

Preliminary Assessment of Nitrous Oxide Offsets in a Cap and Trade Program

Marc Ribaldo, Jorge Delgado, and Michael Livingston

Nitrous oxide is a powerful greenhouse gas that is emitted from cropland treated with nitrogen fertilizer. Reducing such emissions through nutrient management might be able to produce offsets for sale in a cap and trade program aimed at reducing greenhouse gases. We use the Nitrate Leaching and Economic Analysis Program (NLEAP) model and data from the Agricultural and Resource Management Survey to examine what changes in rate, timing, or method of application a farmer would take to produce offsets. We find that reducing the application rate is the most favored approach for producing offsets. We also find that some management choices may increase nitrate losses to water.

Key Words: nitrous oxide, nutrient management, cap and trade, NLEAP, greenhouse gas

Most cropping systems are naturally deficient in nitrogen (N). Gaseous nitrogen (N_2) is abundant in the atmosphere, but it cannot be used by living organisms unless it is first converted into usable forms. Leguminous plants and soil microorganisms can contribute significant amounts of fixed nitrogen that can be used by crops, but yields necessary to support growing populations need more nitrogen than can be provided by natural means.

Massive inputs of biologically usable reactive forms of nitrogen, fixed from atmospheric N through the Haber-Bosch process, enable high crop yields but have radically altered the nitrogen balances in aquatic, atmospheric, and terrestrial nitrogen pools. This has led to disruptions in ecosystem function and the supply of valuable ecosystem services (Galloway et al. 2008). One source of concern is nitrous oxide emissions from crop production.

Nitrous oxide (N_2O) is a powerful greenhouse gas (310 times the warming potential of carbon dioxide) and an important source of ozone depletion (Ravishankara, Daniel, and Portmann 2009, Wuebbles 2009). In the United States, about 73

percent of N_2O emissions are from agriculture (U.S. Environmental Protection Agency 2010). N_2O is produced in the soil predominantly by the microbial processes of nitrification (ammonia oxidation) and denitrification (nitrate reduction) (Robertson and Groffman 2007). About 44 percent of all agricultural greenhouse gas emissions are from soil fertilizer management, making it the largest agricultural source (U.S. Environmental Protection Agency 2010). About 28 percent of agricultural greenhouse gas emissions are methane from enteric fermentation from livestock, and 12 percent are various gases from manure handling and storage. Agricultural emissions of N_2O have increased since 2003, largely as a result of increased use of synthetic nitrogen fertilizers associated with rising demand for corn-based ethanol (U.S. Energy Information Administration 2009). Factors affecting N_2O creation in the soil include those that affect available carbon, inorganic nitrogen, and oxygen, as well as soil moisture, soil porosity, and aggregate structure (Robertson and Groffman 2007).

Farmers can reduce N_2O emissions in a variety of ways through fertilizer, soil, water, and crop management. A variety of policy instruments are available to government to induce management changes. One approach is a cap and trade program for mitigating emissions of CO_2 and other greenhouse gases. Current discussions over regional and national greenhouse gas (GHG) cap and trade policies have generally not included agricultural emissions under a cap, but these policies could

Marc Ribaldo and Michael Livingston are Agricultural Economists with the Economic Research Service of the U.S. Department of Agriculture (USDA), in Washington, D.C. Jorge Delgado is Senior Scientist with the Agricultural Research Service of the USDA in Fort Collins, Colorado. The views expressed in this paper are those of the authors and not necessarily those of the Economic Research Service, the Agricultural Research Service, or the USDA.

allow agriculture to provide GHG reductions as offsets that could be purchased by the regulated sectors. For example, in the American Clean Energy and Security Act of 2009 (HR 2454), the cap and trade proposal passed by the U.S. House of Representatives, reductions in N₂O from reduced nitrogen fertilizer use are potentially eligible to be sold as offsets.

In this paper we use the new Nitrogen Loss and Environmental Assessment Package with GIS capabilities (NLEAP-GIS) model (Shaffer et al. 2010, Delgado et al. 2010) and cost data from the Agricultural Resources and Management Survey (ARMS), collected by the U.S. Department of Agriculture (USDA) Economic Research Service-National Agricultural Statistics Service (ERS-NASS), to explore what changes corn farmers might make, given the opportunity to participate in an offset market for N₂O reductions. Corn is the most widely planted crop in the United States, and the biggest user of nitrogen fertilizer. We also examine the potential for tradeoffs with other nitrogen-related environmental problems. Our analysis was conducted across different management scenarios and hydrologic soils (e.g., well-drained soils with a large leaching potential, versus poorly drained soils with a low leaching potential) from a selected county in each of four states: Virginia, Ohio, Pennsylvania, and Arkansas.

Trading Basics

Emission trading is organized around the creation of discharge allowances, which is a time-limited permission to discharge a fixed quantity of pollutant into the environment. Whereas atmospheric quality has characteristics of a public good, making it difficult to control using market-based instruments, a discharge allowance has characteristics of a private good; it is rival and exclusive (Ribaldo et al. 2008). Property rights are enforced by the regulatory agency managing the program.

A regulatory agency creates demand for discharge allowances by restricting the number of allowances in a market. The regulatory agency first determines the maximum amount of discharge of a particular pollutant the environment can absorb and still meet environmental quality goals. This becomes the emissions cap. The cap is used to set a discharge limit for each regulated

firm that becomes part of their discharge permits. Discharge allowances equal to the emissions cap are allocated to all regulated dischargers through an auction or simply allocated free of charge according to some allocation rule (Tietenberg 2006). By allowing the allowances to be traded, a market is created that allocates discharge among regulated firms. If the market operates smoothly, a cap and trade program can achieve environmental goals at a lower cost than command-and-control regulations alone (Tietenberg 2006). Firms that have low pollution control costs will supply a greater extent of the pollution control. A market allows maximum flexibility for firms, in that a firm can meet its obligations by installing pollution control technology, adopting more efficient production technology, rearranging production processes, or purchasing credits (Ribaldo, Horan, and Smith 1999).

When an unregulated sector such as agriculture is included in a market, it can create offsets that can be sold in the market by adopting management practices that reduce the emissions of the regulated pollutant. As long as agriculture can reduce nitrous oxide emissions at a lower unit cost than regulated sources (i.e., power plants), it stands to benefit financially from such a market, and regulated sources can achieve their permit requirements at a lower cost than if they were limited to trading amongst themselves.

Since nitrogen can readily change forms and is highly mobile in soil, water, and air, a strategy for reducing N₂O emissions is to improve overall nitrogen use efficiency (NUE). This would reduce the amount of nitrogen in the soil available to be lost to the environment (Cassman, Dobermann, and Walters 2002). The basic practices for improving NUE are appropriate timing of applications, proper placement, and an agronomic application rate (U.S. Department of Agriculture and Natural Resources Conservation Service 2006).

One of the main factors affecting nitrogen use efficiency is the application rate (Bock and Hergert 1991, Millar et al. 2010, Meisenger, Schepers, and Raun 2008). Nitrogen losses have been shown to increase rapidly when N inputs exceed assimilation capacity (Vanotti and Bundy 1994, Schlegel, Dhuyvetter, and Havlin 1996, Bock and Hergert 1991). Reducing application rates reduces the losses of all forms of reactive nitrogen.

