Case Study Assessment of Halvorson et al. 2013[1]:

Analyzing how the manuscript and related papers adhere to the Climate Action Reserve's Minimum Data Standard[2]

Prepared for the Climate Action Reserve by:

Meredith T. Niles, Ph.D. Candidate
University of California, Davis
mtniles@ucdavis.edu

&

Noel Gurwick, Ph.D.
Principal, Gurwick Consulting
Research Associate (Adjoint), Smithsonian Environmental Research Center
noel.gurwick@gmail.com

October 2013

[1] Halvorson, A.D., Snyder, C.S., Blaylock, A.D., Del Grosso, S.J. 2013. Enhanced-efficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation. Agronomy Journal. 10.
[2] The Climate Action Reserve's Minimum Data Standard currently is found in Appendix D of the Nitrogen Management Project Protocol, Versions 1.0 and 1.1.

Table of Contents

Acknowledgements

We gratefully acknowledge Ardell Halvorson and Steve Del Grosso of the USDA Agricultural Research Service for providing their expert insight and feedback into the studies reviewed herein, the Minimum Data Standard and our assessment of how well the Data Standard's criteria were met. Your contributions have been invaluable.

1. Overview and Goal

The Climate Action Reserve (Reserve) has adopted Versions 1.0 and 1.1 of the Nitrogen Management Project Protocol (NMPP) for reducing nitrous oxide (N_2O) emissions from non-irrigated corn across 11 states in the Midwest by reducing nitrogen fertilizer application rate. Originally envisioned to include a wider set of regions, crops, and practices, but currently limited by available data, the protocol was designed to allow for expansion to more crop types and regions and to include other N_2O reducing practices (e.g. nitrification inhibitors, slow release fertilizers, etc.). Proposals to expand the scope of the protocol will necessarily include data sets that demonstrate the relationship of practice changes to N_2O emission reductions.

The Reserve is refining the criteria used to evaluate these data sets by reviewing a long-term data set from extensive work done at the USDA Agricultural Research Service's facility in Fort Collins, Colorado. The objective of this case study is to review work by Halvorson et al. (including a 2013 review paper and associated papers), assess the extent to which the data set does or does not meet the Reserve's current minimum data standard (MDS) and use this analysis to inform the Reserve's further development of the MDS. These studies examined a variety of management practices that can affect N_2O emissions over many years. Cropping systems included irrigated corn, usually continuous, in comparison with corn and bean rotations, and on some instances corn-soy rotations and wheat. The studies assessed a number of tillage practices including strip-till, no-till and conventional till and many nitrogen applications including urea compared with UAN, slow-release fertilizers, polymer coated urea, nitrification and urease inhibitors, and varying nitrogen application rates. Studies also assessed different nitrogen applications including surface banding by hand, mechanically banded, injection and broadcast.

This case study presents a narrative analysis and a spreadsheet that details the publications reviewed and their level of compliance with the MDS. As appropriate we also recommend potential revisions to the MDS and the data submittal process, which will be more thoroughly considered in an evaluation to assess these processes. Finally, this case study is designed to approximate the format and content anticipated in such future data submittals, and this case study and the associated Colorado data will be reviewed by the Reserve and a panel of scientists to make a determination on further expanding the NMPP.

2. Method and Approach

We compiled a list of minimum criteria put forth in the MDS (Appendix A) to succinctly identify the MDS requirements. We then incorporated these criteria into an excel spreadsheet (Appendix B) to produce a "checklist" for assembling the reviewed literature. We began by reviewing Halvorson et al. (2013), a review paper detailing multiple studies and years of data. We then read and analyzed these additional studies included in Halvorson et al. (2013) and included all of these relevant articles in Appendix B. In addition, we identified several other papers related to the research in Colorado, which were reviewed and included as well. Appendix C lists the papers reviewed for this project. Compiling the data into a single spreadsheet allows for a simple demonstration of where the reviewed papers consistently met the MDS, or where outstanding questions remained. Using Appendix A as a guide, we compared each portion of the MDS to the reviewed literature to assess overall whether the data represented by these publications (hereafter referred to as "the Colorado Data Set") complies with the MDS, and to identify remaining questions, including ones that require input from the principal investigators. Based on this preliminary analysis, we sent questions to Ardell Halvorson and Steve Del Grosso ("the researchers") for their comments and received feedback.

We also held a call with them to discuss these questions and others. These early conversations helped us create a more complete case study assessment. We sent a draft case study assessment to the researchers for their feedback and assessment and then a single follow up round of clarifying questions. Their feedback and perspectives have been incorporated into this case study.

3. Data Standard Review

The narrative assessment that follows is organized according to each section of the MDS and follows the order of Appendix A.

3.1. Data Collection Type Criteria

Chamber Type (MDS Section D.2.1)

MDS statement: The MDS states that datasets should utilize chamber-based or tower-based methods.

Finding: The Colorado Data Set complies with this standard. All studies either utilize a vented, non-steady state chamber or a static, vented chamber.

MDS statement: The MDS further suggests that if datasets have used chamber methods that they should follow the USDA ARS GRACEnet[3] trace gas flux measurement protocol.

Finding: Per feedback from the Steve DelGrosso and Ardell Halvorson we determined that their sampling and analysis methods were consistent with the GRACEnet protocol.

Recommendations:

1) While the researchers here have utilized GRACEnet throughout their experimental design we advise the Reserve not to require all potential data submittal processes to adhere to GRACEnet. There are other high-quality protocols that can provide equal rigor and data quality that may be in use by researchers, and they should equally be included. These would include protocols in the Soil Science Society of America methods book, the Canadian Society of Soil Science methods book, and the LTER methods book. The Reserve should consider data submittals that rely on these reputable protocols.

