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Model estimates of nitrous oxide emissions from agricultural lands in the United States

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Abstract. The Denitrification-Decomposition (DNDC) model was used to elucidate the role of climate, soil properties, and farming practices in determining spatial and temporal variations in the production and emission of nitrous oxide (N_2O) from agriculture in the United States. Sensitivity studies documented possible causes of annual variability in N_2O flux for a simulated Iowa corn-growing soil. The 37 scenarios tested indicated that soil tillage and nitrate pollution in rainfall may be especially significant anthropogenic factors which have increased N_2O emissions from soils in the United States. Feedbacks to climate change and biogeochemical manipulation of agricultural soil reflect complex interactions between the nitrogen and carbon cycles. A 20% increase in annual average temperature in °C produced a 33% increase in N_2O emissions. Manure applications to Iowa corn crops enhanced carbon storage in soils, but also increased N_2O emissions. A DNDC simulation of annual N_2O emissions from all crop and pasture lands in the United States indicated that the value lies in the range 0.9 - 1.2 TgN. Soil tillage and fertilizer use were the most important farming practices contributing to enhanced N_2O emissions at the national scale. Soil organic matter and climate variables were the primary determinants of spatial variability in N_2O emissions. Our results suggest that the United States Government, and possibly the Intergovernmental Panel on Climatic Change (IPCC), have underestimated the importance of agriculture as a national and global source of atmospheric N_2O. The coupled nature of the nitrogen and carbon cycles in soils results in complex feedbacks which complicate the formulation of strategies to reduce the global warming potential of greenhouse gas emissions from agriculture.

1. Introduction

Nitrous oxide (N_2O) is the most problematical greenhouse gas from the perspective of the more than 150 nations who signed the United Nations Framework Convention on Climate Change (FCCC). The FCCC maps out a strategy, including reductions in greenhouse gas emissions, intended to diminish the likelihood of future damaging rates of climate change. However, recent reviews clearly document that the scientific basis for estimating most natural and anthropogenic sources of N_2O is inadequate [e.g., *Khalil and Rasmussen*, 1992; *Williams et al.*, 1992; *Matson and Vitousek*, 1990]. Thus, the creditability of most proposals to reduce emissions of N_2O could be easily challenged.

Global and national emission inventories and budgets support the supposition that human activities have become an important source of atmospheric N_2O [e.g., *Khalil and Rasmussen*, 1992; *Robertson*, 1991]. Evidence that significant anthropogenic emissions of N_2O may come from more than a dozen identified sources is a complicating factor, and additional sources continue to be discovered. Agricultural sources of N_2O are better understood than most other sources due to laboratory and field measurements which began almost three decades ago [e.g., *Bremner and Blackmer*, 1978; *Bremner et al.*, 1980; *Cates and Keeney*, 1987; *Hutchinson and Mosier*, 1979].

Williams et al. [1992] reviewed the literature on N_2O emissions from soil and documented the considerable spatial and temporal variability in emission data. They concluded that linkages among the microbial, physical, and chemical variables that influence nitrification, denitrification, decomposition, and N_2O transport in soils occur over many temporal and spatial scales which makes interpretation of the available data difficult. To overcome this difficulty, *Williams et al.* [1992] recommended that models be developed which can simulate the processes responsible for production, consumption, and transport of N_2O at all relevant temporal and spatial scales for developing emission inventories.

This paper reports the results of a model-based estimate of N_2O emissions for agricultural lands in the United States. A unique feature of the Denitrification-Decomposition (DNDC) model used in this study is the capability to independently simulate the effects of weather, crop type, and farming practices on N_2O emissions. In addition to providing a possible methodology for estimating large-scale emission inventories, the DNDC model can be used to evaluate how N_2O emissions respond to variations in specific forcing factors. The details of the DNDC model structure, parameters, and comparisons to field measurement data are described by *Li et al.* [1992a,b; 1994a,b].

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2. Sensitivity of N_2O Emissions to Variations in Climate and Agricultural Practices

Land cover and land use change generally result in fundamental long-term changes to the soil nitrogen cycle and N_2O emissions [*Luizao et al.*, 1989; *Keller et al.*, 1993]. Nitrous oxide emissions from agricultural soils are known to be highly variable over hourly-to-interannual timescales [*Hutchinson and Mosier*, 1979; *Duxbury et al.*, 1982; *Terry et al.*, 1981]. Short-term temporal variability of N_2O emissions is influenced by interactions of variations in weather and climate with changes in agricultural practices [*Colbourn*, 1992; *Breitenbeck and Bremner*, 1986; *Buresh et al.*, 1991; *Li et al.*, 1994a,b]. Longer-term variability may also be influenced by changes in soil composition, especially in soil organic content [*Li et al.*, 1992a]. To better understand sources of variability in the United States agricultural system, we conducted a systematic study of the sensitivity of N_2O emissions from an agricultural site planted with corn to variations in climate and farming practices. These sensitivity studies address questions relevant to issues of how climatic change might influence emissions (e.g., feedbacks), and how changes in farming practices might be used to mitigate emissions. Most importantly, our sensitivity studies demonstrated that scientific modeling tools can be developed and applied in a relatively sophisticated way to problems of cause and effect of changes in N_2O emissions from soils.

The baseline conditions for the sensitivity studies are typical of climatic conditions, soil properties, and farming practices in the corn growing areas in Iowa (see note a in Table 1). The effect of each climate variable or farming practice on N_2O emissions was tested by varying the single factor and holding all other parameters at baseline values. Variations in annual average temperature and precipitation were limited to approximately ±20% of the baseline condition to maintain viable corn growing conditions. More extreme variations were tested for nitrate concentrations in rainfall and farming practices. Some of the farming practices simulated would not be adopted by today's farmers for economic reasons, but they do not violate the rule of maintaining viable growing conditions.

