Meta-analysis of Enhanced Efficiency Fertilizers in Corn Systems in the Midwest

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Rachel Cook, Southern Illinois University

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Introduction

The 4R approach to nutrient stewardship has helped develop a better context for driving best management practices in production agriculture. As the agricultural community becomes more involved in exploring the three aspects of sustainability, including the economic, social, and environmental triple bottom line, the 4Rs (right source, right rate, right time, and right place) provide a framework for better management of fertilizer applications.

The exceedingly large number of possible combinations of source, rate, time, and place, even within one cropping system, can make it difficult to compare results from studies located in different regions, with different climate, soils, and accepted management practices. To prevent needless duplication of study parameters and suggest future study directions, the soil fertility and fertilizer community needs to systematically compile what we know in order to move forward in the most efficient manner possible.

Out of the 87 million acres of corn harvested in the US in 2013 (USDA NASS, 2013), over 47 million acres were harvested in the Midwest alone (Illinois, Iowa, Indiana, Ohio, Missouri, Michigan, Minnesota, and Wisconsin). Unfortunately, this magnitude of corn production and its

high nitrogen requirement makes the region a major contributor to eutrophication and the hypoxic zone in the Gulf of Mexico. Therefore corn cropping systems in the upper Midwest are arguably the most important agricultural production systems for studying ways to more efficiently manage nitrogen fertilizers.

Nitrogen has remained at the forefront of sustainability issues surrounding agriculture. Nitrate contamination in groundwater and in surface waters as well as nitrous oxide emissions to the atmosphere have brought environmental scrutiny and threats of regulation. At the same time, economic and social pressures encourage farmers to push for increasingly higher yields with increasing use of nitrogen fertilizers. Enhanced-efficiency fertilizers including controlled-release products and amendments such as nitrification and urease inhibitors offer additional nitrogen management tools to reduce environmental impact and increase crop yields.

Environmental Outcomes

Protecting nitrogen from transformation and subsequent losses is highly environmentally-dependent and requires a host of sound management practices for optimizing yield while minimizing environmental degradation. Selection of the right nitrogen source and stabilizer for the environmental conditions is one means by which to mitigate against nitrogen losses following nitrification which can result in nitrate movement in subsurface drainage or leaching to groundwater, through surface runoff, and through denitrification and volatilization. An up-to-date meta-analysis of how enhanced-efficiency fertilizer practices such as using nitrification inhibitors, urease inhibitors, and controlled-release fertilizers can decrease adverse environmental impacts and improve plant utilization will help inform the agricultural community and will provide enhanced best management practices for Midwestern corn production.

Nitrogen losses

Nitrate is the dominant form of nitrogen found in soil water and is therefore the most important contributor to N leaching losses (Jacinthe et al., 1999). Leaching of nitrogen into groundwater and runoff into surface waters results in eutrophication and is a well-documented environmental consequence of production agriculture (Carpenter et al., 1998; McIsaac et al., 2001; in Gardner and Drinkwater, 2009). Subsurface losses of nitrate from continuous corn have tended to be higher than other types of crop rotations (Weed and Kanwar, 1996).

Nitrification inhibitors can prevent nitrogen losses to leaching and denitrification by slowing the conversion of ammonium to nitrate. Nitrification inhibitors can provide a useful tool to growers to keep applied nitrogen fertilizer in the ammonium form, thereby reducing losses to leaching, denitrification, and N_2O emissions (Wolt, 2004). Delaying nitrification is especially important in spring applications to maintain nitrogen in the soil profile until plants increase uptake. Most corn hybrids take up about 40% of N applied at preplant during the grain-filling stage (Ciampiti and Vyn, 2011) and so maintaining N in the soil profile throughout this period of crop growth is integral to efficient N use and restriction of N losses from the soil profile.