[3] Parkin, T.B. and Venterea, R.T. 2010. Sampling Protocols. Chapter 3. Chamber-Based Trace Gas Flux Measurements. IN Sampling Protocols. R.F. Follett, editor. p. 3-1 to 3-39. Available at: www.ars.usda.gov/research/GRACEnet

Chamber Design, Sample Collection, Gas and Data Analysis (MDS Section D.2.1)

MDS statement: The MDS requires that data sets indicate their chamber design, sample collection and handling, gas analysis and data analysis. The Reserve requires that these analyses and collection methodologies comply with the most recent accepted best practices within peer-reviewed literature.

Finding: The reviewed literature and confirmation with Steve DelGrosso and Ardell Halvorson indicates broad compliance with the MDS. All of the articles reviewed indicate use of vented, non-steady state closed chambers.

Finding: The reviewed papers gave varying levels of detail regarding how samples were collected and how gas samples and data were analyzed. The papers analyzed utilized ANOVA or general linear models for data analysis. The researchers indicated that all of their site specific and experimental conditions were consistent with standard published methods.

Recommendations:

1) The Reserve may want to seek additional information about the description of the chamber design or consider whether a visual, qualitative description would be useful.

2) It is recommended that the Reserve pay particular attention to PVC round chambers and how these are placed within an experiment. Given their relatively small size, it is possible they could be placed in areas that could affect the overall results (in a furrow, in a fertilizer band, etc.)

3) While the peer-reviewed literature can provide a useful guide for best practices, we recommend a screening process that is both more flexible and more robust. Standard methods often appear in books such as those identified above; these may or may not be considered peer-reviewed literature. More importantly, many laboratories and research groups have developed robust protocols that draw from accepted methods but are not published in their entirety. For example, N_2O flux rates for individual chambers are calculated from several gas samples taken from the chamber over a period of time; it is often reasonable to exclude one of those vials from the analysis (perhaps because of poor evacuation or machine error during the analysis). These fine-scale decisions generally rest with investigator judgment, and the Reserve's guidance needs to be developed with that in mind.

   Further, the peer-review process is not without errors or faults. Usually two or three qualified reviewers have looked at a paper before it is published, but the quality of these reviews and the attention an editor gives to any one paper are highly variable and may depend on the publication. To be sure that a method meets the high standards needed to support an offset protocol requires a higher bar such as the close attention of the Science Advisory Committee, who understand both the science and the application.

Flux Chamber Surface Area (MDS Section D.2.2.2)

MDS statement: The MDS states that chambers should be large enough to capture potential small-scale variability. It suggests as a best practice that chambers cover at least 300 cm^2.

Finding: All of the reviewed literature indicated chambers that were 78.6 x 39.3 cm or 3,088.98 cm^2 (and 10 cm height), in solid compliance with the MDS.

3.2. Temporal Criteria (MDS Section D.2.2.1)

Weekly Flux Measurements

MDS statement: The MDS states that weekly flux measurements are necessary for compliance.

Finding: In all of the reviewed literature we found that the dataset complies with this standard by having measurements taken at least once a week and often three times a week during the growing season. These measurements were often taken mid-morning, consistent with the best practice of taking measurements when temperatures are near the daily average.

Additional clarification was sought from the principal investigators on how measurements were handled following environmental or agronomic events as indicated in the MDS. Though not a requirement, the MDS strongly advises project proponents to use data that has higher frequency measurements following significant events. Several papers indicate unique events (e.g. Halvorson et al. 2011 with hail damage; Halvorson et al. 2012 with slug damage). The researchers did not increase sampling frequency at these times, but their baseline sampling frequency was much higher than the recommended MDS standard. Additionally, the researchers noted that slug damage events as well as other biological or meteorological events (i.e. rainfall) did not affect their greenhouse gas emissions data. Finally, they underscored the importance in their region of measuring N_2O emissions within 2 days of N application and for up to 60 days following application.

Recommendations:

1) We recommend that the Reserve require within the data submittal process specific clarification and details regarding the environmental and agronomic events that occurred throughout the experiment. In this clarification we recommend that researchers specify whether there was significant crop damage, because crop damage can leave additional N in the soil and can indicate changes in other biophysical conditions that affect the nitrogen cycle.

2) We recommend the Reserve consider increasing the frequency of data sampling required during the growing season immediately following N additions and up to 60 days thereafter. The researchers indicated that sampling immediately following N additions and for approximately 60 days following was extremely important because fluxes can be elevated within the immediate days following fertilization and remain high. With only one day per week required for sampling, we are concerned that if this sampling were to occur several days following fertilization the data would fail to capture a significant flux of N_2O. Specific requirements for high frequency sampling are to some extent place-specific based on different climates and management practices. For example, in regions where freeze/thaw cycles are common it may be necessary to increase sampling around these events as they can cause high N_2O emissions that may not be captured with once per week sampling. We would suggest that sampling twice per week could significantly increase the capacity of researchers to capture this variability; however, we also suggest that if the Reserve seeks to consider this type of climate (which is not indicative of the Colorado case study) that they seek feedback from the Science Advisory Committee.

Growing Season Minimum Data Requirement

MDS statement: The MDS requires that data extend over at least one growing season.

Finding: The reviewed literature indicates that this was always the case with the dataset and that in many cases there were two complete growing seasons of data.

