IPNI and TFI 4R N Management and Nitrous Oxide (N_2O) Emissions Science Project Report and Proposal to Improve the Fertilizer N-Related N_2O Emissions Estimator in the Field to Market Fieldprint Calculator

EXECUTIVE SUMMARY

Nitrous oxide (N_2O) is a potent greenhouse gas (GHG) with a global warming or radiative forcing effect approximately 300 times that of an equivalent mass of carbon dioxide (CO_2), has an atmospheric lifetime exceeding 100 years, and is currently the largest atmospheric contributor to ozone depletion. The Field to Market Alliance for Sustainable Agriculture Fieldprint Calculator (FtM FPC) currently relies on a constant factor multiplied times the farmer's nitrogen (N) input rate to estimate field direct plus indirect N_2O-N emissions. Relying on an N-rate only based estimation approach to N_2O-N emissions in the FPC results in identical N_2O-N emissions for the same N input rate in California as in Florida, with no sensitivity to N rate management by the farmer or to local soils and environmental conditions. The FPC N_2O-N emissions estimator was developed before 2011, and more recent science has shed light on how N_2O-N emissions from managed agricultural soils depend on many factors in addition to input N rate.

In 2015, the International Plant Nutrition Institute (IPNI) and The Fertilizer Institute (TFI) volunteered to coordinate and financially support a science-based effort to align FtM FPC N_2O-N emissions estimation with current United States Department of Agriculture (USDA) modeled N_2O-N emissions. The USDA-modeled N_2O-N emissions vary with Natural Resources Conservation Service (NRCS) Land Resource Region, surface soil texture, crop or crop system, N input rate, and prevailing environmental and climatic conditions. Additionally, recent research efforts have documented emission reduction impacts of managing practice combinations of N source, rate, time, and place of application (4R N Stewardship) to enhance crop yield and productivity while lessening the potential for a buildup of N in the plant-soil system. Such 4R N management may not only help reduce direct N_2O-N emissions from farm fields, but also lower the indirect emissions associated with other N losses to air and water resources from farm fields.

The IPNI-TFI project was initiated with a March 2015 invitational science workshop involving 20 leading N management and N_2O-N government and university scientists. Seven N management frameworks having three tiers (Basic, Intermediate, Advanced/Emerging**)** of N best management practices that achieve incremental improvements in N use efficiency and effectiveness were developed and unanimously approved by the workshop scientists and the project's science advisory group (SAG). Then, a 4R N management data analysis, representing corn production systems at several U.S. and Canada locations (funded through the fertilizer industry 4R Research Fund), was conducted by scientists at Purdue University and the USDA Agricultural Research Service (ARS). The analysis evaluated relationships between actual, measured N_2O-N emissions and key plant N management factors including applied N rate and source, time and place of application, total plant N uptake, corn grain N uptake (i.e. crop harvest N removal), crop N recovery efficiency, and plant-soil system partial net N balance (sometimes referred to as "N surplus"). Beyond N input rate, the strongest relationship with N_2O emissions was plant-soil system partial net N balance (calculated as the difference between the crop harvest N removal and the N input rate applied (*i.e. fertilizer N in this report, where those N input rates accounted for legumes in the rotations*). The IPNI-TFI project further explored and identified science indicating that adopting optimum combinations of 4R practices (i.e. moving incrementally from typical practice toward improved suites of 4R N management), allowed emissions of N_2O-N to be more accurately accounted for and reduced. Implementation of improved suites of 4R N management practices is expected to result in increased crop yields and lower plant-soil system net N balances. Linking partial net N balance with N management and Land Resource Regions significantly improves the estimation of N_2O-N emission reductions. The project methods, results, and

a proposed method to improve the FtM FPC N_2O-N emission estimation through integration of the latest USDA hybrid-modeling approach coupled to suites of improved 4R N management practices, are explained in this project report and its Appendices.

We propose revision of the current FtM FPC N_2O-N estimator for alignment with the current USDA hybrid model-based N_2O-N emissions estimation that is sensitive to crop, Land Resource Region, soil texture, and farmer-applied N rate (Excel file will be separately provided to FtM FPC Science and Research Director). To further improve those N_2O-N emission estimations, and to provide farmers with the opportunity to adopt, implement, and adapt to emerging cropping system and N management technologies, we propose inclusion of a 7% and a 14% reduction in the USDA model-based N_2O-N emissions estimates when farmers implement science-based Intermediate or Advanced/Emerging suites of 4R N management practices, respectively. Implementation of Intermediate or Advanced/Emerging suites of 4R N management practices are expected to help lower the system partial net N balance, through improved cropping system uptake and recovery. Those system level efficiency and effectiveness improvements are conservatively estimated to confer N_2O emission reductions of 7 and 14%, respectively; beyond those crop, soil texture, Land Resource Region, and N input rate modeling estimates by the USDA. This FtM FPC N_2O-N estimation improvement will also enable FtM members and cooperating farmers to have greater confidence that the FPC is more considerate of 4R N management and nutrient stewardship, which are known to strongly influence crop yields, crop and soil system productivity and N recovery, other N loss pathways, soil fertility maintenance, system partial net N balance, and sustainability.

INTRODUCTION AND JUSTIFICATION

Field to Market: The Alliance for Sustainable Agriculture (FtM) developed the Fieldprint Calculator (FPC) to estimate key sustainability metrics addressing land use, water quality, soil conservation, irrigation water use, energy use, and greenhouse gas (GHG) emissions for leading U.S. agricultural field crops (corn, soybean, wheat, cotton, rice, and potatoes) (Field to Market, 2012 v2). Currently, that FPC nitrous oxide (N_2O) estimation relies on a simple nitrogen (N)-rate dependent multiplier to estimate fertilizer nitrogen impacts on N_2O-N emissions, with some broad consideration of nitrification inhibitors. Currently, the FPC does not consider complete 4R nutrient management (applying the right nutrient source at the right rate, the right time and in the right place); with the exception of rate it does not consider impacts of source, time and place. Scientists have known, at least since 1990 (Eichner, 1990) that there are multiple manageable and unmanageable factors that affect nitrous oxide emissions from soils (**Table 1**); including the 4Rs, as well as crop rotation or previous crop.

Table 1- Brief list of factors that affect nitrous oxide emissions from soils; manageable and unmanageable, with 4R N management affects highlighted (adapted from Eichner, 1990).

MANAGEMENT PRACTICES		ENVIRONMENTAL FACTORS
Fertilizer type	**SOURCE**	Temperature
Application rate	**RATE**	Precipitation
Application technique	**PLACE**	Soil moisture content
Timing of application	**TIME**	Organic carbon (C) content
Tillage practices		Oxygen availability
Use of other chemicals		Porosity
Crop type (including crop rotation or prior crop)		pH
Irrigation		Freeze and thaw cycle
Residual N and C from crops and fertilizer		Microorganisms

The Intergovernmental Panel on Climate Change (IPCC) emission factor for direct and indirect (associated with N deposition from leaching, runoff, volatilization) emissions of N_2O-N are 0.01 and 0.0035, respectively. Currently, the FtM FPC uses a liberal estimation by upwardly rounding the sum of those direct and indirect N_2O-N emissions factors, to arrive at a 0.014 (0.01 + 0.0035; 1.4%) value for the farmer-applied N rate multiplier to estimate field-scale N_2O-N emissions. However, the IPCC N-rate based N_2O-N emission factors were intended for country or national-level emissions estimates, and were never considered appropriate or intended for farm- or field-scale N_2O-N emissions estimation (De Klein et al., 2006; Smith et al., 2007).

Science has advanced since FtM established the current (i.e. before 2011) estimation of field-scale N_2O-N emissions in the FPC, and the extremely large uncertainty in the IPCC country-level direct N_2O-N emissions from managed soils is now better understood by more scientists for some production agriculture sectors (Hatfield and Venterea, 2014). Some stakeholders are beginning to appreciate that the mean IPCC multiplication factor for country-level estimation (i.e. for national inventory estimation purposes only) of direct N_2O-N emissions, as a function of applied N rate is 0.01, and has an uncertainty of 0.003 - 0.03 (i.e. plus or minus 300%).

PROJECT DESCRIPTION AND METHODS

Through collaborative leadership by the International Plant Nutrition Institute (IPNI) N Program, and stewardship leaders in IPNI and The Fertilizer Institute (TFI), an industry-sponsored (IPNI-TFI) project was planned, proposed, and accepted by FtM in early 2015. The IPNI-TFI project (hereafter referred to as "Project") goals were to:

1) Consider current N management and N_2O-N emissions science for corn, soybean and wheat systems in the U.S. (including USDA Technical Bulletin 1939 by Eve et al. (2014))
2) Convene and conduct a science workshop (hereafter referred to as "Workshop") in March 2015, with an open science discussion on opportunities to improve cropping system N management. There was roundtable science discussion (with no IPNI or TFI project manager science comment), and each invited scientist independently contributed his or her N management science results and experiences. All discussion was facilitated and recorded by independent meeting facilitators.
3) Develop frameworks with suites of 4R (right source, rate, time and place of application) N management practices by leading USDA and university N management and N_2O-N scientists, which; i) were consistent with current science, ii) informed by expert knowledge, iii) reflective of improved N use efficiency and effectiveness, and iv) would most likely lead to:
    a. improved crop yields and cropping system productivity,
    b. greater crop uptake and soil retention of applied N, and
    c. reduced direct emissions of N_2O-N, while also reducing risks and magnitudes of N loss via other loss pathways (leaching/drainage, runoff, and volatilization) which also affect indirect N_2O emissions.
4) Establish science-based N_2O-N emission reduction modifiers for each suite (Basic, Intermediate, Advanced/Emerging) of N management practices for major U.S. corn, soybean, and wheat production systems. Corn, soybean, and wheat were selected for this project based on available, published science and because they utilize the largest volume of crop fertilizer N in the U.S.

The Project identified leading cropping system N management and N_2O-N emission scientists from within the United States Department of Agriculture (USDA) and leading agricultural universities, and invited them to the science coordination and consensus-building Workshop. More than 25 N scientists were invited, and ultimately 20 scientists accepted the invitation and attended the March 2015 Workshop. All N scientists who were approached by the IPNI N Program Director (Dr. C.S. Snyder) were keenly interested, but several had prior meeting and work commitments which prevented their participation. The invited PhD scientists who participated in the Workshop, and their locations, are identified and illustrated in **Figure 1**.

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

Invited Scientists Who Participated in IPNI-TFI-CFI March 2015 Nitrogen (N) Management Workshop

N Agronomists

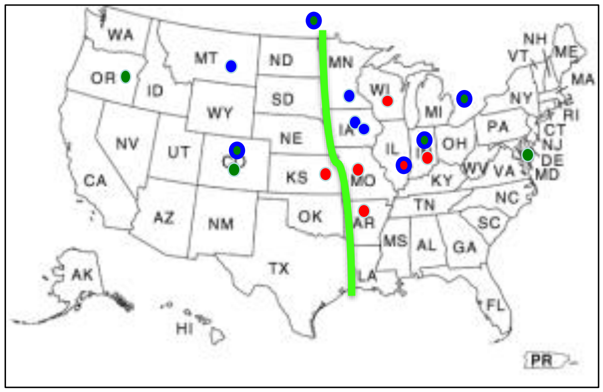
- Peter Scharf – U of MO
- Dave Franzen – ND State U
- Jim Camberato – Purdue U
- Dave Mengel – KS State U
- Carrie Laboski– U of WI
- Cameron Pittelkow – U of IL
- Trent Roberts – U of AR

N_2O Scientists

- Rick Engel – Montana State U.
- Rod Venterea – MN, USDA-ARS
- Tony Vyn- Purdue U
- Jerry Hatfield – IA, USDA-ARS
- Tim Parkin – IA, USDA ARS
- Keith Paustian/ Steve Ogle – CO State U.
- Steve Del Grosso – CO, USDA ARS
- Adam Chambers – OR, USDA NRCS
- Marlen Eve – DC, USDA Ofc. Chief Sci.

Canadian Scientists

- Claudia Wagner-Riddle - U of Guelph
- Mario Tenuta, U of MB
- David Burton, Dalhousie U (formerly Nova Scotia Ag. College)
- Miles Dyck, U of Alberta



Scientific Advisory Group member

IPNI

In advance of the March 2015 Workshop, invited scientists were provided information that included:

1) the Workshop agenda
2) Chapter 3 - Quantifying Greenhouse Gas Sources and Sinks in Cropland and Grazing Land Systems (Ogle et al., 2014) in the USDA Technical Bulletin Number 1939: Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory (Eve et al., 2014).
3) Recent review papers by Decock (2014), Halvorson et al. (2014), and Snyder et al. (2014) which addressed 4R science impacts on N_2O-N emissions mitigation.
4) Science Discussion Document (SDD), which included seven DRAFT 3-tiered 4R N management frameworks (provided to FtM as separate file).
5) A 4R N_2O-N Scientific Advisory Group decision survey to assess the "fitness" of the four technical resources (i.e. published papers and SDD) as technical seed documents for the Workshop discussions (provided to FtM as separate file).

