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IMPROVING NITROGEN USE EFFICIENCY IN CROP AND LIVESTOCK PRODUCTION SYSTEMS

More Food, Low Pollution (Mo Fo Lo Po): A Grand Challenge for the 21st Century

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Abstract

Synthetic nitrogen fertilizer has been a double-edged sword, greatly improving human nutrition during the 20th century but also posing major human health and environmental challenges for the 21st century. In August 2013, about 160 agronomists, scientists, extension agents, crop advisors, economists, social scientists, farmers, representatives of regulatory agencies and nongovernmental organizations (NGOs), and other agricultural experts gathered to discuss the vexing challenge of how to produce more food to nourish a growing population while minimizing pollution to the environment. This collection of 14 papers authored by conference participants provides a much needed analysis of the many technical, economic, and social impediments to improving nitrogen use efficiency (NUE) in crop and animal production systems. These papers demonstrate that the goals of producing more food with low pollution (Mo Fo Lo Po) will not be achieved by technological developments alone but will also require policies that recognize the economic and social factors affecting farmer decision-making. Take-home lessons from this extraordinary interdisciplinary effort include the need (i) to develop partnerships among private and public sectors to demonstrate the most current, economically feasible, best management NUE practices at local and regional scales; (ii) to improve continuing education to private sector retailers and crop advisers; (iii) to tie nutrient management to performance-based indicators on the farm and in the downwind and downstream environment; and (iv) to restore investments in research, education, extension, and human resources that are essential for developing the interdisciplinary knowledge and innovative skills needed to achieve agricultural sustainability goals.

Humankind faces a vexing problem of nourishing about 9.5 billion people by 2050 while still maintaining the integrity of the soil and water resources and the global climate system that food production requires. The early 20th century invention of the Haber-Bosch process to synthetically convert inert atmospheric dinitrogen (N_2) gas to more reactive forms, initially to provide munitions to Germany during World War I and later harnessed for producing chemical fertilizers, has transformed our modern agricultural system and has enabled the current human population to swell to more than 7 billion people (Erisman et al., 2008). Although there are still about 1 billion undernourished people in the world, we are, on average, better nourished than at any time in human history. Moreover, the American Farm Bureau Federation (2011) estimates that on average, the work of a single US farmer can feed about 150 people, thus freeing most of us to pursue other professional, economic, and cultural endeavors.

However, this transformation of 20th-century agriculture has come at considerable environmental cost, calling into question the future sustainability of this model (Sutton et al., 2013). Indeed, it has been suggested that we have already exceeded a planetary boundary with respect to human-mobilized reactive nitrogen (Steffen et al., 2015). Averaged globally, about half of the fertilizer nitrogen (N) applied to farms is typically removed with the crops, while the other half either remains in the soils or is lost from the farmers' fields (Lassaletta et al., 2014). Losses occur mostly as nitrate (NO_3^-) and dissolved organic nitrogen (DON) leaching into groundwater and surface waters, or as ammonia (NH_3), nitric oxide (NO), nitrous oxide (N_2O), and N_2 gases emitted to the atmosphere (Galloway et al., 2004; Sutton et al., 2013). Of these possible unintended fates of fertilizer N, only the return to N_2 gas is environmentally innocuous. In contrast, NO_3^- and DON contribute to unwanted eutrophication and harmful algal blooms in downstream aquatic ecosystems, NO_3^- is a regulated pollutant in drinking water, NO is a precursor to tropospheric ozone pollution, NH_3 and NO are precursors to

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Abbreviations: CEAP, Conservation Effects Assessment Project; CP, crude protein; DON, dissolved organic nitrogen; ESN, Environmentally Smart N; NUE, nitrogen use efficiency; TDN, total dissolved nitrogen.

particulate matter air pollution and contribute to N deposition onto downwind ecosystems, and N_2O is both a potent greenhouse gas and a significant stratospheric ozone-depleting substance (Davidson et al., 2012; Galloway et al., 2003). Additional pathways for these soluble and gaseous N losses occur when crops are fed to livestock (Galloway et al., 2007), which produces N-rich manure that must also be managed. As global mean per capita meat and dairy consumption rise at the same time that population also grows, the challenges of making our food production systems efficient with respect to N use will be compounded.

Improving NUE in Crop and Livestock Production Systems: Existing Technical, Economic, and Social Impediments and Future Opportunities

In August 2013, about 160 agronomists, scientists, extension agents, crop advisors, economists, farmers, representatives of regulatory agencies and nongovernmental organizations, and other agricultural experts gathered at a conference, Improving Nitrogen Use Efficiency in Crop and Livestock Production Systems: Existing Technical, Economic, and Social Impediments and Future Opportunities, to discuss this vexing challenge at a conference in Kansas City, MO, cosponsored by the Soil Science Society of America, the American Geophysical Union, a National Science Foundation Research Coordination Network project on Reactive Nitrogen in the Environment, the International Plant Nutrition Institute, The Fertilizer Institute, and the International Nitrogen Initiative. Much knowledge and many techniques already exist to advance the dual goals of making agriculture more productive and environmentally sustainable, yet many economic and social barriers stand in the way of widespread adoption of these practices by farmers. Specifically, this interdisciplinary group of experts was asked the question:

> What are the technical, economic, and social impediments and opportunities for increased nitrogen use efficiency in crop and animal production systems?

