MICHIGAN STATE UNIVERSITY | Extension

Climate Change and Agriculture Fact Sheet Series—MSU Extension Bulletin E3152 November 2014

# MANAGEMENT OF NITROGEN FERTILIZER TO REDUCE NITROUS OXIDE ($N_2O$) EMISSIONS FROM FIELD CROPS

Neville Millar[1], Julie E. Doll[1] and G. Philip Robertson[1,2]
[1]W.K. Kellogg Biological Station, Michigan State University
[2]Dept. of Plant, Soil and Microbial Sciences, Michigan State University

**Improving the management of nitrogen fertilizer for field crops can improve nitrogen use efficiency (saving farmers money) and reduce nitrous oxide emissions (helping the climate).**

## What is nitrous oxide and why is it important?

Nitrous oxide ($N_2O$) is an important greenhouse gas that contributes to climate change. Because it has a long atmospheric lifetime (over 100 years) and is about 300 times better at trapping heat than is carbon dioxide[1], even small emissions of $N_2O$ affect the climate.

Nitrous oxide is produced by microbes in almost all soils. In agriculture, $N_2O$ is emitted mainly from fertilized soils and animal wastes—wherever nitrogen (N) is readily available. In the United States, agriculture accounts for approximately 8 percent of all greenhouse gas emissions but contributes about 75 percent of all $N_2O$ emissions linked to human activity[2]. Of the three major greenhouse gases emitted naturally—carbon dioxide, methane and $N_2O$—$N_2O$ is the most important in all field crops but rice[3].

This fact sheet explains how better management of N fertilizer can reduce $N_2O$ emissions from crop fields.

Automated greenhouse gas sampling chambers in a wheat field on the KBS Long-term Ecological Research site. These chambers measure nitrous oxide, carbon dioxide and methane emissions multiple times every day throughout the year, allowing researchers to accurately estimate greenhouse gas emissions. *Photo: J.E.Doll, Michigan State University.*

## How does nitrogen fertilizer increase nitrous oxide emissions?

Farmers add new N to fields either as synthetic fertilizers such as urea or anhydrous ammonia, or as organic fertilizers such as manure. Most synthetic fertilizer N is readily available for uptake by plants; most of the N in organic fertilizer must be converted to inorganic N before its N is available for uptake. When not taken up by plants, most fertilizer N is mobile, hard to contain in the field and susceptible to loss. Nitrogen from fertilizer can be lost as nitrate to groundwater or as the gases $N_2O$, dinitrogen ($N_2$) or ammonia. Typically only about half of the fertilizer N applied to a crop is taken up by the crop during that growing season[4] (Figure 1).

Nitrogen applied in excess of crop needs is particularly susceptible to loss. Though the amounts of carbon and oxygen available in soil also affect microbial $N_2O$ production, the presence of inorganic N usually matters most.

## How can nitrogen fertilizer management decrease nitrous oxide emissions?

Because of the strong link between inorganic N in the soil and $N_2O$ production, some emissions are unavoidable. But management that prevents the buildup of inorganic N reduces $N_2O$ emissions. Numerous management strategies can keep soil N in check and minimize $N_2O$ emissions[5]. Many of these strategies also help to keep other forms of N from being lost, including nitrate and ammonia. In general, practices that reduce $N_2O$ emissions increase N use efficiency (NUE), which keeps more of the added N in the crop.

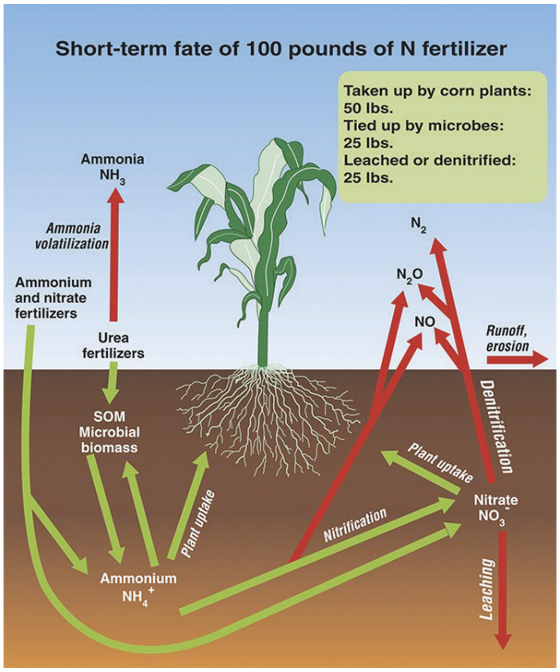


**Figure 1:** This simplified nitrogen (N) cycle shows the typical fate of 100 pounds of N fertilizer applied to a corn field. The exact amounts vary with soil type, weather and crop. (Source: *Ecologically Based Farming Systems*, 2007[6].)

