Suites of 4R Nitrogen Management Practices for Sustainable Crop Production and Environmental Protection

By Cliff Snyder

September 2016

Impacts of crop production nitrogen (N) inputs and losses to the environment *are a growing public concern. A U.S. national N management and nitrous oxide emission science workshop, aided by science input from Canada scientists, resulted in seven crop- and region-sensitive N management frameworks. Each framework has three tiers or suites of 4R N management practices to improve economic, social, and environmental outcomes. Intelligent implementation of improved 4R suites of N management practices can result in greater crop recovery of applied N, sustained and improved soil fertility and health, and cleaner water and air; while reducing emissions of nitrous oxide.*

Farmers around the world face multiple challenges in managing nitrogen (N) inputs for their crops/cropping systems each growing season. Weather uncertainty is among the largest and most difficult factors to be considered, but is well beyond a farmer's or crop adviser's control (SSSA, 2007; Tremblay et al., 2012). Still, weather uncertainty should be given serious consideration in arriving at sound 4R N management (right N source, at the right rate, time, and place of application; Bruulsema et al., 2009; IPNI, 2012; see IPNI history and resources on 4R Nutrient Stewardship at http://www.ipni.net/4R) decisions to simultaneously provide sustained and increased:

- crop yields
- farmer profitability
- soil fertility and system productivity (e.g., soil organic matter and soil organic N)
- reductions in losses of N to the environment via
  - o ammonia volatilization
  - o leaching/drainage/runoff losses of nitrate-N (NO_3^--N)
  - o gaseous emissions of nitrous oxide (N_2O) and di-nitrogen (N_2) from wet or waterlogged/saturated soils

The return of N_2 from soil and water to the atmosphere is a natural process and helps explain why our atmosphere is 78% non-reactive N_2. Yet, excessive losses of other N forms (reactive N; Galloway and Cowling, 2002; Sutton et al., 2009) to the environment can pose serious economic threats to farm profitability, and contribute to risks of harmful algae growth or water quality contamination, and air quality impairment (Compton et al., 2011; Davidson et al., 2012; Sobota et al., 2015; Zhang et al., 2015; Davidson et al., 2016).

To identify ways in which U.S. agriculture can optimize management of fertilizer N in leading corn, soybean, and wheat cropping systems in the U.S., the International Plant Nutrition Institute (IPNI) and The Fertilizer Institute

(TFI; represented by Lara Moody) conducted a science coordination and consensus-building workshop (hereafter referred to as Workshop) in March 2015. Corn, soybean, and wheat systems were selected by IPNI and TFI for this N science effort because that is where the most published science exists, and because those crops account for the majority of crop fertilizer N use in the U.S. The principal aim of the Workshop was to identify suites of 4R N management practices to reduce N_2O emissions, while minimizing other N losses and achieving the other N management objectives noted above. Multiple members of the food supply chain, who are also members of the U.S. Field to Market Alliance for Sustainable Agriculture (https://www.fieldtomarket.org/) have emphasized their industry greenhouse gas (GHG) emissions reduction goals, and publicly committed to sizeable GHG reductions within the next 5 to 20 years. Those food supply chain industry members recognize that in the U.S., agriculture contributes less than 10% of the annual national carbon dioxide (CO_2) equivalent GHG emissions. Less than 6% of the U.S. annual national CO_2 equivalent GHG emissions are due to N_2O emissions. Yet, agriculture contributes 75 to 79% of those annual national N_2O emissions (primarily managed soils; including fertilizer, manure, and biologically-fixed N inputs; (U.S. EPA, 2016). Many more people also understand that: i) the global warming or radiative forcing effect of N_2O is about 300 times that of an equivalent mass of carbon dioxide, ii) N_2O has an atmospheric lifetime exceeding 100 years, and iii) it is currently the largest atmospheric contributor to ozone depletion (UNEP, 2013; Snyder et al., 2014).

About 25 prominent cropping system N management and N_2O emission scientists from within the USDA and leading agricultural Land Grant Universities were invited to the Workshop, and ultimately 20 scientists accepted the invitation and attended. All N scientists who were approached by the IPNI N Program Director (Dr. C.S. Snyder) were interested, but several had prior meeting and work commitments which prevented their participation. The Workshop communications and discussions were facilitated by The Prasino Group based on previous experience facilitating open science discussions and a role in coordinating the International Organization for Standardization (ISO)-based N management Nitrous Oxide Emissions Reduction Protocol (NERP; http://www1.agric.gov.ab.ca/$Department/deptdocs.nsf/all/cl14145) in Alberta, Canada. The March 2015 U.S. N management Workshop discussions, decisions, and science-vetting were transparent and adhered to ISO standards, with oversight by the Project Science Advisory Group (SAG). The list of invited Ph.D. scientists who participated in the Workshop and those chosen to serve on the formal IPNI-TFI Project Science Advisory Group (SAG) are as follows (and as shown in **Figure 1**)

USDA: Dr. Steve Del Grosso, ARS Research Soil Scientist; Dr. Marlen Eve, USDA ARS National Program Leader (Soil and Air) - Natural Resources and Sustainable Ag Systems (formerly Senior Adviser for Climate Change, USDA Office of the Chief Scientist); Dr. Adam Chambers, Leader - NRCS National Air Quality and Atmospheric Change Team.

University: Dr. Tony Vyn, Purdue University; Dr. Stephen Ogle and Dr. Keith Paustian, Colorado State University; Dr. Mario Tenuta, University of Manitoba; Dr. Claudia Wagner-Riddle, University of Guelph; Dr. David Burton, Dalhousie University (President elect Canadian Society of Soil Science) and Dr. Myles Dyck, University of Alberta. (Canada scientist participation in the workshop was supported by Fertilizer Canada (FC), formerly the Canadian Fertilizer Institute).