Nitrogen use efficiency (NUE), defined here as the ratio of N removed in the harvest to the N inputs from fertilizers, manures, N fixation, and other amendments, has increased during the last several decades in most developed countries (Lassaletta et al., 2014). In the United States, fertilizer N use has leveled off while crop yields continue to increase (Davidson et al., 2012). Techniques responsible for increasing crop yields and livestock production and improving NUE include improved irrigation and water management, new crop varieties and animal breeds, controlled-release fertilizers and urease and nitrification inhibitors, improved soil and plant testing to match nutrient applications with crop demands, use of winter cover crops, precision agriculture technologies, improved nutrition management of livestock, and increasing availability of decision support tools for farmers and crop advisors. The "4-R Nutrient Stewardship" concept is being actively promoted by university extension and industry groups, based on sound scientific understanding of applying the **R**ight source of nutrients at the **R**ight rate, **R**ight time, and **R**ight place (Snyder et al., 2014). Improving NUE has the potential of creating win-win outcomes for both the farmer and the environment by increasing yield and profitability while decreasing N surplus that may be lost to the environment (Fig. 1).

Nevertheless, while agronomic science and technology may permit further improvement in NUE, many effective current technologies are not utilized because economic and social barriers impede their adoption. Unlike many scientific conferences that focus almost exclusively on agricultural science and technology, considerable time was devoted at the Kansas City conference to articulating and examining the social and economic impediments to improving NUE. Some common themes summarized in a conference consensus statement (Kansas City Consensus, 2013) include the following:

1. Economic signals regarding the cost of nitrogen fertilizers are mixed. Many farmers say that N fertilizer is expensive enough to incentivize them to improve NUE, but most also agree that the economic risk of applying too little N is high. In short, fertilizer N application provides an important economic margin of safety, much like relatively affordable insurance.
2. A lack of visible or tangible local environmental and economic consequences of N losses from farming operations can make further improvements of NUE a difficult sell.
3. Agricultural extension services have diminishing reach, and sociological research shows that most US farmers now obtain the majority of their information about management

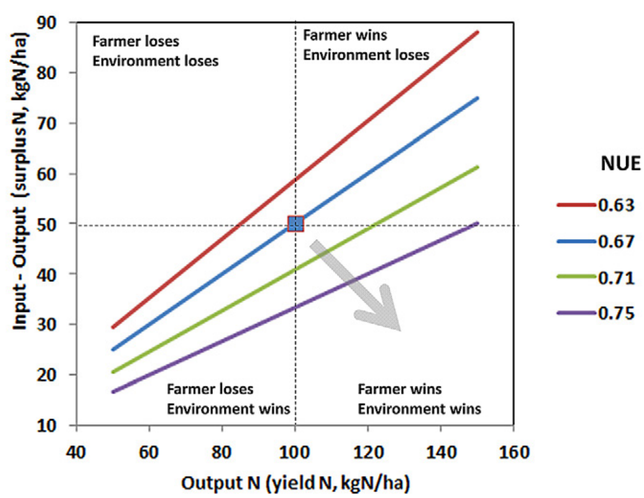

Fig. 1. Illustration of nitrogen use efficiency (NUE) values plotted as functions of N outputs (defined as the N removed from the field in the harvested crop) and N surplus (defined as total N inputs to the site from fertilizers, manures, and other amendments minus the N in the harvested crop removed from the site). The point at the center is for a hypothetical farm with a NUE of 0.67 (100/150) from applying 150 kg N ha^{-1} yr^{-1} and removing 100 kg N ha^{-1} yr^{-1} in the harvest, leaving a N surplus of 50 kg N ha^{-1} yr^{-1}. These are reasonable values for corn grown in the midwestern United States. The arrow points in the direction of increasing NUE, increasing harvested crop-N, and decreasing N surplus relative to the hypothetical starting point, which would be win-win progress for the farmer and the environment. Plotting input–output data this way over time would demonstrate the trajectory of progress for improving yield while decreasing N losses. While this example is presented for a single farm, the same approach could be applied to aggregated data at watershed, state, or national scales. See Zhang et al. (2015) for further development of farmer-profit/environmental-benefit trade-offs.

from family members, retailers, and private sector crop advisors (Fig. 2). Hence, the most effective role of extension may now be to train the retailers and crop advisors so that these private sector stakeholders may then become the trusted sources of up-to-date nutrient management information for the majority of farmers.

4. The younger generation of farmers is increasingly well educated and is willing to consider new technologies and to try Web-based decision support tools; nevertheless, abandoning their parents' and grandparents' tried-and-true practices remains a barrier. Most farmers have significant demands on their time and labor. Learning and adopting new practices requires that the proposed innovations are compelling, easily implemented, and worth their time.

In this special section of the *Journal of Environmental Quality*, we provide another product of the 2013 Kansas City conference. This collection of 14 papers authored by conference participants presents studies of many of the technical, economic, and social impediments to improving NUE in crop and animal production systems. The papers include original field research on the efficacy of NUE technologies and management practices, case studies of past and current voluntary and regulatory programs designed to improve NUE and to reduce N pollution from agricultural fields, and economic analyses of the effects of fertilizer-to-crop price ratios on adoption of NUE technologies. In the following section, we provide brief summaries and highlights of these papers.