Reference Data Minimum Requirement

MDS statement: The MDS also suggests that reference data (see below for definition) should extend across two growing seasons. The MDS notes that data from additional growing seasons may be necessary if the two consecutive growing seasons of reference data exhibit anomalous weather conditions. Our interpretation is that the Reserve seeks data sets that include at least two growing seasons.

Finding: This reviewed data set covers at least two growing seasons. As a result, it clearly meets the MDS.

Recommendations:

The term "reference data" is unclear both in its current definition and the way in which it interacts with minimum growing season data. Reference data is currently defined in the MDS as, "new source data generated during new measuring campaigns or existing data from, inter alia, the following sources…: scientific and technical articles in books, journals and reports; universities and extension services; United States Department of Agriculture; sectoral experts, commodity and stakeholder organizations, and industry groups." This current definition is vague with particular regards to how "new measuring campaigns or existing data" are defined. We suggest that the Reserve consider how to define "reference data" and in particular how to define what it encompasses. Do these measuring campaigns and existing data need to meet the other requirements that the Reserve has put forth for new data submittals? Do they need to adhere to the same protocols and analysis standards? Do they need to satisfy requirements for peer-review? These are especially important to assess with regards to the minimum growing season data necessary to comply with the MDS. For example, if a researcher only has one season of data but two years of reference data (from other sources) to what extent would this satisfy the MDS? If the reference data was from existing data from a non-peer-reviewed industry group or sectoral expert would this be accepted in the same fashion as a peer-reviewed university and extension study? Currently this level of detail is unclear in the definition and the Reserve should think clearly about the term reference data and its implications for the MDS and new data submittals.

3.3. Spatial Criteria (MDS Section D.2.2.2)

Chamber Placement

MDS statement: The MDS requires that chambers be placed in multiple locations to best capture inter-field variability inherent in agricultural experiments. The MDS suggests a minimum of two chambers per functional location.

Finding: Review of the data suggests that this dataset complies with this recommendation because there were always two chambers with duplicate flux measurements made in each treatment/plot. The researchers suggested that the two-chamber requirement is particularly important where small round PVC chambers are used, to adequately characterize the treated plus untreated area if nitrogen fertilizer was applied in bands.

Recommendations:

1) The Reserve should consider how to define "functional location" within the MDS, as it explicitly does for field and replicate plot.

2) We also recommend that the Reserve reconsider "suggesting" a minimum of two chambers per functional location. If the experiment uses small round PVC chambers, then we suggest the Reserve require two chambers per location if the fertilizer was banded. Otherwise, these chambers would not capture the treated and untreated area.

Replicate Plots

MDS statement: The MDS requires that datasets have a minimum of three replicate plots per management practice and field.

Finding: Review of the dataset finds that this standard has been met with all studies having at least three replicates per management practice.

Finding: The current MDS requirement applies to experimental designs that rely on comparing two or more discrete treatments, using paired t-tests or Analysis of Variance, for example. However, other experimental designs are possible, in particular gradient-based studies that measure response (in this case, N_2O emissions from soil) along a gradient. In that case, including more "locations" along the gradient may provide more power than having more replicates at any one point. The Reserve should consider broadening the MDS to include alternative experimental designs like the gradient approach.

MDS statement: The MDS also recommends implementing more than one potential management practice compared to baseline conditions (such as the application of a nitrification inhibitor for a side-by-side comparison with one treatment representing the baseline scenario and the other a project scenario).

Finding: The dataset satisfies the recommendation to implement many potential project treatments by designing several different studies that aim to test the greenhouse gas emissions from a variety of tillage types, nitrogen application levels, and nitrogen fertilizer types. The baseline scenarios in the studies differed based on the treatment (for example, urea compared to a slow-release fertilizer or conventional tillage compared to no-till or conservation tillage). Several studies implemented reference cases, such as zero N applications, in addition to "business as usual" baseline scenarios. In follow up questions the researchers indicated that they believed a zero N applied control treatment was necessary to include in their experimental design in order to assess N emissions resulting from soil and natural processes. While we agree that this method is useful to understand biogeochemical cycles in agricultural fields, we believe it is unnecessary for the purposes of evaluating how N_2O emissions differ between "business as usual" management practices and alternative management practices. In an applied context for the Reserve these types of controls are not necessary.

MDS statement: The MDS requires a data set to include multiple fields located across different sites and geographic locations (specifically different counties or states).

Finding: Per our conversation with the researchers we confirmed that the data set does not meet the MDS in this area. All of the data set experiments were conducted at the Colorado State University, Agriculture Research Development and Education Center near Fort Collins, Colorado. We recognize that this is typical of academic and government research; agricultural experiments are often conducted within a field research facility and do not encompass broader geographic regions. The researchers indicated to us that the major barrier to implementing a study across large geographic areas is the cost and time required to manage such a project. Nitrous oxide emission measurements are time intensive and require significant staff time. Implementing projects across multiple states and/or counties would only be possible with increased staff time on the ground in those locations, which significantly increase the cost of the experiments. As a result of this, we believe that many potentially submitted data sets may face similar problems. Given the difficulty of establishing multiple field sites for a single experiment across multiple states, the Reserve will need to consider both how additional resources might be directed towards such experiments and whether alternatives to this requirement in the MDS can meet the Reserve's objectives.

Considering alternative MDS requirements raises questions about the requirements for extrapolating from a single site and the confidence that the research community might place on such extrapolations. Admittedly, the question does not lend itself to standard research methods, but it is possible that an expert working group convened to address this specific question, with appropriate facilitation, could yield helpful guidance for the Reserve.