2.1. Sensitivity to Variations in Physical and Chemical Climate

Increasing annual average temperature increased soil nitrogen mineralization and nitrogen gas fluxes to the atmosphere (Table 1 and Figure 1). The influence of increasing temperature was nonlinear with nitrogen mineralization rates and N_2O emissions increasing more rapidly at higher temperatures. A 20% increase in temperature resulted in a 33% increase in N_2O emissions. Varying annual precipitation had less effect on N_2O emissions. A 20% increase in precipitation produced a 4% increase in N_2O emissions, but showed a more pronounced influence on the ratio of N_2O/N_2O+N_2 emitted than did a similar increase in temperature. The increase in total denitrification at higher annual precipitation probably reflects the influence of more frequent and extended periods of low oxygen tension in saturated soil microenvironments [*Linn and Donan*, 1984]. The response of the simulated Iowa agricultural soil to variations in precipitation was much less pronounced than was observed and simulated for an organic-rich Florida agricultural soil [*Li et al.*, 1994b]. Soil organic carbon concentrations are a critical factor influencing spatial differences in N_2O production as we illustrate further in a following section of this paper.

Varying the nitrate concentration in precipitation produced a much larger effect on N_2O emissions and total denitrification than we expected. In the baseline scenario 150 kg N/ha/yr was

Table 1. Sensitivity of N_2O Emission to Climate Change at A Corn Field in Iowa

Scenario	Atmospheric N Deposition, kg N/ha/yr	Soil N Mineralization, kg N/ha/yr	Flux, kg N/ha/yr			Ratio of $N_2O/(N_2O+N_2)$
			N_2O	N_2	N_2O+N_2	
Baseline [a]	12.9	190.1	4.7	15.4	20.1	0.23
Annual average temperature (°C)						
- 7.8	12.9	171.4	3.7	14.4	18.2	0.21
- 8.8	12.9	180.8	4.2	14.9	19.1	0.22
- 10.8	12.9	199.6	5.3	16.0	21.3	0.25
- 11.8	12.9	211.9	6.3	16.6	22.8	0.27
Annual precipitation (cm)						
- 78.7	10.1	180.8	5.5	11.1	16.7	0.33
- 88.7	11.3	185.2	5.1	12.0	17.1	0.30
- 108.7	14.2	201.2	5.0	17.7	22.7	0.22
- 118.7	15.3	203.1	4.9	20.3	25.2	0.19
N content in rainfall (mg N/l)						
- 0.5	4.0	190.4	4.0	8.2	12.2	0.33
- 1.0	8.0	190.3	4.4	11.7	16.1	0.27
- 2.0	16.1	190.0	4.9	17.7	22.6	0.22
- 3.0	24.1	189.8	5.7	22.4	28.2	0.20
- 4.0	32.1	189.5	7.2	24.9	32.0	0.22

[a] Baseline scenario: annual average temperature 9.8 °C, precipitation 98.7 cm, N concentration in rainfall 1.6 mg N/l; soil texture loam (clay 19%), pH 6.0, bulk density 1.4 g/c.c., SOC 0.025 Kg C/kg; fertilizers (37.5 kg nitrate-N, 37.5 kg ammonium-N, and 75.0 kg anhydrous ammonia-N/ha) applied on April 25 at surface; soil tilled with disks on April 15 and with moldboard on October 15; neither manure nor irrigation applied.

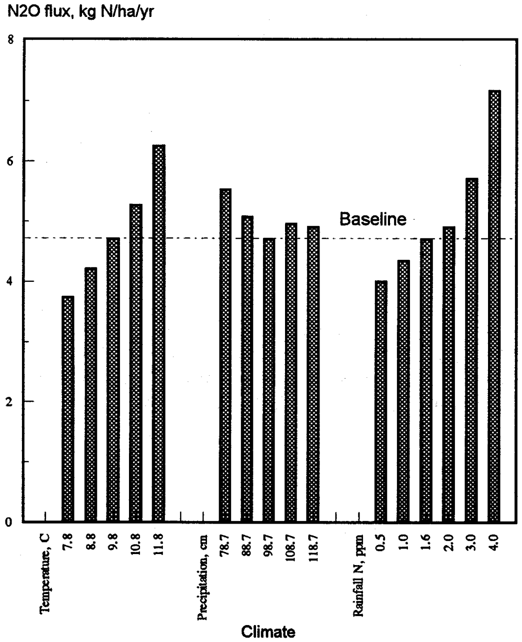

Figure 1. Sensitivity of N_2O flux to climate change at a corn field in Iowa. A 20% increase in temperature resulted in a 33% increase in N_2O emissions. Varying annual precipitation had less effect on N_2O emissions. Varying the nitrate concentration in precipitation produced a much larger effect on N_2O emissions.

applied to the soil as fertilizer, along with 12.9 kgN/ha/yr as nitrate in atmospheric deposition. In one simulation of changing atmospheric nitrate inputs, the fertilizer input remained constant and atmospheric nitrate deposition was increased 12%. The 12% increase in nitrate deposition produced a 52% increase in N_2O emissions, and a 59% increase in N_2O+N_2 emissions. The influence of nitrate in atmospheric deposition was nonlinear, increasing at higher deposition rates over the range studied. The sensitivity of the soil studied to nitrate inputs by atmospheric deposition may reflect an efficient titration to denitrifiers in surface layers by individual rainfall events. In contrast, a one-time injection of fertilizer creates a carbon-limiting condition for denitrification, coincides with maximum plant uptake, and is subject to extensive leaching of nitrate to groundwater.

2.2. Sensitivity to Agricultural Practices

Manure additions had the most pronounced impact on N_2O emissions of the agricultural practices simulated (Table 2 and Figure 2). This result is consistent with previous studies which have documented the importance of carbon limitation in N_2O production [e.g., *Li et al.*, 1992a; *Robertson*, 1991]. Spreading of manure is a touted process for both waste management and for maintaining soil carbon. However, the addition of manure enhances soil nitrogen mineralization and increases the efficiency of N_2O production. The net effect on the global warming potential of greenhouse gas emissions to the atmosphere will depend on site specific soil properties and climate characteristics.