The goal of appropriate methods and placement of fertilizer is to provide nutrients to plants for rapid uptake and to reduce the potential for environmental losses. Studies have shown that efficiency can be doubled under some conditions by incorporating fertilizers in the soil, rather than “broadcasting” them on the surface (Malhi and Nyborg 1991, Power, Wiese, and Flowerday 2001). Liquid or gaseous forms of nitrogen can be injected directly into the soil with specialized equipment. Solid forms can be broadcast on the surface and immediately incorporated into the soil by disking. Such placement reduces the opportunity for losses to the atmosphere and through surface runoff. For situations where ammonia volatilization is a significant pathway for nitrogen loss, the method of application can significantly reduce losses (Meisinger and Randall 1991, Peoples, Mosier, and Freney 1995, Fox, Piekielek, and Macneal 1996, Freney, Simpson, and Denmead 1981).

The research on improving nitrogen use efficiency in crop production has emphasized the need for greater synchronization between crop nitrogen demand and the supply of nitrogen from all sources throughout the growing season (Doerge, Roth, and Gardner 1991, Cassman, Dobermann, and Walters 2002, Meisinger and Delgado 2002). Balancing supply and demand implies maintaining low levels of inorganic nitrogen in the soil when there is little plant growth, and providing sufficient inorganic nitrogen fertilizer during periods of rapid plant growth (Alva et al. 2006, Doerge, Roth, and Gardner 1991). For example, the corn plant’s need for nitrogen is not very high until about four weeks after emergence, which in the major corn producing states is June through July (Baker 2001). Ideally, to ensure that growing crops have adequate N and to minimize losses from the soil, a farmer could split nitrogen applications or “spoon feed” nitrogen when using center-pivot sprinkler irrigation systems from June through July-August using information from soil tests and/or advanced remote sensing techniques (Bausch and Delgado 2003). However, there is a cost to doing this. Workload, seasonal fertilizer price differences, the risk associated with not being able to apply at the right time, application costs, the possibility of compacting the soil, and possible damage to growing crops all must be considered; nonetheless, splitting nitrogen applications can increase nitrogen use

efficiency and reduce nitrogen losses to the environment (Doerge, Roth, and Gardner 1991, Westermann, Kleinkopf, and Porter 1988, Westermann and Kleinkopf 1985, Alva et al. 2006, Delgado and Bausch 2005).

It should be noted that there are a number of other practices that influence soil nitrogen processes, including cover crops and conservation tillage. Research has found the influences of these practices on N₂O emissions to be small and that the application rate is the single largest factor affecting emissions (Millar et al. 2010, Jarecki et al. 2009, Wagner-Riddle and Thurtell 1998).

Corn receives about 66 percent of all nitrogen fertilizers applied to field crops in the United States, making it the most important crop in terms of potential N₂O emissions. We assessed the percentage of corn acres practicing “good” nitrogen management with data from the 2005 corn Agricultural and Resource Management Survey¹. For this study the appropriate rate is defined as 40 percent more nitrogen than what is removed with crop harvest, which is consistent with NRCS treatment of application rate evaluation in their assessment of the Upper Mississippi Basin (U.S. Department of Agriculture 2010). Appropriate timing is defined as no fall applications. Appropriate method is defined as injection or incorporation immediately after surface application. About 30 percent of the 76 million acres of corn that received nitrogen fertilizer in 2005 met the timing, rate, and method criteria (Table 1). This implies there may be ample opportunity for corn producers to produce nitrous oxide offsets in the presence of a market for greenhouse gas reductions.

While meeting the rate, timing, and method criteria for good nitrogen management may improve overall nitrogen use efficiency, the impacts on N₂O emissions are not so clear-cut. Applying all nitrogen during the planting and growing seasons

¹ ARMS is an annual survey of farm and ranch operators administered by USDA's National Agricultural Statistics Service (NASS). Survey data on field-level production practices, farm business accounts, and farm households are collected. ARMS is a multiple-phase survey. In the fall, NASS interviews producers of major commodities, such as feed grains, food grains, or cotton, to collect information about production practices and land use for a selected field on their operation. In the spring, NASS reinterviews farmers who successfully completed the fall survey. Spring data collection focuses on the structural and economic characteristics of the farm business and farm operator households. This approach helps link commodity production activities and conservation practices with the farm business and operator household.

Table 1. Percentage of Corn Acres Meeting Criteria for “Good” Nitrogen Management

Nitrogen Management Criteria Met ¹	Percentage of Treated Acres
All	30.4
Rate and Timing	15.0
Rate and Method	12.0
Timing and Method	10.5
Rate	6.2
Timing	8.3
Method	8.1
None	8.0

¹The three criteria are agronomic application rate, inject/incorporate, and no fall application.

Source: 2005 corn ARMS survey

increases overall NUE. Some research has found higher N₂O emissions with fall applications (Hao et al. 2001, Hultgreen and Leduc 2003). However, applying nitrogen in the spring, with its warmer and wetter conditions, may actually increase N₂O emissions (Delgado et al. 1996, Hernandez-Ramirez et al. 2009, Rochette et al. 2004, Tilsner et al. 2003, Wagner-Riddle and Thurtell 1998), even though overall NUE is higher than for fall applications.

Injecting or incorporating fertilizer into the soil so that it is closer to the plant roots and away from the surface can reduce the risk of nitrogen loss and improve overall nitrogen use efficiency. But again, the impact of fertilizer placement on nitrous oxide emissions is difficult to generalize. Liu et al. (2006) found that injection of liquid urea ammonium nitrate at deeper levels resulted in 40 percent to 70 percent lower N₂O emissions compared to shallow injection or surface application. Studies have reported that incorporation increases N₂O emissions (Wulf, Maeting, and Clemens 2002, Flessa and Beese 2000). Drury et

al. (2006) found that emissions of N₂O were on average 26 percent higher with deep placement of ammonium nitrate in a clay loam compared to shallow placement.

The impact of rate on N₂O emissions is more certain. A large set of studies indicates that excessive nitrogen inputs contribute to increases in N₂O emissions (Bouwman, Boumans, and Batjes 2002, Jarecki et al. 2009, McSwiney and Robertson 2005). Bouwman, Boumans, and Batjes (2002) reported a range of N₂O emissions from 1.1 kg N₂O-N ha⁻¹y⁻¹ with zero nitrogen inputs, to 6.8 kg N₂O-N ha⁻¹y⁻¹ for nitrogen fertilizer rates greater than 250 kg N ha⁻¹. Ruser et al. (1998) reported N₂O emissions for low and high nitrogen fertilizer rates applied to potato fields at 8 kg and 16 kg N₂O ha⁻¹, respectively.

Jarecki et al. (2009) reported not only that the rate of N₂O emissions increased with excessive N fertilizer applications above 10 kg N₂O-N ha⁻¹y⁻¹, but also that the increase in emissions was not linear. In other words, excessive nitrogen inputs accelerated the rate of N₂O emissions when nitrogen was applied at higher-than-necessary rates. They found that at nitrogen input rates of about 375 kg N ha⁻¹, the N₂O emissions were about 12 kg N₂O-N ha⁻¹y⁻¹. A nonlinear response in N₂O emissions was also reported by McSwiney and Robertson (2005), Hyde et al. (2006), and Millar et al. (2010).

Model and Data

We used the new Nitrogen Loss and Environmental Assessment Package with GIS capabilities (NLEAP-GIS) model to assess how changes in nitrogen management practices on corn affect the losses of nitrate (to water), nitrous oxide (to air), and ammonia (to air) (Delgado et al. 2010, Shaffer et al. 2010). The NLEAP model has been used extensively across national and international systems (Delgado et al. 2008). This tool is capable of simulating the effects of management practices and generating reasonable assessment values that are similar to measured field studies conducted across small-scale plots and large commercial field operations (e.g., water budgets, nitrate leaching, residual soil nitrate, crop uptake, nitrogen dynamics, and N₂O emissions) (Beckie et al. 1995, Delgado et al. 2001, Shaffer and Delgado 2001, Xu, Shaffer, and Al-kaisi 1998).