The four main management factors that help reduce $N_2O$ emissions from applied N fertilizer are commonly known as the 4R's:

- Right N application rate;
- Right formulation (fertilizer type);
- Right timing of application; and,
- Right placement.

### *Matching nitrogen fertilizer application rate to crop requirement*

Nitrogen availability — the amount of inorganic N in soil at any given time — is the single best predictor of $N_2O$ fluxes in cropped ecosystems[7,8]. Michigan State University researchers have shown that $N_2O$ emissions are especially high when N fertilizer is applied at rates greater than crop need. The emission rate grows exponentially with increases in fertilizer rate (see Figure 2), so at higher rates of fertilizer application $N_2O$ emissions increase disproportionately, particularly after crop N demands are met[9].

Recent fertilizer recommendations for Michigan corn crops provide farmers an improved capacity to predict crop N needs[10]. These recommendations are based on dozens of field fertilizer response trials that define the *maximum return to N rate* (MRTN), which is the rate at which adding any additional N is not repaid by higher yields. This rate is typically a bit lower than the *agronomically optimum N rate* (AONR: the maximum level to which crops respond) by a margin that depends on the price of fertilizer vs. the price of grain[11]. Typically, using the MRTN approach rather than the older yield-goal approach allows farmers to realize N fertilizer savings. Because both $N_2O$ emissions[12] and nitrate leaching[13] increase exponentially when N fertilizer exceeds crop N demand, these N savings also can result in substantially lower losses of $N_2O$ and nitrate.

Better estimating the amount of fertilizer N needed by a crop is an effective way to reduce $N_2O$ emitted from cropped fields.

### *Improving nitrogen fertilizer formulation*

Fertilizer formulations also can alter $N_2O$ emissions in some cropping systems. For example, in corn-soybean rotations, emissions can be two to four times greater following anhydrous ammonia than following urea ammonium nitrate or broadcast urea[14]. The trend toward using more urea in corn in the United States may help reduce $N_2O$ emissions.

Fertilizer additives can also reduce $N_2O$ emissions. Nitrification inhibitors such as nitrapyrin[15], which delay the microbial transformation of soil ammonium to nitrate, can delay the formation of nitrate until closer to the time that plants can use it. Likewise, urease inhibitors can delay urea fertilizer's dissolving in soil water. Slow-release formulations such as polymer coatings can have the same effect. For example, in irrigated no-till corn, $N_2O$ emissions can be reduced by using polymer-coated urea or a combined nitrification

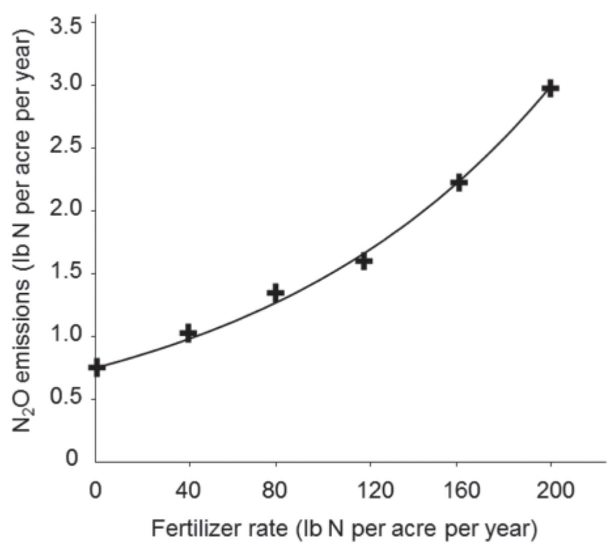


**Figure 2:** Data from Michigan corn fields[12] showing how nitrous oxide ($N_2O$) emissions increase exponentially with increasing fertilizer N rate. By more precisely estimating crop fertilizer N needs, farmers can greatly reduce $N_2O$ emissions from their fields.

and urease inhibitor with urea ammonium nitrate, compared with using either urea or urea ammonium nitrate alone[16]. As yet, however, there have been too few field studies to fully judge the benefit of additives or fertilizer formulations for $N_2O$ emissions.