Industry: Dr. Cliff Snyder, IPNI; Lara Moody, TFI; and Clyde Graham, FC, along with two representatives (Karen Haugen-Kozyra, Matt Sutton-Vermeulen) of The Prasino Group served as the Project Steering Committee.

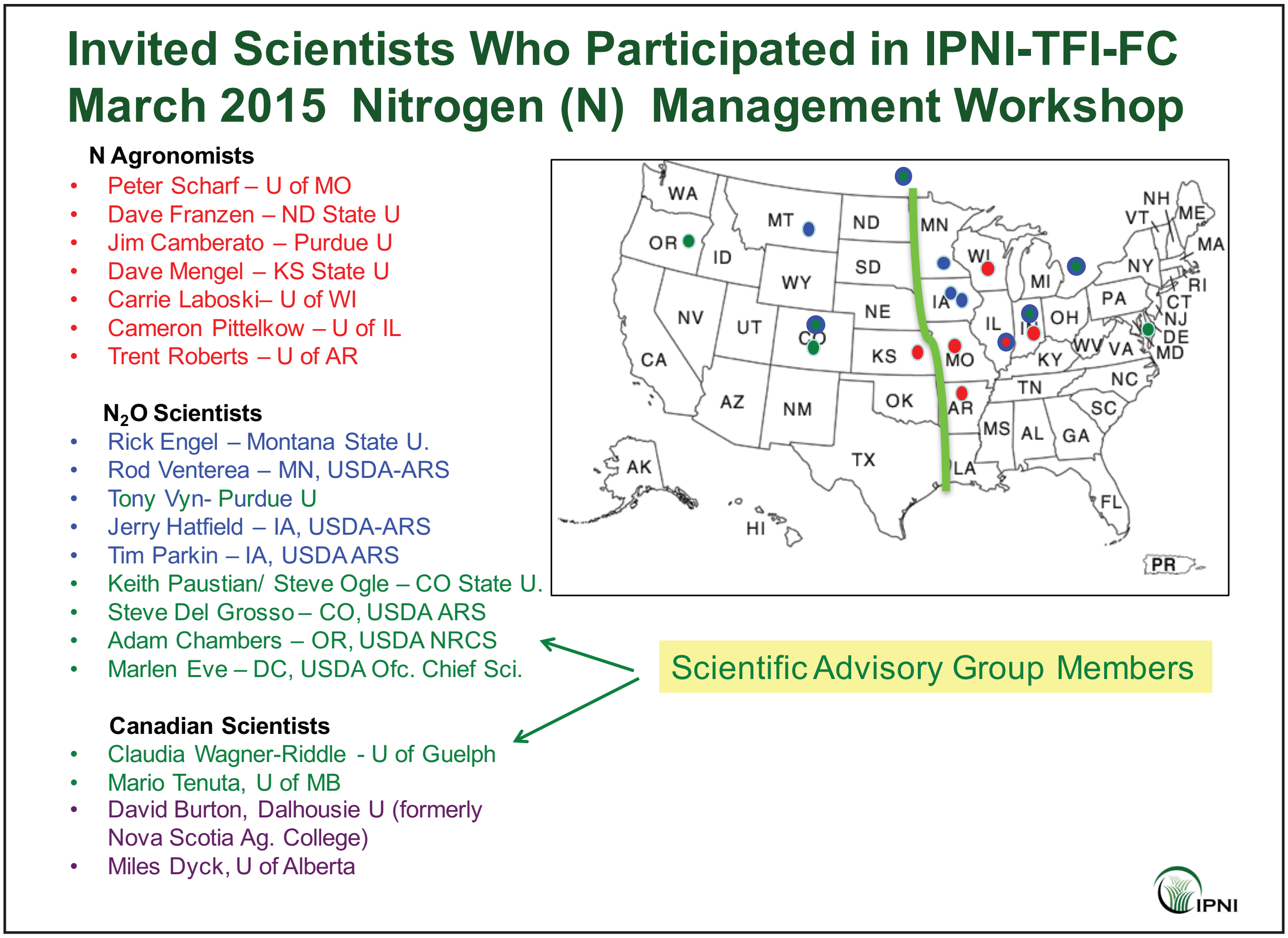

Figure 1. List of invited N management and N_2O scientists, their respective institutions, and location.

Although strictly a U.S. project, we sought to include relevant cropping system N management and N_2O-N emissions science input from those respective Canadian scientists to avoid the potential for any unintended or “artificial” N science and interpretation “boundaries” between the two countries.

Draft frameworks were developed for major U.S. corn, soybean, and wheat systems by IPNI scientists in North America for review and discussion by invited N scientists at the Workshop. Seven N management frameworks having three tiers **(Basic, and 4R Intermediate, 4R Advanced/Emerging)** or suites of 4R-N management best practices, that achieve incremental improvements in N use efficiency and effectiveness, resulted from that Workshop and were unanimously approved by the participating Workshop scientists (scientists from IPNI, staff from TFI, and observing Workshop guests were not allowed to vote). Workshop scientists agreed that there are many challenges and opportunities to raise N management implementation and technology adoption by farmers, their crop advisers, and input and service providers.