Most of the remaining variations in agricultural practices simulated showed little effect, or reduced N_2O emissions relative to the baseline scenario (Table 2 and Figure 2). Some of the scenarios (e.g., reductions in fertilizer and use of a nitrate-only fertilizer) would reduce corn yields and would not be adopted by farmers. The interesting scenarios from a policy perspective are the sensitivity of N_2O emissions to fertilizer application timing and tillage regime. These techniques are being used, along with others, in an evolution to high precision agriculture. This change in farming practices uses a variety of new technologies to gain higher efficiencies in the use of inputs (e.g., fertilizer, seeds, irrigation water, etc.). As these techniques mature, it is reasonable to imagine an approach to agriculture that optimizes on yield versus environmental costs at local scales. Results in Table 2 indicated that changes in tillage practices could reduce N_2O emissions to the lowest level observed in any scenario. The reductions in N_2O flux by going to no-till agriculture are a result of reductions in soil nitrogen mineralization rates and changes in soil moisture dynamics. More efficient storage and retention of moisture in the untilled soils reduces episodic wetting and drying and increases the potential for low oxygen conditions, producing less substrate for denitrification and a lower N_2O/N_2O+N_2 ratio.

The results of these preliminary sensitivity studies should be confirmed with controlled field experiments. The highest priority should be given to studies which elucidate why nitrate in atmospheric deposition may be converted to N_2O much more efficiently than fertilizer nitrogen. The magnitude of the no-till and manure effects on N_2O emissions and soil carbon storage should be quantified with emphasis on benefits to soil fertility versus net reduction in the global warming potential of soil gas emissions.

3. Model-based N_2O Emissions Inventory for U.S. Agriculture

Most studies and discussions of N_2O emissions associated with agriculture have emphasized fertilizer as the primary source of anthropogenic nitrogen. The sensitivity studies discussed above indicated that the use of fertilizers was only one of several farming practices that enhanced N_2O emissions from soils. On the basis of the excellent performance of the DNDC model at sites where field measurements were available for model evaluation [*Li et al.*, 1992a,b; 1994a,b], it seemed reasonable to attempt a model-based national N_2O emissions inventory for United States agriculture. Our model-based inventory also benefited from the relatively high quality of the input data for climate conditions, soil properties, and farming practices over the entire United States The sources of data are referenced throughout this text and on tables and figures. The specific input data used for each scenario are available on request from the lead author.

3.1. Experimental Design for Calculating Emissions

Most of the input data on land use, climate, soil properties, and agricultural practices required to calculate N_2O emissions with the DNDC model is available on a county or state basis for the United States. In this study, all data were aggregated to the state scale. The exploratory nature of this research, and the paucity of field data for detailed model evaluations, does not justify publishing inventories at the county scale. The following

Table 2. Sensitivity of N_2O Emission to Changes in Farming Practices at A Corn Field in Iowa

Scenario	Mineralization Rate, kg N/ha/yr	Flux, kg N/ha/yr			Ratio of $N_2O/(N_2O+N_2)$
		N_2O	N_2	N_2O+N_2	
Baseline [a]	190.1	4.7	15.4	20.1	0.23
Fertilizer amount (kg N/ha/yr)					
- 50	190.3	3.8	16.9	20.7	0.18
- 100	190.1	4.5	15.6	20.1	0.23
- 200	190.1	4.9	15.4	20.3	0.24
- 300	190.0	5.4	15.1	20.5	0.26
Fertilizer type					
- nitrate	190.4	3.0	17.1	20.1	0.15
- ammonium	190.0	4.3	15.2	19.5	0.22
- urea	190.0	4.3	15.2	19.5	0.22
- anhydrous ammonia	190.1	4.8	15.4	20.2	0.24
Fertilizing depth (cm)					
- 10	190.1	4.6	15.7	20.3	0.22
- 20	190.2	4.0	16.9	20.9	0.19
- 30	191.4	3.8	17.2	21.0	0.18
Fertilizing timing					
- June 15	191.4	6.3	15.6	21.9	0.29
- July 15	193.1	5.4	17.2	22.6	0.24
- August 15	195.5	3.4	18.9	22.3	0.15
- September 15	194.3	2.6	17.3	19.9	0.13
Tillage					
- conservation (spring) [b]	160.9	4.6	15.0	19.7	0.24
- conservation (fall)	160.3	2.7	15.4	18.0	0.15
- no-till	146.9	2.6	15.0	17.7	0.15
Manure amount (kg C/ha/yr)					
- 1000	253.5	5.2	15.6	20.8	0.25
- 2000	322.0	5.6	16.6	22.2	0.25
- 3000	391.0	6.9	15.8	22.7	0.30
- 4000	459.7	8.0	14.6	22.6	0.35
- 5000	528.1	8.6	14.5	23.1	0.37

[a] Baseline scenario: annual average temperature 9.8 °C, precipitation 98.7 cm, N concentration in rainfall 1.6 mg N/l; soil texture loam (clay 19%), pH 6.0, bulk density 1.4 g/c.c., SOC 0.025 Kg C/kg; fertilizers (37.5 kg nitrate-N, 37.5 kg ammonium-N, and 75.0 kg anhydrous ammonia-N/ha) applied on April 25 at surface; soil tilled with disks on April 15 and with moldboard on October 15; neither manure nor irrigation applied.

[b] Soil is tilled once a year with chisel.

paragraphs briefly describe the sources of the input data used, and the methodology used for estimating a range in N_2O emissions for agriculture in each state.

Data on land use and farming practices were obtained from statistical databases maintained by the U. S. Department of Agriculture (USDA) and the Tennessee Valley Authority (TVA). Agricultural lands in the United States in 1990 totalled 162 million hectares of cropland and 262 million hectares of pasture. Crop categories used for this study were corn, winter wheat, soybeans, oats, barley, sorghum, cotton, vegetables, sugar cane, legume hay, and nonlegume hay. One crop (rice), and three states (Alaska, Rhode Island, and Hawaii), were not included in this study due to the unique nature of the Hawaiian soils and the insignificant contribution these sources would make to a national emissions inventory. Detailed data on crop and pasture distribution by state were obtained from *USDA* [1991].

