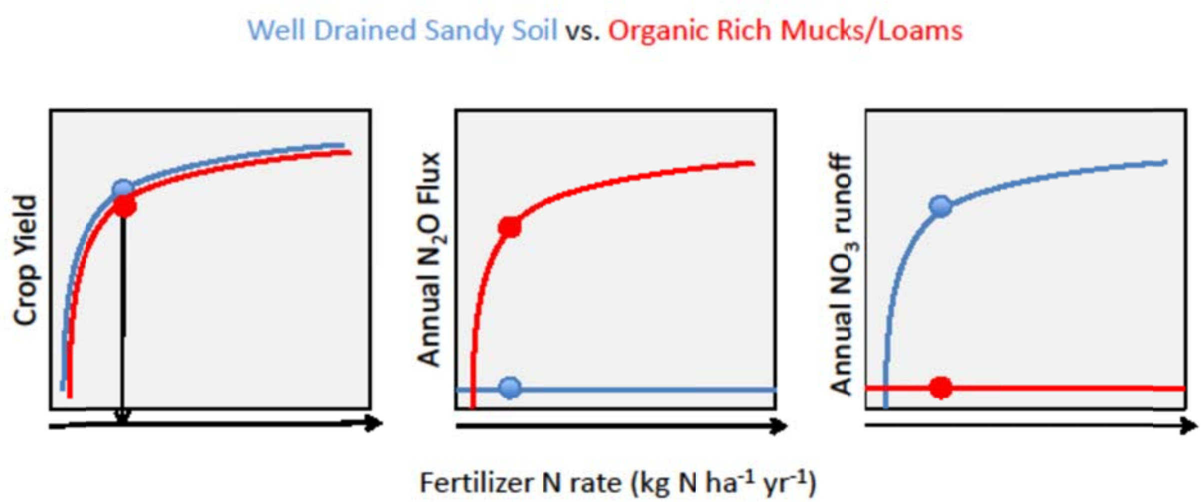

Figure 1. Schematic of anticipated relationships between N rate and yield, N_2O, and NO3. Here they are modified by soil drainage class. The proposed research will determine these relationships for different fertilizer management practices, climate zones, and soils.

Methodology

Beginning with the database on fertilizer management practices and N_2O emissions that was completed in 2011, this study will search for and review existing databases of field study observations. Data sources may be as simple as tables documented in review articles or more complex. These will be assessed as to their suitability for expansion and adaptation in the current application.

Using review articles as a starting point, and literature databases (e.g., Web of Science), we will then search for field studies that document N losses as affected by 4R nutrient management. Studies should be published and peer-reviewed, although gray literature may be included if carefully reviewed for quality. Calibrated models and gray literature may also be used to fill in gaps on a qualitative basis. Observations for inclusion can be at the field-scale or from plot studies (each study may have multiple observations), and will be limited to corn-dominated systems, at least in the initial stages of the review. The focus for 4R nutrient management will be on synthetic fertilizer, but manure will also be considered where it is an important nutrient source.

Data compilation

Database construction will include documenting the following factors, as available, for each observation: 4R management treatment(s), other treatment(s), irrigation status, crop yield, N uptake (could be estimated from yield), N losses (N_2O, NO_3 leaching, other, could be estimated from NUE), and details of climate and soil type (both could be estimated from location and climate/soil maps). Soil details will include texture, drainage, depth, and possibly tillage history.

Since economic implications of 4R nutrient management may vary by region or practice, any relevant information about such factors will also be recorded. This can include necessary adaptations to equipment, labor, management time (training etc.), and non-fertilizer inputs. The meta-analysis component of this project will focus on physical results, but future extensions or research on costs will find such information valuable. As well, other economic, environmental, or social implications may be relevant. In this vein, the database construction will note any changes in planting or harvest dates, crop drying, or other items mentioned in the research studies that may affect on-farm economics, the local community, or the surrounding environment.

Data Analysis

Using data collected, we will construct N fertilizer and N excess response curves for yield, N_2O emissions, and NO_3 leaching losses. The core relationships are thus these three key outputs as affected by both absolute fertilizer rate and by fertilizer excess (i.e., fertilizer N applied minus N uptake). In cropping systems, we tend to assume that crop plants have first priority for available N. Therefore, the relationship between absolute N rate and N losses will likely show more variability and noise than those that relate N excess to losses. The contrast of the two variables is therefore valuable.

The remaining 3 R's of fertilizer management (placement, timing, and source) as well as climate and soil characteristics will then be used to explain the residuals in these relationships, thus determining whether (and how) the response curves differ when considering other variables. We will use meta-regression analysis to quantify these effects. For example, the relationship between fertilizer rate and crop yield may vary by soil texture class (see Figure 2). Possible alternative dependent variables for these models include % N lost and proportion lost as N_2O versus NO_3 leaching.