The tiered 4R-N management levels and current farmer implementation were identified at the Workshop, as follows:

- Below Basic BMPs (best management practices) – 25% of the growers
- **Basic** – practices adopted by approximately 50% of growers
- **Intermediate** – 4R practices adopted by approximately 20% of growers
- **Advanced/Emerging** – 4R practices adopted by approximately 5% of growers

More valuable tools and technologies are accessible to U.S. farmers today than at any time in the past (Snyder et al., 2014; Erickson et al., 2015; Phillips, 2015). Educational resources on 4R Nutrient Stewardship were developed and are being increasingly used to raise farmer (and crop adviser) 4R knowledge (IFA, 2009a b; IPNI, 2012). North American fertilizer industries have voluntarily stepped forward to invest in more research since 2014, to expand the science of 4R Nutrient Stewardship (http://www.ipni.net/article/IPNI-3366). Nutrient use efficiency and effectiveness terms are being advanced by agronomic practitioners and scientists in the U.S. and around the world (Cassman et al., 2002; Doberman, 2007; Snyder and Bruulsema, 2007). Farmers, industry partners and their stakeholder friends are being encouraged to monitor and track nutrient performance over time, by relying on key performance indicators across several years or growing seasons (IPNI Scientists, 2014).

More 4R N management educational resources are being made available online by IPNI (e.g., http://www.ipni.net/specifics-en, http://www.ipni.net/nitrogennotes). More science reports are making clear that there is no single solution, technology, or action that in and of itself leads to agronomically and environmentally optimized N management (Snyder et al., 2014). Instead, it is through the combined effects of the 4Rs, in the context of the full cropping system management, and combined with other sound soil and water conservation practices, that our greatest gains in improved crop and soil N recovery and environmental N loss reduction are most likely to be accomplished (Hatfield and Venterea, 2014; Smith et al., 2014; Fixen et al., 2015; Venterea et al., 2016). In addition, those 4R practices and their environmental loss impacts are being increasingly recognized as site-specific and Land Resource Region sensitive (see **Figure 2** and USDA NRCS, 2006) (Decock, 2014; Eve et al., 2014; Ogle et al., 2014).

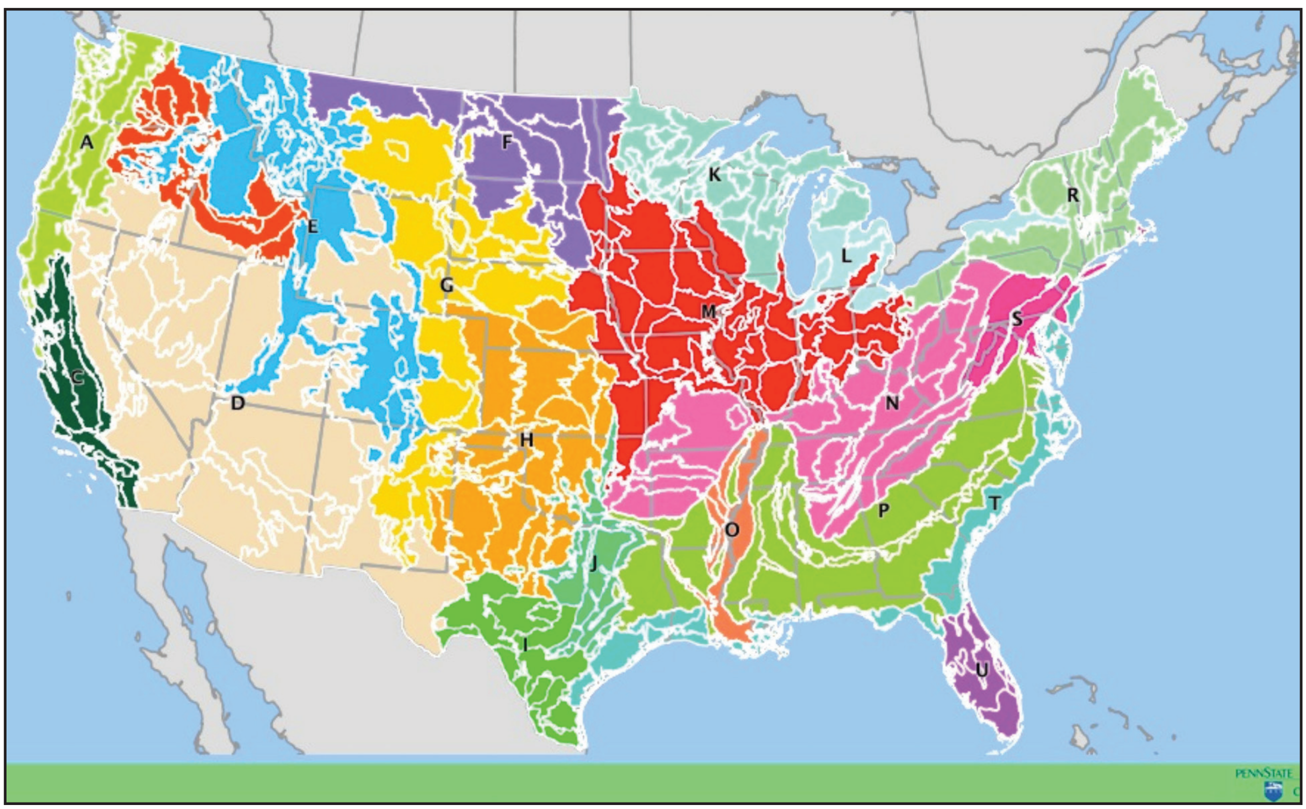

Figure 2. Example illustration of USDA NRCS Land Resource Regions (LRRs) in the U.S. http://apps.cei.psu.edu/mlra/. Also see LRR map of conterminous U.S. by USDA NRCS at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051846.pdf

NOTE

The seven 3-tiered 4R-N management frameworks provided on the following pages (shown after the references list), with relevant USDA Natural Resources Conservation Service (NRCS) Land Resource Regions identified, should be viewed as general 4R N management guidance. More specific N and other nutrient management guidelines are available from state Land Grant Universities, as well as some local on-farm networks.