To guide this discussion it is important to note that the researchers suggested that several landscape variables should be taken into account in deciding how far to extrapolate estimation tools. These variables included: precipitation amount and distribution, soil organic matter content, soil texture or soil series, irrigation system/type, crop production methods, fertilizer type, amount, and placement, and crop type. Specifically they considered precipitation at the time of planting and fertilizer application very important to extrapolation. The researchers also suggested informing the ability to extrapolate data by using currently available data from other single field studies in the western U.S. with similar characteristics. They suggested that data could be compared to other data sets from similar climates and soils; distance of extrapolation could be significant (up to 1,000 miles for example) but only if field conditions and management practices and climate were the same. They indicated that weld/loam soils with low soil organic matter and no-till sprinkler irrigation systems would be characteristics they would look for to replicate their data in other regions. Finally, they indicated that even if data could not meet multiple field criteria that it could be used for model validation.

Recommendations:

1) Given that we anticipate many future data submittals will also fail to meet this portion of the MDS, the Reserve will need to evaluate whether the estimation functions based on data from a single site can be extrapolated to large areas, and how models and similar data from other regions might be used in this effort.

2) We suggest that the Reserve require new data submittals that fail the multiple field requirement to submit a list of comparable experiments in similar climates and soil types that they believe can be utilized for a data comparison. Data and analysis products from these sites need to be robust; peer-reviewed literature provides one but not the only metric of rigor.

3) We suggest the Reserve require new data submittals to include a list of places that they would consider priority sites for conducting comparative field studies if given the funding to do so, and the reasons for choosing those places. This list can assist the Reserve in understanding the specific geographic places to which researchers believe their work could be extrapolated.

4) Given the likelihood that the Reserve will continue to face challenges in this area in the future we recommend that the Reserve elicit feedback from experts to understand how to potentially extrapolate data from a single site. This expert judgment could come from the scientific advisory committee, a focus group, a commissioned study or another similar means. We recommend that the Reserve specifically inquire about the level of error that is introduced the further away from a core research site in a given area one extrapolates data. Such expert work groups, when skillfully convened and facilitated, can often elicit expert judgment that is hard for individual research scientists or project groups to offer to the management and policy community. Questions we posed to the researchers in this case study could serve as an initial guide for the objectives of such an expert work group. Additionally, we suggest that the Reserve aim to understand how much additional confidence is gained as each additional site is added in an experimental design.

3.4. Outliers (MDS Section D.2.3)

MDS statement: The MDS strongly recommends not removing outliers from data sets.

Finding: The researchers indicated that they did remove outliers if out of six observations one was 3x greater or less than the other 5. For suspiciously low or negative outliers the researchers checked for evidence of potential sampling error and interpolated data between the previous and next dates for values. If the samples were legitimate they were included in the analysis even if they were negative. When removal of outliers did occur it was from single chambers at single points in time. The removal of outliers occurred infrequently according to the researchers (approximately less than 1/1000 observations), which they estimated would have affected their overall annual flux rates less than 1% (though a formal analysis was not completed).

Recommendations:

1) We recommend the Reserve alter the MDS to require that project proponents explain clearly how they treated outliers and, if possible, to include estimates of annual N_2O fluxes with and without outliers (as defined below).

2) We recommend the Reserve distinguish between three types of outliers.

    a. Individual gas samples collected from chambers over a time course are used to estimate the rate of N_2O emissions from soil in that chamber. Of four samples collected over 20 minutes, 3 may fall on a line and one may be far off that line. In this case, it is reasonable laboratory procedure to discard the outlier and use the other three points to estimate the N_2O flux for that chamber. There are many plausible reasons that a single gas sample could be inaccurate, including inadequate evacuation of the vial or gas chromatograph (GC) error. It would be unreasonable to ask a laboratory to recalculate all their data by including each and every vial.

b. Each chamber at each sampling date-time has an estimated N_2O flux rate, calculated from the aggregate of a set of individual vials from that specific date-time-chamber. Some laboratory groups may exclude values, at this level, particularly if they seem “unreasonably” high or low on the assumption that they represent measurement error rather than real variation in flux rates over space and time. Excluding outliers at this level can result in greater potential uncertainty if that flux estimate is based on at least 3 vials with a good linear fit. A high value relative to other chambers should always be reported someplace; if investigators believe the value does not accurately represent the actual biophysical processes at the site, they should explain why.

c. Flux rates are often averaged across multiple chambers in a plot or treatment on a sampling date-time. It is very difficult to justify removing outliers at this level because the values integrate many individual vials. Excluding estimates at this level should only occur when strong evidence of error at levels (a) and (b) has been established.

3.5. Applicability Criteria (MDS Section D.3)

MDS statement: The MDS suggests that researchers submit information about the area to which their data could be extrapolated based on weather/climate, soil characteristics and management practices within that region. This information will also inform the MDS about the potential to extrapolate relationships derived from data collected at a single location to large areas. The MDS also asks that researchers include summaries of typical conditions, growing season and experimental conditions.

Finding: We find that the data set meets this requirement as these environmental characteristics are described extensively in several studies.

MDS statement: The MDS suggests using typical soils for the region within experiments.

Finding: The researchers indicated to us in follow up conversations that the soil used in their experiments is typical for their region.