Table 2. Relationships Used to Develop Yields and Nitrogen Rates across Study Sites

Tillage Practice	Recommended Rate	Excess Rate	Deficient Rate
Yield (bushels per acre)			
Conventional	x^1	1.01x	0.9x
No-Till	0.9x	0.0909x	0.81x
N Rate for Fertilizer-only Scenarios (lbs. N per acre)			
Conventional	z^2	1.75z	0.75z
No-Till	y^3	1.75y	0.75y
N Rate for Manure with N Fertilizer Scenarios (lbs. N per acre)			
Conventional	$z(\text{man})+0.5z(\text{fert})$	$1.75z(\text{man})+0.875z(\text{fert})$	$0.75z(\text{man})+0.375z(\text{fert})$
No-Till	$y(\text{man})+0.5y(\text{fert})$	$1.75y(\text{man})+0.875y(\text{fert})$	$0.75y(\text{man})+0.375y(\text{fert})$

Man=manure; fert=fertilizer

¹The x values are 131, 101, 103, and 107 corn bushels per acre for OH, VA, PA, and AR, respectively. The x values were 40, 27, 37, and 27 soybean bushels per acre for OH, VA, PA, and AR, respectively.

²The z values are 132, 121, 100, 120, and 125 lbs. of N per acre for OH, VA, PA, AR (Hydrology A), and AR (Hydrology D), respectively for conventional tillage.

³The y values are 116, 109, 90, 100, and 105 lbs. of N per acre for OH, VA, PA, AR (Hydrology A), and AR (Hydrology D), respectively for no-till.

Because NLEAP is a field-level model, we selected eight different soils in four states (Arkansas, Ohio, Pennsylvania, and Virginia) to assess changes in nitrogen emissions to the environment from management changes in nonirrigated corn production. Four of the soils are type A or B soils (well drained) and four are type D soils (relatively poorly drained). The slopes for these soils were 0 percent to 6 percent, with low erosion potential. For each soil, we examined two rotations (corn-corn and corn-soybeans); two tillage practices (conventional and no-till); two sources of nitrogen (inorganic fertilizer and inorganic fertilizer + animal manure); two application methods (surface and inject/incorporate); two timing choices (fall and spring growing season); and two application rates (agronomic rate and overapplication). In total, 64 different scenarios were modeled for each soil (512 scenarios in all).

To evaluate these systems, some basic assumptions are made to simplify the evaluation process, which is very complex due to the nature of the nitrogen cycle and management interactions with environmental factors (Shaffer and Delgado 2001).

Nitrogen Inputs and Uptake

Nitrogen fertilizer inputs and crop yields are critical inputs to NLEAP. They determine the amount of nitrogen entering the system and how much is removed from the system at harvest. The nitrogen remaining in crop residue, soil profile, and soil nitrogen pools is available for cycling to air or water. We assume an agronomic nitrogen application rate that supplies just enough nitrogen to meet expected yields, given unavoidable losses in the soil.

Table 3. Variable Cost per Acre of Management Practices

Management Choice	Commercial N Only		Commercial N and Manure	
	Cost (per acre)*	Pr > t	Cost (per acre)	Pr > t
Continuous corn	131.23	.0001	165.63	.1330
Rotation with soybeans	124.02		158.06	
Conventional tillage	128.79	.1554	162.94	.6671
Reduce/no-till	126.46		160.75	
Fall/broadcast	127.84	.0582	158.89	.1587
Fall/incorporate	128.39	.0557	155.25	.1867
Spring/broadcast	132.54	.0001	158.53	.2078
Spring/incorporate	121.74		174.70	
No irrigate	133.33	.0009	164.11	.7292
Irrigate	121.92		159.58	
No HEL	124.92	.0088	157.98	.2013
HEL	130.34		165.71	
No N inhibitor	125.34	.0832	153.80	.0441
N Inhibitor	129.92		169.88	
No conservation cropping	131.83	.0004	163.25	.6278
Conservation cropping	123.42		160.44	
No nutrient plan	127.87	.8475	157.63	.1461
Nutrient plan	127.39		166.06	
No variable rate technology	125.45	.1522	155.39	.2945
Variable rate technology	129.81		168.30	
No tiles	128.79	.2095	168.02	.0366
Tiles	126.46		155.67	

* Values are Least Square Means with Tukey-Kramer adjustment for multiple comparisons.
Data from 2001 corn ARMS survey.

We used state average yields for corn and soybeans derived from the USDA Census of Agriculture, rather than maximum expected yields. For agronomic nitrogen application rates, we used the recommended best management practices for site-specific state and/or soil as described by Espinoza and Ross (2008) for Arkansas; Alley et al. (2009) for Virginia; Beegle and Durst (2003) for Pennsylvania; and Vitosh et al. (1995) for Ohio.

For no-till systems, we had to account for two factors that influence agronomic nitrogen application rates. First, we assumed that yields under no-till are about 10 percent less than under con-

ventional tillage (Ma et al. 2007, Halvorson et al. 2006). This leads us to simulate a lower N application rate, which is based on yields. In addition, since a similar rate of uptake per unit of bushel was used for both systems, the removal of nitrogen in harvested grain from the no-till system is also lower than the removal of nitrogen in the grain from the higher-yield conventional system. This implies a larger carryover of nitrogen for succeeding crops in the residue, which an agronomic application rate would have to account for. Initial surface residue cover was simulated at 100 percent, 90 percent, 40 percent, and 30 percent for

Table 4. Nitrogen Application Rates per Acre by Management Practice

Management Choice	Commercial N Only		Commercial N and Manure	
	Pounds per Acre*	Pr > t	Pounds per Acre	Pr > t
Continuous corn	136.24	.1544	218.36	.0420
Rotation with soybeans	139.79		191.65	
Conventional tillage	136.99	.3583	201.89	.6433
Reduce/no-till	139.05		208.12	
Fall/broadcast	142.74	.0001	191.09	.8382
Fall/incorporate	140.70	.0042	201.51	.9950
Spring/broadcast	140.07	.0001	219.80	.9428
Spring/incorporate	128.56		207.62	
No irrigate	129.30	.0002	210.00	.7692
Irrigate	146.74		200.01	
No HEL	138.77	.5955	221.64	.0353
HEL	137.27		188.37	
No N inhibitor	134.90	.0847	189.42	.1354
N Inhibitor	141.14		220.59	
No conservation cropping	143.16	.0017	174.93	.0001
Conservation cropping	132.88		235.08	
No nutrient plan	137.13	.6002	197.07	.2950
Nutrient plan	138.91		212.94	
No variable rate technology	138.05	.9899	224.52	.3175
Variable rate technology	138.00		185.50	
No tiles	138.89	.4957	214.11	.2384
Tiles	137.16		195.90	

*Values are Least Square Means with Tukey-Kramer adjustment for multiple comparisons.
Data from 2001 corn ARMS survey.

no-till corn-corn, no-till corn-soybeans, conventional corn-corn, and conventional corn-soybeans, respectively.