The most well-known nitrification inhibitors include nitrapyrin (sold as N-Serve and Instinct) and DCD (sold in Agrotainplus and SuperU). Nitrapyrin has traditionally been added during fall anhydrous ammonia application to prevent subsurface losses (Randall et al., 2003). The more recently available micro-encapsulated, liquid version of nitrapyrin (Instinct) has undergone much field testing and is allowing for increased use of nitrification inhibitors as an adjunct to liquid N applications. One recent study showed that the micro-encapsulated formulations of nitrapyrin significantly improved ammonium retention in the soil and reduced nitrous oxide emissions by up to 44% (Omonode and Vyn, 2013). These recent findings suggest that present-day use nitrification inhibitors may help reduce nitrate-N losses due to leaching or gaseous loss in a manner consistent with earlier studies (Wolt, 2004).

Experiments with fall-applied controlled-release fertilizers in some areas have shown greater yield than fall-applied urea. However, the potential for increased nitrate leaching is substantial compared to spring fertilizer application. Recent evidence has shown approximately 30% of fall-applied, controlled release fertilizer (ESN) in central Illinois could be lost by planting time (Karl Williard, personal communication)

Information regarding the magnitude of the effects of commonly used nitrification inhibitors, such as nitrapyrin and DCD, and controlled-release fertilizers needs to be compiled and analyzed for a better understanding of the possible environmental benefits as well as under what circumstances use of these products benefits corn yield in the Midwest.

Nitrous oxide emissions

Agricultural activities contribute up to 58% of anthropogenic non-CO_2 greenhouse gas emissions. Nitrous oxide is about 310 times more potent than CO_2 in global warming potential (Smith et al., 2007) and has been shown to increase exponentially with increasing nitrogen application rates (Millar et al., 2010). Use of nitrification inhibitors has been shown to reduce N2O emissions by 30–80% across a broad spectrum of agricultural soils (Akiyama et al., 2010). In contrast, urease inhibitors may not have much impact on nitrous oxide emission, while controlled-release fertilizers have been shown in only some cases to be effective (Halvorson and Del Grosso, 2012). A better understanding of the differences between these enhanced-efficiency fertilizers is required to better understand how nitrogen management in Midwestern crop production could reduce N_2O emissions.

Ammonia volatilization

Ammonia volatilization can lead to significant losses of N from urea based fertilizers leading to yield decline. Soil pH and CEC have been shown to be important factors influencing NH3 emissions following N application (Nelson, 1982). In addition, urease inhibitors may discourage volatile ammonia losses because they function to reduce amount of NH_3 volatilized during urea hydrolysis by inhibiting the urease enzyme.

It has been established that NBPT, the most commonly used urease inhibitor can increase yields when used with urea and UAN, especially in surface applications (Hendrickson, 1992). The combined effect of nitrification and urease inhibitors may furthermore have an additive effect in reducing NH_3 volatilization compared to use of nitrification inhibitors alone (Zaman and Blennerhassett, 2010), though these results have not been replicated on a wide enough range of conditions to make generalizations of efficacy (Kim et al., 2012). However, under controlled experimental conditions, a urease inhibitor (NBPT) and a nitrification inhibitor (DCD) combined with urea actually caused an increase in NH_3 volatilization by maintaining higher soil pH and soil NH4+ for greater duration, thereby offsetting the benefits of the urease inhibitor (Soares et al., 2012). A current meta-analysis on volatile ammonia losses due to nitrification and urease inhibitors and enhanced-efficiency fertilizers would help to clarify these effects and contribute to better management practices for reducing N losses.

Crop Utilization

Appropriate fertilizer N rate and timing are key in reducing N losses. Attaining optimal fertilizer rate is probably the most important factor for limiting N losses (Power and Schepers, 1989), and may contribute greatly to the variable yield responses measured with enhanced-efficiency fertilizers. Variable response in crop yield to use of nitrification inhibitors, urease inhibitors, and controlled-release fertilizers is often attributed to the timing, quantity, and frequency of rainfall after fertilizer application, as well as soil texture (Nelson et al., 2008).

Spring application of N with nitrapyrin has shown variable results and needs further review as to circumstances where it is most effective. In one study crops fertilized with spring-applied N with nitrapyrin showed significantly increased yield and increased crop value, in excess of the cost of nitrapyrin (Christensen and Huffman, 1992), but other studies have found no clear yield or economic advantage with nitrapyrin use (Blackmer and Sanchez, 1988). Additionally, there has been limited evidence of increased yields reported with use of

DCD (Barber et al., 1992).