4. Additional Criteria and Questions

In addition to the required considerations set forth in the MDS, a number of other factors and management practices should be considered in the data set approval process because they could greatly affect greenhouse gas emissions and the extrapolation of data. These include:

- Tillage practices
- Types of N applied
- Crop rotation and whether cover crops were grown
- Soil characteristics including soil texture or series and soil organic matter content
- Irrigation type
- Residue handling
- Precipitation amount and distribution
- Freeze/thaw cycles

- How nitrogen was placed and applied (banded, broadcast, injected, etc.)
- Other inputs used (i.e. starter fertilizer, phosphorus, etc.)
- Yields

Furthermore, yields can directly affect gas fluxes from soil and N availability in the soil, and unusual yields often indicate atypical conditions that could easily influence soil GHG emissions.

In our summary of each study (Appendix B), we included a number of these additional considerations as well as a number of other general categories. For example, descriptors of study location, crop type, soil type, data collection years, and plot size distinguish the studies from each other. The researchers also indicated caution with regards to yields to ensure that N_2O emissions would be considered per unit of crop produced. They also suggested that data on ammonia volatilization would be valuable if available.

Recommendations:

1) We recommend that the MDS include that these factors be disclosed in the new data submittal process.

5. Conclusion

The experiments and results discussed in Halvorson et al. (2013) and other relevant literature coupled with our multiple interactions with the researchers present a strong data set that has considered a number of management systems using varying nitrogen sources and applications. These data appear to adequately meet almost all requirements of the MDS but fall short in critical areas, particularly in the multiple field requirement. Furthermore, this case study highlights numerous areas in which the data submittal process and MDS can be changed to make the process more robust, clear and ultimately able to produce a better protocol. Future tasks will consider how these changes may be best implemented in the process to enable additional datasets to be considered.

Appendix A. Current Minimum Data Standard Checklist

Data Collection Type Criteria

1) Chamber-based or tower-based micrometeorological methods
    a. Chamber methods- best to follow USDA ARC GRACEnet trace gas flux measurement protocol
2) A brief description of the chamber design, sample collection and handling, gas analysis and data analysis should be provided
3) Surface area of flux chamber should be large enough to capture small-scale variability in N_2O. Chamber surface areas typically cover between 300 and 3000 cm^2

Temporal Criteria

1) Flux measurements taken at least once per week
    a. Strongly advised to increase measurement frequency following agronomic or environmental events- daily flux measurements should continue until N_2O emissions return to pre –event levels.
    b. Lag effect of N_2O responses should be incorporated into the sampling design
    c. One flux measurement per day is valid if it corresponds to the daily average temperature
2) Minimum one complete growing season of flux measurements
    a. Year round is preferable
    b. Reference data should extend over at least two consecutive growing seasons

Spatial Criteria

1) Strategically placed in multiple locations to represent inter-field variety. Minimum of two chambers per location recommended.
2) Reference data should have a minimum of 3 replicate plots per management practice and field.
    a. Implementing more than one potential project treatment is recommended baseline
3) Fields should be representative of the region; multiple fields are to be used that are located at different sites and geographic locations (counties, states).

Outliers Criteria

1) Reserve strongly discourages removing outliers.

Applicability Criteria

1) Geographic applicability to which the data set may be extrapolated to include:
    a. Weather/climate
    b. Soil characteristics
    c. Management practices in the study site and the region
2) Summaries of growing season and experimental conditions should be included along with typical/average conditions
3) Typical soil type, texture, water holding capacity, SOC for the region should be considered when selecting replicate plots

Appendix B. Spreadsheet of Reviewed Data Sets

Please see attached spreadsheet.

Appendix C. List of Reviewed Studies

Halvorson, A.D., Snyder, C.S., Blaylock, A.D., Del Grosso, S.J. 2013. Enhanced-efficiency nitrogen fertilizers: Potential role in nitrous oxide emission mitigation. Agronomy Journal. 10.

Halvorson, A.D. and S.J. Del Grosso. 2013. Nitrogen placement and source effects on nitrous oxide emissions and yields of irrigated corn. Journal of Environmental Quality. 42:312—322.

Halvorson, A.D., Del Grosso, S.J., Jantalia, C.P. 2011. Nitrogen source effects on soil nitrous oxide emissions from strip-till corn. Journal of Environmental Quality. 40: 1775-1786.

Halvorson, A.D., Del Grosso, S.J., Alluvione, F. 2010. Nitrogen source effects on nitrous oxide emissions from irrigated no-till corn. Journal of Environmental Quality. 39: 1554-1562.

Halvorson, A.D. and S.J. Del Grosso. 2012. Nitrogen source and placement effects on soil nitrous oxide emissions from no-till corn. Journal of Environmental Quality. 41: 1349-1360.

Halvorson, A.D., Del Grosso, S.J., Alluvione, F. 2010. Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems. Soil Science Society of America Journal. 74: 436-445.

Halvorson, A.D., Del Grosso, S.J., Reule, C.A. 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems. Journal of Environmental Quality. 37:1337-1344.

Mosier, A.R., Halvorson, A.D., Reule, C.A., Liu, X.J. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern Colorado. Journal of Environmental Quality. 35: 1584-1598.

Liu, X.J., Mosier, A.R., Halvorson, A.D., Zhang. F.S. 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. Plant and Soil. 276: 235-249.

Mosier, A.R., Halvorson, A.D., Peterson, G.A., Robertson, G.P., Sherrod, L. 2005. Measurement of net global warming potential in three agroecosystems. Nutrient Cycling in Agroecosystems. 72: 67-76.