The farming practice scenarios for crops and pasture in each state were developed by studying the comprehensive information compiled by *USDA* [1990] and *TVA* [1989]. Fertilizer applications used were 150 kg N/ha for corn, 80 kg N/ha for cotton, 60 kg N for wheat, oats, barley and sorghum, 200 kg N/ha for vegetables, and 20 kg N/ha for soybeans. Our baseline scenario for the national emissions inventory used a fertilizer mix of anhydrous ammonia (50%), ammonium nitrate (25%), and urea (25%). Fertilizers were applied five days before planting for all crops except vegetables. Vegetable crops received two applications of 100 kg N/ha, in spring and fall. Because our emissions inventory does not include home use of fertilizers, fruit orchards, or commercial forests, the total amount of fertilizer used in the simulations was 8.1 TgN, compared with the 10.6 TgN consumed in the United States in 1990.

Tillage practices were characterized as conventional tillage, conservation tillage, and no-till. In conventional tillage the soil is tilled twice annually to depths of 15-25 cm. In conservation tillage the soil is tilled once a year, 15 days before planting. In the DNDC scenario for no-till the soil is mulched with crop

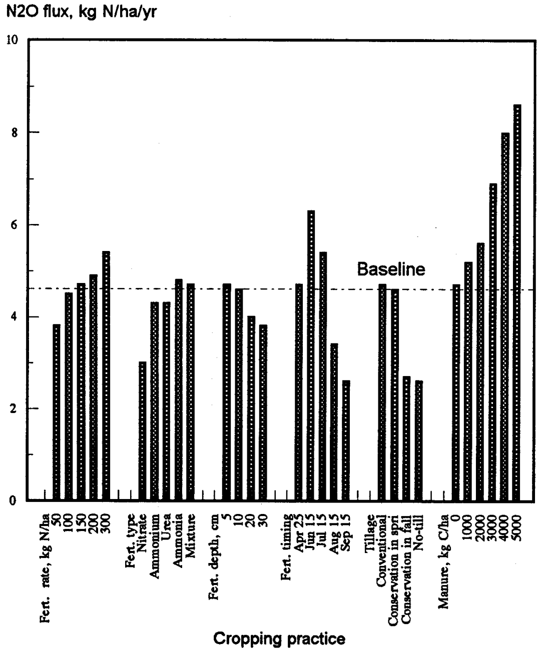

Figure 2. Sensitivity of N$_2$O flux to agricultural practices. Manure additions had the most pronounced impact on N$_2$O emissions of the agricultural practices simulated. Fertilizer application timing and tillage regime also had impacts on N$_2$O emissions.

residue, but not physically disturbed. A state-by-state cultivation scenario was developed using the Purdue University database on United States agricultural practices [*Lai*, 1989].

Manured area was estimated for each state based on cattle populations. Annual manure production per cow is equivalent to about 2 t of dry matter containing 70 kg of N [*Sutton et al.*, 1983]. We assumed that 50% of the manure produced was applied to croplands. Manure is primarily used on corn fields in the United States [*USDA*, 1990].

The irrigation scenarios used in DNDC were based on data by *Hanson et al.* [1980] and *USDA* [1991]. An average value for water demand was determined for each crop in each state. If precipitation during a month was below crop water demand, irrigation water was applied to cover the deficit.

Climate data for 1990 were obtained from *Teigen* [1992]. Concentrations of nitrogen in precipitation were estimated from data by *Barchet* [1988].

3.2. Modeling N$_2$O Emissions at State Scale

Single-year simulations were conducted for each crop and cropping practice scenario in each state. N$_2$O emissions are given by

$$EMISS_{i,k} = \Sigma(R_{i,j,k} \bullet A_{i,j,k}) + \Sigma(IR_{i,j,k} \bullet IA_{i,j,k}) + \Sigma(MF_{i,k} \bullet MA_{i,k}) \qquad (1)$$

where $EMISS_{i,k}$ is N$_2$O emission from crop i in state k, $R_{i,j,k}$ is N$_2$O flux from a unit nonirrigated area of crop i with tillage system j in state k, $A_{i,j,k}$ is nonirrigated area of crop i with tillage j in state k, $IR_{i,j,k}$ is N$_2$O flux from a unit irrigated area of crop i with tillage system j in state k, $IA_{i,j,k}$ is irrigated area of crop i with tillage j in state k, $MF_{i,k}$ is manure-increased N$_2$O flux from a unit manured area of crop i in state k, and $MA_{i,k}$ is manured area of crop i in state k.

The decision to calculate emissions for the total area of each crop and for pasture by state requires a procedure for including uncertainties due to variations in soil properties. We selected seven states, representing a wide range of climate and soil conditions, for a series of model sensitivity experiments to determine how to best capture the influence of variations in soil properties on N$_2$O emissions. One-year simulations were conducted with scenarios which set each soil input parameter at lowest and highest reported values. The range in N$_2$O flux to the atmosphere from the complete range of soil conditions reported for seven states is illustrated in Figure 3. These results are consistent with our earlier findings which indicated that soil organic carbon is the dominant variable in soils influencing N$_2$O production [*Li et al.*, 1992b; 1994b]. These results indicated that calculating N$_2$O emissions at minimum and maximum values of soil organic carbon reported for each state should capture the majority of the variability due to the heterogeneity of soils. In the national inventory, discussed in the next section, N$_2$O emissions are calculated for each crop and pasture lands in each state using median values for all soil input parameters, except for soil organic carbon where minimum and maximum values are used as inputs to estimate the possible range in emissions.