The Workshop communications and discussions were facilitated by The Prasino Group based on previous experience facilitating open science discussions and 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 IPNI-TFI Project SAG included N management and N_2O-N emission scientists as follows:

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

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

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.

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.

RESULTS - N Science Workshop and Three-Tiered 4R N Management Suites of Best Practices

The Science Discussion Document and supporting chapters and articles were approved by the SAG and invited Workshop participants as representing the current state of the science on 4R N management and N_2O-N emissions. In advance of the Workshop, a set of 3-tiered 4R N management frameworks were drafted by IPNI scientists in North America, and provided as a starting point for consideration. During the March 2015 Workshop, the draft frameworks were reviewed, discussed, and modified by the invited scientists. Six of the seven 3-tiered 4R N management frameworks were refined at the March Workshop and unanimously approved, using a double-blind voting and science consensus process at the Workshop. ***Workshop representatives from IPNI, TFI, FC and observers were excluded from voting.***

The tiered N management levels and associated practices were developed to afford farmers, their advisers, and the industry the opportunity to continuously improve their 4R sustainable N management practices, while reducing crop agriculture N_2O N emissions; without sacrificing crop yields or soil productivity. In the approved frameworks (provided in the Appendix), the tiered N management levels (which cover both fertilizer and manure N inputs) were identified as follows, relative to current grower adoption in 2015; as determined and approved by all the scientists participating in the 2015 Workshop.

- Below Basic BMPs (best management practices) – currently performed by 25% of 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

Six crop agroecosystem 4R N management frameworks (see frameworks in document by Snyder (2016), included in the Appendix of this report) were refined and approved during the Workshop.

- Non-irrigated Corn-Soybean in the West
- Non-irrigated Corn-Soybean in the North Central Upper Mid-West
- Non-irrigated Corn-Soybean in the East Central
- Irrigated Corn-Soybean in the North
- Wheat in the Northern Great Plains
- Wheat in the Southern Great Plains

Due to time constraints at the Workshop, refinement and ratification of the 3-tiered 4R N management framework for "Irrigated Corn-Soybean in the South" was deferred. IPNI's N Program Director Dr.

Snyder subsequently worked with University of Arkansas N scientist Dr. Trent Roberts (who attended the Workshop and who volunteered to assist) to enlist the help of three Southeast corn system N management scientists (Dr. Wayne Ebelhar, Mississippi State University; Dr. H.J. "Rick" Mascagni, Louisiana State University; and Dr. Glen Harris, University of Georgia) to refine the framework. The completed framework was then presented to the SAG, which then unanimously approved all seven U.S. cropping system 4R N management frameworks.

To address spatial variability of emissions, the developed regional frameworks needed to be associated with NRCS Land Resource Regions (LRRs). Discussion leaders, elected at the Workshop by each framework discussion group, were invited to identify pertinent LRRs (**Figure 2**; USDA NRCS, 2006) for each framework, with input from the respective Workshop scientists within that framework discussion group.

Figure 2- Example map of USDA NRCS Land Resource Regions (credit: Pennsylvania State Univ.). (Also see LRR map of conterminous U.S. by USDA NRCS at: http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_051846.pdf)

The SAG and Workshop scientists unanimously-approved seven, 3-tiered crop agroecosystem 4R-N management frameworks with state and Land Resource Region designation are included in the **Appendices** at the end of this report and proposal, and were published by Snyder (2016). This N_2O-N emission reduction challenge and the Project's objectives, methods, and explanation of the N management science Workshop activities were presented before many (>100) scientists and agronomic practitioners at the 2015 North Central Industry-Extension Soil Fertility Conference in Des Moines, Iowa, and published in that Conference Proceedings (Snyder, 2015). In addition, those frameworks were overviewed in presentations to the Coalition on Agricultural Greenhouse Gases (C-AGG) at their July 2016 conference in Denver, Colorado. A webinar was delivered on September 28, 2016 that included an overview of the N management and N_2O emission science and those 4R N management frameworks presented here (*recording available at:* https://youtu.be/bBnNrbZHLFQ); with attendance by several hundred participants from around the world. Those public presentations allowed opportunity for considerable feedback on the approaches presented in this report and proposal, by agronomic practitioners, additional scientists, and agricultural greenhouse gas groups; all of which served to reinforce and validate our approach to improve the nitrous oxide estimator in the FtM Fieldprint Calculator.

Although, the March 2015 N science Workshop was successful in establishing seven three-tiered 4R N management frameworks for improved crop N recovery, N use efficiency and effectiveness, the Workshop scientists were not quite ready to assign specific N_2O-N emission reduction modifiers to each of the approved 3-tiered suites of 4R-N management practices. During that March 2015 Workshop, the Project Science Advisory Group (SAG) and participating Workshop scientists suggested that the USDA-supported agriculture N_2O-N emission modelers (*who lead the U.S. annual agricultural greenhouse gas (GHG) inventory report to the U.S. Environmental Protection Agency*) consider performing model runs using one or more of the approved 3-tiered 4R N management frameworks. IPNI N Program Director Snyder subsequently met with N_2O-N emission modelers, Dr. Stephen Ogle with Colorado State University and Dr. Steve Del Grosso with USDA ARS, in Ft. Collins, CO in April 2015 to discuss modeling of selected N management frameworks. The discussions addressed the potential for DAYCENT and DNDC-hybrid N_2O-N emission model runs, to determine if N_2O-N emissions reductions are well-simulated, and are associated with improved N use efficiency when moving from the Basic, to 4R Intermediate, to 4R Advanced/Emerging N management suites of N management practices. However, because those models may not currently include sensitivity to the respective 4Rs, it was decided that such modeling of selected N management frameworks would be postponed until additional efforts to better understand the relationship between N_2O-N emissions and N recovery efficiencies were completed; and until the prospects for funding such work improved.

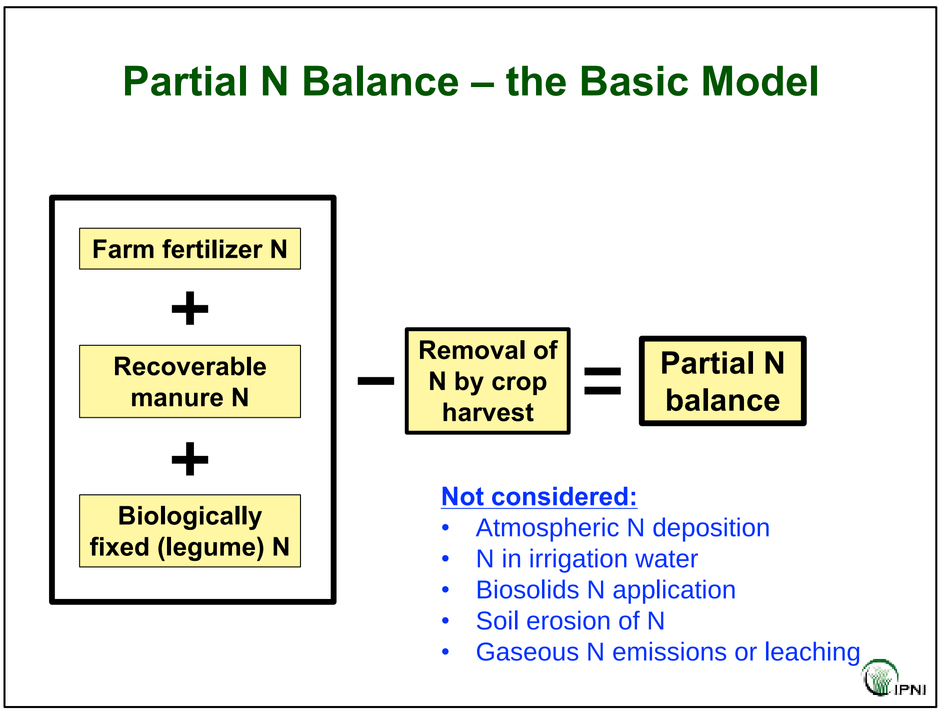
RESULTS –Data Analyses from Research-Measured Field N_2O-N Emissions vs. Measured Crop N Factors

Consistent with the charge of the Project's SAG, and as a next step in advancing the Project's science scope and analyses, Dr. Tony Vyn at Purdue University was invited by IPNI to submit a two-part research proposal to the 4R Research Fund: **Relationships of Nitrous Oxide Emissions to Fertilizer Nitrogen Recovery Efficiencies in Rain-fed and Irrigated Corn Production Systems: 1) Data Review and 2) Research Foundation Building** (http://research.ipni.net/project/IPNI-2015-USA-4RN27 and http://research.ipni.net/project/IPNI-2015-USA-4RN28) (Vyn et al., 2016).

The two research proposals were subjected to critical review by the 4R Research Fund Technical Advisory Group (TAG), scrutinized by the Fund's Management Committee, and ultimately approved for funding (http://www.nutrientstewardship.com/4r-research-fund) support in August 2015. Dr. Vyn began the data analyses work in October 2015, in collaboration with Dr. Ardell Halvorson with the USDA ARS (retired) and Dr. Rex Omonode (post-doctoral scientist) with Purdue University; with cooperation provided by several other leading N management and N_2O-N emissions scientists in the U.S. (and Canada). They assembled and analyzed existing data on corn yield response to ranges of N rates, as well as available N source, time, and place of application treatments. The cooperating scientists' work specifically included data on measured actual corn N uptake and estimations of nitrogen use efficiency (i.e. crop recovery of applied N) and direct measurements of growing season N_2O-N emissions. The objectives of the data analysis study by Dr. Vyn and others were to assess the relationships between growing season cumulative N_2O-N emissions and total plant N uptake (NU, kg N/ha), corn N recovery efficiency (NRE, %; (calculated as: (crop N uptake with applied N – crop N uptake with no N applied)/applied N rate)*100) and the plant/soil partial N balance (NB; calculated as the difference between the N input rate applied and the crop harvest N removal as grain, or grain plus stover, or total biomass, in kg N/ha; in the context of pertinent N management decision factors (4R: source, rate, time, and place of application). The approach that was used to estimate the plant/soil partial N balance is illustrated in **Figure 3**.

NOTE: For the purposes of this Project report, the partial N balance terms (Dobermann, 2007; Snyder and Bruulsema, 2007; Norton et al., 2015) - "partial net N balance", "net N balance", "N surplus" and "system N balance" are considered equivalent.

Figure 3 – Example of method used to estimate cropping system partial N balance (IPNI, 2012).



Although it does not have direct bearing on the N_2O-N emission estimation revision in the Fieldprint Calculator, which we are proposing in this report, we would briefly mention:

> *The European Commission uses a similar gross N balance estimation, but additionally includes atmospheric deposition, seeds and planting material as N inputs; however, they consider seed and planting material inputs as "negligible" (http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_gross_nitrogen_balance). Zhang et al. (2016) also considered a "N surplus" estimation in their paper on managing N for sustainable development; with that "N surplus" or partial net N balance defined as [(fertilizer + manure + biologically fixed N + atmospheric N deposition) minus (N removed in harvested crop products)]. Zhang et al. (2016) used a national country-level atmospheric N (wet plus dry) deposition value for their U.S. national estimates. The U.S. annual atmospheric total N*

deposition has averaged less than 9 kg/ha (~ 8 lbs/A), has been declining each year since about 2000 (NADP, 2016), and is highly variable from year to year; especially among and within different geographic regions (http://nadp.sws.uiuc.edu/committees/tdep/tdepmaps/preview.aspx#n_tw).

In assessing the N rate relationship with N_2O and NU across locations, Vyn et al. (2016) included only data from experiments that involved three (3) or more N rates (including control). Data were from the USDA GRACEnet network and several corn/nutrient management systems in typical rain-fed (Indiana, Kentucky, Minnesota, Quebec (Quebec City and L'Acadie) and irrigated systems (Colorado, Nebraska and Minnesota). Manure application data were not included in their data analyses. However, several of the studies included in the data analyses study by Vyn et al. (2016) relied on fertilizer N input rates used by the research scientists, which were informed and affected by N in the previous crop (i.e. "rotation" crop N effects), any previous manure history, and N in the irrigation water. A total of 338 treatment mean values/observations of cumulative growing season N_2O-N emissions (179 from six rain-fed states or provinces, and 159 from irrigated systems in Colorado, Minnesota, and Nebraska) were derived from 23 published studies (and 1 unpublished study from Indiana), together with their respective corn yield, grain N, and whole-plant N uptake (NU) mean values.