### *Improving nitrogen fertilizer timing*

Applying N fertilizer when it is most needed by plants can also help reduce $N_2O$ emissions. Applying the majority of fertilizer a few weeks after planting rather than at or before planting increases the likelihood that the N will end up in the crop rather than be lost to groundwater or the atmosphere. Sidedressing N fertilizer at the V-6 stage in corn, for example, can increase N use efficiency[17]— especially if application is preceded by a pre-sidedress-nitrate test (PSNT) to allow residual N to be taken into account[18].

Adding N fertilizer in the fall or spreading manure on frozen fields often leads to especially large nitrate[19] and $N_2O$[20] losses. In such cases, fertilizer applications are way out of sync with the timing of crop needs.

### *Improving nitrogen fertilizer placement*

Placing N fertilizer close to plant roots also can reduce $N_2O$ emissions. For example, applying urea in narrow bands next to the plants rather than broadcasting across the field can reduce $N_2O$ emissions. Likewise, emissions are lower when canola and wheat are side-banded rather than banded midrow[21]. In corn, shallow rather than deep placement of ammonium nitrate or anhydrous ammonia has led to reduced $N_2O$ emissions[22].

Precision fertilizer application can also improve NUE by tailoring N application to soil spatial variability. Adding less N to those parts of a field with low yield potential, as measured by yield monitoring, will avoid wasting N on locations in the field that are not as likely to respond to N fertilizer. In one study, precision fertilizer application reduced the average N fertilizer rate by 22 lb N per acre (25 kg N per hectare)[23], substantially reducing $N_2O$ emissions.

Aerial view of the KBS Long-term Ecological Research experiment showing corn's response to varying levels of nitrogen fertilizer rates. Data from this and other experiments across Michigan showed how nitrogen rates can be reduced, resulting in lower nitrous oxide emissions without harming crop yield. *Photo: K.Stepnitz, Michigan State University*

## How can we best reduce nitrous oxide emissions from field crop agriculture?

An integrated approach is best suited to reduce $N_2O$ emissions from field crop agriculture. The same principles of N fertilizer best management practices for increased NUE hold true for reducing emissions:

- Apply fertilizer at the economically optimum rate;
- Use an appropriate fertilizer formulation;
- Apply as close to the time of crop need as possible; and,
- Apply as close to the crop's root zone as possible.

Following these practices will, in general, result in more N in the crop and less lost to the environment. These and further potential $N_2O$ mitigation strategies for croplands are summarized in Table 1[24].

## Earning Carbon Credits for Nitrous Oxide Reductions

As previously mentioned, even small amounts of $N_2O$ in the atmosphere can greatly affect the climate. Because of this, there is great interest in reducing emissions of $N_2O$ from various economic sectors, including field crop agriculture. By using the N management practices described in this bulletin, farmers can reduce $N_2O$ emissions from their fields without reducing crop yield or economic return. This is the basis for programs offered through carbon credit organizations in the United States that use the marketplace to pay farmers for these reductions.

Most straightforward and accessible programs use a methodology that estimates $N_2O$ emissions reductions on the basis of the reduction of N fertilizer rate. This methodology is based on data collected on commercial Michigan farms[25,26] and was developed primarily by Michigan State University scientists. It allows farmers to convert their $N_2O$ emissions reductions to equivalent units of carbon dioxide. These can then be traded as carbon credits on environmental markets to generate income (http://www.deltanitrogen.org/).

Reductions in N fertilizer input without crop yield loss can best be achieved through the use of an integrated approach that uses corn and fertilizer prices to estimate recommended N rates, and improves management of the formulation, timing and placement of N fertilizer.

These changes in management practice, in combination with programs that pay for the environmental benefits they deliver, help to ensure the long-term sustainability of field crop agriculture, N use, and a stable climate.