Contents of the Special Section

The Quest for Environmental and Economic Win-Win Options

Zhang et al. (2015) present a case study on corn (*Zea mays* L.) production in the US Midwest to demonstrate how their NUE Economic and Environmental impact analytical framework model (NUE[3]) can be applied to farmers' economic decision making and to policy analyses. The model uses data that relate adoption of technologies and management practices to changes in the yield ceiling, the optimal N fertilization rate, and N losses to the environment. Although technology can increase NUE, it can also increase the yield ceiling, which provides an incentive for farmers to apply more N to achieve higher yield. Whether N losses to the environment increase or decrease depends on whether the increase in NUE exceeds the increase in N application. The authors calculate the range of prices and yield responses that both benefit the farmer economically and result in lower N losses to the environment, thus providing a useful modeling framework tool for policy makers to understand how plausible combinations of fertilizer, crop, and technology implementation prices will likely affect the possibility of achieving win-win outcomes for both farmers and the environment.

Kanter et al. (2015) also searched for a "sweet spot" in their economic analyses, including not only the environment and farmers but also the fertilizer industry. The authors pose the question: "Is it possible to improve N management while reducing farmers' costs and increasing the profitability of the fertilizer industry?" Measures to improve NUE include increased demand for more efficient fertilizer technologies and services, which are often patent-protected and sold to farmers by the fertilizer industry. The authors used a cost-benefit analysis of moderate and ambitious NUE targets in corn sectors of the United States and China, projected to 2035, to demonstrate a potential for a "sweet spot" in both countries. Current extensive overapplication of fertilizer in China creates a greater potential for farmers and the fertilizer industry to gain economically from improved N management. Acknowledging large uncertainties in the monetary valuation of the environmental benefits of improving N management, the authors show consistently large monetized environmental benefits compared to economic

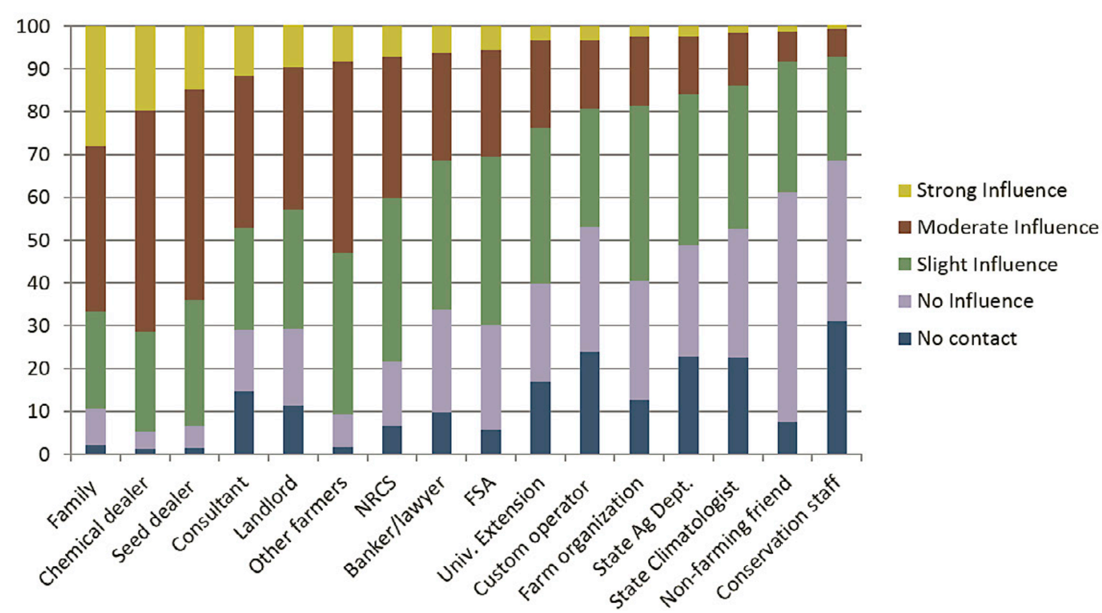

Fig. 2. Results of a 2012 survey of 4778 medium- to large-sized corn producers in the midwestern United States, conducted by scientists from two USDA National Institute of Food and Agriculture–funded projects, the Corn-Based Cropping Systems Coordinated Agricultural Project (www.sustainablecorn.org) and Useful to Usable (www.agclimate4u.org). Results presented are in response to the question, "Please indicate how influential the following groups and individuals are when you make decisions about agricultural practices and strategies." More information about the methodology of this survey and survey findings can be found in Arbuckle et al. (2013) and **Loy et al. (2013)**. FSA, USDA Farm Service Agency.

impacts on farmers and the fertilizer industry from improved NUE measures. This result suggests that, for farmers and industry to be included broadly and effectively in finding a balance of improved NUE and lower losses of N to the environment, policy options may be needed to include economic incentives beyond those currently in the marketplace.