Major findings of the above corn N and N_2O-N data analyses by Vyn et al. (2016) are indicated below (complete public report is available at: **http://research.ipni.net/project/IPNI-2015-USA-4RN27**):

- The portion of the variation in cumulative growing season N_2O-N emissions (i.e. regression r^2 value) explained by the independent N factors, depended on how growing season cumulative N_2O-N emission was expressed: area-scaled/based ($N_2O_{(AS)}$), yield-based ($N_2O_{(YS)}$) or as % of site-year maximum (relative N_2O-N).
- Expressing growing season cumulative N_2O-N loss as relative N_2O-N almost always doubled the resultant r^2 values (i.e. more of the variation in crop growing season N_2O-N emissions was explained)
- Within experimental locations, relationships between cumulative N_2O-N and total corn N uptake (NU) ranged widely (r^2: 0.004-0.74) but were, on average, fairly weak.
- Contrary to expectation, the relationships between cumulative growing season N_2O-N and both NU and nitrogen recovery efficiency (NRE) were generally weak ($r^2 \leq 0.16$).
- A fairly strong ($r^2 = 0.30$) and linear positive relationship existed between N rate and cumulative area-scaled N_2O-N
  - However, the quantity of N_2O-N emitted per unit N rate varies substantially, but is consistently lower for the relatively drier Colorado than for more humid environments in the Midwestern USA and eastern Canada.
- Within locations, the relationships between cumulative growing season N_2O-N and partial net N balance (NB) also varied considerably (r^2: 0.05-0.27), and were mostly positive (and linear).
- A strong, and consistently positive, linear relationship existed between N_2O-N and partial net N balance (NB), across locations.
  - Where N rates and sources were compared, the multiple linear regression models indicated that area-scaled N_2O-N response to N management systems was more related to net NB than to any other plant N factor at crop maturity.
  - Net NB accounted for 19 of the overall 29% variability of N_2O-N emissions that was explained by the chosen N based parameters, while NU accounted for 6% and NRE for 4% of the remaining 29%.
  - Similarly, partial net NB explained, respectively, 26 of 28% and 13 of 24% of the total variability associated with relative N_2O-N and yield-scaled N_2O-N.

Overall, the results from the data analyses by Vyn et al. (2016) indicated that both total corn N uptake (NU) and nitrogen recovery efficiency (NRE) appeared to be poor indicators of growing season N_2O-N emissions, due in part to the variability associated with the dataset, inadequate corresponding data on total corn N uptake, and perhaps because other reactive N sources (including ammonia and nitric oxide) were not considered in the analyses. Across locations, the significant positive linear relationships indicated that N_2O-N emissions were likely to increase as partial net N balance increased, or vice-versa.

The stronger relationships observed by Vyn et al. (2016) for the effects of crop-soil system partial net N balance on relative % N_2O-N emissions are illustrated in **Table 2**, and may be compared to the partial net N balance effects on the actual area-scaled N_2O-N emissions shown in **Table 3**. Relative % N_2O-N emissions are primarily of value to research scientists and are generally not applicable for direct farmer use. Relative % N_2O-N emissions and area-scaled N_2O-N emissions are strongly related. However, because actual area-scaled N_2O-N relationships versus the crop-soil system partial net N balance relationships allow quantitative N_2O-N emissions estimation, area-scaled N_2O-N emissions were used in subsequent analyses and interpretations that are provided in the remainder of this Project report. Although we (i.e. Project Leaders) recognize the need for, and importance of, reporting N_2O-N emissions on a yield-scaled basis, a number of Field to Market members have emphasized the need to also know agricultural N_2O-N emissions on an area-scaled basis; so, we accommodated those interests with area-scaled N_2O-N emissions values presented in this report.

Table 2 –Relationships between relative % N_2O-N emission and partial net N balance across and within study locations. (Relative N_2O-N is % of maximum N_2O-N emission within the site-location-year; y= % relative N_2O-N, x= partial net N balance in kg of N/ha)

Data source in Vyn et al. (2016)	State or province location (4R treatments)	Observations or n	r-square[1]	Predictive equation
Fig. 2b	All (rates & locations)	130	0.40***	y=0.29x+36.96
Fig. 7d	IN (across management systems)	75	0.44***	y=0.31x+30.33
Fig. 9c	KY (sources)	14	0.07ns	y=0.16x+40.37
Fig. 10c	MN (rate, source, time)	24	0.50***	y=0.29x+67.32
Fig. 11d	Quebec-Quebec City (rate, source)	30	0.30***	y=0.14x+74.98
Fig. 12d	Quebec-L'Acadie (rates)	24	0.22*	y=0.24x+43.65
Fig. 13d	CO, irrigated (across multiple treatment combinations)	141	0.21**	y=0.21x+35.20
Fig. 15c	MN, irrigated (source, placement)	32	0.24ns	y=0.29x+27.94

[1] Portion of variability in "y" explained by "x".

*, **, and *** respectively, represent statistical significance (Pr. >F) as follows: < 0.05 and >0.01; <0.01 and >0.001; <0.001; ns = not significant.

Table 3 –Relationships between actual area-based N_2O-N emission and partial net N balance across and within study locations. (y= area-scaled N_2O-N in kg of N_2O-N/ha, x= partial net N balance in kg of N/ha)

Data source in Vyn et al. (2016)	State or province location (4R treatments)	Observations or n	r-square[1]	Predictive equation
Table 2 & Appendix Fig. IId	All (across treatments & locations)	274	0.18***	y=0.007x+0.80
Table 2 & App. Fig. IV	IN (across management systems)	75	0.24***	y=0.01x+0.87
Table 2 & App. Fig. VIc	KY (sources)	14	0.07ns	y=0.01x+2.41
Table 2 & App. Fig. VIIc	MN (rate, source, time)	24	0.47***	y=0.003x+0.64
Table 2 & App. Fig. IXc	Quebec-Quebec City (rate, source)	30	0.21**	y=0.05x+16.20
Table 2 & App. Fig. Xd	Quebec-L'Acadie (rates)	24	0.22**	y=0.008x+1.59
Table 2 & App. Fig. XIe	CO, irrigated (across multiple treatment combinations)	141	0.26***	y=0.005x+0.57
Table 2 & App. Fig. XIIc	MN, irrigated (source, placement)	32	0.24ns	y=0.006x+0.55

[1] Portion of variability in "y" explained by "x".

*, **, and *** respectively, represent statistical significance (Pr. >F) as follows: < 0.05 and >0.01; <0.01 and >0.001; <0.001; ns = not significant.

Using the equations in **Table 3,** which resulted from the data analyses by Vyn et al. (2016), we evaluated the impacts of reductions in crop-soil system net N balances on reductions in area-scaled N_2O-N emissions. Those results are presented in **Tables 4 and 5**. We chose 30 kg of N/ha as a fairly representative farm field partial net N balance (more N input than removed in harvested crop (i.e. grain, or grain plus stover, or silage, etc.) under typical cropping system and N management in the U.S., because the U.S. national average partial net N balance has ranged roughly between 20 to 30 kg of N/ha/year since about 2007 (Cavigelli, et al., 2012; and also http://nugis.ipni.net/About%20NuGIS/). **Figure 4** illustrates the relatively recent partial net N balances over time across cropping systems and soils within each of the five major river watersheds (Upper Mississippi, Ohio-Tennessee, Missouri, Lower Mississippi, Arkansas-Red), within the larger Mississippi -Atchafalaya River Basin. The general tendency for declining net N balances in recent years is apparent in **Figure 4**, and the rise in partial net N balances that can occur during a drought year (i.e. 2012, in much of the northcentral and upper Midwest) is clearly shown. The data in **Figure 4** reflect the sensitivity of annual partial net N balance estimates to soil and crop management, and also the prevailing growing season environmental (i.e. climate, weather) conditions.

Figure 4 – Cropping system partial net N balance in five major river sub-basins in the U.S., as estimated using IPNI Nutrient Use Geographic Information System (NuGIS) software (IPNI, 2012). (*Note: Crop and manure data in NuGIS are all from the USDA; county-level fertilizer N consumption data are all from Association of American Pant Food Control Official annual reports. Chart is from paper presented by C. S. Snyder at annual meetings of the Soil and Water Conservation Society in July 2016, which relies on the partial net N balance estimation method depicted above in Figure 3)*)

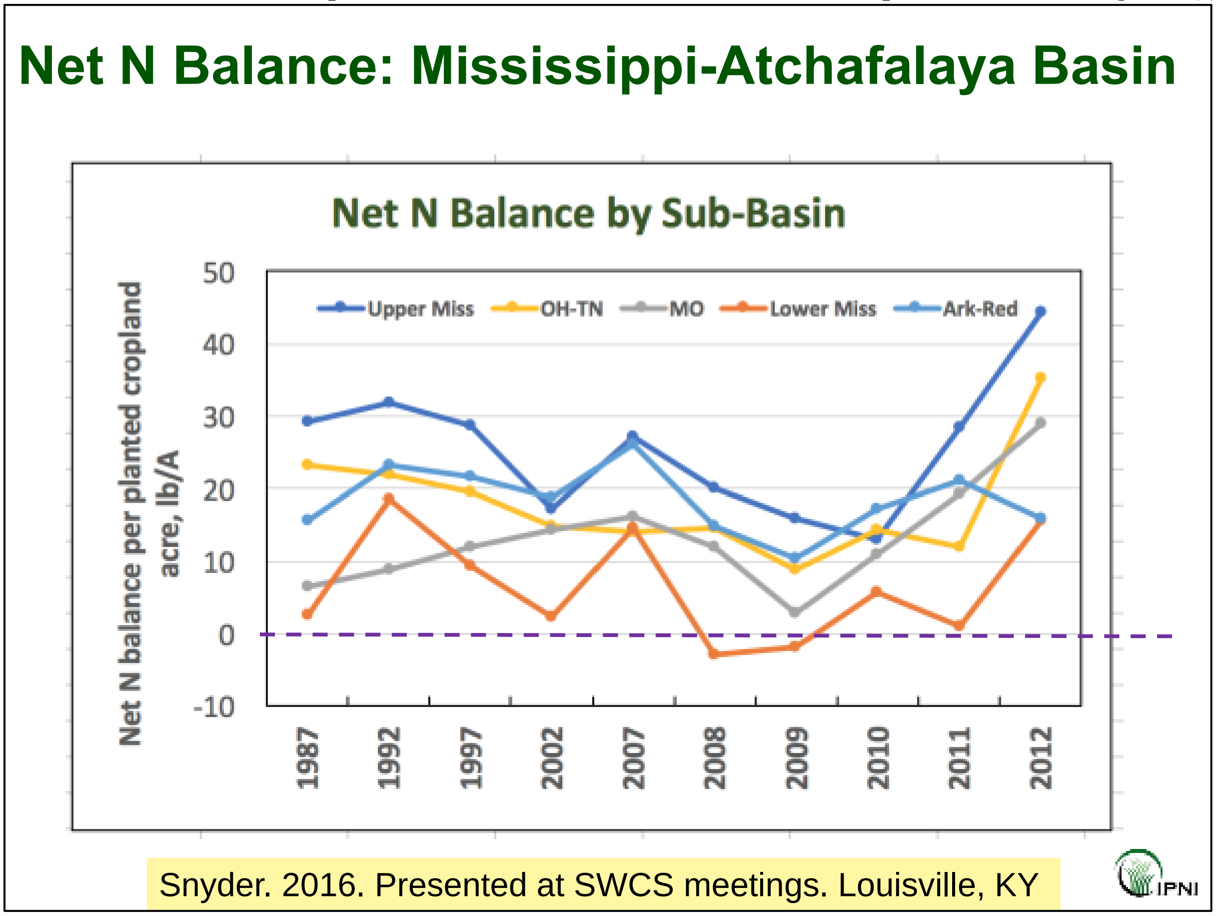


Table 4 – Calculations to answer the questions:
a) What would the area-scaled predicted N_2O-N emissions be, if the partial net N balance were reduced 1/3 (from 30 to 20 kg N/ha)? [1]
b) What % reduction in area-scaled N_2O-N emissions would result from such a reduction in partial net N balance?