Appendix B. Spreadsheet of Reviewed Data Sets

	Paper Source	Halvorson et al. 2013 or cited therein	Halvorson et al. 2013 or cited therein	Halvorson et al. 2013 or cited therein
	Citation	Halvorson et al. 2013. Enhanced efficiency nitrogen fertilizers: potential role in nitrous oxide emission mitigation (REVIEW)	Halvorson, del Grosso. 2013. JEQ. Nitrogen placement and source effects on nitrous oxide emissions and yields of irrigated corn	Halvorson et al. 2011. Nitrogen source effects on soil nitrous oxide emissions from strip-till corn
Project Management Information	Location	Northeastern CO Semi-arid	Northeastern CO Semi-arid	Northeastern CO Semi-arid
	Crop	Irrigated corn with either continuous corn, corn-barley or corn-bean rotations	Irrigated corn	Irrigated corn. Continuous corn.
	Year(s) of data collection	2002-2012	2010, 2011	2009-2010
	Soil Type	clay loam	clay loam	clay loam
	Management Practices	No-till, strip still, conventional till	Strip till and no-till (2011 only)	Strip-till with UAN or urea compared with five alternatives
	Treatments	6 treatments: urea, urea-NH4NO3 (UAN), and controlled released, polymer coated urea, stabilized urea source (superU), stabilized UAN source, slow release UAN	Surface banding near corn row versus broadcasting of urea, polymer coated urea and stabilized urea with urease and nitrification inhibitors	UAN or urea compared with five alternatives: controlled release polymer urea, stabilized urea, UAN with nitrification and urease inhibitors and UAN slow release.
	N Application Type	-	Surface banding; broadcast	Surface band applied. Subsurface ESN band
	Irrigation Type	NA	lateral-move sprinkler irrigation	linear move sprinkler irrigation; lateral move sprinkler as needed during growing season with Watermark soil moisture sensors

	Residue Handling		59% of aboveground residue has been removed from the NT plot area each year for 4 years including 2011; residue left on surface in strip-till plots	Residue left on soil surface
Data Collection Type	Chamber Type		vented, non-steady state closed chamber	vented, non-steady state closed chamber
	If chamber- GRACEnet?	GRACEnet design	GRACEnet design	GRACEnet design
	Description of chamber design?	-	Rectangular alumnium chamber.	Rectangular alumnium chamber.
	Description of sampling, gas analysis and data analysis?		yes	yes
	surface area of chamber (should be >300cm)		78.6x39.3x10cm	78.6x39.3x10cm
Temporal	At least 1X per week?		Yes. 2-3 times a week before irrigation mid-morning.	Yes. 1-3 times per week, midmorning.
	If event, 1X daily at average temp?		unknown events	mention of hail storm in 2008 that defoliated 50% of leaves. No discussion of additional measurements.
	One complete growing season?		YES.2 growing seasons for strip till, 1 for no-till	Yes. 2 growing seasons
	Reference data over two growing seasons?		yes	yes
	Treatment plot size		ST: 3.0M long x 4.6m wide with 0.61m wide alleyways; NT: 2.74m x 4.6m with 0.61m wide alleyways	3m long x 4.6m wide with 0.61m wide alleyways
Spatial	At least 2 chamber per location?		Yes. Duplicate flux measurement sites	Yes. Duplicate flux measurement sites
	At least 3 replicate plots per practice/field?		Yes. 6 gas measurements per treatment per date	Randomized, complete block design with three replicates. 6 gas measurements per treatment

	multiple fields at different sites/locations?		No	No
Applicability	Summary of growing season/ experiment conditions?		Yes.	Yes
	Use of typical soils, WHC, SOC, etc. for replicate plots?		Yes	Yes
	Outliers removed?	2003 was separated from the other years for abnormally wet soil conditions	no outliers	no outliers
Things to note		2003 separated from other years as a result of abnormally wet soil conditions		additional ESN treatment at emergence; note plants were cut if bent for several weeks.

	Paper Source	**Halvorson et al. 2013 or cited therein**	**Halvorson et al. 2013 or cited therein**	**Halvorson et al. 2013 or cited therein**
	Citation	**Halvorson et al. 2010b. Nitrogen source effects on nitrous oxide emissions from irrigated no-till corn.**	**Halvorson et al. 2012. Nitrogen source and placement effects on soil nitrous oxide emissions from no-till corn**	**Halvorson et al. 2010. Tillage and inorganic nitrogen source effects on nitrous oxide emissions from irrigated cropping systems**
Project Management Information	Location	Northeastern CO Semi-arid	Northeastern CO Semi-arid	Northeastern CO Semi-arid
	Crop	Irrigated corn. Continuous corn except barley 2003 and dry bean 2005	Irrigated corn. Continuous corn except barley 2003 and dry bean 2005	Continuous corn, corn-drybean, corn-barley
	Year(s) of data collection	2007-2008	2009-2010	2007-2008
	Soil Type	clay loam	clay loam	clay loam
	Management Practices	No-till	No-till	No-till and conventional till continuous corn; no-till corn-drybean, corn-barley