Powell and Rotz (2015) use the Integrated Farm Simulation Model (IFSM) to illustrate differences in feed and fertilizer N use and N outcomes of two representative dairy farms in Wisconsin. Dairy farms that import all grain and protein supplements have more than double the amount of manure-N to manage per hectare and therefore incur much higher NH_3 losses per hectare compared with farms that grow their own corn and import only protein supplements. The authors use these simulations, along with analyses of regional studies, long-term field experiments, nutrition trials, and other published information, to demonstrate the importance of integrating NUE across mixed crop and animal production systems. For example, a 20 kg ha^{-1} yr^{-1} reduction in fertilizer-N use would decrease fertilizer costs and N losses but may decrease overall profits per cow due to a need to purchase more protein supplements to compensate for lower dietary crude protein (CP) concentrations in corn silage. However, because about 50% of lactating dairy cows in Wisconsin are fed dietary CP in excess of the optimum, reductions in fertilizer-N use and accompanying CP reductions in corn silage may actually provide desirable outcomes both in the form of reduced fertilizer costs and in reduced dietary CP, and the latter would reduce urinary urea N and therefore losses of NH_3 and N_2O. This study demonstrates how process-level, whole-farm simulation provides a useful tool for evaluating the economic and environmental tradeoffs of strategies to improve N use and reduce N loss from dairy production.

Assessing NUE Improvements Needed to Reach Environmental Goals

McCrackin et al. (2015) simulated the mitigation efforts that would be needed to reduce export of total dissolved nitrogen (TDN) from land to sea in the United States by about 25% by the year 2030. Concentrations of TDN in rivers are important because N enrichment is associated with eutrophication of lakes and estuaries, drinking water contamination, and increased frequency and severity of harmful algae blooms and hypoxia that affect fishing and tourism industries. The authors estimated total US riverine export of 2.1 Tg TDN yr^{-1} for the year 2005 using the Nutrient Export from Watersheds model, which compared well with measured exports across 29 catchments representing 65% of land surface area for the continental United States. The model was then used to simulate 2030 export rates of 2.2 Tg N yr^{-1} in a "business as usual" scenario and 1.6 Tg N yr^{-1} with "ambitious" approaches to nutrient management. Agriculture was the source of nearly half of these TDN riverine exports. The ambitious scenario includes an aggressive 25% improvement in agricultural nutrient use efficiency, a 20% reduction in N runoff from croplands, and a 30% reduction in NH_3 emissions from agriculture, while still allowing fertilizer N inputs to increase from 10.8 to 11.3 Tg N yr^{-1} in the United States to meet food production demands. The authors acknowledge many uncertainties in their scenario projections, but their work demonstrates that given substantive investments of resources, reductions in coastal N loads are possible.

van Grinsven et al. (2015) compared and contrasted historical trends of N budgets and emissions to air and water and the associated lessons learned in the European Union (EU) and the United States. Generally, nutrient surplus problems were more acute and severe in the EU than the United States during the 1970s and 1980s, but removal of fertilizer subsidies and regulation-driven changes have since reduced EU environmental N loads and brought them closer to US conditions. In contrast, fertilizer use in the United States has mostly stabilized without strong regulation, although NH_3 emissions are still increasing. The authors analyzed these differences using statistical data from 1900 to 2005 and the global IMAGE model. A reduced fertilizer scenario indicated that even a 25% reduction in application rates is insufficient to achieve policy targets of a 45% reduction in N loads to the Gulf of Mexico. The EU river loads under this scenario could achieve policy targets for Northeast Atlantic and the Baltic Sea, but such drastic measures have a risk of yield reduction and could "export" environmental problems by expanding crop production area elsewhere. On the other hand, an integrated manure management scenario indicated substantial potential to increase agricultural N recovery and reduced N load to rivers in both the United States and the EU.

Insights from Social Science Studies

David et al. (2015) used both on-farm biophysical measurements and social science surveys to evaluate five management practices (drainage management, constructed wetlands, woodchip bioreactors, fertilizer timing and cover crops) designed to help reduce NO_3^- loading from tiled drained fields under corn or soybean [*Glycine max* (L.) Merr.] of two watersheds in east-central Illinois. Both rivers exceeded the USEPA drinking water standard of 10 mg N L^{-1}. All methods except drainage water management resulted in some level of reductions in NO_3^- losses at the farm scale. However, there was no evidence at the watershed scale that stream NO_3^- concentrations have decreased during the last 21 yr. Although farmer surveys revealed moderate concern about water quality and general expression of strong environmental and stewardship ethics, fewer than 20% of farmers perceived NO_3^- as a water quality problem. Out-of-pocket expenses were quoted as being the greatest factor limiting farmers' ability and willingness to implement water quality nutrient management, followed closely by lack of government funds for cost sharing and concerns about reduced yields. The surveys indicated that financial incentives and more readily available evidence demonstrating effective local pollution reduction would have the greatest effect on adoption rates. In summary, the study reveals that the NO_3^- mitigation methods had some effectiveness at the farm scale but had little acceptance socially and would have to be implemented on a grand scale to be effective.