For the manure system, manure was applied every 2 years. For the corn-corn rotation, manure was applied in the first year, and only commercial fertilizer was applied in the second year. The manure rate was calculated for each system to match the fertilizer rate. However, since manures have a large fraction of organic nitrogen that is not immediately available (Davis, Iversen, and Vigil 2002, Eghball et al. 2002), an additional 50 percent of the recommended rate was added as inorganic nitrogen fertilizer. In other words, the total nitrogen input during the first year of corn-

corn rotation was 150 percent of the total application rate of the inorganic nitrogen fertilizer scenario (Table 1). This is consistent with a recommendation that manure applications be supplemented with commercial fertilizer to insure growing crops receive sufficient nitrogen (Iowa Soybean Association 2008). The corn-corn rotation did not receive any manure application in the second year, and the corn received the same rate of nitrogen fertilizer as in the nitrogen-fertilizer-only scenario. Thus, over the two-year period, the manure scenario for corn-corn received an average 25 percent more nitrogen input per year.

The corn-soybean rotation did not receive any nitrogen fertilizer or manure during the soybean

year (Table 1). Additionally, nitrogen cycling from the leguminous soybean crop was credited, as is recommended for each state, so the calculated nitrogen inputs for the corn in the corn-soybean rotation were lower than in the corn-corn system.

The yield effect of excessive nitrogen application rates was derived from the corn yield and nitrogen input response curve from Bock and Hergert (1991). For this study, we defined over-application as 75 percent more than the recommended, agronomic-based rate. This is at the upper limits of application rates for corn observed in the ARMS data. Based on Bock and Hergert (1991), we assumed that overapplication increased yields by only 1 percent. We believe that our approach of using average yields to evaluate the effects of management on the nitrogen use efficiency of commercial systems is a valid one, as reported by Shaffer and Delgado (2001), Delgado (2001), Delgado, Follett, and Shaffer (2000), and Delgado et al. (2001). A summary of the nitrogen inputs we used in the NLEAP scenarios is presented in Table 2. Differences in yields were valued at \$4.50 per bushel.

Long-Term Evaluations

All scenarios were evaluated with NLEAP over the long term to arrive at average annual losses of nitrogen compounds from the field. The NLEAP model was run for a 24-year period, using long-term weather data for the given county. The first 12 years were used to reach an equilibrium, and years 13 to 24 were used to evaluate the effect of management practices on nitrogen use efficiency and on reactive losses to the environment (Delgado et al. 2010, Delgado et al. 2008).

Costs

Changing management practices to reduce N₂O emissions can entail costs for a farmer, in terms of changes in production costs and yields. We used data from the 2001 corn ARMS survey to estimate average per-acre production costs for farms with different sets of management practices². We assumed that differences in management costs represented the long-term costs of shifting from

one set of management practices to another. We assumed farmers would maintain the same basic cropping system (crop rotation and tillage), only altering timing, method, or application rate to improve nitrogen use efficiency and reduce N₂O emissions.

Total variable costs (TVC) were defined as the costs of seed, fertilizer, manure, pesticides, custom work, and fuel lubricants. We specified a model of TVC as a function of the following variables:

- 1) Use of Bt or herbicide resistant corn
- 2) Use of rotation with soybeans
- 3) Use of nitrogen inhibitor
- 4) Tillage (conventional till vs. reduced/no till)
- 5) Timing (fall vs. spring application)
- 6) Method (broadcast vs. inject/incorporate)
- 7) Conservation cropping (contour or strip)
- 8) Presence of nutrient management plan
- 9) Use of variable rate technology
- 10) Presence of irrigation
- 11) Presence of HEL soils (yes or no)
- 12) Presence of tile drains
- 13) Growing season (northern tier, middle tier, southern tier)
- 14) Farm size (total corn acres on farm)
- 15) Yield goal

An interaction term for timing and method (fall/no fall–incorporate/broadcast) was also included. The cost model was run separately for those farms that do not use manure and for those farms that use both manure and commercial fertilizer. About 16 percent of U.S. corn acres receive manure.

Since most of the variables are class variables, we used the SAS General Linear Model procedure (GLM) to estimate the model. The R-Squares of the no manure and manure cost models are 0.21 and 0.16 respectively, and the models are significant at the 1 percent level. The majority of the explanatory variables are statistically significant at the 5 percent level. Least-square means of the production costs (\$/acre) under the different management systems are presented in Table 3, along with an indication of whether the difference is statistically significant. Of interest to this study is that the cost under the preferred method/timing combination (spring/incorporate) is significantly lower than the costs under the less-preferred, alternative combinations

² The 2001 corn survey had field level production costs associated with each observation. This was not the case for the 2005 corn ARMS survey.

(at the 5 percent and 10 percent levels) for those farms that use only commercial fertilizer (84 percent of treated corn acres). No significant differences in costs were found for farms that use both manure and commercial fertilizer.

Part of the difference in costs observed with the ARMS data are due to differences in chemical application rates. Since the NLEAP scenarios assumed the management changes were independent, altering the rate, timing, and method in different combinations, we needed to separate out the nitrogen fertilizer cost from the total of changing management. We ran the same models, but with nitrogen application rate as the dependent variable. Both the models were significant, with R-squares of 0.23 and 0.24. Differences in application rates between the spring/inject and the other management combinations were positive (as expected) and significant at the 1 percent level for farms using only commercial fertilizer (Table 4). The difference in nitrogen fertilizer costs was subtracted from the cost difference derived from the cost model, using a nitrogen fertilizer price of \$0.30/lb.

The cost of adopting the appropriate method (assuming no change in the fertilizer application rate) was estimated to be \$7.35/acre, appropriate timing \$3.01 per acre, and both appropriate method and timing \$1.86/acre. For farms using manure, we assumed no differences in costs.

Each of the 512 NLEAP scenarios was treated as the baseline for a model farm. We used the NLEAP results and the cost estimates to identify the management option (reduced rate, improved timing, or improved application method) that reduced nitrous oxide emissions at least net cost for each baseline scenario, while meeting a requirement that total nitrogen emissions (the sum of $\text{NO}_3\text{-N}$, $\text{N}_2\text{O-N}$, and $\text{NH}_3\text{-N}$ losses) did not increase. We then used the NLEAP model results to estimate the economic return from selling offsets for a price of \$15 per ton/ CO_2 equivalent (based on EPA analysis of the American Clean Energy and Security Act of 2009, H.R. 2454).

Results and Discussion

Table 5 summarizes which nitrogen management systems the model farmers would adopt in order to produce credits at least cost, given baseline practices and soils. For example, of the 64 farm types not meeting any of the three criteria in the

baseline (“None” in the Baseline criteria column), 17 would reduce application rate to the criterion rate, 10 would reduce rate and inject/incorporate, 1 would reduce rate and spring apply, and 36 would adopt all three management choices. The choice depends on the soil type, climate, rotation, tillage practice, and nitrogen source.

The results highlight the importance of meeting the application rate criterion for reducing both N_2O and total reactive nitrogen. For all farms not meeting the rate criterion in the baseline, reducing the application rate, either alone or in combination with another practice, was selected to reduce N_2O . Method or timing was never the sole practice adopted by farms to reduce N_2O emissions. The modeling also indicates that 148 of the 512 farming systems will not be able to reduce N_2O emissions by meeting the rate, timing, or method criteria. For example, none of the 64 farm types meeting the rate and method criteria in the baseline can reduce N_2O emissions by also meeting the timing criterion.

Table 6 provides more detail for one soil in Ohio. It shows the reduction in N_2O that would be generated for each decision a farmer in a particular baseline situation would make, and offset revenue earned assuming a carbon price of \$15 per ton of CO_2 equivalent. The range of N_2O reductions presented here is similar to those found in the other soils modeled with NLEAP.