**Table 1.** Proposed and potential nitrous oxide ($N_2O$) mitigation technologies and practices for croplands. Adapted from Cavigelli et al., 2012[24].

| Technology or Management Practice | Effectiveness and Comments |
|---|---|
| Right N fertilizer application rate (applied at the economically optimum rate): N fertilizer refers to both synthetic and organic fertilizers (such as manure). | May reduce $N_2O$ emissions substantially where N fertilizer is applied at rates greater than the economic optimum rate. |
| Right N fertilizer source: N fertilizer sources include urea, anhydrous ammonia, urea ammonium nitrate, ammonium nitrate and manure; slow-release fertilizers, such as polycoated urea, are not widely used because of increased costs. | Urea, urea ammonium nitrate and polycoated ureas can decrease $N_2O$ emissions by 50 percent or more compared with anhydrous ammonia in some locations, but there is no impact in other locations. |
| Right N fertilizer placement: N fertilizer may be broadcast or applied in bands, applied on the surface or below the surface. | Incorporating bands of N in soil can improve nutrient use efficiency and can reduce $N_2O$ emissions by about 50 percent compared with broadcast application in some locations. |
| Right N fertilizer timing: N fertilizer should be applied as close as possible to when the crop needs it. | Applying N at planting or at times of peak crop N demand can increase nutrient use efficiency and would be expected to decrease $N_2O$ emissions, but results from field studies are mixed. |
| N process (nitrification and urease) inhibitors | Can decrease $N_2O$ emissions by 50 percent in dry climates, but results are mixed for humid climates. |
| Cover crops | Winter cover crops can reduce N losses (for example, leaching and runoff), but may not affect $N_2O$ emissions. |
| Crop selection | Low N-demanding crops can reduce $N_2O$ emissions by more than 50 percent in many places. |
| Improved irrigation management: timing, application rate and application method | Reducing application rates to minimize soil wetness can reduce $N_2O$ emissions. Subsurface drip irrigation can reduce $N_2O$ emissions compared with overhead sprinkler irrigation because soil moisture is better regulated, but data are limited. |
| Reduced tillage | A long-term no-till strategy can reduce $N_2O$ emissions by up to 50 percent, but data are limited. Short-term no-till results are more mixed. |

Notes: The effectiveness of many mitigation options is influenced by soil type and climate, and there are major uncertainties about the effectiveness of most mitigation strategies.

## References:

[1] IPCC. 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Stocker, T.F., D. Qin, G.K. Plattner, et al. [eds.]). Cambridge, United Kingdom, and New York, NY, USA: Cambridge University Press.

[2] U.S. Environmental Protection Agency 2014. Inventory of U.S. greenhouse gas emissions and sinks: 1990-2012. EPA. Available online at: http://epa.gov/climatechange/emissions/usinventoryreport.html.

[3] Robertson, G.P., E.A. Paul and R.R. Harwood. 2000. Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. Science 289:1922-1925.

[4] Cassman, K.G., A. Dobermann and D.T. Walters. 2002. Agroecosystems, nitrogen use efficiency and nitrogen management. Ambio 31:132-140.

[5] Follett R.F., S.R. Shafer, M.D. Jawson, et al. 2005. Research and implementation needs to mitigate greenhouse gas emissions from agriculture in the USA. Soil and Tillage Research 83:159-166.

[6] Thelen, K., C. Laboski, J. Smeenk, et al. 2007. Field crop production systems. pages 40-59 in Ecologically Based Farming Systems (Deming, S., L. Johnson, D. Lehnert, et al. [eds.]). Extension Bulletin E-2983. East Lansing, MI, USA: Michigan State University.

[7] Bouwman, A.F., L.J.M. Boumans and N.H. Batjes. 2002. Emissions of $N_2O$ and NO from fertilized fields: Summary of available measurement data. Global Biogeochemical Cycles 16:1058-1070.

[8] Shcherbak, I., N. Millar and G.P. Robertson. 2014. A global meta-analysis of the nonlinear response of soil nitrous oxide ($N_2O$) emissions to fertilizer nitrogen. Proceedings of the National Academies of Sciences, 111: 9199-9204.

[9] Millar, N., G.P. Robertson, P. Grace, et al. 2010. Nitrogen fertilizer management for nitrous oxide ($N_2O$) mitigation in intensive corn (Maize) production: An emissions reduction protocol for US Midwest agriculture. Mitigation and Adaptation Strategies for Global Change 15:185-204.

[10] Warncke, D., J. Dahl and L. Jacobs. 2009. Nutrient Recommendations for Field Crops in Michigan. Extension Bulletin E2904. East Lansing, MI: Department of Crop and Soil Sciences, Michigan State University. See also the Soil Fertility and Nutrient Management Program website at http://www.soil.msu.edu/.