Osmond et al. (2015) synthesized results from informant surveys in 13 watersheds of the USDA Conservation Effects Assessment Project (CEAP) study, supplemented with field surveys from three nutrient-impaired watersheds in North Carolina. The CEAP results indicate that farmers generally did not follow nutrient management plans or basic soil test recommendations even when they had them. Reasons included lack of trust in university extension recommendations for N applications, preference for fertilizer dealer recommendations, and a perception of abundant N as insurance. In the North Carolina study, the data indicated that many farmers were making their fertilizer application decisions based on little technical advice. More successes were achieved in CEAP watersheds where there were project investments in education, outreach to small farmer groups, and financial incentives such as cost sharing. The authors warn that without better dialogue with farmers, as well as meaningful investment in strategies that reward farmers for taking what they perceive as risks relative to nutrient reduction, little progress in true adoption of nutrient management is probable.

Weber and McCann (2015) examined the factors that predicted farmer adoption of three different NUE technologies: soil N testing, N transformation inhibitors, and plant tissue testing. Data from the USDA Agricultural Resource Management Survey of corn growers were used in an adoption decision model to test several hypotheses about factors related to these NUE technologies. Of the 1840 observations, 27% of the farmers in the study received their application recommendations from a fertilizer retailer, whereas 50% said they did not receive any recommendations from anyone. Data also showed that 21% of farmers had conducted soil N tests, 10% used controlled release fertilizer or some sort of N transformation inhibitor, and only 3% adopted the use of plant tissue sampling. Adoption of plant tissue testing was positively linked to the use of other innovations, such as conservation tillage. Results did not support the authors' hypothesis that higher education led to higher NUE adoption rates, but the hypothesis that younger farmers were more likely to use these technologies was supported. Moreover, farmers who had not sought outside recommendations for fertilizer usage had lower NUE technology adoption, and those who received recommendations from a retailer rather than a crop advisor also had lower adoption rates. Financial incentives for past adoption practices were positively associated with adoption of both soil N and plant testing. The authors recommend that research is needed to determine how other variables, such as local soil conditions, the use of the Internet as an information source, and educational outreach efforts tailored to farmers' needs, may be related to adoption of NUE technologies.

Perez (2015) studied how the policy-making process affected farmer compliance and nutrient management practices from 2001 to 2008 in Delaware, Maryland, and Virginia, the three states of the Delmarva Peninsula, which contributes runoff to the Chesapeake Bay. All three states required farmers to follow a state-certified nutrient management plan to optimize crop yields and minimize environmental losses, although the policy-making processes in each state were different. In Maryland, farmers had little role in policy-formation negotiations and felt they were ostracized from the process. In contrast, Delaware farmers were engaged and included as members of a nutrient management commission. Maryland farmers initially had poor compliance rates for developing nutrient management plans, although compliance was nearly complete by the final year of the study. Delaware enjoyed a successful initial start, but about 30% of acreage was still not compliant at the end of the study. In Virginia, the majority of farmers in the regulated area needed only a manure transport plan rather than a nutrient management plan, and thus compliance was excellent throughout the study period. A survey of 60 farmers revealed that 60% were unaware of the size of penalty for noncompliance. Without a credible likelihood of detection of or consequences for violations in any of the states, compliance to the regulatory requirement and subsequent following of the nutrient management plans were effectively voluntary. Next, the author asked the question: Did having the laws improve nutrient management practices? Good adoption (>60% responding) was reported in interviews for possessing a current plan, taking soil and manure nutrient tests, and split-applying N fertilizer. Poor adoption (<60%) was reported for taking residual N credits for previous legume crops or manure use, keeping manure-free setbacks next to surface waters, avoiding manure application in winter, and frequent calibration of manure spreaders. The author concludes that the experiences in these states demonstrate the desirability of obtaining strong farmer buy-in by engaging farmers early in the policy deliberation process, and that compliance enforcement must also be clear and feasible for policy to achieve its goals.

Recent Applications of Technological Advances

Fernández et al. (2015) examined the role of different N sources on N_2O emissions in tile-drained continuous corn in Illinois. The study found that a polymer-coated urea (Environmentally Smart N [ESN]) reduced N_2O emission in only 1 of 3 yr, which was a warm wet year. Under conditions favorable for high N_2O emissions, ESN reduced N losses by 30% compared with untreated urea. Interestingly, ESN did not delay the N_2O flux. Slightly higher losses were observed for anhydrous ammonia. Overall, 2.85% of the applied N was lost by N_2O emissions. The use of ESN also increased grain yield by 16% relative to urea. While a 2 to 3% loss of fertilizer N may not provide economic benefits, a 16% increase in grain yield would be sufficient to provide economic incentive. The lack of response in 2 of the 3 yr complicates the benefits and acceptance of using ESN.

Soares et al. (2015) found that nitrification inhibitors reduced N_2O emissions from fertilized sugarcane (*Saccharum officinarum* L.) fields in Brazil by more than 90%, but a controlled-release fertilizer was ineffective. Reducing N_2O emissions is an important challenge for the use of sugarcane for producing biofuels because N_2O emissions negate some of the potential greenhouse gas mitigation resulting from substituting biofuels for fossil fuel combustion. Although showing considerable potential to reduce N_2O emissions, the authors note that nitrification inhibitors are not commonly used in Brazil because they are costly, they do not always bring crop yield increases, and losses of fertilizer-N through N_2O emissions and nitrate leaching are a small fraction of fertilizer costs. The authors conclude that mitigating N_2O emissions from agriculture may require broader approaches to incentivize farmers to adopt technical solutions such as nitrification inhibitors.

