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Changsheng Li
University of New Hampshire - Main Campus

Steve Frolking
University of New Hampshire - Main Campus, steve.frolking@unh.edu

Tod A. Frolking
Denison University

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A Model of Nitrous Oxide Evolution From Soil Driven by Rainfall Events: 2. Model Applications

CHANGSHENG LI

The Bruce Company, Washington, D. C.

STEVE FROLKING

Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham

TOD A. FROLKING

Department of Geology and Geography, Denison University, Granville, Ohio

Simulations of nitrous oxide (N_2O) and carbon dioxide (CO_2) emissions from soils were carried out with a rain-event model of nitrogen and carbon cycling processes in soils (Li et al., this issue). Model simulations were compared with five field studies: a 1-month denitrification study of a fertilized grassland in England; a 2-month study of N_2O emissions from a native and fertilized grassland in Colorado; a 1-year study of N_2O emissions from agricultural fields on drained, organic soils in Florida; a 1-year study of CO_2 emissions from a grassland in Germany; and a 1-year study of CO_2 emissions from a cultivated agricultural site in Missouri. The trends and magnitude of simulated N_2O (or $N_2O + N_2$) and CO_2 emissions were consistent with the results obtained in field experiments. The successful simulation of nitrous oxide and carbon dioxide emissions from the wide range of soil types studied indicates that the model, DNDC, will be a useful tool for studying linkages among climate, land use, soil-atmosphere interactions, and trace gas fluxes.

1. INTRODUCTION

Estimates of nitrous oxide (N_2O) emissions from agricultural soils are of considerable interest because of the importance of N_2O as an atmospheric trace gas and the significance of fertilized agriculture as a source of N_2O to the atmosphere [*Davidson,* 1991]. N_2O is important as a greenhouse gas; *Rodhe* [1990] estimates that N_2O contributes about 5% of the total anthropogenic greenhouse effect. N_2O has a current concentration of about 310 parts per billion by volume and is increasing at about 0.25%/year [*Elkins and Rossen,* 1989]. With an atmospheric lifetime of about 150 years, N_2O plays an important role in the stratospheric ozone budget [*Warneck,* 1988]. Finally, N_2O emissions are a significant pathway for the loss of nitrogen from soil [*Bowden,* 1986]. Emission rates could therefore be important to both ecosystem nitrogen budgets and agronomic practices.

Microbial denitrification activity is strongly dependent on decomposition processes for the production of the principal substrates, dissolved organic carbon and nitrate [e.g., *Sahrawat and Keeney,* 1986], and so a model of denitrification in the field should include the actions and interactions of both processes. A companion paper [*Li et al.*, this issue] describes the development, structure, and sensitivity of a rain-event model of denitrification and decomposition processes in agricultural soils. The model, denitrification and decomposition (DNDC), contains three interacting submodels. The thermal-hydraulic submodel uses soil texture, air temperature, and precipitation data to calculate soil temperature and moisture profiles and soil water fluxes through time. This information is fed into either the denitrification submodel or the decomposition submodel. The denitrification submodel calculates hourly denitrification processes and N_2 (dinitrogen) and N_2O production during wet periods. The decomposition submodel calculates daily decomposition, nitrification, ammonium volatilization processes, and CO_2 production. Effects of anthropogenic activities (fertilization, tillage, amendment of manure, and other agricultural practices) are incorporated into the model. As we were unable to obtain data from a field experiment where both CO_2 and N_2O fluxes were measured simultaneously, in this paper we report on simulations of three field studies of denitrification (N_2O or $N_2O + N_2$) emission, and simulations of two field studies of soil CO_2 emissions, which we consider to be an indicator of soil carbon dynamics during decomposition.

2. MODEL APPLICATIONS

Five field studies were chosen to validate the DNDC model: (1) a 1979 field study of N_2O emissions from a native shortgrass prairie (control and urea fertilized) near Fort Collins, Colorado [*Mosier et al.,* 1981]; (2) a 1979 field study of N_2O emissions from drained, cultivated organic soils in Belle Glade, Florida [*Terry et al.*, 1981]; (3) a 1980 field study of denitrification loss from a grassland soil in a field receiving different rates of nitrogen fertilizer in Berkshire, England [*Ryden,* 1983]; (4) a 1979 field study of CO_2 emissions from an uncultivated grassland in Heidelberg, Germany [*Dorr and Munnich,* 1987]; and (5) a 1982 field study of CO_2 emissions from a tilled and fertilized winter wheat field in Columbia, Missouri [*Buyanovsky et al.*, 1986]. These environments represent a wide range of soil characteristics and thus a significant challenge to the model. A summary of the input parameters and simulation results for each of the tests follows.

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2.1. *Case 1: N_2O Emissions From Prairie in Colorado*

Field measurements of N_2O emissions were carried out by *Mosier et al.* [1981] in a native shortgrass prairie from June 21 to August 22, 1979. The study site was located in the Central Plains Experimental Range, 56 km northeast of Fort Collins, Colorado. The soil type was Olney fine sandy loam; bulk density is 1.2 g/cm^3; *p*H is 7; organic carbon content is 0.0057 kg C/kg soil; nitrate (NO_3^-) content is 1.6 kg N/ha; and ammonium (NH_4^+) content is 2.3 kg N/ha [*Mosier et al.*, 1981; *Parton et al.*, 1988]. Urea equivalent to 450 kg N/ha was added uniformly to the surface of treatment plots in 1.5 cm of irrigation water at the beginning of the field experiment period. Nothing was added to the control plots. Four rainfall events (greater than 1 cm) and one irrigation event occurred during the experiment (Table 1).