The Basic tier of management includes (and assumes) soil testing and nutrient recommendations are followed, consistent with public Land Grant University guidance. In the Basic tier, suites of N management practices are implemented at least at the farm level, but most often at the individual field management level. In the Intermediate tier, suites of practices are implemented at least on an individual field-by-field management level, and often include a formal nutrient management plan. At the Advanced/Emerging tier, suites of practices include implementation of within-field N management. Intermediate and Advanced/Emerging suites of practices include and build upon practices in the Basic tier. A farmer should have the large majority (i.e., over two thirds) of his/her implemented N management practices falling within the named tier (i.e., Basic or Intermediate or Advanced/Emerging) to "qualify" as having implemented that specific N management tier or suite of practices.

The original seven 4R frameworks (or tables) resulting from the 2015 IPNI-TFI 4R N management science Workshop are recorded elsewhere, to preserve their integrity. The seven tables of 4R N management included in this Issue Review article reflect only minimal attempts by IPNI to unify the language and practice terminology across the seven regional frameworks, to aid general reader understanding.

Disclaimer

Compliance with all local and state laws is expected; and the mentioned suites of 4R N management frameworks may need to be subjected to state-level N management scientist scrutiny to be sure no conflicts with local or state ordinances arise. Any mention of trade names, products or technologies does not necessarily imply endorsement, nor exclusion of those not mentioned.

Acknowledgement

Sincere thanks are gratefully expressed for:

- continued cooperation and interest expressed by Field to Market leaders and members
- support of the 4R Research Fund by the North American members of the fertilizer industry, which enabled expanded data analyses research by Dr. Tony Vyn and Dr. Rex Omonode at Purdue University; with cooperation by Dr. Ardell Halvorson (retired) with USDA ARS
- cooperation by Dr. Rod Venterea and others in the USDA ARS GRACEnet project for data sharing and science discussions
- budget management and logistical oversight on this Workshop project by TFI staff
- support by IPNI scientists, administration, and staff in North America
- support by Fertilizer Canada to enable Workshop attendance by N management scientists from Canada
- communicative and facilitative support by members of the Prasino Group
- contributions and science exchange by all March 2015 N management Workshop participants and the Science Advisory Group
- the special assistance by each science reporter/discussion leader noted for each of the 4R-N management frameworks and the respective suites of N management practices

The author, Dr. Snyder, is Director of the IPNI Nitrogen Program; E-mail: csnyder@ipni.net.

References

Bruulsema, T., J. Lemunyon, and B. Herz. 2009. Crops Soils 42:13-18.

Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. Ambio 31:132-140.

Compton, J.E., J.A. Harrison, , R.L. Dennis, T.L. Greaver, B.H. Hill, S.J. Jordan, H. Walker, and H.V. Campbell. 2011. Ecol. Ltrs. 14:804-815.

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. Issues in Ecology 15:1-16. Ecological Society of America, Washington, DC.

Davidson, E.A., R.L. Nifong, R.B. Ferguson, C. Palm, D.L. Osmond, and J.S. Baron. 2016. J. Environ. Stud. Sci. 6:25-38.

Decock, C. 2014. Environ. Sci. Technol. 48:4247-4256.

Dobermann, A. 2007. *In,* Fertilizer Best Management Practices: General Principles, Strategy for their Adoption and Voluntary Initiatives vs. Regulations, Proc. IFA International Workshop on Fertilizer Best Management Practices. Brussels, Belgium, 7-9 March 2007. pp.1-28. International Fertilizer Industry Association, Paris, France.

Erickson, B. and D.A. Widmar. 2015. Available online at: http://agribusiness.purdue.edu/precision-ag-survey. Accessed May 31, 2016.

Eve, M., D. Pape, M. Flugge, R. Steele, D. Man, M. Riley-Gilbert, and S. Biggar. (Eds). 2014. Technical Bulletin Number 1939. July 2014. Office of the Chief Economist, U.S. Department of Agriculture, Washington, DC. p.606.

Fixen P., F. Brentrup, T. Bruulsema, F. Garcia, R. Norton and S. Zingore. 2015. *In,* P. Drechsel, P. Heffer, H. Magen, R. Mikkelsen, and D. Wichelns (Eds). Managing Water and Fertilizer for Sustainable Agricultural Intensification. International Fertilizer Industry Association, International Water Management Institute, International Plant Nutrition Institute, and International Potash Institute. First edition, Paris, France. pp.8-38.

Galloway, J.N. and E.B. Cowling. 2002. Ambio 31:64-71.

Hatfield, J.L. and R.T. Venterea. 2014. Agron. J. 106:1-2. [See related articles in Journal's special section: (https://dl.sciencesocieties.org/publications/aj/tocs/106/2)].

IFA. 2009a. The Global "4R" Nutrient Stewardship Framework for Developing and Delivering Fertilizer Best Management Practices. IFA Task Force on Fertilizer Best Management Practices. International Fertilizer Industry Association. Paris, France. http://www.fertilizer.org//en/ItemDetail?iProductCode=9677Pdf&Category=AGRI . Accessed 10 May 2016.

IFA. 2009b. Fertilizers, Climate Change and Enhancing Agricultural Productivity Sustainably. IFA Task Force on Climate Change. International Fertilizer Industry Association. Paris, France.

IPNI. 2012. 4R Plant Nutrition Manual: A Manual for Improving the Management of Plant Nutrition, T.W. Bruulsema, P.E. Fixen, and G.D. Sulewski (Eds), International Plant Nutrition Institute, Norcross, GA, USA.