Jarecki et al. (2015) estimated N_2O emissions for corn production across the state of Iowa. They were able to develop a database of soil information, weather, corn production, and fertilizer used as input variables in the biogeochemical model Denitrification-Decomposition (DNDC). The model estimated a range of 2.2 to 4.7 kg N ha^{-1} yr^{-1} for N_2O emissions across the state, with higher emissions associated with regions that had higher corn yields and thus higher N fertilizer inputs. The Intergovernmental Panel on Climate Change default value is 1% of N inputs with an uncertainty range of 0.3 to 3%. In some cases, the experimental data suggested emissions close to the 3% threshold. The DNDC-simulated emission values were lower than measured values, which may have been due to higher emissions resulting from winter freeze–thaw cycles. A well-calibrated model such as DNDC is a valuable tool to test N management strategies based on soil, crop, and climatic regions.

Lacey and Armstrong (2015) explore the option of using cover crops to retain N applied in the fall. Fall application, which is a common practice in the US Corn Belt, can lead to high losses of N and low NUE. One estimate is that 25% of corn producers applied N in the fall, but in one watershed in Illinois 55% of producers applied N in the fall. Tillage radish (*Raphanus sativus* L.), a fall cover crop that dies during the winter, and cereal rye (*Secale cereale* L.), a winter cover crop, reduced spring profile NO_3^- from 220 kg N ha^{-1} to 180 and 130 kg N ha^{-1}, respectively. Corn silage yield and N uptake were not affected by the cover crops. While this strategy might help reduce N losses of fall-applied N, the cost of the cover crop and the lack of a yield benefit needs evaluation. The impact of cover crops on N losses via tile drains or gaseous-N emissions should be evaluated as well.

A Success Story with Cautions

One of the few examples of partially successful regulated agricultural N management is in the Platte River Valley of Nebraska (Ferguson, 2015). Groundwater management districts were formed by the state legislature in the late 1980s in response to widespread NO_3^- contamination of groundwater, which reached levels of 30 to 40 mg NO_3^--N L^{-1} and sometimes greater. The average fertilizer-N application rate of 154 kg N ha^{-1} yr^{-1} has been nearly constant from 1967 to 2010, yet corn production has increased steadily, resulting in a near doubling of NUE. Increased NUE has resulted from both regulatory policies and nonregulatory trends, including (i) appropriate credits for legume-N, soil-N, and N in irrigation water; (ii) realistic yield expectations; (iii) economically based N-rate recommendations; (iv) better timing of fertilizer application to match plant-N needs; and (v) improved corn hybrids. The end result is that the difference in applied N and recommended N decreased from 34 kg N ha^{-1} in 1988 to 19 kg N ha^{-1} in 2012, and groundwater NO_3^- concentrations have declined on average by 0.15 mg N L^{-1} yr^{-1}, with residue soil NO_3^--N declining by 2.4 kg N ha^{-1} yr^{-1}. A shift from furrow irrigation to sprinkler irrigation was estimated to be responsible for 50% of the change in groundwater NO_3^- concentrations. However, although 25 yr of intensive mitigation significantly decreased groundwater NO_3^-, the concentration remains above 10 mg NO_3^--N L^{-1}. It should also be noted that this region is characterized by sandy soils with a shallow aquifer, thus quick to be contaminated but also quick to recover, suggesting that results of mitigation may be even slower in other regions. Ferguson suggests that the mitigation potential of adopting current technologies may have reached a limit in this case and that the development, refinement, and adoption of the next-generation of nutrient management techniques, such as fertigation, controlled release fertilizers, and crop canopy sensors for variable rate N application, may be required for further significant gains in NUE.

Recommendations for Interdisciplinary Research and Policy Development

This collection of papers highlights how important economic and social considerations are for the adoption of existing and new technologies to improve NUE. The goals of producing more food with low pollution will not be achieved by technological developments alone but will also require policies that recognize the economic and social factors affecting farmer decision making. A few success stories chronicled herein have a common theme of tailoring regulations, incentives, and outreach to local conditions, administered and enforced by local entities, and where local buy-in has been obtained. Rather than targeting individual farmers with nationally administered programs, small groups of farmers, consultants, academics, and regulators, working together to solve common production or conservation issues, can be much more effective.

The traditional role of university-based and government-based agricultural extension agents is also changing (Prokopy et al., 2015). Several studies in this collection clearly document that most US farmers now consider retailers and private sector crop advisors as their most trusted sources of information regarding nutrient management. Therefore, it is imperative that good science-based advice is provided through these trusted sources. This conduit of extension information could be an effective means of reducing farmers' perceptions of risk and their perceived need to apply additional fertilizer-N as insurance, but it will require more cooperation among university-based extension and research and private sector advisors and retailers.

Finally, long-term sustainability of agriculture will depend on innovative management of crop and animal production systems, including technological, economic, and social innovations. Investments in research, education, extension, and human resources will be essential for developing the interdisciplinary knowledge and skills needed for such innovation and to achieve sustainability goals.