State or province location (4R treatments)	**Predictive equation from Table 2 (above)**	**Partial net N balance**		**Reduction of area-scaled N_2O-N emissions, with 1/3 reduction in partial net N balance**
		30 kg of N/ha	**20 kg of N/ha**	
		predicted kg N_2O-N/ha		%
All (across treatments & locations)	y=0.007x+0.80	1.01	0.94	7
IN (across management systems)	y=0.01x+0.87	1.17	1.07	9
KY (sources)	y=0.01x+2.41	2.71	2.61	4
MN (rate,	y=0.003x+0.64	0.73	0.70	4

source, time)				
Quebec-Quebec City (rate, source)	y=0.05x+16.20	17.70	17.20	3
Quebec-L'Acadie (rates)	y=0.008x+1.59	1.83	1.75	4
CO, irrigated (across multiple treatment combinations)	y=0.005x+0.57	0.72	0.67	7
MN, irrigated (source, placement)	y=0.006x+0.55	0.73	0.67	8
[1] Farmer implementation of an **Intermediate** tier (or suite) of 4R N management practices is expected to reduce partial net N balance by 1/3 compared to Basic or typical farmer N management practices.				

Table 5 – Calculations to answer the questions:
a) What would the area-scaled predicted N_2O-N emissions be, if the partial net N balance were reduced by 2/3 (from 30 to 10 kg N/ha)? [1]
b) What % reduction in area-scaled N_2O-N emissions would result from such a reduction in partial net N balance?

State or province location (4R treatments)	**Predictive equation from Table 2 (above)**	**Partial net N balance**		**Reduction of area-scaled N_2O-N emissions, with 2/3 reduction in partial net N balance**
		30 kg of N/ha	**10 kg of N/ha**	
		predicted kg N_2O-N/ha		%
All (across treatments & locations)	y=0.007x+0.80	1.01	0.87	14
IN (across management systems)	y=0.01x+0.87	1.17	0.97	17
KY (sources)	y=0.01x+2.41	2.71	2.51	7
MN (rate, source, time)	y=0.003x+0.64	0.73	0.64	12
Quebec-Quebec City (rate, source)	y=0.05x+16.20	17.70	16.70	6
Quebec-L'Arcadie (rates)	y=0.008x+1.59	1.83	1.67	9
CO, irrigated (across multiple treatment combinations)	y=0.005x+0.57	0.72	0.62	14
MN, irrigated (source, placement)	y=0.006x+0.55	0.73	0.61	16
[1] Farmer implementation of an **Advanced/Emerging** tier (or suite) of 4R N management practices is expected to reduce partial net N balance by 1/3 compared to Basic or typical farmer N management practices.				

These key relationships (e.g. Tables 4 and 5), the data analyses report by Vyn et al. (2016), and the draft N_20-N estimation spreadsheet (and methods), were shared with and approved by the Project SAG (Science Advisory Group) in the summer of 2016.

Based on the Vyn et al. (2016) research data analysis results across locations (mentioned above), and the observed relationship between partial net N balance and N_2O-N emissions, by implementing **Intermediate** suites of 4R N management practices the partial net crop-soil N balance would be expected to be lowered by up to 1/3, with a corresponding average decrease in N_2O-N emissions of **7%**. Implementing **Advanced/Emerging** suites of 4R N practices (explained above) would be expected to lower the crop-soil system partial net N balance 1/3 to 2/3 from the Basic or lower N management, and reduce N_2O-N emissions by **14%**. This science argument for the benefits of 4R N management, which helps to protect and increase crop yields while lowering net crop-soil partial net N balance and reducing N_2O-N emissions, is strongly supported by newly-published work; Venterea et al. (2016) reported that combined N management, that would represent **Advanced/Emerging** suites of practices (*personal communication with R.T. Venterea, May 2016*), resulted in partial net N balance reductions >20 kg of N/ha and N_2O-N emissions reductions >20 to 50%.

These results of the work by Vyn et al. (2016) are in agreement with the meta analysis study by Decock (2014), who stated that N-surplus (i.e. partial net N balance) at the agroecological region scale can be a good predictor of N_2O-N emissions, when variability due to differences in environmental characteristics is partially removed. These corroborative results support our strong argument for Land Resource Region-specific 4R suites of N management practices to optimize crop production, improve crop recovery of applied N inputs; while minimizing soil partial net N balance and N_2O-N emissions.

The term "N surplus" has been frequently used as a proxy for determining N losses in many cropping systems (Zhao et al., 2016). However, we wish to emphasize here that it would be scientifically inaccurate to refer to partial net N balance as "N surplus" in many systems; especially because there are many reports that in some cropping systems where corn is rotated with soybean, negative partial net N balances have been measured or estimated (Castellano et al., 2012; David et al., 2010; Drinkwater et al., 1998; Gentry et al., 2009; Jaynes et al., 2001; Jaynes and Karlen, 2008). Where such negative partial net N balances occur, there is a threat to sustained productivity, as soil organic matter and soil organic N pools are being "mined". This soil N pool "mining" risk is not just a U.S. concern, but has also been recognized as a global sustainability concern in cereal cropping systems, based on recent N budget estimates by Ladha et al. (2016). A very recent report by Poffenbarger et al. (2017) showed that long-term (14 to 16 years) applications of N at agronomic optimum rates resulted in greater crop residue production and greater soil organic carbon (SOC) storage than at N rates above or below the agronomic optimum. The SOC balances were negative where no N was applied but neutral or positive in corn-soybean or continuous corn systems, respectively, in Iowa.

Although some other scientists have reported a strong curvilinear or exponential increase in N_2O-N emissions with increasing N rates, (Van Groenigen et al., 2010; Hoben et al., 2011; Venterea et al., 2011; Kim et al., 2013), the data analyses by Vyn et al. (2016) showed a more linear relationship when more N is applied than is accumulated by the crop (e.g. grain and vegetative matter). We cannot offer a clear explanation for the differences between those studies and the data analyses by Vyn et al. (2016). Yet, it is possible that the studies included in the data analyses by Vyn et al. (2016) were conducted by skilled agronomists and soil scientists who had a long history of field research at their respective study sites, and knowledge about other cropping system and soil management that may have served to better optimize the full corn system performance; including management of the many other inputs and factors that may affect risks for and magnitude of N_2O-N losses (both direct and indirect) (Eichner, 1990). In addition, with the exception of the reports by Van Groenigen et al. (2010) and Venterea et al. (2011), the other reports did not address the relationships between partial net N balance (i.e. "N surplus") and yield-scaled emissions, but instead focused on emissions relationships with N input rates; ignoring the impacts on crop yields and crop N uptake and recovery.

RESULTS – Alignment with USDA Hybrid N_2O Emission Model

Through cooperation of the USDA Climate Change Office of the Chief Economist (personal communications with Dr. Marlen Eve and Marci Baranski with USDA) and Dr. Stephen Ogle at Colorado State University, a spreadsheet was developed to include the following columns (**Table 6**) of USDA hybrid DAYCENT/DNDC modeled N_2O-N emissions data (DAYCENT reference, Del Grosso et al., 2006; DNDC reference - http://www.dndc.sr.unh.edu/ and DNDC, 2012). **NOTE:** the full Excel file and spreadsheet has been provided to FtM Science and Research Director- Allison Thomson, along with this peer-reviewed Project report and proposal.

Table 6 – Columns of data from USDA hybrid DAYCENT/DNDC modeled direct N_2O-N emissions.

A	B	C	D	E	F
LRR	**Crop**	**Surface Soil Texture**	**USDA Typical fertilizer N rate, kg/ha**	**Zero N N_2O emission, kg N_2O-N/ha**	**USDA Typical emission, kg N_2O-N/ha**

Column A, LRR, refers to USDA NRCS Land Resource Region (USDA NRCS, 2006). Column C, soil texture, is the general surface soil texture (coarse, medium fine), based on the 12 USDA soil textural (or particle size) triangle classes (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167). Column D, USDA typical fertilizer N rate, is derived from the 2010 USDA Agricultural Resource Management Survey (USDA ARMS, 2014).

Within the FtM FPC, when a farmer selects his/her field boundary, the USDA LRR may be automatically determined from the USDA STATSGO/SSURGO functions (http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/geo/?cid=nrcs142p2_053631) and uploaded into FPC tools (personal communication with Stewart Ramsey, IHS Global Insights; January 2016). As illustrated below (**Table 7**), the actual farmer's field applied N rate will be entered (Column H) to allow calculation of the proportionately adjusted direct N_2O-N emissions at the typical USDA ARS 2010-surveyed N rate (Column I). Next, the zero-N rate N_2O-N emission for the given LRR, crop, and soil texture (Column E, not shown) is added to that proportionately adjusted farmer N rate direct N_2O-N emission to derive an estimated actual farmer's field total direct N_2O-N emission (Column J), as illustrated in the **Table 7** below. The indirect N_2O-N emissions (associated with N losses from leaching, drainage, runoff, volatilization, atmospheric deposition) are estimated using the IPCC 0.0035 factor (De Klein et al., 2006) times the farmer's applied N rate (Column K). Finally, the total direct and indirect N_2O-N emissions are added to provide the direct plus indirect N_2O-N emissions sum for the respective farmer's field (Column L).

Table 7. Farmer applied N rate and methods to estimate direct N_2O-N emissions (based on USDA modeled emissions, **Table 5**), indirect emissions, and the sum of the estimated farmer's direct and indirect N_2O-N emissions. **Note:** Column letter matches specific column in spreadsheet provided to Field to Market.

H	I	J	K	L
Farmer's actual (or average) N rate applied on selected field (kg N/ha)	**Proportionately adjusted direct emission: (farmer N rate divided by "typical" N rate), times the difference in ("typical" flux minus "zero N" flux). So, (Column H divide by column D), times the difference of (Column F minus Column E) (kg N_2O-N/ha)**	**Total direct emissions for field: Column I plus Column E (kg N_2O-N/ha)**	**Indirect emission estimate: Column H multiplied by IPCC factor 0.0035 (kg N_2O-N/ha)**	**Estimated farmer direct plus indirect emission: Column J plus Column K (kg N_2O-N/ha)**

The Project leaders performed, and shared with the SAG, a USDA-modeled direct N_2O-N emissions sensitivity analyses to determine if the USDA-modeled annual (i.e. full calendar year) emissions estimates were reasonably consistent with actual growing season-measured direct N_2O-N emissions; based on relatively recent published studies of field-measured growing season N_2O-N emissions. The results of those USDA-modeled versus actual research-measured emissions are shown in **Table 8**, and indicated that the current USDA hybrid model tends to under-estimate the growing season emissions, more often than it may over-estimate the N_2O-N emissions. This under-estimation tendency is recognized by those USDA and university scientists who model and submit the U.S. agricultural greenhouse gas emissions inventory annually for the full U.S. annual GHG inventory report (U.S. EPA, 2016), and there is an effort underway to remedy that underestimation; with corrections possibly available in late 2016 or early 2017 (personal communication with S. Ogle and S. Del Grosso, 2016).

Table 8 - Comparison of USDA modeled annual direct N_2O-N emissions with actual measured growing season N_2O-N emissions, as reported in the example cited journal articles.

Crop	**State**	**LRR**	**Soil texture**	**N rate**[1]	**USDA Model vs. measured emissions L= Lower, H=Higher, S=Similar**[2] **kg N_2O-N/ha**	**Magnitude of USDA-modeled (*proportionately adjusted*) difference from research measured (%)**	**Reference for growing season (or full year) measured N_2O-N**
Corn	MN	M	Coarse	100	H	47	Venterea -J. Environ. Qual. 45:1186–1195 (2016)
Corn, irrigated	CO	H	Fine	200	H	194	Halvorson et al. - Agron. J. 106:715–722 (2014)
Corn	IA	M	Medium	168	L	62	Parkin and Hatfield -Agron. J. 105:1–9 (2013)
Corn	TN	P	Medium	252	L	52	Thornton and Velente -Soil Sci. Soc. Am. J. 60:1127-1133 (1996)
Corn	IL	M	Medium	135	L	58	Smith et al. -J. Environ. Qual. 42:219–228 (2013)
Corn	IN	M	Medium	180	L	24	Burzaco et al. - Environ. Res. Lett. 8 (2013) 035031 (11pp)
Cotton	AL	P	Coarse	101	L	51	Watts et al. - J. Environ. Qual. 44:1699–1710 (2015)
Rice, drilled	CA	C	Fine	150	L	36	Adviento-Borbe et al. - J. Environ. Qual. 42:1623–1634 (2013)
Rice, continuous flood	CA	C	Medium	200	H	230	Pittelkow et al. – Agric., Ecosyst. Environ. 177: 10–20 (2013)
Rice, drilled	AR	O	Medium	168	L/S	3	Adviento-Borbe et al. - J. Environ. Qual. 42:1623–1634 (2013)
Potato	MN	M	Coarse	270	H/S	11	Hyatt et al. - Soil

	(*not FL*)						Sci. Soc. Am. J. 74:419–428 (2010)
Soybean	IA	M	Fine	0	L	75	Parkin and Kaspar - J. Environ. Qual. 35:1496–1506 (2006)
Soybean	IL	M	Medium	0	L	46	Smith et al. -J. Environ. Qual. 42:219–228 (2013)
Winter wheat	MT	G	Medium	82	H	66	Dusenberry et al. -J. Environ. Qual. 37:542–550 (2008)
Winter wheat	NE	H	Medium	0	L	54	Kessavalou et al. -J. Environ. Qual. 27:1094-1104 (1998)
SUMMARY					**4H, 2S, 9L**	**Range: 75% lower to 230% higher than measured in cited research studies**	

[1] N rate (assumed agronomic optimum) reported by the respective agronomic and soil science research scientists, in the references noted.