Even though our sample of cropping conditions is very small, we believe we can still make some general inferences from the results. We found that if in the baseline system our criterion application rate is exceeded, the application rate will be reduced to produce offsets, either alone or in combination with timing or method; reducing the application rate is generally the most cost-effective means of reducing N_2O emissions. This is consistent with the findings in the literature concerning the importance of the application rate in addressing nitrous oxide emissions (Kim and Dale 2008, Millar et al. 2010). Adopting method and/or timing BMPs either cannot reduce N_2O emissions or can do so only by reducing overall nitrogen use efficiency, which is not permitted under our simulated market rules.

Farms already meeting both the rate and method criteria will only be able to reduce N_2O emissions by reducing their application rate below recommended rates. We explored this further by using NLEAP to assess potential reductions in

Table 5. Least-Cost N Management Systems in Corn Production for Reducing N₂O Emissions for 512 Model Farms, Assuming a Credit Price of \$15 per Ton of CO₂ Equivalent, Based on NLEAP Modeling

Criteria ¹ Met after Changing Management	Method	Rate	Timing	Rate and Method	Rate and Timing	Timing and Method	Rate, Timing, and Method	Total Model Farms
Number of Model Farms								
Criteria ¹ Met in Baseline								
None		17		10	1		36	64
Method		16		17	3		28	64
Rate		19		42			3	64
Timing					63		1	64
Rate and Method				64				64
Rate and Timing		3		23	1		37	64
Timing and Method				31			33	64
Rate, Timing, and Method							64	64

¹Criteria are appropriate rate, timing, and method of nitrogen application.

Note: There are a total of 512 cropping systems evaluated with NLEAP, 128 in each of Arkansas, Ohio, Pennsylvania, and Virginia. Each system defines a soil type (A or D), a rotation (continuous corn, corn soybeans), tillage practice (conventional, no-till), nutrient source (inorganic, manure+inorganic), timing of application (before planting, at/after planting), method (inject/incorporate, broadcast) and application rate (meet criterion, 75 percent over criterion).

nitrous oxide from reducing application rates below the recommended rate by 25 percent. Based on the nitrogen-yield response curve of Bock and Hergert (1991), a 25 percent reduction in nitrogen was assumed to reduce yields by 10 percent. The NLEAP modeling indicates only small reductions in N₂O when the application rate is reduced to below the criterion rate. This is consistent with field studies that indicate a non-linear relationship between excessive N application rates and N₂O emissions (Jarecki et al. 2009, McSwiney and Robertson 2002). For example, reducing the application rate from the criterion rate to 25 percent below the recommended

rate only reduces N₂O by between 0.2 pounds and 1.3 pounds per acre for the Class A (well-drained) soil in Ohio, depending on the cropping system. Assuming a credit rate of \$15 per ton CO₂ equivalent, this translates into a payment of between \$0.46 and \$3.02 per acre. These rates are insufficient to cover the reduction in corn yields. Even for smaller N reductions, it is unlikely that revenue from GHG offsets would be sufficient to cover the increased yield risk from cutting N application rates. However, higher offset prices could increase the incentive to cut application rates to reduce N₂O emissions, even when yields might be reduced.

Table 6. How a Corn Farm Producer May Change N Management Practices to Participate in a Market for N₂O GHG Emissions with a Credit Payment of \$15/ton CO₂ Equivalent, for a Model Ohio Farm on Ottoke Soil

Baseline Practice	Practices after N ₂ O Credit Offered	N ₂ O Reduction (lbs. per acre)	Credit Revenue (\$/acre)
CC-CON-MF			
M	RTM	0.9	2.09
RM	NO CHANGE	0	0
R	RM	0.3	0.70
RTM	NO CHANGE	0	0
RT	RM	3.4	7.90
TM	RT	3.0	6.98
T	RT	4.4	10.23
NONE	RTM	0.8	1.86
CC-CON-OF			
M	RTM	0.3	0.70
RM	NO CHANGE	0	0
R	RM	0.6	1.40
RTM	NO CHANGE	0	0
RT	RTM	2.7	6.28
TM	RT	0.9	2.09
T	RT	3.1	7.21
NONE	RTM	0.8	1.86
CC-NT-MF			
M	RTM	0.2	0.46
RM	NO CHANGE	0	0
R	NO CHANGE	0	0
RTM	NO CHANGE	0	0
RT	RTM	0.5	1.16
TM	RT	3.3	7.67
T	RT	2.8	6.51
NONE	RM	0.9	2.09
CC-NT-OF			
M	R	1.1	2.58
RM	NO CHANGE	0	0
R	RM	0.2	0.46
RTM	NO CHANGE	0	0
RT	RTM	1.7	3.95
TM	RT	1.4	3.26
T	RT	2.8	6.51

Table 6 (continued)

	NONE	R	0.9	2.09
CS-CON-MF				
	M	RTM	0.6	1.40
	RM	NO CHANGE	0	0
	R	RM	0.2	0.46
	RTM	NO CHANGE	0	0
	RT	RM	1.3	3.02
	TM	RT	1.6	3.72
	T	RT	1.7	3.95
	NONE	RTM	0.2	0.46
CS-CON-OF				
	M	RTM	0.2	0.46
	RM	NO CHANGE	0	0
	R	RM	0.3	0.70
	RTM	NO CHANGE	0	0
	RT	RTM	1.2	2.79
	TM	RTM	1.1	2.56
	T	RT	1.2	2.79
	NONE	RTM	0.5	1.16
CS-NT-MF				
	M	RT	0.2	0.46
	RM	NO CHANGE	0	0
	R	NO CHANGE	0	0
	RTM	NO CHANGE	0	0
	RT	RM	0.8	1.86
	TM	RT	1.4	3.26
	T	RT	1.4	3.26
	NONE	RM	0.5	1.16
CS-NT-OF				
	M	R	0.2	0.46
	RM	NO CHANGE	0	0
	R	RM	0.2	0.46
	RTM	NO CHANGE	0	0
	RT	RTM	1.3	3.02
	TM	RTM	1.1	2.56
	T	RT	1.4	3.26
	NONE	R	0.5	1.16

Note: CC=continuous corn, CS=corn-soybeans, CON=conventional till, NT=no-till, MF=manure+inorganic N, OF=inorganic N, M=N incorporated/injected, R=recommended rate, T=spring application.

When we apply these results to the survey data summarized in Table 1, we could conclude that treated corn acres meeting the rate, timing, and method criteria or the rate and method criteria (about 42 percent of all corn acres) will not likely participate in a GHG cap and trade program that would allow farmers to sell offsets from N₂O reductions. These farms cannot make any management changes to reduce N₂O without reducing overall nitrogen use efficiency, which would violate a market rule. The treatment of these prior adopters (often called “good stewards”) in an emissions trading program is an important policy issue.

Another finding is that the potential revenue from GHG offsets produced by reducing N₂O appears to be quite small. In our Ohio example, only a few situations are capable of producing credit revenue of over \$5.00 per acre, assuming a credit price of \$15 per ton of CO₂ equivalent (and the results are similar for the other states we studied). These rates are less than those farmers could receive for nutrient management from EQIP, which is a measure of what farmers are willing to accept for the practice (program data for the Environmental Quality Incentive Program, 1997-2008). In general, farms overapplying nitrogen and broadcasting fertilizer can produce the largest reductions in N₂O. However, only 8.3 percent of corn acres fell in this category in 2005. While we found that changes in operating costs after changing management are near 0 or even negative in most cases, we did not consider short-term adjustment costs, changes in risk, or the administrative costs of participating in an offset program.