IPNI Scientists. 2014. Issue Review, August 2014. Ref #14061. International Plant Nutrition Institute. http://www.ipni.net/issuereview. Accessed 10 May 2016.

Ogle, S.M., P.R. Adler, J. Breidt, S. Del Grosso, J. Derner, A. Franzluebbers, M. Liebig, B. Linquist, P. Robertson, M. Schoeneberger, J. Six, C. van Kessel, R. Venterea, and T. West. 2014. *In,* M. Eve et al. (Eds), USDA Technical Bulletin Number 1939. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory. pp.141.

Phillips, S. 2015. Achieving Sustainable Improvements in Nutrient Efficiency with Precision Agriculture. "Building Productive, Diverse and Sustainable Landscapes", Proc. 17th ASA Conference. 20–24 September 2015. Hobart, Australia. pp.8. www.agronomy2015.com.au

Smith P., M. Bustamante, H. Ahammad, H. Clark, H. Dong, E.A. Elsiddig, H. Haberl, R. Harper, J. House, M. Jafari, O. Masera, C. Mbow, N. H. Ravindranath, C.W. Rice, C. Robledo Abad, A. Romanovskaya, F. Sperling, and F. Tubiello. 2014. *In,* O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel, and J.C. Minx (Eds). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Snyder, C.S. 2015. *In,* J.E. Sawyer (Ed.), Proc. of the 45th North Central Extension-Industry Soil Fertility Conference. 31:6-13. (Des Moines, IA). International Plant Nutrition Institute, Norcross, GA, USA.

Snyder, C.S. and T.W. Bruulsema. 2007. Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit. Ref #07076. International Plant Nutrition Institute, Norcross, GA, USA.

Snyder, C.S. E.A. Davidson, P. Smith, and R.T. Venterea. 2014. Curr. Opin. Environ. Sustain. 9-10:46-54.

Sobota, D.J., J.E. Compton, M.L. McCrackin, and S. Singh. 2015. Environ. Res. Lett. 10:025006

SSSA. 2007. Managing Crop Nitrogen for Weather. *In,* T.W. Bruulsema (Ed), Proceedings of the Symposium "Integrating Weather Variability into Nitrogen Recommendations", sponsored by Divisions S-4 and S-8 of the Soil Science Society of America. Indianapolis, Indiana, USA, 15 November 2006. pp.136. International Plant Nutrition Institute, Norcross, GA, USA.

Sutton, M.A., S. Reis, and K. Butterbach Bahl. 2009. Agric. Ecosyst. Environ. 133:135–138.

Tremblay, N. Y.M. Bouroubi, C. Bélec, R.W. Mullen, N.R. Kitchen, W.E. Thomason, S. Ebelhar, D.B. Mengel, W.R. Raun, D.D. Francis, E.D. Vories, and I. Ortiz-Monasterio. 2012. Agron. J. 104:1658–1671.

UNEP. 2013. Drawing Down N_2O to Protect Climate and the Ozone Layer. A UNEP Synthesis Report. United Nations Environment Programme (UNEP), Nairobi, Kenya.

USDA NRCS. 2006. Land Resource Regions and Major Land Resource Areas of the United States, the Caribbean, and the Pacific Basin. United States Department of Agriculture, Natural Resources Conservation Service Handbook 296. Land Resource Regions and Major Land Resource Areas for the Conterminous U.S. Map - http://www.nrcs.usda.gov/wps/portal/nrcs/detail/?cid=nrcs143_013721 .

U.S. EPA. 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014. 558 pp. EPA 430-R-16-002

Venterea, R.T., J.A. Coulter, and M.S. Dolan. 2016. J. Environ. Qual. 45:1186–1195.

Zhang, X., E.A. Davidson, D.L. Mauzerall, T.D. Searchinger, P. Dumas, and Y. Shen. 2015. Nature 528:51-59.

Abbreviations and terms used in the following seven frameworks

CRF = controlled release fertilizer
DAP = diammonium phosphate
EEF = enhanced efficiency N fertilizer = slow- and controlled-release, urease inhibitor-treated, nitrification inhibitor-treated, or both urease and nitrification inhibitor-treated fertilizer
ESN = ESN® SMART NITROGEN, a polymer-coated urea; a controlled-release N fertilizer
LGU = Land Grant University
LGU guidelines = regional soil fertility extension approved guidelines
MAP = monoammonium phosphate
MRTN = Maximum Return to Nitrogen
NBPT= N-(n-butyl) thiophosphoric triamide (nBTPT), a urease inhibitor with trade name Agrotain®
NH_3 = anhydrous ammonia
NI = nitrification inhibitor
NMP = nutrient management plan
NUE = nitrogen use efficiency
PCU = polymer-coated urea (ESN is an example PCU with controlled-release characteristics)
PPNT= pre-plant nitrate test
PSNT = pre-sidedress nitrate test
Regional soil fertility specialist= regional LGU extension soil specialist
ROI = return on investment
UAN = urea ammonium nitrate solutions
UI = urease inhibitor
VR = variable rate