[2] "Similar" is used here to represent modeled emissions within about 10% of the measured research emissions.

RESULTS – Use of Three-Tiered 4R N Management Suites of Practices to Adjust the USDA Hybrid-Modeled N_2O Emissions in a Manner Consistent with Current Science and Technology

Examples are provided in **Table 9** to illustrate the opportunity to improve the FtM FPC N_2O-N estimator and provide a 4R N management-sensitive means for farmers to adopt, implement, and adapt to emerging technologies. Column A provides N_2O-N emissions estimates with the current FtM FPC N-rate-based approach. Column B contains examples of crop, USDA Land Resource Region (LRR), soil texture and USDA farmer-surveyed N-rate effects on modeled direct N_2O-N emissions, and Column C represents the IPCC-based indirect emissions. Then, we show the reductions in USDA-modeled and IPCC estimated N_2O-N emissions that may be expected when **Intermediate** or **Advanced/Emerging** suites of 4R N management practices are implemented (Column E and F), as compared or opposed to the typical or **Basic** (or below) N management (**Table 9**).

Unfortunately, it was not possible for the USDA and its partners to model all crop, Land Resource Region (LRR), and soil texture combinations because of budget constraints (Eve et al, 2014; personal communication S. Ogle). As a consequence, it is necessary to provide a "default" procedure for N_2O-N emissions estimations for crop, LRR, soil texture and N rate combinations that are not currently directly available from the USDA modeling output. Those respective "default" N_2O-N emissions estimates follow the same calculation procedure as outlined above (Table 6 and 7, and related text), except that the USDA 2010 ARMS survey N rate, and the typical emission, and zero-N emissions for a given crop and soil texture would be averaged across the available USDA modeled LRRs; within each respective corn, soybean, or wheat crop (or other crop) (**Table 9**).

Table 9- Example comparisons of direct and indirect N_2O-N emissions by the existing Field to Market Fieldprint Calculator method contrasted with the proposed method which considers USDA modeled emissions according to crop, Land Resource Region, surface soil texture, farmer-applied N rates and 4R suites or tiers of N management practices.

	A	B	C	D	E	F
	------------ N RATE ONLY APPROACH -------------				4R- N MANAGEMENT[1]	
					INTERMEDIATE	ADVANCED
Crop, State, Land Resource Region, soil texture, applied N rate (kg of N/ha)	Current FTM FPC estimate of combined direct plus indirect emission, (N rate x (.01 + 0.004))	USDA-hybrid modeled total direct emission, with proportionately adjusted N rate	IPCC-based estimate of indirect emission, (0.0035 x applied N rate)	USDA-hybrid modeled direct plus IPCC-indirect emissions, (column B + C)	7% further reduction of USDA direct plus IPCC indirect emissions, ((column D) minus (7% of column D))	14% further reduction of USDA direct plus IPCC indirect emissions, ((column D) minus (14% of column D))
	-- kg of N_2O-N/ha --					
Corn, IN, M, Medium, 190	2.66	2.78	0.67	3.45	3.21	2.97
Corn, PA, S, Fine, 190	2.66	3.33	0.67	4.00	3.72	3.44
Irrig. Corn, MS, O, Fine, 190	2.66	3.70	0.67	4.37	4.06	3.76
Irrig. Corn, NE, H, Coarse, 190	2.66	0.93	0.67	1.60	1.49	1.38
Winter Wheat, ND, F, Medium, 90	1.26	1.17	0.32	1.49	1.39	1.28
Winter Wheat, KS, H, Medium, 90	1.26	1.28	0.32	1.60	1.49	1.38
Winter Wheat, TX, J, Medium,	1.26	1.22	0.32	1.54	1.43	1.32

90						
Winter wheat, KY, N, Medium, 120 [2]	1.68	1.37	0.42	1.79	1.66	1.54
Winter wheat, AR, O, Fine, 120 [2]	1.68	1.90	0.42	2.32	2.16	2.00
Soybean, AR, O, Fine, 18 [2]	0.25	1.75	0.06	1.82	1.69	1.57
Soybean, IA, M, Fine, 18	0.25	1.90	0.06	1.96	1.82	1.69
Soybean, NE, H, Coarse, 18 [2]	0.25	1.05	0.06	1.11	1.03	0.95

[1] **NOTE:** If the farmer's N management tier (or suite) is **Basic** (or below), no further reduction (e.g. column E or F) in direct and indirect N_2O-N emission can be justified; and the resulting direct plus indirect estimated N_2O-N emission for the respective field, is simply that shown in Column D of Table 8 above.

[2] **NOTE:** Estimates based on the "default" averaging procedure (*emissions values averaged within a given soil texture and crop, across LRRs*) as explained in the text above, because USDA-modeled emissions output data were not available for this specific crop, LRR, soil texture combination.

The results shown above in **Table 9** clearly indicate that the current FtM FPC N_2O-N loss estimates are insensitive to variations in cropping system, Land Resource Region, soil texture, N management (more than just N rate), and local prevailing conditions. These results also indicate that the current FtM FPC N_2O-N emissions estimation method may also be fairly consistently under-estimating field N_2O-N emissions.

At some locations in the U.S. (and Canada), in some years, some specific individual 4R N management practices (e.g. change in N source, change in N timing, change in N placement) can provide N_2O-N emission reductions frequently in excess of 25 to 33% (or more), compared to more standard farmer N management practice (Snyder et al., 2014; Venterea et al., 2016). **Figure 5** illustrates those practice change effects on reducing N_2O-N emissions.

Figure 5 – Example of changes in the source, rate, time, and place of N application on reductions in N_2O-N emissions, based on recent peer-reviewed journal articles.

Recent Examples of N Management Changes on N_2O Emission Reduction (1 of 4)

Comparison technology or N practice	Reference technology or fertilizer N practice	Emission reduction (%)	Comment [COSUST paper reference]
Urea with urease inhibitor (UI)	Urea alone	Nil	Meta analysis; 35 studies [36] [1]
Nitrification inhibitor (NI) or polymer coated urea (PCU)	Conventional N, no inhibitor or polymer coating	35-38	
Urea	Anhydrous ammonia	50	15-yr.-old corn-soybean system [33] [2]
Change in time, source, place	Standard or reference N management	20-80	Summary of >20 studies [37] [1]
Urea ammonium nitrate (UAN) with NI	UAN with no inhibitor	19-67	Side-dressed UAN, subsurface colter-applied at V4-V6 [41] [2]

[1] range of agricultural crops [2] corn (maize)
Snyder et al. (2014). Curr. Opin. Environ. Sustain.

Recent Examples of N Management Changes on N_2O Emission Reduction (2 of 4)

Comparison technology or N practice	Reference technology or fertilizer N practice	Emission reduction (%)	Comment [COSUST paper reference]
Fertilizer N with UI and NI	Fertilizer N with no inhibitor	38	Meta analysis; 3 studies, 20 observations [42] [2]
Fertilizer placement >5cm deep	Fertilizer placement <5 cm deep	>30	Meta analysis; reduced tillage [26] [3]
Urea with NI	Urea with no inhibitor	81-100	Full growing season measurements (217–382 days); fertilizer banded >5 cm deep, 20 cm from plant row; clay loam soil . PSCU emissions lower than urea, first 20 days after application [43] [4]
Polymer sulfur coated urea (PSCU)	Urea with no coating	-35 to -46	

[2] corn (maize) [3] range of agricultural crops, excluding rice [4] sugarcane, residue removed or burned
Snyder et al. (2014). Curr. Opin. Environ. Sustain.

Recent Examples of N Management Changes on N_2O Emission Reduction (3 of 4)

Comparison technology or N practice	Reference technology or fertilizer N practice	Emission reduction (%)	Comment [COSUST paper reference]
Fertilizer N (including urea with UI and NI, urea–ammonium nitrate (UAN) with UI and NI, urea, UAN, ammonium nitrate, or PCU)	Poultry litter	46-81	Humid region; surface broadcast, not incorporated [39] [2]
Commercial fertilizer	Manure	40	Meta analysis; 9 studies, 73 observations [42] [2]
Calcium ammonium nitrate	Manure (poultry, or liquid swine, or liquid dairy)	54	Surface applied N, incorporated by tillage, day of application [40] [2]

[2] corn (maize)
Snyder et al. (2014). Curr. Opin. Environ. Sustain.

Recent Examples of N Management Changes on N_2O Emission Reduction (4 of 4)

Comparison technology or N practice	Reference technology or fertilizer N practice	Emission reduction (%)	Comment [COSUST paper reference]
UAN with UI and NI	UAN with no inhibitor	41	Full growing season N_2O measurements; irrigated; no-till and tilled; surface banded N near emerged corn row [35] [2]
	Urea with no inhibitor	61	
UAN with methylene urea & urea triazone	UAN	28	
	Urea	57	
PCU	UAN	14	
PCU	Urea	42	
Urea with UI and NI	Urea with no inhibitor	37	Dairy cows excluded 2 months prior; plant N recovery: 50 to 85% [38] [5]

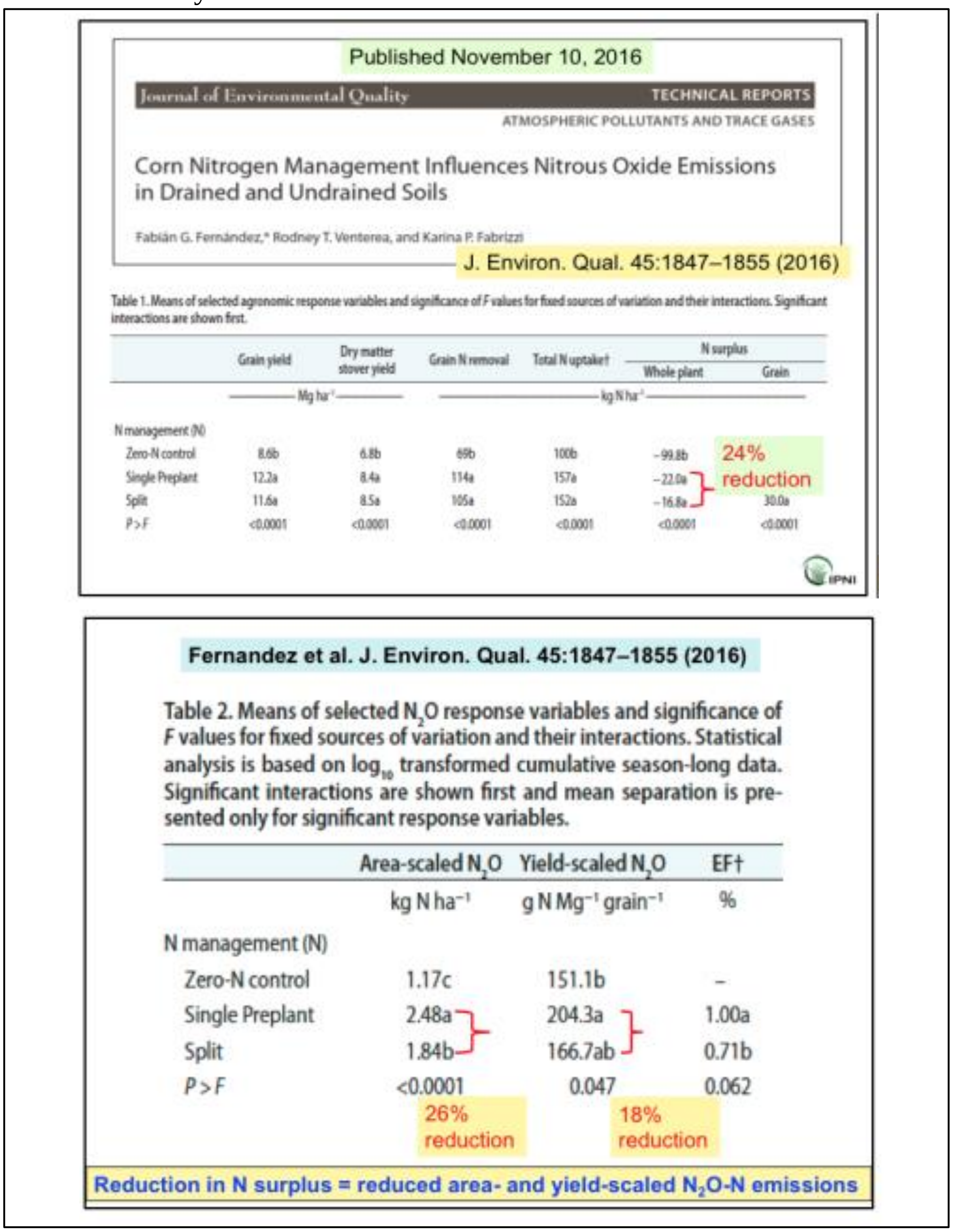
[2] corn (maize) [5] using perennial ryegrass (*Lolium perenne* L.)/white clover (*Trifolium repens* L.) pasture
Snyder et al. (2014). Curr. Opin. Environ. Sustain.