One of the issues we investigated is the possibility that reducing N₂O could increase nitrate losses to water. It might seem that allowing only management changes that do not increase total losses of nitrogen would prevent this, but we found otherwise. In 25 percent of the cases where management changes were made to reduce N₂O, NO₃ losses to water increased, even though total nitrogen emissions fell. This occurred almost exclusively when the rate criterion was already being met and injection/incorporation was adopted as an additional practice. While overall N₂O and total nitrogen losses decreased, water quality was made worse. Such an outcome would be a concern in regions trying to address important water quality problems, such as the Gulf of

Mexico, where corn production is a major source of nitrogen at the root of the hypoxia problem (Goolsby et al. 2001). An offset program may address this issue by recognizing the creation of offsets only from reduced nitrogen application rates.

An important factor in assessing farmers’ response to a GHG market is that carbon sequestration also generates offsets. Long-term no-till is generally the practice that sequesters carbon without converting cropland to some other use, such as trees. If adopting no-till also reduces N₂O emissions, then farmers would benefit from producing both carbon sequestration and N₂O reductions for a market. Results from the NLEAP modeling indicate that switching from conventional tillage systems to less intensive, reduced tillage systems, without making any other changes to nitrogen management other than adjusting the application rate if expected yield changes, generally reduces N₂O emissions on fine-grained soils (hydrologic class D). However, N₂O emissions on well-drained soils (hydrologic class A) increase. In cases where switching to less intensive no-till systems does not produce N₂O reductions, a farmer must decide which approach produces the greatest economic benefit. For farmers already using no-till prior to a trading program, N₂O reductions may be the only option available to reduce emissions.

A Note on New, Advanced Fertilizers

Since N₂O emissions are produced via the biological reactions of nitrification and denitrification, new fertilizers such as controlled-release fertilizers and nitrification inhibitors have become available. These fertilizers have been proven to slow these biogeochemical reactions. Slowing the conversion of NH₃ or NH₄ (nitrogen inputs) to the nitrate form of N significantly reduces the emissions of N₂O (Delgado and Mosier 1996, Minami 1994). These new fertilizers can also slow the rate of losses via other pathways, such as leaching, and contribute to the synchronization of nitrogen inputs with nitrogen uptake without reducing yields. For example, Shoji et al. (2001) were able to use about 50 percent of the commercial nitrogen fertilizer rate without reducing total potato tuber yields in Colorado. Additionally, other amendments such as nitrification inhibitors could

also slow down these reactions and contribute to lower N₂O emissions (Bronson and Mosier 1993, Minami 1994, Delgado and Mosier 1996). NLEAP can be used to simulate the effects of these new types of fertilizers. One factor to consider is that these new fertilizers have a higher cost than the traditional urea fertilizer. Since these fertilizers are not currently used in a large percentage of the area in corn, we did not analyze them in this scenario.

Summary

A market for greenhouse gases could provide an incentive to reduce nitrous oxide emissions from cropland. Our findings suggest that not all farms will benefit from a market for N₂O reductions. Those already meeting rate, timing, and method criteria for good nitrogen management, and those meeting rate and method criteria, cannot make any improvements to nitrogen management that reduce N₂O without increasing total nitrogen emissions, except by reducing the application rate below the recommended rate or by switching to crops that use less nitrogen. Over 40 percent of corn acres fit in these categories. However, to reduce nitrogen application rates below recommended levels would not make economic sense unless the credit price was much higher than the \$15 per ton CO₂ equivalent we assumed.

Our findings are also relevant for any program that pays farmers to reduce nitrous oxide emissions. Our findings also point out the importance of considering the entire nitrogen cycle when targeting one particular nitrogen compound. Altering management practices to reduce N₂O emissions could increase the loss of NO₃ to water resources through increased leaching to groundwater and subsurface flow to surface water. In regions trying to deal with nutrient enrichment to water resources, increased nitrate losses would not be welcome. A trading program could address this problem by restricting the types of practices that could be used to reduce N₂O emissions. Based on our findings, reduced application rates provide the best opportunity to reduce N₂O emissions and NO₃ losses.

This research is an initial look at the implications of a financial incentive approach to reducing nitrous oxide emissions from corn production. Additional research that is more representative of corn production in the United States, and that

considers the cost of increased yield variability that reduced application rates, advanced fertilizers (controlled-release fertilizers, nitrification inhibitors, etc.), and/or advanced management techniques such as remote sensing and split nitrogen applications are likely to bring, is a logical next step.

References

- Alley, M.M., M.E. Martz, Jr., P.H. Davis, and J.L. Hammons. 2009. *Nitrogen and Phosphorus Fertilization of Corn*. Virginia Cooperative Extension, Virginia Polytechnic Institute and State University, Blacksburg, Virginia.
- Alva, A.K., S. Paramasivam, A. Fares, J.A. Delgado, D. Mattos, Jr, and K. Sajwan. 2006. "Nitrogen and Irrigation Management Practices to Improve Nitrogen Uptake Efficiency and Minimize Leaching Losses." *Journal of Crop Improvement* 15(2): 369-420.
- Baker, J.L. 2001. "Limitations of Improved Nitrogen Management to Reduce Nitrate Leaching and Increase Use Efficiency." *TheScientificWorldJOURNAL* 1(Suppl 2): 10-16.
- Bausch, W.C., and J.A. Delgado. 2003. "Ground-Based Sensing of Plant Nitrogen Status in Irrigated Corn to Improve Nitrogen Management." In T. VanToai, D. Major, M. McDonald, J. Schepers, and L. Tarpley, eds., *Digital Imaging and Spectral Techniques: Applications to Precision Agriculture and Crop Physiology*. Madison, WI: ASA, CSSA, and SSSA.
- Beckie, H.J., A.P. Moulin, C.A. Campbell, and S.A. Brandt. 1995. "Testing Effectiveness of Four Simulation Models for Estimating Nitrates and Water in Two Soils." *Canadian Journal of Soil Science* 75(1): 135-143.
- Beegle, D.B., and P.T. Durst. 2003. *Nitrogen Fertilization of Corn*. College of Agricultural Science Cooperative Extension, The Pennsylvania State University, University Park.
- Bock, B.R., and W. Hergert. 1991. "Fertilizer Nitrogen Management." R.F. Follett, D.R. Kenney and R.M. Cruse, eds., *Managing Nitrogen for Groundwater Quality and Farm Profitability: Proceedings of a Symposium*. Madison, WI: Soil Science Society of America.
- Bouwman, A.F., L.J.M. Boumans, and N.H. Batjes. 2002. "Emissions of N₂O and NO from Fertilized Fields: Summary of Available Measurement Data." *Global Biogeochemical Cycles* 16(4): 1058-1070.
- Bronson, K.F., and A.R. Mosier. 1993. "Nitrous Oxide Emissions and Methane Consumption in Wheat and Corn-Cropped Systems in Northeastern Colorado." In L.A. Harper, A.R. Mosier, J.M. Duxbury, and D.E. Rolston, eds., *Agricultural Ecosystems Effects on Trace Gases and Global Climate Change*. Madison, WI: ASA.
- Cassman, K.G., A. Dobermann, and D.T. Walters. 2002. "Agroecosystems, Nitrogen-Use Efficiency, and Nitrogen Management." *Ambio* 31(2): 132-140.
- Davis, J.G., K.V. Iversen, and M.F. Vigil. 2002. "Nutrient Variability in Manures: Implications for Sampling and Regional Database Creation." *Journal of Soil and Water Conservation* 57(6): 473-478.
- Delgado, J.A. 2001. "Use of Simulations for Evaluation of Best Management Practices on Irrigated Cropping Systems." In M.J. Shaffer, L. Ma, and S. Hansen, eds., *Modeling Carbon and Nitrogen Dynamics for Soil Management*. Boca Raton, FL: Lewis Publishers.