[11] Sawyer, J., E. Nafziger, G. Randall, et al. 2006. Concepts and Rationale for Regional Nitrogen Rate Guidelines for Corn. Report PM 2015, Ames, Iowa. Iowa State University - University Extension.

[12] Hoben, J.P., R.J. Gehl, N. Millar, et al. 2011. Nonlinear nitrous oxide ($N_2O$) response to nitrogen fertilizer in on-farm corn crops of the US Midwest. Global Change Biology 17:1140-1152.

[13] Gehl, R.J., J.P. Schmidt, C.B. Godsey, et al. 2006. Post-harvest soil nitrate in irrigated corn: Variability among eight field sites and multiple nitrogen rates. Soil Science Society of America Journal 70:1922-1931.

[14] Venterea, R.T., M.S. Dolan and T.E. Ochsner. 2010. Urea decreases nitrous oxide emissions compared with anhydrous ammonia in a Minnesota corn cropping system. Soil Science Society of America Journal 74:407-418.

[15] Randall, G.W., and J.E. Sawyer. 2008. Nitrogen Application Timing, Forms and Additives. Pages 73-85 in: Final Report: Gulf Hypoxia and Local Water Quality Concerns Workshop. St. Joseph, Mich., USA: Upper Mississippi River Sub-basin Hypoxia Nutrient Committee, American Society of Agricultural and Biological Engineers.

[16] 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.

[17] Zebarth, B.J., P. Rochette, D.L. Burton, et al. 2008. Effect of fertilizer nitrogen management on $N_2O$ emissions in commercial corn fields. Canadian Journal of Soil Science 88:189-195.

[18] Sogbedji, J.M., H.M. van Es, C.L. Yang, et al. 2000. Nitrate leaching and nitrogen budget as affected by maize nitrogen rate and soil type. Journal of Environmental Quality 29:1813-1820.

[19] Randall, G.W., and D.J. Mulla. 2001. Nitrate-N in surface waters as influenced by climatic conditions and agricultural practices. Journal of Environmental Quality 30:337-344.

[20] Wagner-Riddle, C. and G.W. Thurtell. 1998. Nitrous oxide emissions from agricultural fields during winter and spring thaw as affected by management practices. Nutrient Cycling in Agroecosystems 52:151-163.

[21] Hultgreen, G., and P. Leduc. 2003. The Effect of Nitrogen Fertilizer Placement, Formulation, Timing and Rate on Greenhouse Gas Emissions and Agronomic Performance. Final Report, Project No. 5300G. Regina, Sask., Canada: Saskatchewan Department of Agriculture and Food.

[22] Breitenbeck, G.A., and J.M. Bremner. 1986. Effects of rate and depth of fertilizer application on emission of nitrous oxide from soil fertilized with anhydrous ammonia. Biology and Fertility of Soils 2:201-204.

[23] Sehy, U., R. Ruser and J.C. Munch. 2003. Nitrous oxide fluxes from maize fields: Relationship to yield, site-specific fertilization and soil conditions. Agriculture, Ecosystems and Environment 99:97-111.

[24] Cavigelli, M.A., S.J. Del Grosso, M.A. Liebig, et al. 2012. US agricultural nitrous oxide emissions: context, status, and trends. Frontiers in Ecology and the Environment 10:537-546.

[25] Millar, N, G.P. Robertson, A. Diamant, et al. 2012. Methodology for Quantifying Nitrous Oxide ($N_2O$) Emissions Reductions by Reducing Nitrogen Fertilizer Use on Agricultural Crops. American Carbon Registry, Winrock International, Little Rock, Arkansas. http://americancarbonregistry.org/carbon-accounting/msu-epri-methodology-v1.

[26] Millar, N., G.P. Robertson, A. Diamant, et al. 2013. Quantifying $N_2O$ Emissions Reductions in US Agricultural Crops through N Fertilizer Rate Reduction. Verified Carbon Standard. Washington DC, USA. http://v-c-s.org/methodologies/VM0022.

MICHIGAN STATE UNIVERSITY | Extension

MICHIGAN STATE UNIVERSITY | AgBioResearch

KBS LTER Kellogg Biological Station Long-term Ecological Research