It may be important to note here that when using ammonium or urea-based fertilizer N, use of a nitrification inhibitor has been among those 4R practices that have most consistently resulted in reductions in N_2O-N emissions (Decock, 2014; Qiao et al., 2015). Yet, nitrification inhibitors are generally not recommended by Land Grant Universities in many states - especially in the southern U.S.; possibly because the prevailing warm, moist environmental conditions can favor rapid nitrification and overwhelm the efficacy of nitrification inhibition; resulting in limited crop yield response, limited nitrification inhibition, and reduced economic returns (Frye, 2005; Roberts et al, 2016; Touchton and Boswell, 1980). Nitrification inhibitor effects on N_2O-N emissions reduction in the southern U.S. remain largely unknown.

Halvorson and Bartolo (2014) measured "N surplus" over three years in a continuous corn study in Colorado, and found that polymer coated urea reduced the three-year sum of "N surplus" 34% (*i.e. lowered it from 84 down to 55 kg of N/ha in the three-year sum; or stated another way, from an average annual "N surplus" of 28 down to 18, respectively*) compared to conventional urea nitrogen. That N source change, in the context of other N management practices in their study, would be considered as a 4R "Intermediate" suite of N management. That work by Halvorson and Bartolo (2014) lends additional support for the "N surplus" or partial net N balance reduction argument for an "Intermediate" suite of 4R practices, that we illustrate in **Table 4** above.

A recently published study by Fernandez (2016) showed that by splitting the corn N application in Minnesota, as opposed to a single pre-plant application, led to a decreased soil partial net N balance, and reduced the area-scaled and yield-scaled N_2O-N emissions (**Figure 6**). This splitting of the N application and management regime by Fernandez (2016) would correspond to an "Intermediate" suite of 4R practices for that respective Land Resource Region and cropping system; providing a reduction in partial net N balance of 24% and corresponding N_2O-N emissions reductions ranging from 18 to 24%. Those corresponding emission reductions are considerably greater than the conservative 7% N_2O-N emission reduction proposed by the Project leaders to Field to Market, when a farmer implements an Intermediate suite of 4R practices.

Figure 6 – Split N applications on corn in Minnesota lowered soil partial net N balance and reduced area-scaled and yield-scaled N_2O-N emissions.



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ATMOSPHERIC POLLUTANTS AND TRACE GASES

Corn Nitrogen Management Influences Nitrous Oxide Emissions in Drained and Undrained Soils

Fabián G. Fernández,* Rodney T. Venterea, and Karina P. Fabrizzi

J. Environ. Qual. 45:1847–1855 (2016)

Table 1. Means of selected agronomic response variables and significance of F values for fixed sources of variation and their interactions. Significant interactions are shown first.

	Grain yield	Dry matter stover yield	Grain N removal	Total N uptake†	N surplus Whole plant	N surplus Grain
	Mg ha⁻¹	Mg ha⁻¹	kg N ha⁻¹	kg N ha⁻¹	kg N ha⁻¹	kg N ha⁻¹
N management (N)						
Zero-N control	8.6b	6.8b	69b	100b	−99.8b	
Single Preplant	12.2a	8.4a	114a	157a	−22.0a	
Split	11.6a	8.5a	105a	152a	−16.8a	30.0a
P > F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

24% reduction

IPNI

Fernandez et al. J. Environ. Qual. 45:1847–1855 (2016)

Table 2. Means of selected N_2O response variables and significance of F values for fixed sources of variation and their interactions. Statistical analysis is based on $\log_{10}$ transformed cumulative season-long data. Significant interactions are shown first and mean separation is presented only for significant response variables.

	Area-scaled N_2O	Yield-scaled N_2O	EF†
	kg N ha⁻¹	g N Mg⁻¹ grain⁻¹	%
N management (N)			
Zero-N control	1.17c	151.1b	–
Single Preplant	2.48a	204.3a	1.00a
Split	1.84b	166.7ab	0.71b
P > F	<0.0001	0.047	0.062

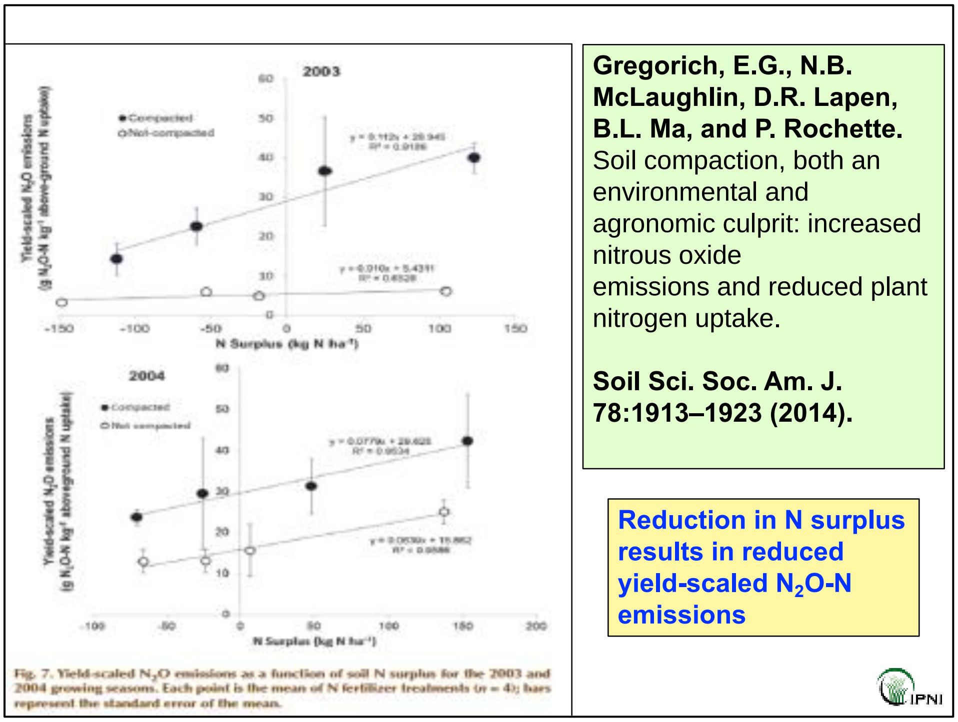
26% reduction

18% reduction

Reduction in N surplus = reduced area- and yield-scaled N_2O-N emissions

Although our discussion here in this Project report addresses 4R (source, rate, time, and place) N management effects, it is important to recognize that partial net N balance ("N Surplus") may also be affected by factors like soil compaction, wetness, and aeration which were mentioned among the multiple factors affecting N_2O-N emissions by Eichner (1990). **Figure 7** illustrates how soil compaction can influence conditions (lower soil porosity, higher moisture) which are conducive to increased partial net N balance and N_2O-N emissions.

Figure 7– Increased soil compaction can affect crop production, crop N uptake, partial net N balance, and contribute to increased yield-scaled N_2O-N emissions.



Site-specific, N-sensor-based variable rate N management falls within the "Advanced/Emerging" suites of 4R practices, and can provide reductions in partial net N balance or residual soil N, which also confer a reduction in N_2O-N emissions. It is extremely difficult to conduct static chamber-based measurements of N_2O-N emissions in farmer fields where such technologies have been employed; as part of a suite of improved N management practices. Li et al. (2016) performed a modeling analysis of crop sensor-based N management case study in Lincoln County, Missouri, and reported the following:

- Fertilizer N use was reduced by 11% with no loss in corn grain yield;
- Soil N_2O-N emissions were reduced by 10%,
- Volatilized ammonia loss was reduced by 23%, and
- Leaching losses of nitrate-N were reduced by 16%.

Six large-scale N rate management studies were conducted in producer corn fields in earlier research in Missouri (Hong et al., 2007), which measured residual soil nitrate (sometimes used as a surrogate for partial net N balance). The authors of that report stated that their techniques and results might represent what would be experienced with deployment of sensor, aerial imagery, soil test or landscape attribute-based variable rate N management, and observed the following:

- The economic optimum N rate (EONR) at sampling sites varied from 49 to 228 kg N/ha, depending on site and year.

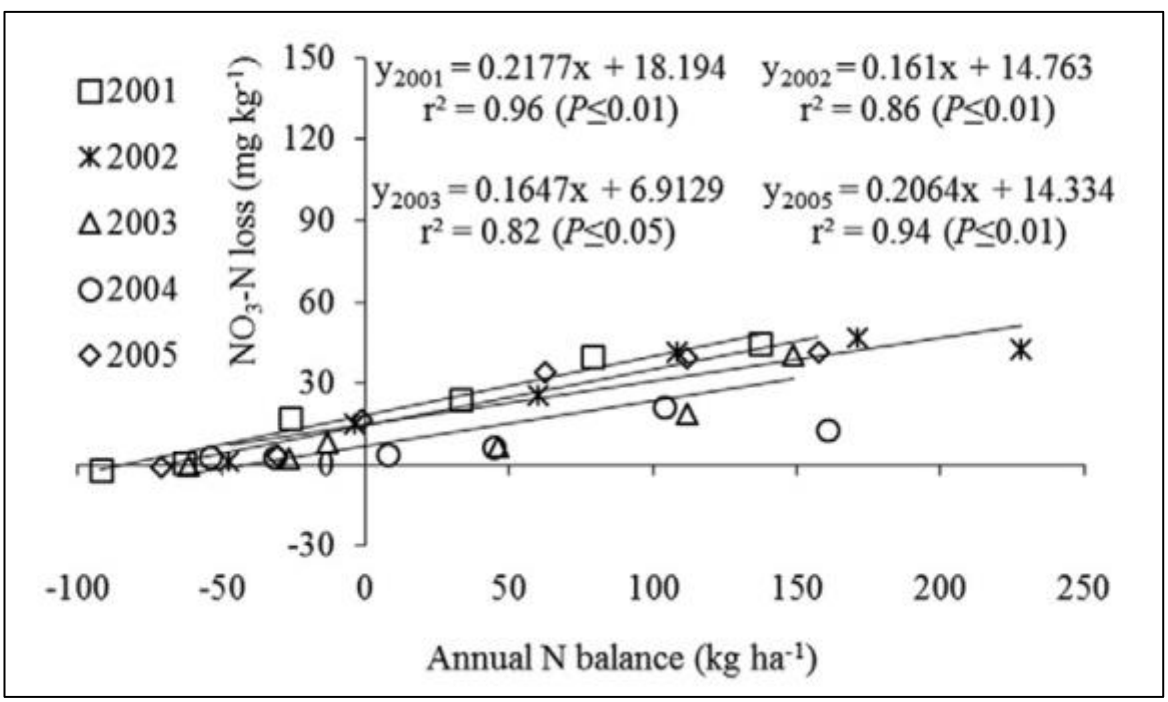
- The estimated average post-harvest residual soil nitrate at the EONR was 33 kg N/ha in the 0.9-m soil profile: 12 kg N/ ha lower (on average) than residual soil nitrate at the producers' N rates.

Therefore, variable N rates for specific areas or zones in the field, which might be accomplished through precision technology adoption, translated into an average 27% reduction in residual soil nitrate-N.

In another site-specific variable rate N management study with a sugarbeet system that rotated to continuous corn (in a Nitrate Vulnerable Zone in Italy) on a 13.6 ha (~34 acres) field, Basso et al. (2016) observed that variable rate N management had an average soil nitrate-N concentration in the top foot of soil (0 to 30 cm) of 55 parts per million (ppm), while the uniform N rate exhibited an average 64 ppm concentration. Stated a different way, measured soil nitrate-N concentrations with the variable rate N management were 16% lower compared to a uniform application rate approach.

As indicated above, declines in partial net N balance (and anticipated declines in N_2O-N emissions) which may be accomplished though implementation of improved suites of 4R practices, also provide benefits in reducing nitrate-N leaching losses and nitrate-N concentrations in shallow groundwater. In a just-published paper on corn N fertilization in New York by Sadeghpour et al. (2017), declines in partial net soil N balance led to reductions in nitrate-N leaching losses, with the highly significant relationships varying across years (**Figure 8**); just as would be typically expected from year to year in farmer's fields.