- Delgado, J.A., and W.C. Bausch. 2005. "Potential Use of Precision Conservation Techniques to Reduce Nitrate Leaching in Irrigated Crops." *Journal of Soil and Water Conservation* 60(6): 379-387.
- Delgado, J.A., R.F. Follett, and M.J. Shaffer. 2000. "Simulation of Nitrate-Nitrogen Dynamics for Cropping Systems with Different Rooting Depths." *Soil Science Society of America Journal* 64(3): 1050-1054.
- Delgado, J.A., C.M. Gross, H. Lal, H. Cover, P. Gagliardi, S.P. McKinney, E. Hesketh, and M.J. Shaffer. 2010. "A New GIS Nitrogen Trading Tool Concept for Conservation and Reduction of Reactive Nitrogen Losses to the Environment." In D.L. Sparks, ed., *Advances in Agronomy, Vol. 105*. San Diego: Academic Press.
- Delgado, J.A., and A.R. Mosier. 1996. "Mitigation Alternatives to Decrease Nitrous Oxides Emissions and Urea-Nitrogen Loss and their Effect on Methane Flux." *Journal of Environmental Quality* 25(5): 1105-1111.
- Delgado, J.A., A.R. Mosier, R.H. Follett, R.F. Follett, D.G. Westfall, L.K. Klemmedtsson, and J. Vermeulen. 1996. "Effects of N management on N₂O and CH₄ fluxes and ¹⁵N." *Nutrient Cycling in Agroecosystems* 46(2): 127-134.
- Delgado, J.A., R.J. Ristau, M.A. Dillon, H.R. Duke, A. Stuebe, R.F. Follett, M.J. Shaffer, R.R. Riggenbach, R.T. Sparks, A. Thompson, L.M. Kawanabe, A. Kunugi, and K. Thompson. 2001. "Use of Innovative Tools to Increase Nitrogen Use Efficiency and Protect Environmental Quality in Crop Rotations." *Communications in Soil Science and Plant Analysis* 32(7-8): 1321-1354.
- Delgado, J.A., M.J. Shaffer, H. Lal, S.P. McKinney, C.M. Gross, and H. Cover. 2008. "Assessment of Nitrogen Losses to the Environment with a Nitrogen Trading Tool (NTT)." *Computers and Electronics in Agriculture* 63(2): 193-206.
- Doerge, T.A., R.L. Roth, and B.R. Gardner (eds.). 1991. *Nitrogen Fertilizer Management in Arizona*. Tucson, AZ: College of Agriculture, University of Arizona.
- Drury, C.F., W.D. Reynolds, C.S. Tan, T.W. Welacky, W. Calder, and N.B. McLaughlin. 2006. "Emissions of Nitrous Oxide and Carbon Dioxide: Influence of Tillage Type and Nitrogen Placement Depth." *Soil Science Society of America Journal* 70(2): 570-581.
- Eghball, B., B.J. Wienhold, J.E. Gilley, and R.A. Eigenberg. 2002. "Mineralization of Manure Nutrients." *Journal of Soil and Water Conservation* 57(6): 470-473.
- Espinoza, L., and J. Ross. 2008. Fertilizer and Liming. In L. Espinoza and J. Ross, eds., *Corn Production Handbook*. Little Rock, AR: University of Arkansas, Cooperative Extension Service.
- Flessa, H., and F. Beese. 2000. "Laboratory Estimates of Trace Gas Emissions following Surface Application and Injection of Cattle Slurry." *Journal of Environmental Quality* 29(1): 262-268.
- Fox, R.H., W.P. Piekielek, and K.E. Macneal. 1996. "Estimating Ammonia Volatilization Losses from Urea Fertilizers Using a Simplified Micrometeorological Sampler." *Soil Science Society of America Journal* 60(2): 596-601.
- Freney, J.R., J.R. Simpson, and O.T. Denmead. 1981. "Ammonia Volatilization." *Ecological Bulletin* 33: 291-302.
- Galloway, J.N., A.R. Townsend, J.W. Erisman, M. Bekunda, Z. Cai, J.R. Freney, L.A. Martinelli, S.P. Seitzinger, and M.A. Sutton. 2008. "Transformation of the Nitrogen Cycle: Recent Trends, Questions, and Potential Solutions." *Science* 320(5878): 889-892.
- Goolsby, D.A., W.A. Battaglin, B.T. Aulenbach, and R.P. Hooper. 2001. "Nitrogen Input to the Gulf of Mexico." *Journal of Environmental Quality* 30(2): 329-336.
- Halvorson, A.D., A.R. Mosier, C.A. Reule, and W.C. Bausch. 2006. "Nitrogen and Tillage Effects on Irrigated Continuous Corn Yields." *Agronomy Journal* 98(1): 63-71.
- Hao, X., C. Chang, J.M. Carefoot, H.H. Janzen, and B.H. Ellert. 2001. "Nitrous Oxide Emissions from an Irrigated Soil as Affected by Fertilizer and Straw Management." *Nutrient Cycling in Agroecosystems* 60(1): 1-8.
- Hernandez-Ramirez, G., S.M. Brouder, D.R. Smith, and G.E. Van Scoyoc. 2009. "Greenhouse Gas Fluxes in an Eastern Corn Belt Soil: Weather, Nitrogen Source, and Rotation." *Journal of Environmental Quality* 38(3): 841-854.
- 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, ADF#19990028, Saskatchewan Department of Agriculture and Food, Regina, Saskatchewan, Canada.
- Hyde, B.P., M.J. Hawkins, A.F. Fanning, D. Noonan, M. Ryan, P. O'Toole, and O.T. Carton. 2006. "Nitrous Oxide Emissions from a Fertilized and Grazed Grassland in the South East of Ireland." *Nutrient Cycling in Agroecosystems* 75(1-3): 187-200.
- Iowa Soybean Association. 2008. "Manure Plus 50 Trials Suggest Benefits from Additional Nitrogen Fertilizer." *On-Farm Network Update* (April): 7.
- Jarecki, M.K., T.B. Parkin, A.S.K. Chan, T.C. Kaspar, T.B. Moorman, J.W. Singer, B.J. Kerr, J.L. Hatfield, and R. Jones. 2009. "Cover Crop Effects on Nitrous Oxide Emission from a Manure-treated Mollisol." *Agriculture, Ecosystems and Environment* 134(1-2): 29-35.
- Kim, S., and B.E. Dale. 2008. "Effects of Nitrogen Fertilizer Application on Greenhouse Gas Emissions and Economics of Corn Production." *Environmental Science & Technology* 42(16): 6028-6033.
- Liu, X.J., A.R. Mosier, A.D. Halvorson, and F.S. Zhang. 2006. "The Impact of Nitrogen Placement and Tillage on NO, N₂O, CH₄ and CO₂ Fluxes from a Clay Loam Soil." *Plant and Soil* 280(1-2): 177-188.
- Ma, L., R.W. Malone, P. Heilman, D.B. Jaynes, L.R. Ahuja, S.A. Saseendran, R.S. Kanwar, and J.C. II Ascough. 2007. "RXWQM Simulated Effects of Crop Rotation, Tillage, and Controlled Drainage on Crop Yield and Nitrate-N Loss in Drain Flow." *Geoderma* 140: 260-271.
- Malhi, S.S., and M. Nyborg. 1991. "Recovery of ¹⁵N-labelled Urea: Influence of Zero Tillage, and Time and Method of Application." *Fertilizer Research* 28(3): 263-269.
- McSwiney, C.P., and G.P. Robertson. 2005. "Nonlinear Response of N₂O Flux to Incremental Fertilizer Addition in a Continuous Maize (*Zea mays* L.) Cropping System." *Global Change Biology* 11(10): 1712-1719.
- Meisenger, J.J., and G.W. Randall. 1991. "Estimating N Budgets for Soil-Crop Systems." In R.F. Follet, ed., *Managing Nitrogen for Groundwater Quality and Farm Productivity*. Madison, WI: American Society of Agronomy.
- Meisenger, J.J., J.S. Schepers, and W.R. Raun. 2008. "Crop Nitrogen Requirement and Fertilization." In J.S. Schepers and W.R. Raun, eds., *Nitrogen in Agricultural Systems*. Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.
- Meisinger, J.J., and J.A. Delgado. 2002. "Principles for Managing Nitrogen Leaching." *Journal of Soil and Water Conservation* 57(6): 485-498.

- Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl, and J.P. Hoben. 2010. "Nitrogen Fertilizer Management for Nitrous Oxide (N₂O) Mitigation in Intensive Corn (Maize) Production: An Emissions Reduction Protocol for U.S. Midwest Agriculture." *Mitigation and Adaptation Strategies for Global Change* 15(2):185-204.
- Minami, K. 1994. "Effect of Nitrification Inhibitors and Slow-Release Fertilizer on Emissions of Nitrous Oxide from Fertilized Soils." In K. Minami, A.R. Mosier and R. Sass, eds., *CH₄ and N₂O Global Emissions and Controls from Rice Fields and Other Agricultural and Industrial Sources*. Tsukuba, Japan: National Institute of Agro-Environmental Sciences.
- Peoples, M.B., A.R. Mosier, and J.R. Freney. 1995. "Minimizing Gaseous Losses of Nitrogen." In P.E. Bacon, ed., *Nitrogen Fertilization in the Environment*. New York, NY: Marcel Dekker, Inc.
- Power, J.F., R. Wiese, and D. Flowerday. 2001. "Managing Farming Systems for Nitrate Control: A Research Review from Management Systems Evaluation Areas." *Journal of Environmental Quality* 30(6): 1866-1880.
- Ravishankara, A.R., J.S. Daniel, and R.W. Portmann. 2009. "Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century." *Science* 326(5949): 123-125.
- Ribaldo, M., L. Hansen, D. Hellerstein, and C. Greene. 2008. *The Use of Markets to Increase Private Investment in Environmental Stewardship*. Economic Research Report 64, USDA/Economic Research Service, Washington, D.C.
- Ribaldo, M., R.D. Horan, and M.E. Smith. 1999. *Economics of Water Quality Protection from Nonpoint Sources: Theory and Practice*. Agricultural Economic Report 782, USDA/Economic Research Service, Washington, D.C.
- Robertson, G.P., and P. Groffman. 2007. "Nitrogen Transformations." In E.A. Paul, ed., *Soil Microbiology, Ecology, and Biochemistry*. New York: Academic/Elsevier.
- Rochette, P., D.A. Angers, M.H. Chantigny, N. Bertrand, and D. Côté. 2004. "Carbon Dioxide and Nitrous Oxide Emissions following Fall and Spring Applications of Pig Slurry to an Agricultural Soil." *Soil Science Society of America Journal* 68(4): 1410-1420.
- Ruser, R., H. Flessa, R. Schilling, H. Steindl, and F. Beese. 1998. "Soil Compaction and Fertilization Effects on Nitrous Oxide and Methane Fluxes in Potato Fields." *Soil Science Society of America Journal* 62(6): 1587-1595.
- Schlegel, A.J., K.C. Dhuyvetter, and J.L. Havlin. 1996. "Economic and Environmental Impacts of Long-term Nitrogen and Phosphorus Fertilization." *Journal of Production Agriculture* 9(1): 114-118.
- Shaffer, M.J., and J.A. Delgado. 2001. "Field Techniques for Modeling Nitrogen Management." In R.F. Follet and J.L. Hatfield, eds., *Nitrogen in the Environment: Sources, Problems, and Management*. New York: Elsevier Science B.V.
- Shaffer, M.J., J.A. Delgado, C. Gross, R.F. Follet, and P. Gagliardi. 2010. "Simulation Processes for the Nitrogen Loss and Environmental Assessment Package (NLEAP)." In J.A. Delgado and R.F. Follett, eds., *Advances in Nitrogen Management for Water Quality*. Ankeny, IA: Soil and Water Conservation Society.
- Shoji, S., J. Delgado, A. Mosier, and Y. Miura. 2001. "Use of Controlled Release Fertilizers and Nitrification Inhibitors to Increase Nitrogen Use Efficiency and to Conserve Air and Water Quality." *Communications in Soil Science and Plant Analysis* 32(7-8): 1051-1070.
- Tietenberg, T.H. 2006. *Emissions Trading: Principles and Practice*. Washington, D.C.: Resources for the Future.
- Tilsner, J., N. Wrage, J. Lauf, and G. Gebauer. 2003. "Emission of Gaseous Nitrogen Oxides from an Extensively Managed Grassland in NE Bavaria, Germany. I. Annual Budgets of N₂O and NO_x Emissions." *Biogeochemistry* 63(3): 229-247.
- U.S. Department of Agriculture. 2010. *Assessment of the Effects of Conservation Practices on Cultivated Cropland in the Upper Mississippi Basin*. USDA/Natural Resources Conservation Service, Washington, D.C.
- U.S. Department of Agriculture, Natural Resources Conservation Service. 2006. *Natural Resources Conservation Service Conservation Practice Standard: Nutrient Management*. Washington, D.C.
- U.S. Energy Information Administration. 2009. *Emissions of Greenhouse Gases Report*. U.S. Department of Energy, Washington, D.C.
- U.S. Environmental Protection Agency. 2010. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2008*. EPA 430-R-10-006, Washington, D.C.
- U.S. Environmental Protection Agency. 2010. *Methane and Nitrous Oxide Emissions from Natural Sources*. EPA 430-R-10-001, Office of Atmospheric Programs, Washington, D.C.
- Vanotti, M.B., and L.G. Bundy. 1994. "An Alternative Rationale for Corn Nitrogen Fertilizer Recommendations." *Journal of Production Agriculture* 7(2): 243-249.
- Vitosh, M.L., J.W. Johnson, and D.B. Mengel. 1995. *Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat and Alfalfa*. Extension Bulletin E-2567. Michigan State University, The Ohio State University, and Purdue University. Available at <http://ohioline.osu.edu/e2567/index.html> (accessed June 2010.)
- 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(2-3): 151-163.
- Westermann, D.T., and G.E. Kleinkopf. 1985. "Nitrogen Requirements of Potatoes." *Agronomy Journal* 77: 616-621.
- Westermann, D.T., G.E. Kleinkopf, and L.K. Porter. 1988. "Nitrogen Fertilizer Efficiencies on Potatoes." *American Potato Journal* 65(7): 377-386.
- Wuebbles, D.J. 2009. "Nitrous Oxide: No Laughing Matter." *Science* 326(5949): 56-57.
- Wulf, S., M. Maeting, and J. Clemens. 2002. "Application Technique and Slurry Co-fermentation Effects on Ammonia, Nitrous Oxide, and Methane Emissions after Spreading: I. Ammonia Volatilization." *Journal of Environmental Quality* 31(6): 1789-1794.
- Xu, C., M.J. Shaffer, and M. Al-kaisi. 1998. "Simulating the Impact of Management Practices on Nitrous Oxide Emissions." *Soil Science Society of America Journal* 62(3): 736-742.