4. N$_2$O Emissions From United States Agriculture

A summary of 1990 N$_2$O emissions from United States agriculture is presented in Table 3. The N$_2$O flux rates ranged from lower than 1 (e.g., Nevada) to higher than 10 (e.g., Florida) kg N/ha per year. The flux rates were generally higher in the eastern states than the western ones because of the soil and climate conditions (Figure 4). Total emissions for our low/high soil carbon scenarios ranged from 0.85 to 1.23 Tg N$_2$O-N. Emissions from crop and pasture lands in individual states are highly variable as would be expected from the differences in climate, soil properties, and agricultural practices. Three crops (corn, winter wheat, soybeans) accounted for 54-60% of total N$_2$O-N emissions from United States agriculture. Eight states (Florida, Iowa, Illinois, Kansas, Minnesota, North Dakota, Oklahoma, Texas) accounted for approximately 40% of total emissions (Figure 5). The calculated range in emissions is highest in Florida primarily due to extreme variations in soil organic carbon [*Li et al.*, 1994b]. Emissions from California are lower than expected for an important agricultural state, most likely due to the exclusion of orchards and minor specialty crops (e.g., grapes) from the inventory.

There are two important conclusions which should be drawn from this initial effort to develop a model-based N$_2$O emissions inventory for United States agriculture: (1) The total N$_2$O flux to the atmosphere estimated by the DNDC model is approximately 10 times higher than current estimates for agricultural emissions in an official United States Department of Energy assessment [*USDOE*, 1995]. (2) A program of field measurements to evaluate the model-based N$_2$O emission estimates, and to support an improved empirical estimate based on field data

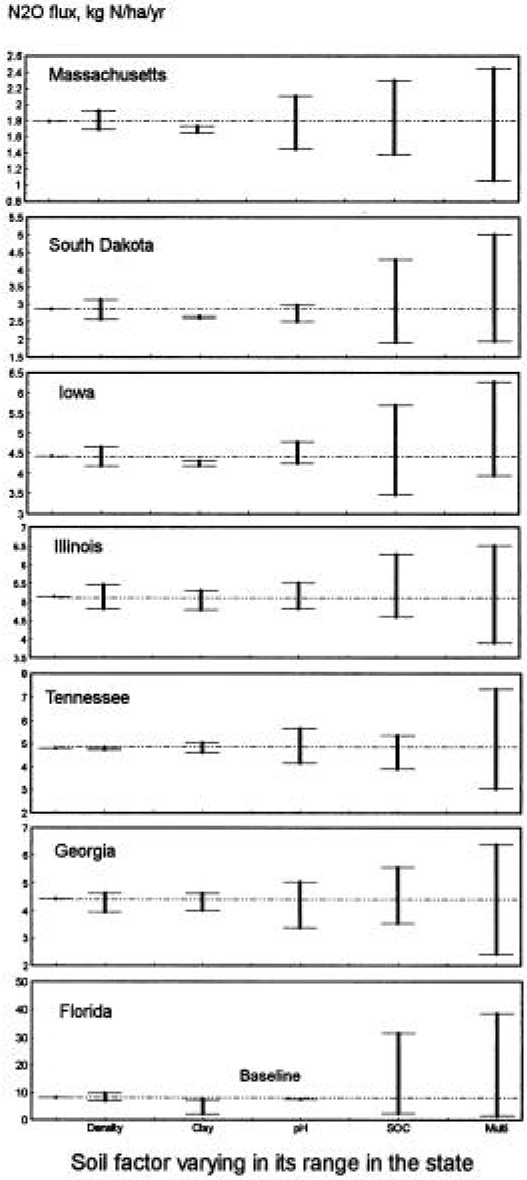

Figure 3. Seven states were arbitrarily selected for testing the sensitivity of N_2O flux to soil parameters. In the tests, run DNDC with one soil parameter varied over a given range that was typical of the expected range for that state, and with other parameters constant as their averages. Simulation was also conducted with the soil parameters each set at their extreme values. The latter simulations represented extreme situations, which would occur rarely under the natural conditions although. The tests revealed that SOC was the most sensitive factor involved in soil N_2O fluxes. The N_2O fluxes produced under varying SOC not only covered the range of the fluxes caused by varying other soil parameters but also accounted for 34-80% of the extreme value ranges of the all soil parameters.

should focus on the relatively few crops and geographic areas that produce approximately 50% of total emissions.

5. Effect of Farming Practices on N_2O Emissions From United States Agriculture

The relative contribution of specific farming practices to total N_2O emissions from United States agriculture were estimated by conducting separate national inventory simulations without any use of fertilizers, tillage, irrigation, or manure. The purpose of these experiments was to attempt to estimate the relative contribution of each individual farming practice to total emissions. We were especially interested in the fertilizer contribution to total emissions since the United States Government median estimate of the anthropogenic N_2O flux from agriculture is based on the assumption that the only source is a 1% loss of fertilizer nitrogen [*USDOE*, 1995].

The results of our simulations indicate that fertilizer use may be less important than previously suggested as a determinant of N_2O emissions from U. S. agriculture (Table 4). Modern farming practices, as used in the United States in 1990, enhanced N_2O emissions by approximately 30-40% above the level derived from nitrogen released during mineralization of soil organic matter. Our sensitivity studies and national inventory indicate that fertilizer may be less important than tillage as a factor contributing to anthropogenic emissions from agriculture. Conventional tillage increased N_2O emissions by 81% compared to a no-till scenario in our sensitivity studies on Iowa corn field soils (Table 2).

6. Implications for Science and Policy

For biogeochemists the results of this model-based study of the spatial variability of N_2O emissions from agricultural soils across the United States has posed a number of testable hypotheses. The most important are as follows: (1) The flux of N_2O from agricultural soils is determined by soil organic matter concentrations, soil tillage, nitrate concentrations in precipitation, soil temperature, and fertilizer use. Nitrogen fertilizer additions to the soil may be less important to N_2O production than suggested by previously published emission inventories. Comprehensive field measurements along carefully determined gradients in each variable are important to understanding what, where, when, and how each factor contributes to the production, destruction, and transport of N_2O in agricultural soils. These data will be essential to making progress on the question: How well can the flux of N_2O from agricultural soils be determined? (2) The intimate coupling of the carbon and nitrogen cycles through decomposition and denitrification processes will have to be much better understood in order to define anthropogenic versus natural contributions to N_2O flux from agricultural soils. Residual carbon reservoirs from natural sources may, at least partially, fuel denitrification processes for unknown, perhaps decade-to-century, time periods after natural land cover has been removed for agricultural land uses. The measured net N_2O flux from most agricultural sites includes a residual natural component.