Figure 8 – Soil nitrate-N leaching declined with reductions in soil partial net N balance in a corn study in New York, evaluating six fertilizer N rates: 0, 56, 112, 168, 224, and 280 kg N/ha (Sadeghpour et al., 2016; *adapted from Figure 6 in that paper*).

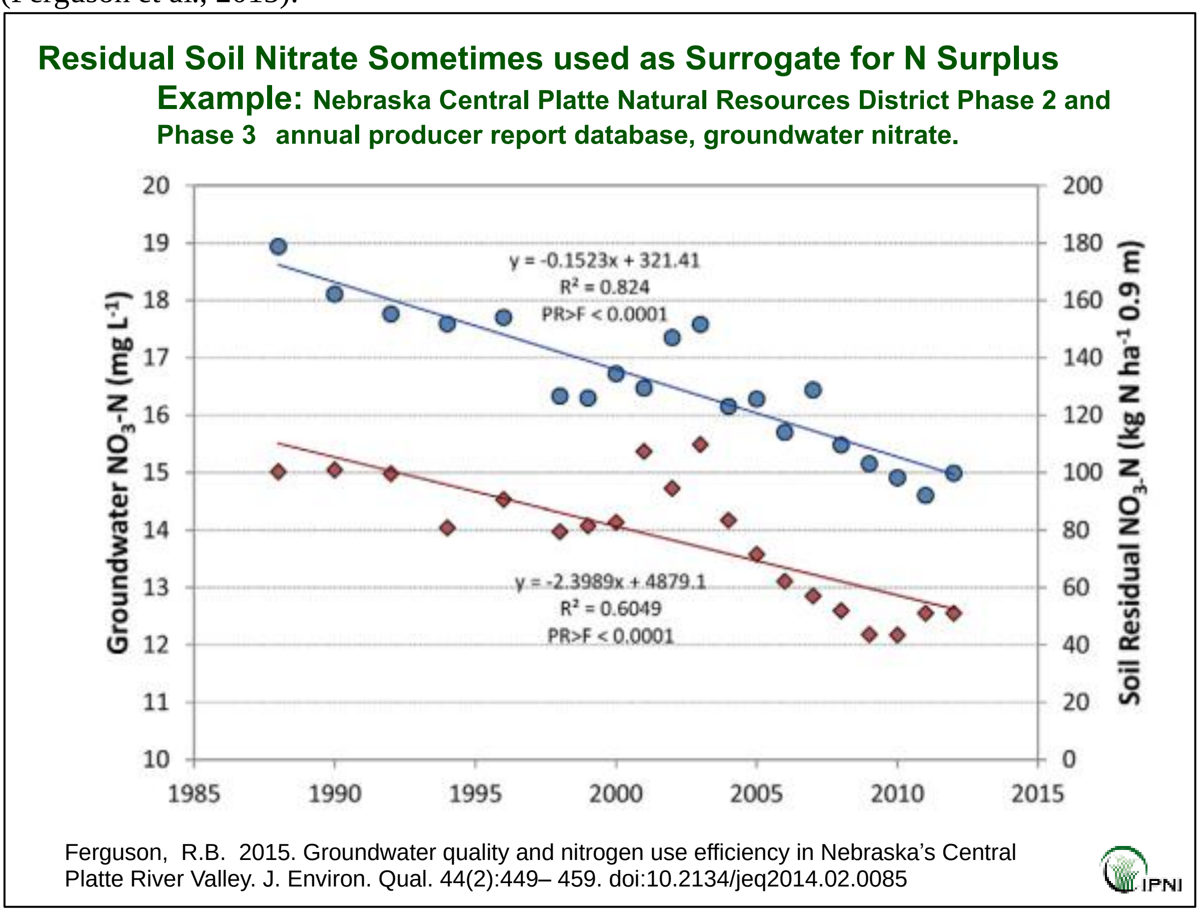


Similarly, summarization of farmer-submitted long-term data in the Platte River Valley in Nebraska (Ferguson et al., 2015) has shown that as residual soil nitrate-N has decreased, the concentration of nitrate-N in the shallow groundwater has also declined (**Figure 9**). These declines in soil and groundwater nitrate-N represented an average over both irrigated and rainfed conditions, and occurred even though there was no change in the applied fertilizer N rate of 154 kg N/ha, between 1967 and 2010. According to Ferguson (2015):

> *"This tremendous increase in efficiency is due to several factors, including adoption of N management practices that include accounting for N credit from legumes, mineralization from soil organic matter, nitrate in irrigation water, manures, and other sources; realistic expected yields and accompanying economically based N rate recommendations; an increasing use of split and sidedress N application timing; and improved hybrids and other cultural practices that allow increased efficiency of N fertilizer use by the crop."*

Those N management practice changes in the Central Platte River Valley may be viewed as a shift by farmers and their crop advisers, away from "Basic" or "below Basic" N management and more into the 4R "Intermediate" suites of N management practices for that Land Resource Region. While these N management and cropping system improvements have taken many years (decades) of concerted education, outreach, and partnering efforts by the University of Nebraska, the Central Platte Natural Resources District, and other partners, … the results show improved groundwater quality (i.e. lower nitrate-N concentration). Reducing residual nitrate-N in those Nebraska systems may be analogous to reducing the partial net N balance or reducing the surplus N levels (**Figure 9**).

Figure 9 – Improved cropping system N management and irrigation management have lowered residual soil nitrate and groundwater nitrate levels in the Central Platte River Valley of Nebraska (Ferguson et al., 2015).



The published examples mentioned above illustrate how 4R practices and other management can lower partial net N balance (i.e. "N Surplus"), and also lower N_2O-N emissions (and other losses of N from fields). It is important to recognize that few research studies investigate two or more combinations of different N sources, timing, and placement; especially across more than a single N rate (Hatfield and Venterea, 2014). Therefore, N_2O-N emission reduction effects of **Intermediate** or **Advanced/Emerging** suites of 4R practices are conservatively estimated in this Project report and Fieldprint Calculator revision proposal; at 7 and 14%, respectively. Those emission reductions with suites of 4R N management practices are suggested by the expert views of the Project leaders and affirmation by the Project's Science Advisory Group.

CONCLUSION AND PROPOSAL TO REVISE FIELD TO MARKET FIELDPRINT CALCULATOR N_2O-N EMISSIONS

Recent science referred to and discussed in this Project report has revealed opportunities to improve cropping system N management through implementation of improved 4R N management suites of practices. In view of the more recent science and the Project results presented above, we propose revision of the current FtM FPC N_2O-N estimator for alignment with current USDA hybrid model-based N_2O-N emissions estimation that is sensitive to crop, Land Resource Region, soil texture, and farmer-applied N rate (Excel file has been separately provided to the FtM FPC Science and Research Director). To further improve those N_2O-N emission estimations, and to provide farmers with the opportunity to adopt, implement, and adapt to emerging cropping system and N management technologies, we propose inclusion of a **7% reduction** and a **14% reduction** in the USDA model-based N_2O-N emissions estimates when farmers implement science-based **Intermediate** or **Advanced/Emerging** suites of 4R N management practices, respectively. This FtM FPC N_2O-N estimation improvement will also enable FtM members and cooperating farmers to have greater confidence that the FPC is aligned with 4R N management science and nutrient stewardship practices, which are known to strongly influence crop yields, crop and soil system productivity and N recovery, other N loss pathways, soil fertility maintenance, system partial net N balance, and sustainability. The seven frameworks with three-tiered (**Basic, Intermediate, Advanced/Emerging**) N management practice suites for major corn, soybean and wheat systems in the U.S., approved by unanimous N management and N_2O-N emissions science consensus at the IPNI-TFI Project sponsored science Workshop in 2015, are provided to Field to Market in the Appendices of this report (APPENDICES: Tables 1-7 in the pasted version of Snyder (2016), included below).

The concepts, principles, and approaches presented in this Project report may be adapted to other crops or cropping systems of interest to Field to Market; where the science may enable the identification of comparable 4R suites of N management, as we have presented in APPENDIX Tables 1-7 below. Those suites of improved N management practices are expected to also reduce emissions of ammonia, nitrate leaching and runoff losses of N that may affect water quality, and which also impact indirect emissions of N_2O-N.

As new research results reveal opportunities for continued farmer adaptation of newer tools and technologies that are Land Resource Region–sensitive, the N_2O-N emission reductions for Intermediate and Advanced/Emerging suites of practices may need to be adjusted, accordingly; perhaps every three to five years.

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REFERENCES

Adviento-Borbe, M.A. C.M. Pittelkow, M. Anders, C. van Kessel, J.E. Hill, A.M. McClung, J. Six, and B.A. Linquist. 2013. Optimal fertilizer nitrogen rates and yield-scaled global warming potential in drill seeded rice. J. Environ. Qual. 42:1623–1634.

Basso, B., B. Dumont, D. Cammarano, A. Pezzuolo, F. Marinello, and L. Sartori. 2016. Environmental and economic benefits of variable rate nitrogen fertilization in a nitrate vulnerable zone. Science of the Total Environment 545–546: 227–235.

Burzaco, J.P., D.R. Smith and T.J. Vyn. 2013. Nitrous oxide emissions in Midwest U.S. maize production vary widely with band-injected N fertilizer rates, timing and nitrapyrin presence. Environ. Res. Lett. 8: 035031. doi:10.1088/1748-9326/8/3/035031

Castellano, M.J., M.J. Helmers, J.E. Sawyer, and L. Christianson. 2012. Nitrogen, carbon, and phosphorus balances in Iowa cropping systems: Sustaining the soil resource. Integrated Crop Management Conference Proceedings, pp. 145-156. Iowa State University. Available online at: https://www.researchgate.net/publication/273141000_Nitrogen_carbon_and_phosphorus_balances_in_Iowa_cropping_systems_Sustaining_the_soil_resource

Cavigelli, M.A., S.J Del Grosso, M.A. Liebig, C.S. Snyder, P.E. Fixen, R.T. Venterea, A.B Leytem, J.E. McLain, and D.B. Watts. 2012. US agricultural nitrous oxide emissions: context, status, and trends. Front. Ecol. Environ.10(10): 537–546.

David, M.B., L.E. Drinkwater, and G.F. McIsaac. 2010. Sources of nitrate yields in the Mississippi River Basin. J. Environ. Qual. 39:1657–1667.

Decock, C. 2014. Mitigating nitrous oxide emissions from corn cropping systems in the Midwestern U.S.: potential and data gaps. Environ. Sci. Technol. 48: 4247−4256.

De Klein, C., R. S.A. Novoa , S. Ogle, K.A. Smith, P. Rochette, T.C. Wirth, B.G. McConkey, A. Mosier, K. Rypdal , M. Walsh and S.A. Williams. 2006. Ch. 11 N_2O emissions from managed soils and CO_2 emissions from lime and urea application. Volume 4: Agriculture, Forestry and Other Land Use. 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

Del Grosso, S.J., W.J. Parton, A.R. Mosier, M.K Walsh, D.S. Ojima and P.E. Thornton. 2006. DAYCENT national-scale simulations of nitrous oxide emissions from cropped soils in the United States. J. Environ. Qual. 35:1451–1460.

DNDC. 2012. User's Guide for the DNDC Model (version 9.5). August 25, 2012. Institute for the Study of Earth, Oceans and Space. University of New Hampshire.

Drinkwater, L.E., P. Wagoner, and M. Sarrantonio. 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396(19):262-265.

Dusenberry, M.P., R.E. Engel, P.R. Miller, R.L. Lemke, and R. Wallander. 2008. Nitrous oxide emissions from a northern Great Plains soil as influenced by nitrogen management and cropping systems. J. Environ. Qual. 37:542–550.

Eichner, M.J. 1990. Nitrous oxide emissions from fertilized soils: summary of available data. J. Environ. Qual.19:272-280.

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.

Fernandez, F., R.T. Venterea, and K.P. Fabrizzi. 2016. Corn nitrogen management influences nitrous oxide emissions in drained and undrained soils. J. Environ. Qual. 45:1847–1855

Field to Market (2012 V2). Environmental and Socioeconomic Indicators for Measuring Outcomes of On-Farm Agricultural Production in the United States: Second Report, (Version 2), December 2012. Available at: www.fieldtomarket.org .

Eve, M., D. Pape, M. Flugge, R. Steele, D. Man, M. Riley ‐ Gilbert, and S. Biggar, (Eds), 2014. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity ‐ Scale Inventory. Technical Bulletin Number 1939. Office of the Chief Economist, U.S. Department of Agriculture, Washington, DC. 606 pages. July 2014.

Frye, W. 2005.Nitrification inhibition for nitrogen efficiency and environment protection. 10pp. In IFA International Workshop on Enhanced-Efficiency Fertilizers. Frankfurt, Germany, 28-30 June 2005.