	Treatments	Urea and UAN compared with two polymer coated urea products and two fertilizers with nitrification and urease inhibitors	Urea and UAN compared with four EEF: polymer coated urea, stabilized urea, UAN plus AgrotainPLUS which has nitrification and urease inhibitors	No-till and conventional till continuous corn: controlled release polymer coated urea and dry granular urea comparison. No-till Corn-DryBean and Corn-Barley: a stabilized urea source compared to urea. No nitrogen plot control included.
	N Application Type	Mechanically Band applied	surface band applied by hand close to the corn row. Also included subsurface banded polymer coated urea	mechanically banded
	Irrigation Type	lateral-move sprinkler irrigation	linear move sprinkler irrigation; lateral move sprinkler as needed during growing season with Watermark soil moisture sensors	sprinkler irrigation; lateral move sprinkler as needed during growing season with Watermark soil moisture sensors
	Residue Handling	No-till with previous crop residue on soil surface.	Half of plots had residue removed 45% in 2009; 34% in 2010	No-till left residues on field
Data Collection Type	Chamber Type	vented, non-steady state closed chamber	vented, non-steady state closed chamber	vented, non-steady state closed chamber
	If chamber- GRACEnet?	GRACEnet design	GRACEnet design	GRACEnet design
	Description of chamber design?	Rectangular alumnium chamber.	Rectangular alumnium chamber.	Rectangular chamber
	Description of sampling, gas analysis and data analysis?	yes	yes	yes
	surface area of chamber (should be >300cm)	78.6x39.3x10cm	78.6x39.3x10cm	78.6x39.3x10cm
Temporal	At least 1X per week?	Yes. 1-3 times per week, midmorning.	Yes 2-3 times a week in growing season. 1 time a week in non-crop period and biweekly in coldest season.	Yes. 1-3 times per week during growing season.
	If event, 1X daily at average temp?	unknown events	unknown events	unknown events
	One complete growing season?	Yes. 2 growing seasons	Yes. 2 growing seasons	Yes.
	Reference data over two growing seasons?	yes	yes	yes

	Treatment plot size	3.55x 5.92m with 0.79m alleyways	2.74m long by 4.6m wide with 0.61m alleyways	3.55x 5.92m with 0.79m alleyways
Spatial	At least 2 chamber per location?	Yes. Duplicate flux measurement sites	Yes. Duplicate flux measurement sites	Yes. Duplicate flux measurement sites
	At least 3 replicate plots per practice/field?	Yes.	duplicate measurement sites within each plot for a total of six gas measurements per treatment per sampling date.	Randomized, complete block design with three replicates. 6 gas measurements per treatment
	multiple fields at different sites/locations?	No	No	No
Applicability	Summary of growing season/ experiment conditions?	Yes	Yes	Yes
	Use of typical soils, WHC, SOC, etc. for replicate plots?	Yes	Yes	Yes
	Outliers removed?	Only if needed.	slug damage to corn in plot in 2009 with full residue cover; grain and stover yields used from partial residue area. No outlier data	Only if needed.
Things to note		Soil temps were cooler during May and June which is normal for all studies.		Plants cut when to large for chambers.

	Paper Source	Halvorson et al. 2013 or cited therein	Halvorson et al. 2013 or cited therein	Additional papers not in Halvorson et al. 2013
	Citation	**Halvorson et al. 2008. Nitrogen, tillage, and crop rotation effects on nitrous oxide emissions from irrigated cropping systems**	**Mosier et al. 2006. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in Northeastern CO.**	**Liu et al. 2005. Tillage and nitrogen application effects on nitrous and nitric oxide emissions from irrigated corn fields. Plant and Soil.**
Project Management Information	Location	Northeastern CO Semi-arid	Northeastern CO Semi-arid	Northeastern CO Semi-arid
	Crop	Continuous corn, corn-drybean, corn-barley	continuous corn, corn-soy	continuous corn
	Year(s) of data collection	2005-2006	Study area initiatied in 1999. Data from 2002-2004	2002, 2003
	Soil Type	clay loam	clay loam	clay loam
	Management Practices	CC CT, NT CC, NT CDb, NT CB. (same as Halvorson et al. 2010 paper)	CC CT NT CC NT Corn soy. 3 N rates	continuous corn conventional till, no-till
	Treatments	Half N subsurface band applied as UAN to corn in 2005, rest surface broadcast as polymer coated urea. N applied as UAN in barley and DB in NT. Corn in 2006 with polymer coated urea applied at emergence and second N as dry urea- both banded application. four kinds of N rate applications monitored in CC systems.	N rates of 0, 134 and 202 kg N ha in 2002 and 0, 67, 134 and 224 kg N ha in 2003, 2004	three variations of N applications (0,134 and 224 kg N as liquid UAN)
	N Application Type	Half N subsurface band applied as UAN to corn in 2005, rest surface broadcast as polymer coated urea. Corn in 2006 banded application.	injected to about 5cm below the soil surface in bands	Injected

	Irrigation Type	sprinkler irrigation; lateral move sprinkler as needed during growing season	lateral-move sprinkler irrigation	lateral-move sprinkler irrigation
	Residue Handling	No-till left residues on field	No-till left previous crop residues on soil surface; conventional tillage had residues incorporated with moldboard plow	No-till left residues on field
Data Collection Type	Chamber Type	vented, non-steady state closed chamber	vented, non-steady state closed chamber	vented, non-steady state closed chamber
	If chamber- GRACEnet?	GRACEnet design	GRACEnet design	GRACEnet design
	Description of chamber design?	vented rectangular alumnimum chamber	high vented rectangular aluminum chambers	vented rectangular aluminum chamber
	Description of sampling, gas analysis and data analysis?	yes	yes	yes
	surface area of chamber (should be >300cm)	78.6x39.3x10cm	78.6x39.3x10cm	78.6x39.3x10cm
Temporal	At least 1X per week?	Yes. 1-3 times per week.	Yes 1-3 times per week	1-3 times per week.
	If event, 1X daily at average temp?	unknown events	unknown events	unknown events
	One complete growing season?	Yes	Yes	Yes. 2 seasons.
	Reference data over two growing seasons?	yes	yes	yes
	Treatment plot size	3.55x 5.92m with 0.79m alleyways	3.55x 5.92m with 0.79m alleyways	3.55x 5.92m with 0.79m alleyways
Spatial	At least 2 chamber per location?	Yes. Duplicate flux measurement sites	Yes. Duplicate flux measurement sites	duplicate flux measurements made in each replicate of each treatment plot for six total measurements per treatment.