Table 1. Non-Irrigated corn-soybean rotation in the West - Land Resource Regions: F, G, and H.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic[1]	• Ammonia (NH_3)-based (fall). • Any source for non-fall N.	• Rate considers how much residual N the growers expects to have[2]. • Apply recommendations recognized by regional soil fertility specialists. • Account for previous crop N credits • Account for manure N credits.	• Ammonia-based if in fall. • Apply fall N when soils cool (as defined by local guidelines) or as spring pre-plant. • No winter urea application. • Manure timing based on nutrient management plan.	• Subsurface band application or broadcast-incorporated. • If broadcast w/o incorporation do prior to precipitation of minimum of quarter inch.
Intermediate	• Use NI (nitrification inhibitor) for fall-applied N. • Use UI (urease inhibitor) for surface-applied UAN/Urea. • Include polymer-coated urea in a urea blend.	• Use recommendations recognized by regional soil fertility specialists. • N recommendations made with an accounting for residual soil nitrate in the upper 2 feet.	• Apply fall N when soils cool (as defined by local guidelines) or as spring pre-plant. • No fall N on soils susceptible to loss (e.g., sandy soils, clay soils). • On these susceptible soils, apply split application of N. • Manure timing based on nutrient management plan.	• NH_3 (anhydrous ammonia) application of at least 4 inches deep.
Advanced/ Emerging	• Apply NI on susceptible soils (e.g., sandy or clay soils) in the spring.	• Accounting for within-field variability using concepts and tools such as zone or landscape position management, and N sensors (e.g., Crop Circle™, Greenseeker® [3]).	• Split application is directed with in-season sensors. • No fall application of N.	• Accounting for within-field variability using concepts and tools such as zone or landscape position management, and N sensors (e.g., Crop Circle™, Greenseeker®).

[1] Based on what 50% of the Growers are doing in this region – our constraint.
[2] Based on soil test; knowledge of regional soil nitrate trends; appropriate crediting of previous crop or other agronomic knowledge.
[3] Mention of tradenames does not necessarily constitute or imply endorsement; nor exclusion of others not mentioned

Includes: Traditional Profile Nitrate Region (Northwest Minnesota, North Dakota, South Dakota, Kansas, Colorado, and some of Nebraska).

Report Lead: Dr. Dave Franzen, North Dakota State University.

Table 2. North Central Upper Mid-West, non-irrigated corn - Land Resource Regions: M and K.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic	• Guaranteed or known analysis for all fertilizer sources or book values for manure. • For fall applications use ammoniacal or ammonium forms. • No fall N on sandy soils. • Any source for spring N.	• In states with the MRTN (Maximum Return to N) approach, use realistic N and crop prices when using the N Rate Calculator. • For recommendations using a yield goal approach, set realistic yield goals using average of last 5 years of production levels with an added small percentage increase. • Properly credit previous legume crops and account for all N sources, including N-containing phosphate fertilizers and manure applications.	• Pre-plant and side-dress applications are preferred over fall applications. • In fall, apply only when soil temperatures at 4-6 inches are sustained below 50°F. • Do not fall-apply N on sandy soils, soils with high permeability, fine-textured poorly drained soils or soils overlaying fractured bedrock. • Do not apply urea (or other N sources) on frozen or snow covered soils. • Apply manure according to manure management plan.	• Any placement.
Intermediate	• For fall applications in higher rainfall areas, include NI. • For pre-plant or side-dress applications on poorly drained soils subject to denitrification or medium textured soils where nitrate loss is likely, use a NI with ammonium sources. • Base manure applications on manure testing. • Controlled-release sources for pre-plant; • If urea/UAN (urea ammonium nitrate) unincorporated, use a UI (urease inhibitor).	• Where appropriate and properly calibrated and supported by local research use PPNT or PSNT (preplant nitrate test or pre-sidedress nitrate test). • Manure application rate should not exceed approved manure management plan.	• No application of primary N source fertilizers in the fall [or N-containing fertilizers like monoammonium phosphate (MAP) or diammonium phosphate (DAP) allowed.] • Fall applied manure N is allowed with a NI (nitrification inhibitor). • Apply a portion of N at pre-plant or seeding; apply remaining N at side-dress after an in-season assessment.	• Under conservation tillage, apply urea or UAN at the surface with a UI (urease inhibitor). • Apply some N at planting adjacent to the seed row.

Continued on next page

Performance Level	Right Source	Right Rate	Right Time	Right Place
Advanced/ Emerging	• Use the following when there are proven, acceptable probabilities of efficacy under local conditions: controlled-release N, sources with multiple inhibitors, or other technological advancements in fertilizer forms. • Use an adaptive management process based on on-farm, replicated studies to evaluate efficacy of new fertilizer technologies, using crop yield response, nitrogen use efficiency (NUE) and return on investment (ROI).	• Use an in-season, plant-based assessment of crop N status, such as a chlorophyll meter or other sensor, coupled with a split N application rate based on calibrated sensor readings; OR • Account for temporal variability in crop need with calibrated decision support systems; OR • Account for spatial variability in crop need using crop sensors, remote sensing, management zones, soil mapping units, or other data layers; OR • Use an adaptive management process based on on-farm, replicated studies for N rates.	• Use an adaptive management process based on on-farm studies. • Use replicated studies to evaluate efficacy of new fertilizer technologies, using crop yield response, NUE and ROI.	• Account for spatial variability in crop need using crop sensors, remote sensing, management zones, soil mapping units, or other data layers.

Includes: Wisconsin, Eastern Minnesota, Iowa, Missouri, and Illinois.

Report Lead: Dr. Cameron Pittelkow, University of Illinois.