From the lessons learned at the Kansas City conference and from this extraordinary collection of papers, we highlight the following recommendations:

- Develop partnerships and networks at local and regional levels among industry, universities, governments, nongovernmental organizations, crop advisors, and farmers to demonstrate and quantify the most current, economically feasible, best management NUE practices for the local situation.
- Improve continuing education to private sector retailers and crop advisors on the most up to date nutrient management practices through professional certification programs by university and government extensions and scientific societies.
- Tie nutrient management to performance-based indicators, including NUE indicators on the farm, with strong incentives for farmers to participate and report data. Similarly, well-defined downwind and downstream environmental quality indicators are also needed and should be tied to monetary values where appropriate and feasible.
- Restore investments in research, education, and extension by federal and state governments; these are essential for

developing the knowledge and skills needed for crop and animal production system innovations. These approaches must integrate agronomic, ecological, economic, and social science knowledge of food production and the related environmental, economic, and social costs to society. Such efforts should emphasize long-term, interdisciplinary, watershed-level research and outreach.

Conclusion

The technological, economic, and social impediments to improve NUE are not insurmountable, but there is no silver bullet, nor silver plow, for solving the challenge of producing more food with low pollution. Synthetic N fertilizer has been a double-edged sword, which greatly improved human nutrition during the 20th century but which also poses other major human health and environmental challenges for the 21st century. Fortunately, the "Mo Fo Lo Po" goal is easy to articulate and understand, and our knowledge base and technological expertise are already good. However, overcoming technical, economic, and social impediments to improving NUE in modern agriculture, while also meeting society's food and energy security needs, will require significant new investments and cross-sectoral partnerships in knowledge-based agriculture.

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References

American Farm Bureau Federation. 2011. Each U.S. farmer feeds 154 people. American Farm Bureau Federation, Washington, DC. http://www.fb.org/assets/files/yourag/2011_FoodandFarmFacts_page8.pdf.

Arbuckle, J., L. Prokopy, T. Haigh, J. Hobbs, T. Knoot, C. Knutson, A. Loy, A.S. Mase, J. McGuire, L.W. Morton, J. Tyndall, and M. Widhalm. 2013. Climate change beliefs, concerns, and attitudes toward adaptation and mitigation among farmers in the midwestern United States. Clim. Change 117:943–950. doi:10.1007/s10584-013-0707-6

David, M.B., C.G. Flint, L.E. Gentry, M.K. Dolan, G.F. Czapar, R.A. Cooke, and T. Lavaire. 2015. Navigating the socio-bio-geo-chemistry and engineering of nitrogen management in two Illinois tile-drained watersheds. J. Environ. Qual. 44:368–381. doi:10.2134/jeq2014.01.0036

Davidson, E.A., M.B. David, J.N. Galloway, C.L. Goodale, R. Haeuber, J.A. Harrison, R.W. Howarth, D.B. Jaynes, R.R. Lowrance, B.T. Nolan, J.L. Peel, R.W. Pinder, E. Porter, C.S. Snyder, A.R. Townsend, and M.H. Ward. 2012. Excess nitrogen in the U.S. environment: Trends, risks, and solutions. Issues in Ecology 15. Ecological Society of America, Washington, DC.

Erisman, J.W., M.A. Sutton, J. Galloway, Z. Klimont, and W. Winiwarter. 2008. How a century of ammonia synthesis changed the world. Nat. Geosci. 1:636–639. doi:10.1038/ngeo325

Ferguson, R.B. 2015. Groundwater quality and nitrogen use efficiency in Nebraska's Central Platte River Valley. J. Environ. Qual. 44:449–459. doi:10.2134/jeq2014.02.0085

Fernández, F.G., R.E. Terry, and E.G. Coronel. 2015. Nitrous oxide emissions from anhydrous ammonia, urea, and polymer-coated urea in Illinois cornfields. J. Environ. Qual. 44: 415–422. doi 10.2134/jeq2013.12.0496

Galloway, J.N., J.D. Aber, J.W. Erisman, S.P. Seitzinger, R.W. Howarth, E.B. Cowling, and B.J. Cosby. 2003. The nitrogen cascade. Bioscience 53:341–356. doi:10.1641/0006-3568(2003)053[0341:TNC]2.0.CO;2

Galloway, J.N., M. Burke, G.E. Bradford, R. Naylor, W. Falcon, A.K. Chapagain, J.C. Gaskell, E. McCullough, H.A. Mooney, K.L.L. Oleson, H. Steinfeld, T. Wassenaar, and V. Smil. 2007. International trade in meat: The tip of the pork chop. Ambio 36:622–629. doi:10.1579/0044-7447(2007)36[622:ITIMTT]2.0.CO;2

Galloway, J.N., F.J. Dentener, D.G. Capone, E.W. Boyer, R.W. Howarth, S.P. Seitzinger, G.P. Asner, C.C. Cleveland, P.A. Green, E.A. Holland, D.M. Karl, A.F. Michaels, J.H. Porter, A.R. Townsend, and C.J. Vorosmary. 2004. Nitrogen cycles: Past, present, and future. Biogeochemistry 70:153–226. doi:10.1007/s10533-004-0370-0

Jarecki, M.K., J.L. Hatfield, and W. Barbour. 2015. Modeled nitrous oxide emissions from corn fields in Iowa based on county level data. J. Environ. Qual. 44: 431–441. doi:10.2134/jeq2014.03.0100

Kansas City Consensus. 2013. http://nitrogennorthamerica.org/pdf/KansasCityConsensus_Final_Nov_2013.pdf.