Timing of nitrapyrin use may alter its impact on crop yield and nitrogen use efficiency. In Ohio, nitrapyrin addition did not affect yield for spring-applied fertilizer but did improve yield in fall-applied plots (Stehouwer and Johnson, 1990). Yield patterns were similar in Minnesota; nitrogen use efficiency was lowest with fall N applications (16%) but was improved with addition of nitrapyrin (26%) and was highest with spring N application irrespective of nitrapyrin use (42–48%).

Synchronizing crop uptake with fertilizer nitrogen availability with controlled-release products may improve nitrogen use efficiency and reduce N losses. In the North Central U.S. (Iowa, Kansas, Nebraska, Minnesota, Missouri, and Wisconsin), preplant controlled-release fertilizers have been shown to maintain similar yields to preplant anhydrous ammonia and urea + NBPT urease inhibitor, but out-yielded ammonium nitrate, urea, and UAN fertilizers by 1, 2, and 10 bu/acre respectively (Nelson et al., 2008). However, drought conditions may decrease yields when using controlled release fertilizers in comparison to urea alone.

Systematic review and meta-analysis

Putting a wide variety of studies regarding enhanced-efficiency fertilizers and their agronomic and environmental effects into context requires a systematic approach. Compiling data will require a systematic review and meta-analysis. Systematic review refers to the review of previously published research following an established unbiased approach to ensure results are objective. The systematic approach to review involves establishing a pre-defined study question, pre-identifying publications and databases and for systematic and thorough search and criteria for study inclusion, assessing the quality of the identified studies, summarizing evidence (including meta-analysis), and interpretation of the findings (Kahn et al., 2003).

Meta-analysis refers to the use of statistical methods to summarize quantitative research results across studies (Arnqvist and Wooster, 1995). These methods differ significantly from statistical analysis of regular experimental data, and tend to work upon standardized measures of effect size derived from the statistical summaries reported within individual studies (Gurevich and Hedges, 2001). Meta-analysis carries certain analytical advantages over narrative or qualitative review in allowing for genuine quantitative synthesis of study results that can produce objective measures of effects, and may reduce some types of statistical error. However, the meta-analysis approach is also not amenable to more familiar analytical approaches such as ANOVA or linear regression, and is subject to its own types of methodological bias and sources of error.

Meta-analysis has been successfully used to produce high-quality published research on topics of interest in agricultural research such as the effect of Bt crops on non-pest invertebrates (Marvier et al., 2007) and the effect of enhanced efficiency fertilizers on N_2O emissions across a broad array of agricultural soils (Akiyama et al., 2010).

Data Collection, Inclusion criteria, and Analysis

We will select a subset of the published scientific literature that fits specified criteria from peer-reviewed literature. Selected publications will: 1) address Midwestern corn systems, 2) be conducted under field conditions in the last 20 years, 3) address nitrification inhibitors, urease inhibitors, and/or controlled release fertilizers, and 4) have appropriate reporting of replication, means, and standard deviations. Grey literature, including results from proprietary industry trials may be included if they meet accepted standards for field research (i.e. sufficient replications, controls, analysis, etc).

We will compile a database that will characterize environmental variables (latitude and longitude, precipitation, soil texture, soil organic matter, and plot size) to the extent reported or available. Agronomic information such as nitrogen rate, source, timing, and placement, nitrogen use efficiency, tillage, and crop yield will be collated. Environmental effects or estimates of leaching, N_2O emission, runoff, etc will be compiled into the database. Ultimately, the terms of the meta-analyses will be driven to some extent by the quantity and quality of data currently available in the literature.

The meta-analysis will build on an upcoming project with Dow AgroSciences to re-evaluate the current literature on nitrapyrin sold as N-Serve. Funding to expand the analysis to include other nitrification inhibitors, urease inhibitors, and controlled release fertilizers will create a more useful and broader-scoped analysis of the environmental and agronomic benefits of these management practices in Midwestern corn production.