Table 3. Non-irrigated corn-soybean rotation in the East - Land Resource Regions: K, L, M, R, S, and northern parts of N, P, and T.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic	• Guaranteed or book value for all sources applied. • Urea, UAN (urea ammonium nitrate), anhydrous ammonia, manure.	• Rate based on evidence recognized by regional soil fertility extension. • Properly accounting for legume and manure N.	• Spring; not on frozen soil. • Apply manure according to a manure management plan.	• Broadcast and incorporated, injected or subsurface band. • If broadcasted urea accompanied by an inhibitor. • UAN with herbicide no more than 40 lbs/A.
Intermediate	• Guaranteed or known analysis for all sources applied; with nitrification inhibitor or controlled release if preplant; with urease inhibitor for urea/UAN surface applied sidedress.	• Rate based on evidence recognized by regional soil fertility extension, including results of local adaptive management research. • Manure analysis required to determine application rate.	• Some or all applied nitrogen in season or if pre-plant used with nitrification inhibitor (NI) or polymer-coated.	• Broadcast and incorporated, injected or subsurface band, surface application allowed only for sidedress urea with UI or dribbled UAN.
Advanced/ Emerging	• Guaranteed or known analysis; with nitrification inhibitor or controlled release if preplant; with urease inhibitor for urea/UAN sidedress.	• Rate based on evidence recognized by regional soil fertility extension, or results of local adaptive management research, AND, in addition, addressing within-field and weather-specific variability using tools such as crop sensors, PSNT, models that allow adjustment of in-season N rates.	• Some or all N applied in-season.	• Broadcast and incorporated, injected or subsurface band, surface application allowed only for sidedress urea with urease inhibitor (UI) or dribbled UAN.

Includes: E. Corn Belt (Indiana and Eastward - Ohio, Pennsylvania, New York, and Maryland).

Report Lead: Dr. Peter Scharf, University of Missouri.

Table 4. Irrigated corn-soybean rotation in the North - Land Resource Regions: K, L, M, and parts of H.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic	• Guaranteed or known analysis for all sources applied. When manure is used, rely on book value for nutrient content.	• Based on land grant university (LGU) guidelines and specific accounting for organic sources of N	• For sands and loamy sands, use split or sidedress applications; no fall N anhydrous. • All ammonium-containing P fertilizer applied prior to or at corn planting in rotation.	• Any placement.
Intermediate	• Guaranteed or known analysis. When manure is used, rely on analyzed sample value. • Use urease inhibitor or incorporate surface-applied urea-containing sources (preplant, sidedress, or topdress). May include nitrification inhibitor or controlled-release urea in the fertilizer blend for preplant.	• Based on LGU guidelines and specific accounting for organic sources of N. • N recommendations made with an accounting for residual soil nitrate in the upper 2 feet (except in sands and loamy sands); if suggested by state LGU. • Account for nitrate in irrigation water[1].	• No fall N anhydrous. • All ammonium-containing P fertilizer applied in spring prior to or at corn planting in rotation. • Minimum of 60% N applied in season on sand or loamy sand. • Minimum of 40% N applied in season on all other soils.	• When combining N application with herbicide, broadcast UAN at rates below 40 lbs/A when residue cover greater than or equal to 50%. • Urea-containing N sources broadcast on soil surface should include urease inhibitor or be incorporated by greater than 0.5 inches irrigation within 48 to 72 hrs of application.
Advanced/ Emerging	• Intermediate plus... • Fluid sources (especially N, and possibly others such as sulfur (S) applied in-season in multiple applications through pivot irrigation system, where applicable.	• Intermediate plus… • An accounting for within-field variability using concepts and tools such as zone or landscape position management, and N sensors (e.g., Crop Circle™, Greenseeker® [2]).	• Intermediate plus... • Minimum of 80% N applied through multiple in-season applications on sand or loamy sand. • Minimum of 70% N applied in season on all other soils.	• Intermediate plus... one or more of the following: • An accounting for within-field variability using concepts and tools such as zone or landscape position management, and N sensors (e.g., Circle™, Green-seeker®). • Application of N fertilizer through pivot irrigation system.

[1] not all states - WI, MN, MI have nitrate concentration data for irrigation water.

[2] mention of tradenames does not necessarily constitute or imply endorsement; nor exclusion of others not mentioned.

Includes: W. Great Lakes region and Nebraska – High permeability soils.

Report Lead – Dr. Carrie Laboski, University of Wisconsin.

Table 5. Irrigated corn-soybean rotation in the South (Midsouth and Southeastern Coastal Plain) - Land Resource Regions: O, P, T, and U.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic	• Guaranteed or known analysis for all sources.	• Follow LGU recommendations; consider changes in soil texture to vary rate; use farm-wide realistic yield goals for N; N-based manure management; credit previous N sources/crops.	• N split between preplant starter and sidedress application timings.	• Preplant N (incorporated in conventional tillage system; surface broadcast application in no-till). • Sidedress N (broadcast/inject/knife-in liquids and surface broadcast granulars).
Intermediate	• Enhanced efficiency fertilizer (EEF) when appropriate - NBPT[1] urease inhibitor for surface-applied urea/UAN and ESN[1] (Environmentally Smart N - a polymer-coated urea) for preplant incorporated N applications.	• Use soil-based or documented historic yield goals for N rate decisions; N or P-based manure management.	• Limit winter applications of manure, apply preplant and incorporate.	• Incorporate manure when possible; liquid band placement of sidedress N in reduced/minimum tillage operations; surface broadcast granular and incorporate in all other tillage systems.
Advanced/ Emerging	• Same as above.	• Apply recommendations to management zones; PSNT (preside-dress nitrate test) where appropriate; N sensors and VR (variable rate) management; monitor plant nutrition with tissue testing.	• Consider using a three-way split including preplant, sidedress and pre-tassel (especially when using urea-containing fertilizer).	• Distribute N spatially according to management zones based on drainage/soil texture or use N sensors to apply variable rate across field.

[1] Mention of tradenames does not necessarily constitute or imply endorsement; nor exclusion of others not mentioned.