For greenhouse gas policy analysts, the results of this study signal a warning. Scientific understanding of the processes regulating N_2O emissions from soils is very preliminary. For N_2O, which frequently exhibits order-of-magnitude variability at

Table 3. 1990 N2O Emissions from Agricultural Lands in the United States

State		Range of N2O Emission (1,000 kg N) From Simulated Agricultural Land *														
		CRN	WWT	SWT	SOY	OAT	BAR	SOR	COT	VEG	SUG	HLH	NLH	FAL	PAS	Total
Alabama	From	863	638	0	818	85	0	60	831	0	0	0	1092	1633	4721	10740
	To	1006	990	0	1190	122	0	85	1166	0	0	0	1738	2602	6766	15665
Arkansas	From	240	3839	0	6579	113	0	640	1728	0	0	39	1488	2669	7715	25051
	To	279	6330	0	9691	157	0	880	2326	0	0	58	2188	4742	10445	37096
Arizona	From	35	78	49	0	0	19	0	583	0	0	87	16	254	18875	19996
	To	38	122	62	0	0	22	0	705	0	0	119	21	372	23089	24549
California	From	679	590	43	0	273	220	0	997	935	0	0	200	620	7314	11872
	To	792	1176	56	0	400	289	0	1352	1143	0	0	408	727	11065	17408
Colorado	From	1345	2646	0	0	90	121	195	0	0	0	426	449	1466	12822	19560
	To	1058	3922	0	0	90	127	199	0	0	0	475	542	1716	13763	21893
Connecticut	From	104	0	0	0	0	0	0	0	0	0	33	117	36	146	435
	To	187	0	0	0	0	0	0	0	0	0	48	165	61	171	632
Delaware	From	407	0	0	324	0	53	0	0	0	0	11	20	80	29	925
	To	354	0	0	298	0	49	0	0	0	0	10	19	86	24	840
Florida	From	289	118	0	105	0	0	0	66	260	9544	0	256	653	7453	18744
	To	2410	2365	0	1477	0	0	0	768	2049	9544	0	3657	11869	86002	120140
Georgia	From	1766	1165	0	1249	571	0	131	639	0	0	0	617	2024	3100	11263
	To	1876	2085	0	1891	856	0	188	900	0	0	0	887	3413	3937	16034
Iowa	From	17024	163	0	8113	1396	0	0	0	0	0	1309	230	10200	2883	41318
	To	28035	293	0	13645	2391	0	0	0	0	0	1964	344	14362	3507	64540
Idaho	From	106	828	234	0	29	408	0	0	0	0	343	56	402	5209	7614
	To	93	959	282	0	36	488	0	0	0	0	504	86	495	7645	10587
Illinois	From	17307	4672	0	11493	886	0	274	0	107	0	740	267	8080	3069	46894
	To	22778	6074	0	15992	1154	0	352	0	145	0	1092	399	9702	3265	60952
Indiana	From	11590	2438	0	7130	290	0	0	0	0	0	582	435	4470	2852	29787
	To	11344	3355	0	6832	296	0	0	0	0	0	593	442	5018	2928	30806
Kansas	From	2375	21036	0	1695	188	0	3084	0	0	0	588	1242	4489	10230	44925
	To	3158	33005	0	2558	273	0	4929	0	0	0	820	1820	6568	10772	63901
Kentucky	From	3040	1800	0	2061	0	33	62	0	0	0	460	2680	2657	7835	20627
	To	3554	2396	0	2524	0	41	77	0	0	0	574	3365	3318	8551	24401
Louisiana	From	623	1099	0	3318	0	0	266	1776	0	0	0	434	1654	3895	13065
	To	970	2034	0	5011	0	0	433	3009	0	0	0	736	3563	5549	21305
Massachusetts	From	80	0	0	0	0	0	0	0	0	0	49	126	45	162	462
	To	76	0	0	0	0	0	0	0	0	0	48	120	49	147	440
Maryland	From	1125	486	0	856	119	130	0	0	0	0	119	214	416	600	4065
	To	1096	646	0	924	133	138	0	0	0	0	129	228	423	579	4296
Maine	From	46	0	0	0	31	0	0	0	0	0	17	159	123	120	497
	To	60	0	0	0	38	0	0	0	0	0	19	167	148	115	547
Michigan	From	5014	1454	0	1915	670	80	0	0	220	0	1801	286	1653	3460	16554
	To	4711	1951	0	2096	679	83	0	0	260	0	1736	265	2675	2704	17160
Minnesota	From	6480	195	2421	3774	1012	736	0	0	273	0	1009	480	5079	1295	22755
	To	16158	628	5519	8814	2033	1682	0	0	660	0	2420	1138	10119	1802	50972
Missouri	From	3710	4418	0	5240	80	0	749	369	0	0	495	3177	4091	11232	33561
	To	4703	6019	0	6184	97	0	909	479	0	0	623	3932	5293	13248	41489
Mississippi	From	558	1357	0	3501	0	0	173	2560	0	0	0	771	2322	4573	15815
	To	582	1848	0	4540	0	0	213	3031	0	0	0	1100	4071	6145	21529
Montana	From	55	1590	1090	0	57	584	0	0	0	0	349	204	521	7252	11702
	To	55	2485	1506	0	79	794	0	0	0	0	577	333	762	9996	16587
North Carolina	From	3507	1329	0	2760	379	75	140	477	0	0	50	723	2179	3226	14846
	To	3893	2071	0	3148	430	89	161	569	0	0	57	836	2867	3186	17307
North Dakota	From	803	344	7366	317	589	1722	0	0	0	0	655	965	1956	3600	18318
	To	2307	1190	23533	1128	2045	5582	0	0	0	0	2512	3539	5236	11264	58335
Nebraska	From	7862	3415	0	1871	543	22	1320	0	0	0	906	1467	3940	12380	33728
	To	10067	4488	0	2553	727	28	1859	0	0	0	1202	1960	4621	13776	41281
New Hampshire	From	29	0	0	0	0	0	0	0	0	0	19	77	18	96	239
	To	35	0	0	0	0	0	0	0	0	0	20	82	20	92	249
New Jersey	From	202	91	0	180	0	14	0	0	0	0	40	128	173	157	985
	To	201	124	0	192	0	15	0	0	0	0	41	130	179	153	1035
New Mexico	From	112	479	0	0	0	0	112	83	0	0	114	30	334	22256	23519
	To	135	616	0	0	0	0	119	83	0	0	114	30	447	18864	20407
Nevada	From	0	0	0	0	0	0	0	0	0	0	67	62	20	8925	9074
	To	0	0	0	0	0	0	0	0	0	0	106	103	20	12643	12872
New York	From	2303	372	0	0	445	0	0	0	0	0	1462	1916	1249	2684	10432
	To	2318	467	0	0	387	0	0	0	0	0	1250	1612	1349	2632	10015
Ohio	From	7276	3419	0	5878	537	0	0	0	0	0	1099	1090	3842	3768	26909
	To	6714	4457	0	5456	496	0	0	0	0	0	887	890	4477	3412	26788
Oklahoma	From	235	14173	0	297	255	27	531	599	0	0	395	1542	2232	18856	39142
	To	259	19868	0	359	310	34	647	685	0	0	536	2072	3166	22717	50652
Oregon	From	48	1048	42	0	47	0	0	0	0	0	275	404	461	8850	11174
	To	67	1514	58	0	65	0	0	0	0	0	325	484	726	11159	14398
Pennsylvania	From	2714	474	0	0	579	114	0	0	0	0	1209	1602	993	2632	10316
	To	2523	709	0	0	567	113	0	0	0	0	1147	1532	1279	2678	10548
South Carolina	From	994	693	0	1070	183	0	65	282	0	0	0	239	980	757	5263
	To	1304	1318	0	1831	306	0	104	431	0	0	0	402	1555	979	8230