Kanter, D.R., X. Zhang, and D.L. Mauzerall. 2015. Reducing nitrogen pollution while decreasing farmers' costs and increasing fertilizer industry profits. J. Environ. Qual. 44: 325–335. doi:10.2134/jeq2014.04.0173

Lacey, C., and S. Armstrong. 2015. The efficacy of winter cover crops to stabilize soil inorganic nitrogen after fall-applied anhydrous ammonia. J. Environ. Qual. 44: 442–448. doi:10.2134/jeq2013.12.0529

Lassaletta, L., G. Billen, B. Grizzetti, J. Anglade, and J. Garnier. 2014. 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland. Environ. Res. Lett. 9:105011. doi:10.1088/1748-9326/9/10/105011

Loy, A., J. Hobbs, J.G. Arbuckle, Jr., L.W. Morton, L.S. Prokopy, T. Haigh, T. Knoot, C. Knutson, A.S. Mase, J. McGuire, J. Tyndall, and M. Widhalm. 2013. Farmer perspectives on agriculture and weather variability in the Corn Belt: A statistical atlas. CSCAP 0153-2013. Cropping Systems Coordinated Agricultural Project, Ames, IA.

McCrackin, M.L., J.A. Harrison, and J.E. Compton. 2015. Future riverine nitrogen export to coastal regions in the United States: Prospects for improving water quality. J. Environ. Qual. 44: 345–355. doi:10.2134/jeq2014.02.0081

Osmond, D.L., D.L.K. Hoag, A.E. Luloff, D.W. Meals, and K. Neas. 2015. Farmers' use of nutrient management: Lessons from watershed case studies. J. Environ. Qual. 44: 382–390. doi:10.2134/jeq2014.02.0091

Perez, M. 2015. Regulating farmer nutrient management: A three-state case study on the Delmarva Peninsula. J. Environ. Qual. 44: 402–414. doi:10.2134/jeq2014.07.0304

Powell, J.M., and C.A. Rotz. 2015. Measures of nitrogen use efficiency and nitrogen loss from dairy production systems. J. Environ. Qual. 44: 336–344. doi:10.2134/jeq2014.07.0299

Prokopy, L.S., J.S. Carlton, J.G. Arbuckle, Jr., T. Haigh, M.C. Lemos, A.S. Mase, N. Babin, M. Dunn, J. Andresen, J. Angel, C. Hart, and R. Power. 2015. Extension's role in disseminating information about climate change to agricultural stakeholders. Clim. Change. doi:10.1007/s10584-015-1339-9.

Snyder, C.S., E.A. Davidson, P. Smith, and R.T. Venterea. 2014. Agriculture: Sustainable crop and animal production to help mitigate nitrous oxide emissions. Curr. Opin. Environ. Sustainability 9–10:46–54. doi:10.1016/j.cosust.2014.07.005

Soares, J.R., H. Cantarella, V.P. Vargas, J.B. Carmo, A.A. Martins, R.M. Sousa, and C.A. Andrade. 2015. Enhanced-efficiency fertilizers in nitrous oxide emissions from urea applied to sugarcane. J. Environ. Qual. 44: 423–430. doi:10.2134/jeq2014.02.0096

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, R. Biggs, S.R. Carpenter, W. de Vries, C.A. de Wit, C. Folke, D. Gerten, J. Heinke, G.M. Mace, L.M. Persson, V. Ramanathan, B. Reyers, and S. Sörlin. 2015. Planetary boundaries: Guiding human development on a changing planet. Science. doi:10.1126/science.1259855.

Sutton, M.A., A. Bleeker, C.M. Howard, M. Bekunda, B. Grizzetti. W de Vries, H.J.M. van Grinsven, Y.P. Abrol, T.K. Adhya, G. Billen, E.A. Davidson, A. Datta, R. Diaz, J.W. Erisman, X.J. Liu, O. Oenema, C. Palm, N. Raghuram, S. Reis, R.W. Scholz, T. Sims, H. Westhoek, and F.S. Zhang. 2013. Our nutrient world: The challenge to produce more food and energy with less pollution. Centre for Ecology and Hydrology, Edinburgh. www.unep.org.

van Grinsven, H.J.M., L. Bouwman, K.G. Cassman, H.M. van Es, M.L. McCrackin, and A.H.W. Beusen. 2015. Losses of ammonia and nitrate from agriculture and their effect on nitrogen recovery in the European Union and the United States between 1900 and 2050. J. Environ. Qual. 44: 356–367. doi:10.2134/jeq2014.03.0102

Weber, C., and L. McCann. 2015. Adoption of nitrogen-efficient technologies by U.S. corn farmers. J. Environ. Qual. 44: 391–401. doi:10.2134/jeq2014.02.0089

Zhang, X., D.L. Mauzerall, E.A. Davidson, D.R. Kanter, and R. Cai. 2015. The economic and environmental consequences of implementing nitrogen-efficient technologies and management practices in agriculture. J. Environ. Qual. 44: 312–324. doi:10.2134/jeq2014.03.0129