	At least 3 replicate plots per practice/field?	Yes, randomized complete block with three replications per cropping system. And duplicate flux measurements for each replicate.	randomized factorial experimental block with three replicates with two tillage systems and N rates. Duplicate flux measurements made within each replicate.	Yes. 3 replicates with CT and NT and 3 N rates.
	multiple fields at different sites/locations?	No	No	No
Applicability	Summary of growing season/ experiment conditions?	Yes	Yes	Yes- description of weather and soil conditions
	Use of typical soils, WHC, SOC, etc. for replicate plots?	Yes	Yes	yes
	Outliers removed?	Only if needed.	Only if needed.	Only if needed.
Things to note		Plants cut when to large for chambers.	P also applied in 1999 and liquid starter fertilizer with P,L, S applied in 2000,2002,2003,2004	

	Paper Source	**Additional papers not in Halvorson et al. 2013**	**Additional papers not in Halvorson et al. 2013**	**Non-N2O quantification relevant papers**
	Citation	**Mosier et al. 2006. Measurement of net global warming potential in three agroecosystems. Nutr. Cycl. Agroecosystems**	**Mosier et al. 2006. Measurement of net global warming potential in three agroecosystems. Nutr. Cycl. Agroecosystems**	**Halvorson and Reule. 2006. Irrigated NT corn and barley response to nitrogen in NO Colorado**
Project Management Information	Location	Michigan and Colorado rainfed. Colorado rainfed had rotations of wheat fallow, wheat corn fallow, wheat corn millet fallow, continuous cropping and prairie grass.	Colorado Irrigated	NE Colorado. Corn and barley CT and NT with varying N rates
	Crop	Michigan- corn-soy; Colorado- wheat-fallow; wheat-corn-fallow; wheat-corn-millet-fallow; continous cropping and prairie grass	Irrigated continuous corn, corn-soy	
	Year(s) of data collection	2002-2004	2002-2004	6 years of data starting in 1999
	Soil Type	loam; fine loam;	clay loam at Fort Collins	clay loam

	Management Practices	conventional till and no-till in Michigan; rainfed site in CO in no-till	no-till continuous corn, no-till corn-soy	NT corn, barley, wth six different N rate applications
	Treatments	N rate in continous corn- 0,134,202 kg N ha; NT Corn-soy- 0 and 202 kg N ha.	corn-soy fertilized at 0 and 202kg N, continuous corn fertilized at 0,134,202 kg N ha	
	N Application Type	Banded	Banded	Band applied UAN
	Irrigation Type	dryland	lateral-move sprinkler irrigation at Fort Collins, CO only, dryland at other locations	
	Residue Handling	Began in 2002	Began in 2002	
Data Collection Type	Chamber Type	vented, non-steady state closed chamber	vented, non-steady state closed chamber	
	If chamber- GRACEnet?	GRACEnet design	GRACEnet design	
	Description of chamber design?	vented rectangular aluminum chamber	vented rectangular aluminum chamber	
	Description of sampling, gas analysis and data analysis?	yes	yes	
	surface area of chamber (should be >300cm)	78.6x39.3x10cm	78.6x39.3x10cm	
Temporal	At least 1X per week?	1-2 times a week mid morning	Yes, 1-3 times a week	
	If event, 1X daily at average temp?	unknown events	unknown events	
	One complete growing season?	Yes	Yes	
	Reference data over two growing seasons?	yes	yes	
	Treatment plot size	3.55x 5.92m with 0.79m alleyways at Fort Collins, unknown at other locations	eight total observation points within each of the six treatments	10.7x15.2
Spatial	At least 2 chamber per location?	eight total observation points within each of the six treatments	Yes duplicate flux measurements made within each replicate of each treatment for six measurements per treatment	

	At least 3 replicate plots per practice/field?	Yes	Yes.	Yes.
	multiple fields at different sites/locations?	No	No	No
Applicability	Summary of growing season/ experiment conditions?	Yes	Yes	Yes
	Use of typical soils, WHC, SOC, etc. for replicate plots?	slug damage to corn in plot with full residue cover; grain and stover yields used from partial residue area.	slug damage to corn in plot with full residue cover; grain and stover yields used from partial residue area.	
	Outliers removed?	Unknown	Unknown	
Things to note				

	Paper Source	**Non-N2O quantification relevant papers**
	Citation	**Halvorson and Reule. 2006. Irrigated corn and soybean response to nitrogen under no-till in Northern CO**
Project Management Information	Location	N
	Crop	
	Year(s) of data collection	five years
	Soil Type	clay loam
	Management Practices	NT, CT corn, soy with six different N rates
	Treatments	
	N Application Type	Band applied UAN
	Irrigation Type	
	Residue Handling	

Data Collection Type	Chamber Type	
	If chamber- GRACEnet?	
	Description of chamber design?	
	Description of sampling, gas analysis and data analysis?	
	surface area of chamber (should be >300cm)	
Temporal	At least 1X per week?	
	If event, 1X daily at average temp?	
	One complete growing season?	
	Reference data over two growing seasons?	
	Treatment plot size	
Spatial	At least 2 chamber per location?	
	At least 3 replicate plots per practice/field?	
	multiple fields at different sites/locations?	No
Applicability	Summary of growing season/ experiment conditions?	Yes
	Use of typical soils, WHC, SOC, etc. for replicate plots?	Note that soybeans are not typically grown within the region.
	Outliers removed?	
Things to note		