Table 3. (continued)

State		Range of N2O Emission (1,000 kg N) From Simulated Agricultural Land *														
		CRN	WWT	SWT	SOY	OAT	BAR	SOR	COT	VEG	SUG	HLH	NLH	FAL	PAS	Total
South Dakota	From	2802	2296	1497	1251	868	380	380	0	0	0	1157	1145	1885	9776	23436
	To	6209	4467	3305	2892	1914	829	787	0	0	0	2504	2472	2912	16659	44951
Tennessee	From	1636	1488	0	2358	0	0	121	1109	0	0	110	2242	1794	5898	16757
	To	1822	2105	0	3028	0	0	154	1363	0	0	148	3039	2866	7865	22389
Texas	From	3885	10138	0	250	1531	0	4182	9263	0	0	81	3044	6677	84582	123634
	To	4012	16266	0	306	1794	0	4880	10336	0	0	118	4366	10410	91089	143579
Utah	From	65	189	0	0	25	78	0	0	0	0	255	71	99	6592	7375
	To	82	229	0	0	30	93	0	0	0	0	323	90	137	10796	11782
Virginia	From	1395	725	0	1059	0	218	0	0	0	0	263	1904	1045	5763	12372
	To	1270	857	0	1062	0	211	0	0	0	0	257	1860	1145	5033	11696
Vermont	From	138	0	0	0	0	0	0	0	0	0	101	239	50	386	914
	To	219	0	0	0	0	0	0	0	0	0	159	379	75	397	1229
Washington	From	124	2567	227	0	56	305	0	0	114	0	284	190	504	2656	7027
	To	149	3346	294	0	76	392	0	0	150	0	373	237	800	4174	9991
Wisconsin	From	5057	341	11	465	1086	78	0	0	388	0	2596	345	1905	2387	14659
	To	4443	411	12	492	1105	83	0	0	938	0	2757	350	1972	2152	14714
West Virginia	From	150	33	0	0	15	0	0	0	0	0	73	601	188	1335	2394
	To	163	43	0	0	17	0	0	0	0	0	88	714	195	1403	2624
Wyoming	From	70	188	0	0	26	65	0	0	0	0	235	227	111	12020	12944
	To	84	239	0	0	32	73	0	0	0	0	287	270	129	14794	15909
Total	From	116268	94412	12981	75930	13056	5480	12487	21360	2297	9544	19903	35268	88272	346428	853686
	To	153647	143469	34627	106116	19133	11256	16976	27203	5345	9544	27020	51546	138737	490131	1234750

* CRN, corn; WWT, winter wheat; SWT, spring wheat; SOY, soybean; OAT, oats; BAR, barley; SOR, sorghum; COT, cotton; VEG, vegetables; SUG, sugarcane; HLH, legume hay; NLH, nonlegume hay; FAL, fallow; and PAS, pasture.

even the smallest temporal and spatial scales studied, the question of determining the accuracy of emission inventories may be unanswerable. Verification and validation of DNDC and other model extrapolations to national scales is probably impossible [*Oreskes et al.*, 1994]. And, it would be equally difficult to design an affordable large-scale environmental monitoring program to determine emission inventories which could justify policies to regulate N_2O emissions from agricultural systems. The sensitivity of N_2O emissions to changes in climate, atmospheric nitrogen deposition, and agricultural practices means