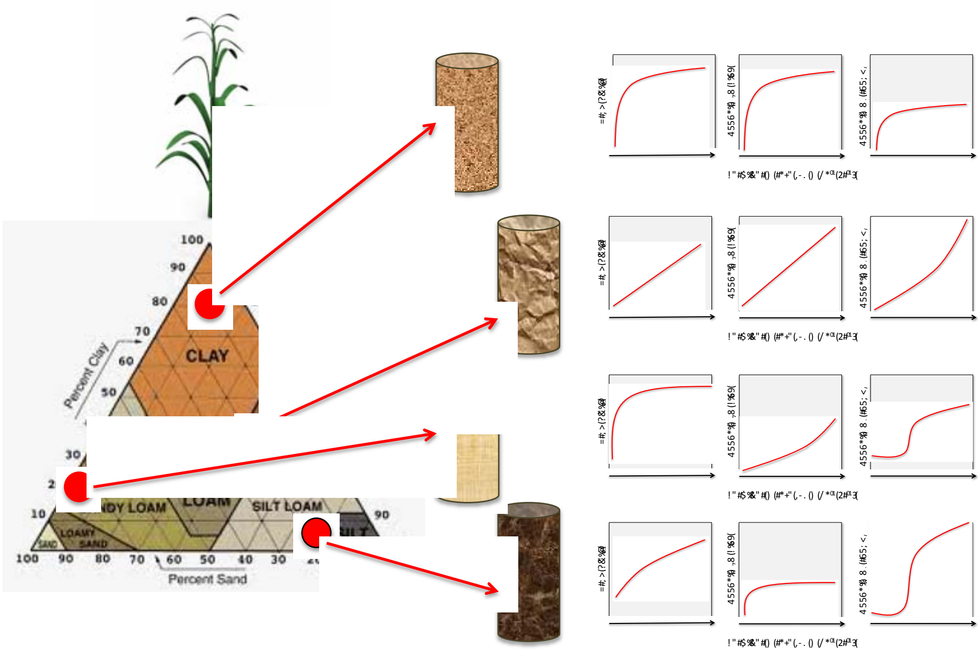

Figure 2. Schematic diagram of the core relationships of fertilizer rate (x-axis on all graphs) affecting yield, N_2O emissions, and NO_3 losses. The proposed meta-analysis is anticipated to inform the differences in these relationships between varying soil texture classes.

Because rate, yield, and at least one loss pathway will be consistently recorded in the data observations, this methodology allows us to utilize nearly all available data to construct the general relationships, and then assess the other – likely more sparse – characteristics on a different analytical level. Thus, the proposed method is preferred over multiple regression, which could result in a large number of missing data points. Other key management characteristics that affect N losses (e.g., irrigation status) must also be considered and interactions between variables will also be explored.

The models of loss pathways and yield in relationship to application will be constrained mechanistically within mathematical bounds, limiting the sum total of N removed (losses and plant uptake) to the total of N added (N fertilizer plus N fixation plus N deposition). Fertilizer management treatments will be either continuous (i.e., rate) or categorical (i.e., timing, placement, and source).

Timing will be examined in two key contrasts, 1) time of year, and 2) division into multiple applications. Time of year in field trials, especially in regions that can grow only one crop per year, most commonly contrasts fall versus spring applications. Split applications can further shift timing to coincide with plant demand, and may take the form of side-dress or fertigation (i.e., contained within multiple irrigation water applications). Timing may also be related to precipitation or irrigation timing, as data permit.

Fertilizer placement treatments in field trials include broadcast, banded, and varying depths. If sufficient data allow, placement by site-specific management zones will also be considered (e.g., see Delgado et al. 2005). Appropriate placement can vary by region, climate, and soil type, so these interactions may play an important role.

Fertilizer N source is most commonly addressed in two different contrasting treatment sets: 1) ammonium-based versus urea, and 2) conventional versus slow-release fertilizer. We will also include manure where it is important. The yield and loss responses to slow-release fertilizer may best be related to the examination of timing, especially that of split applications.

Climate may be constructed as discrete regions (e.g., the USDA ERS regions) or by using precipitation amounts and distribution throughout the year or growing season, in addition to temperature measures. Soil characteristics such as drainage, organic matter content, and texture are the most likely to have significant impact on losses.

Gap Analysis

As the available data are used to construct models that relate yield and losses to 4R fertilizer management, climate, and soil, we will also build a better understanding of the field research gaps in this area. Therefore, a further output will be a matrix that illustrates this gaps analysis. Table 1 demonstrates a possible format for this analysis. The results would help target future research investment to regions with low data or high potential impact.

Table 1. Example format for gaps analysis matrix from literature review (what do we have and what is missing, i.e., what we are able to analyze)

w variable application rate	type (NH_4-based, urea, slow-release)	placement (broadcast, banded)	timing (fall, spring, split)	USDA region (climate)	soil texture	rainfall (total or growing season)	Temperature or other
yield							
N_2O							
NO_3 leaching							
other losses							

Extrapolating implications of 4R management:

We will apply the refined understanding of NUE and N losses as affected by management across soils and climates to estimates of 4R management benefits with widespread adoption. We will assess at a national level (with regions broken out if possible), how the broad application of 4R practices (each one independently and then in combination where interaction data are available) can affect overall NUE, reduce need for N application and reduce N excess and loss. We will use scenarios designed to illustrate implications and use existing data to consider a baseline of current practice application.

Deliverables

1. Database including all field observations, with references. Format could be MS Excel, Stata, or other, as determined in consultation with the International Plant Nutrition Institute.
2. Research manuscript submitted to one of the ASA/CSSA/SSSA journals or a similar publication.
3. Synopsis of the research available as stand-alone report and submitted for publication in trade magazine or research periodical. Also can have a communication focused brief and link to report and data on NI website.
4. Based on the meta-analysis, a key output will be models of management practice (e.g., 4Rs) as affecting crop yield, N_2O emissions, and NO_3 losses. Ideally, these models will be available by soil type and climatic region, with confidence intervals determined for each effect.