Includes: North and South Carolina, Mississippi, Texas, Alabama, Texas, N. Florida, Arkansas, Georgia, Louisiana.

Report Lead: Dr. Trent Roberts, University of Arkansas.

Table 6. Wheat in the Northern Great Plains - Land Resource Regions: F and G.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic	• Ammonium-based formulation for fall. • Any N fertilizers in spring.	• Consistent with the LGU recommendation.	• No urea (or other N source) application on frozen and snow covered ground. • Winter wheat – band application with air seeder in fall or top-dress in the spring. • Spring wheat - Apply after soils cool to 10°C (50°F) in fall.	• Apply pre-plant N in subsurface bands, and • With winter wheat, top-dress broadcast urea or UAN.
Intermediate	• Ammonium-based formulation for fall. • Utilizing one of the following practices: - Polymer-coated urea (PCU) or PCU blends when soil moisture is not limiting. - Urease inhibitor with surface applied urea based N.	• Consistent with the LGU recommendation using 2 foot soil nitrate test for residual N.	• No urea (or other N source) application on frozen and snow-covered ground. • Winter wheat – band application with air seeder in fall or top dress in the spring. • Spring wheat - Apply after soils cool to 10°C (50°F) in fall, with high yield potential consider UAN application post-anthesis.	• Apply pre-plant N in subsurface bands, and • With winter wheat, top-dress broadcast urea with urease inhibitor or surface band UAN.
Advanced/ Emerging	• Ammonium-based fertilizers with nitrification inhibitor in the fall. • Utilizing one of the following practices: - Polymer-coated urea (PCU) or PCU blends when soil moisture is not limiting. - Urease inhibitor with surface applied urea-based N.	• Consistent with the LGU recommendation using 2 foot soil nitrate test for residual N in the fall using zone sampling where supported by local research; or directed by real time crop sensors.	• No urea application on frozen and snow-covered ground. • In-season N based on real time crop sensors. • Winter wheat – band application with air seeder in fall and/or top dress in the spring. • Spring wheat - Apply after soils cool to 10°C (50°F) in fall, with high yield potential consider UAN application post-anthesis directed by real time crop sensors.	• Apply pre-plant N in subsurface bands. • Vary N placement rates using multi-layer zone maps (soil test, satellites, soil characteristics, etc.). • With winter wheat, top-dress broadcast urea with urease inhibitor or surface band UAN.

Includes: Montana, Wyoming, Colorado, North Dakota, South Dakota, Nebraska.

Report Lead: Dr. Dave Franzen, North Dakota State University.

Table 7. Wheat in the Southern Great Plains - Land Resource Regions: H, parts of M in NE and KS, J, N in OK and TX, and parts of G in eastern CO.

Performance Level	Right Source	Right Rate	Right Time	Right Place
Basic (40-45 bu/A target)	• Guaranteed or known analysis for all sources applied. • UAN (urea ammonium nitrate), urea, and anhydrous ammonia.	• Basic soil analysis (0-6 or 0-8 inch depth soil samples), using recommendations recognized by regional LGU soil fertility extension specialists. • Consider previous crop, and N contribution, in making N recommendation	• All non-N fertilizer applied preplant. N applied either in fall or spring.	• Broadcast preplant, surface broadcast for topdress. • Subsurface place anhydrous ammonia. • UAN (broadcast).
Intermediate (50 bu/A target	• Use of anhydrous ammonia (fall only) with nitrification inhibitors. • Spring urea, UAN (consider urease inhibitors). • Large adoption of inhibitors	• Basic soil analysis (0-6 or 0-8 inch depth soil samples), using recommendations recognized by regional soil fertility extension (including chloride). • N recommendations made with an accounting for residual soil nitrate in the upper 2 feet of soil[1]. • Consideration of N available at planting, and soil moisture. • Consider previous crop, and N contribution, in making N recommendation.	• All non-N fertilizer applied preplant. N applied in split (fall/spring) applications[3]. • Small amount N applied in fall. • Bulk of N applied in spring (top dress).	• Broadcast or subsurface band for preplant. surface application for topdress. • N, P, and K applied in fall by subsurface band at time of seeding. • Spring N applied based on fall soil test by surface band. • Consider use of urease and nitrification inhibitors. • Variable rate N based on mapping by management zones.
Advanced/ Emerging (60-70+ bu/A target)	• Guaranteed or known analysis. Use urease inhibitor (with urea-containing N sources) and/ or nitrification inhibitor for surface application (preplant or spring topdress), or controlled-release N for preplant.	• Account for within-field variability using concepts and tools such as zone or landscape position management, and N sensors (e.g., Crop Circle™, Greenseeker® [2]).	• All non-N fertilizer applied preplant. N applied in split (fall/spring) applications. • Multiple spring applications of N[3], with crop growth stage consideration, and where informed by N sensors or plant tissue tests.	• Subsurface band for preplant. Some starter (in seed furrow) fertilizer applied with appropriate rates and sources (especially P) that avoid seedling injury. • Surface application or banded for topdress.

[1] Yield targets reflect the conservative nature of many growers at that yield goal.

[2] Mention of tradenames does not necessarily constitute or imply endorsement; nor exclusion of others not mentioned.

[3] Moisture plays a significant role overall, and split application rates will vary based on expected yield goals.

Includes: Kansas, Oklahoma, Texas, E. Colorado – Central Kansas; Water is everything 10”-25” (Weather plays a significant role overall); *Split application rates will vary based on expected yield goals

Report Lead: Dr. Dave Mengel, Kansas State University

IPNI
International
Plant Nutrition
Institute

ISSUE REVIEW | Ref #16057