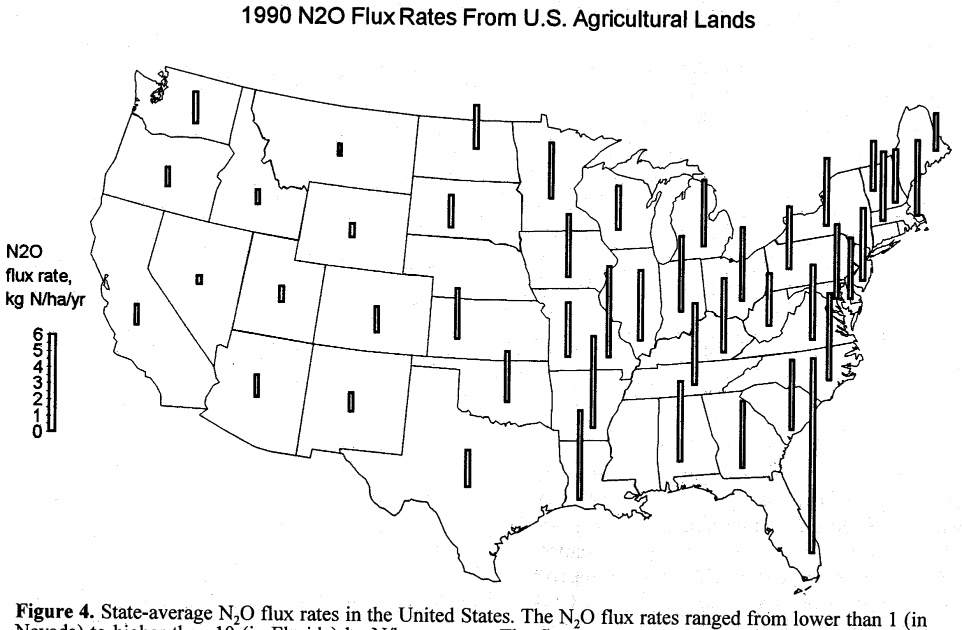

Figure 4. State-average N_2O flux rates in the United States. The N_2O flux rates ranged from lower than 1 (in Nevada) to higher than 10 (in Florida) kg N/ha per year. The flux rates were generally higher in the eastern states because of the soils with higher SOC and the climate. The national average rate was 2.5 kg N/ha per year in 1990. Each bar represents a middle value of the N_2O flux rate range in the state.

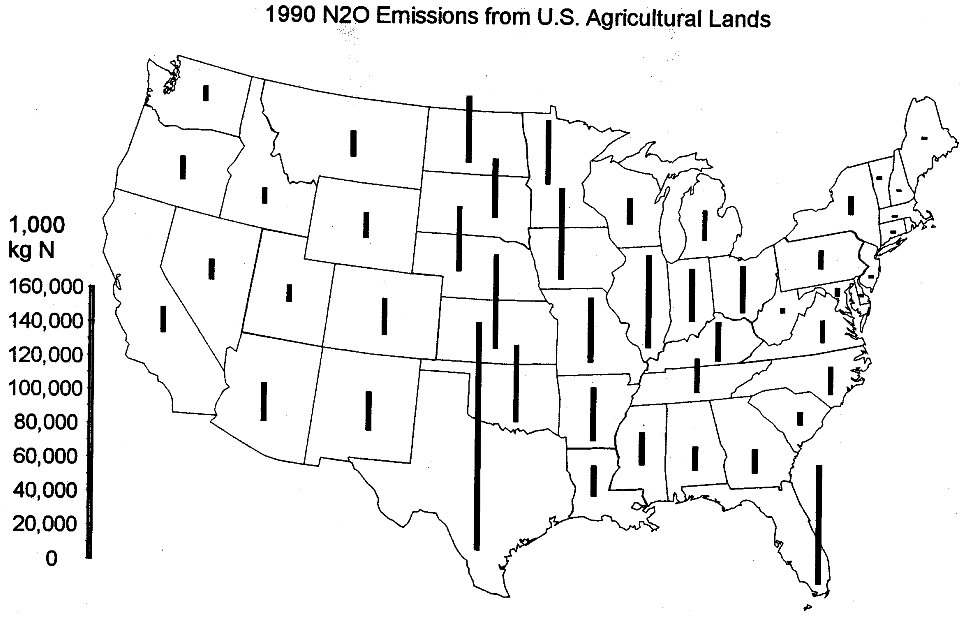

Figure 5. 1990 N_2O emissions from agricultural lands in the United States. Total agricultural N_2O emissions ranged from 0.85 to 1.23 Tg N in the United States in 1990, including 0.50-0.74 from croplands and 0.35-0.49 Tg N from pasture lands. Three crops (corn, winter wheat, soybeans) accounted for 54-60% of total N_2O-N emissions from United States agriculture. Eight states (Florida, Iowa, Illinois, Kansas, Minnesota, North Dakota, Oklahoma, Texas) accounted for approximately 40% of total emissions. Each bar represents a middle value of the N_2O emission range in the state.

that a large-scale emissions inventory determined by an intensive, dedicated field campaign is simply a "snapshot" of a potentially highly variable regional N_2O flux.

Countries around the world are initiating programs to estimate their sources and sinks of greenhouse gases. The Intergovernmental Panel on Climate Change (IPCC), in collaboration with other international organizations, is providing methodologies and encouragement for these country studies. The results of this study indicate that the N_2O emission inventories produced by such studies will have little value. The human and financial resources being used to develop emission inventories could be put to much better use for basic scientific research on relationships between biogeochemical processes and agricultural yields. Moving as quickly as possible to a global adoption of precise agriculture is a better approach to sustainable development than accounting for the ills of current agriculture.

Table 4. Effect of Individual Farming Practices on N_2O Emissions from U.S. Agriculture

Farming Practice	Practice-induced N_2O Emission, Tg N/yr	Percent of Total N_2O Emissions from U.S. Croplands
Fertilizer use	0.07 - 0.08	11 - 14
Tillage	0.08 - 0.18	17 - 24
Irrigation	0.001 - 0.009	0.2 - 1.2
Manure application	0.007 - 0.011	1.4 - 1.5

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