Gentry, L.E., M.B. David, F.E. Below, T.V. Royer, and G.F. McIsaac. 2009. Nitrogen mass balance of a tile-drained agricultural watershed in eastcentral Illinois. J. Environ. Qual. 38:1841–1847.

Gregorich, E.G., N.B. McLaughlin, D.R. Lapen, B.L. Ma, and P. Rochette. 2014. Soil compaction, both an environmental and agronomic culprit: increased nitrous oxide emissions and reduced plant nitrogen uptake. Soil Sci. Soc. Am. J. 78:1913–1923

Halvorson, A.D. and M.E. Bartolo. 2014. Nitrogen source and rate effects on irrigated corn yields and nitrogen-use efficiency. Agron. J. 106:681–693

Halvorson, A.D., C.S. Snyder, A.D. Blaylock and S.J. Del Grosso. 2014. Enhanced-efficiency nitrogen fertilizers: potential role in nitrous oxide emission mitigation. Agron. J. 106: 715-722.

Hatfield, J.L. and R.T. Venterea. 2014. Enhanced efficiency fertilizers: a multi-site comparison of the effects on nitrous oxide emissions and agronomic performance. Agron. J. 106: 1-2. [See related articles in Journal's special section: (https://dl.sciencesocieties.org/publications/aj/tocs/106/2)]

Hoben, J.P., Gehl, R.J., Millar, M., Grace, P.R., Robertson, G.P., 2011. Non-linear nitrous oxide (N_2O) response to nitrogen fertilizer in on-farm corn crops of the U.S. Midwest. Glob. Change Biol. 17: 1140–1152.

Hong, N., P.C. Scharf, J.G. Davis, N.R. Kitchen, and K.A. Sudduth. 2007. Economically optimal nitrogen rate reduces soil residual nitrate. J. Environ. Qual. 36:354–362.

Hyatt, C.R., R.T. Venterea, C.J. Rosen, M. McNearney, M.L. Wilson, and M.S. Dolan. 2010. Polymer-coated urea maintains potato yields and reduces nitrous oxide emissions in a Minnesota loamy sand. Soil Sci. Soc. Am. J. 74:419–428.

IPNI. 2012. A Nutrient Use Information System (NuGIS) for the U.S. Norcross, GA. January 12, 2012. International Plant Nutrition Institute. Available on line: www.ipni.net/nugis .

Jaynes, D.B., D.L. Karlen, C.A. Cambardella, and D.W. Meek. 2001. Nitrate loss in subsurface drainage as affected by nitrogen fertilizer rate. J. Environ. Qual. 30:1305–1314.

Jaynes, D.B., T.C. Kaspar, T.B. Moorman, and T.B. Parkin. 2008. In situ bioreactors and deep drain-pipe installation to reduce nitrate losses in artificially drained fields. J. Environ. Qual. 37:429–436.

Kessavalou, A., A.R. Mosier, J.W. Doran, R.A. Drijber, D.J. Lyon, and O. Heinemeyer. 1998. Fluxes of carbon dioxide, nitrous oxide, and methane in grass sod and winter wheat-fallow tillage management. J. Environ. Qual. 27:1094-1104.

Kim, D-G., G. Hernandez-Ramirez, and D. Giltrap. 2013. Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis Agric. Ecosyst. Environ. 168: 53–65.

Ladha, J.K., A. Tirol-Padre1, C. K. Reddy, K. G. Cassman, S. Verma, D. S. Powlson, C. van Kessel, D. B. Richter, D. Chakraborty and H. Pathak. 2016. Scientific Reports 6, Article number: 19355. Global nitrogen budgets in cereals: A 50-year assessment for maize, rice, and wheat production systems. http://www.nature.com/articles/srep19355#f1

Li, A., B.D. Duval, R. Anex, P. Scharf, J.M. Ashtekar, P.R. Owens and C. Ellis. 2016. A case study of environmental benefits of sensor-based nitrogen application in corn. J. Environ. Qual. 45, 675–683.

NADP. 2016. Total Deposition 2015. National atmospheric Deposition Program. Available online at: http://nadp.isws.illinois.edu/committees/tdep/reports/TDEPreport15_Final.pdf .

Norton, R., T. Bruulsema, T. Roberts, and C. Snyder. 2015. Crop nutrient performance indicators. Agricultural Science, 27 (2): 33-38.

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. Chapter 3-

Quantifying greenhouse gas sources and sinks in cropland and grazing land systems. 141 pp. *In* M. Eve et al. (eds.), USDA Technical Bulletin Number 1939. Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity ‐ Scale Inventory.

Parkin. T.B. and J.L. Hatfield. 2013. Enhanced efficiency fertilizers: effect on nitrous oxide emissions in Iowa. Agron. J. 105:1–9.

Parkin, T.B. and T.C. Kaspar. 2006. Nitrous oxide emissions from corn–soybean systems in the Midwest. J. Environ. Qual. 35:1496–1506.

Pittelkow, C.M., M.A. Adviento-Borbe, J.E. Hill, J. Six, C. van Kessel and B.A. Linquist. 2013. Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. Agric. Ecosyst. Environ. 177: 10-20.

Poffenbarger, J.J., D.W. Barker, M.J. Helmers, F.E. Miguez, D.C. Olk, J.E. Sawyer. J. Six, and M.J. Castellano. 2017. Maximum soil organic carbon storage in Midwest U.S. cropping systems when crops are optimally nitrogen-fertilized. PLoS ONE 12(3): e0172293. doi:10.1371/journal.pone.0172293.

Qiao, C., L. Liu, S. Hu, J.E. Compton, T.L. Greaver, and Q. Li. 2015. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. Global Change Biology 21:1249–1257.

Roberts, T., R. Norman, N. Slaton, and L. Espinoza. 2016. Nitrogen fertilizer additives. FSA 2169. University of Arkansas, Division of Agriculture Research & Extension. Agriculture and Natural Resources FSA2169-PD-2-2016RV.

Sadeghpour, A., Q.M. Ketterings, G.S. Godwin, and K.J. Czymmek. 2017. Under- or over-application of nitrogen impact corn yield, quality, soil, and environment. Agron. J. 109:1–11.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, and O. Sirotenko. 2007. Agriculture. In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, C.M., M.B. David, C.A. Mitchell, M.D. Masters, K.J. Anderson-Teixeira, C.J. Bernacchi, and E.H. DeLucia. 2013. Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. J. Environ. Qual. 42:219–228.

Snyder, C.S. 2015. Improved nitrogen management for the food industry supply chain. *In* J. E. Sawyer (ed.), Proc. of the 45th North Central Extension-Industry Soil Fertility Conference. 31:6-13. (Des Moines, IA). Published by the International Plant Nutrition Institute.

Snyder, C.S. 2016. Suites of 4R Nitrogen Management Practices for Sustainable Production and Environmental Protection. Issue Review. Ref. # 16057. International Plant Nutrition Institute. Available online at: http://www.ipni.net/publication/ireview-en.nsf/beagle?OpenAgent&d=IREVIEW-EN-14063&f=IssueReview-EN-14063.pdf .

Snyder, C.S. and T.W. Bruulsema. 2007. Nutrient Use Efficiency and Effectiveness in North America: Indices of Agronomic and Environmental Benefit. June 2007. Ref. # 07076. International Plant Nutrition Institute.
http://www.ipni.net/ipniweb/portal.nsf/e0f085ed5f091b1b852579000057902e/d58a3c2deca9d7378525731e006066d5/$FILE/Revised%20NUE%20update.pdf

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. Sustain. 9-10: 46-54.

Thornton, F.C. and R.J. Valente. 1996. Soil emissions of nitric oxide and nitrous oxide form no-till corn. Soil Sci. Soc. Am. J. 60:1127-1133.

Touchton, J.T. and F. C. Boswell. 1980. Ch. 5, Performance of nitrification inhibitors in the Southeast. Nitrification Inhibitors—Potentials and Limitations. American Society of Agronomy Special Publication 38: 63-74.

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 .

USDA ARMS. 2014. U.S. Department of Agriculture Agricultural Resource Management Survey. Crop Production practices with nutrient use and management- http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/tailored-reports-crop-production-practices.aspx ; and documentation - http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices/documentation.aspx . Accessed May 20, 2016.

USEPA. 2016. Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990-2014. EPA 430-R-16-002. U.S. Environmental Protection Agency. Washington, DC. https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html

Van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. Van Groenigen, and C. Van Kessel. 2010. Towards an agronomic assessment of N_2O emissions: A case study for arable crops. Eur. J. Soil Sci. 61:903–913. doi:10.1111/j.1365-2389.2009.01217.x

Venterea, R.T., B. Maharjan, and M.S. Dolan. 2011. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. J. Environ. Qual. 40:1521–1531

Venterea, R.T., J.A. Coulter, and M.S. Dolan. 2016. Evaluation of intensive '4R' strategies for decreasing N_2O emissions and N surplus in rainfed corn. J. Environ. Qual. 45:1186–1195.

Vyn, T.J., A.D. Halvorson, and R.A. Omonode. 2016. Relationships of nitrous oxide emissions to fertilizer nitrogen recovery efficiencies in rain-fed and irrigated corn production systems: data review. http://research.ipni.net/project/IPNI-2015-USA-4RN27 . 4R Research Fund Projects, Research Database. International Plant Nutrition Institute.

Watts, D.B., G.B. Runion, K.W. Smith Nannenga, and H.A. Torbert, 2015. Impacts of enhanced-efficiency nitrogen fertilizers on greenhouse gas emissions in a Coastal Plain soil under cotton. J. Environ. Qual. 44:1699–1710.

Zhang, X., E.A. Davidson, D.L. Mauzerall, T.D. Searchinger, P. Dumas, and Y. Shen. 2015. Managing nitrogen for sustainable development. Nature 528: 51–59. doi:10.1038/nature15743

Zhao, X., L.E. Christianson, D. Harmel, C.M. Pittelkow. 2016. Assessment of drainage nitrogen losses on a yield-scaled basis. Field Crops Res. 199:156-166.

APPENDICES

The following Documents were provided directly to the Field to Market Science and Research Director (Allison Thomson):

1) N management and N_2O science Workshop Science Discussion Document (SDD), which included seven DRAFT 3-tiered 4R N management frameworks (were provided to FtM as separate file)
2) A 4R N_2O Scientific Advisory Group decision survey for Workshop scientists to assess the "fitness" of the four technical resources (i.e. SDD and published papers by Decock (2014), Halvorson et al. (2014), and Snyder et al. (2014)) as technical seed documents for the Workshop discussions (were provided to FtM as separate files)
3) Copies of the following published papers (were provided to FtM as separate file): Decock (2014), Halvorson et al. (2014), and Snyder et al. (2014), Venterea et al. (2016)

The Workshop's unanimously approved, science-based 3-tiered crop agroecosystem 4R-N management frameworks for major corn, soybean, and wheat systems in the U.S. – with appropriate Land Resource Region designations – follow, as were published in a separate report by Snyder (2016):

SPECIAL NOTE:
The 3-tiered 4R-N management frameworks that follow may not include all possible fertilizer technologies and tools, and should not be considered exhaustive.

A farmer would be expected to select a tier (**Basic**, **Intermediate**, **Advanced/Emerging**) that best represents the majority of her/his N management practices. Moving from the **Basic** to the higher 4R **Intermediate** or **Advanced/Emerging** tiers of practices constitutes more complexity and requires more skillful N management.

Practices with each successive tier (*i.e. row in the respective Framework*) include and build upon the practices represented in each lower tier of N management. It is unlikely that a farmer would implement every single 4R practice within a given tier. Therefore, for example, if a farmer uses a N source shown in the **Basic** tier but employs N rate, time, and place of application practices that are predominantly within the 4R **Intermediate** or **Advanced/Emerging** tiers of practices, then the tier selected to best represent the farmer's N management practices might appropriately be **Intermediate**, or **Advanced/Emerging,** respectively**.**

1) The following Frameworks should be viewed as general guidance; more specific 4R nutrient management guidelines are available from each state Land Grant University in the U.S.
2) Compliance with all local and state laws is expected.
3) Mention of trade names does not necessarily constitute or imply endorsement; nor exclusion of others not mentioned.
4) The following Frameworks should NOT be viewed as the specific, or only, basis for any environmental compliance requirements in any jurisdiction; and when or if any application or interpretation is considered for policy development, the expertise and knowledge of highly qualified soil scientists and/or agronomists should be consulted.

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

NOTE:

The seven 3-tiered 4R-N management frameworks provided on the following pages, 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 below and in Snyder (2016), 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.

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.

---Summary for Field to Market: Science Director, President and Fieldprint Calculator Leaders---

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