The emissions of N_2O generally increased with the increase of rainfall flux (Figure 1). The modeled N_2O peaks following rain events tend to be much sharper and to occur more quickly than the measured flux peaks. This is also true in the other denitrification studies and is discussed in section 3. Significantly, in the model simulation for the unfertilized soil, N_2O emission during rainfall event 3 was lower than that in rainfall event 4, although rainfall was higher in event 3 (Table 1). Field measurements show the two rain events to have similar N_2O emissions (Figure 1). The simulation records show that nitrate accumulation in the soil increased in the dry period after rainfall event 3 because of a general increase in soil moisture and hence decomposition rates. Low soil NO_3^- in the unfertilized study led to a low ratio of N_2O/N_2 emitted during rain event 3. For the urea-treated soil, since there was sufficient NO_3^- in the soil, N_2O emission during event 3 was higher than that from the unfertilized soil [*Mosier et al.*, 1981].

TABLE 1. Simulated Emissions of N_2O and N_2 From Sandy Loam During Dry Period-Rainfall Cycles From June 21 to August 22, 1979, in Fort Collins, Colorado

Dry period-Rainfall Cycle	Rainfall or Irrigation		Emission of N Gas, kg N/ha			
	No.	Flux, cm	N_2O^a	N_2O^b	N_2	N_2O+N_2
			Native Soil			
June 21-July 4	1	2.5	0.0005	0.005	0.126	0.132
July 5-July 31	2	1.8	0.0013	0.022	0.010	0.033
Aug. 1-Aug. 10	3	6.4	0.0005	0.020	0.419	0.440
Aug. 11-Aug. 16	4	5.2	0.0003	0.119	0.350	0.469
Aug. 17-Aug. 21	5	2.1	0.0006	0.083	0.360	0.444
Total		18.0	0.0032	0.249	1.265	1.517
			Urea Treated Soil			
June 21-July 4	1	2.5	0.0200	0.054	0.139	0.213
July 5-July 31	2	1.8	0.0014	0.022	0.010	0.033
Aug. 1-Aug. 10	3	6.4	0.0005	0.150	0.053	0.204
Aug. 11-Aug. 16	4	5.2	0.0004	0.103	0.232	0.335
Aug. 17-Aug. 21	5	2.1	0.0006	0.069	0.384	0.454
Total		18.0	0.0229	0.398	0.818	1.239

[a] N_2O evolved during nitrification.
[b] N_2O evolved during denitrification.

2.2. *Case 2: N_2O Emissions From Organic Soil in Florida*

Field measurements of N_2O emissions were carried out by *Terry* et al. [1981] in a fallow area in Belle Glade County, Florida, over a 377-day period from April 1979 to April 1980. The soil is the Pahokee muck (a Euic Lithic Medisaprist), the most prevalent soil series in the Everglades agricultural area. Surface bulk density is 0.34 g/cm^3; *p*H is 5.6; and organic carbon content is 0.429 kg C/kg soil [*Terry et al.*, 1981].

During the annual sampling period, 37 rainfall events (rainfall higher than 0.5 cm for each event) occurred [*Terry et al.*, 1981; *D. J. Smith*, personal communication, Southeast Regional Climate Center, Florida, 1990]. No fertilizer application occurred in the sampling period. The nitrogen mineralization rate for this soil has been estimated to range from 1000 to 1500 kg N/ha/yr [*Terry*, 1980].

The N_2O emission intensity was related to rainfall (Figure 2). Overall, the timing and relative magnitude of N_2O emissions from the model simulation are consistent with the field measurements. High soil temperature, high soil moisture, and hence high decomposition rates promote high N_2O emissions during the summer months. For example, the similar rainfall of events 18 (11.0 cm) and 28 (11.6 cm) produced contrasting N_2O emissions of 31.8 and 8.2 kg N/ha, respectively. The simulation records show that soluble carbon concentration and CO_2 emission were higher in event 18 than in event 28 (Table 2), indicating greater microbial activity. In this simulation, soluble carbon was the limiting factor for N_2O evolution in most rainfall events.

2.3. *Case 3: Denitrification Loss From Grassland in England*

Total denitrification loss (N_2O + N_2) from a loam soil under a cut ryegrass sward was measured for a 30-day period from May 28 to June 28, 1980, using the acetylene-inhibition technique [*Ryden*, 1983]. The experimental plots were located in Berkshire, England. The soil at the study site is a loam in the Wickham series overlying London clay. In the upper 20 cm of the profile, *p*H is 6.3; bulk density is 1.06 g/cm^3; organic carbon content is 0.033 kg C/kg soil; and initial NO_3^- content is 2 mg N/kg soil [*Ryden*, 1983; *Ryden and Dawson*, 1982]. Twelve rainfall events occurred during the measuring period. No irrigation was applied. The air temperature averaged 17°-18°C. Ammonium nitrate equivalent to 125 kg N/ha was applied at the beginning of the measuring period.

The two peaks of simulated denitrification emission are consistent with the two peaks obtained in the field experiments and show the close relationship between N_2O+N_2 flux and major soil-wetting events (Figure 3 and Table 3). Again, the modeled N_2O+N_2 emission rates peak and decline more rapidly than the measured rates after a major rainfall (see discussion below). The model predicts that denitrification produces most of the N_2O flux (>99%) and that most nitrogen loss through denitrification would be as N_2O (>97%), with little N_2 evolved.

2.4. *Case 4: CO_2 Emissions From Grassland in Germany*

Measurements of CO_2 emissions from a loamy, uncultivated, grass-covered soil near Heidelberg, Germany,

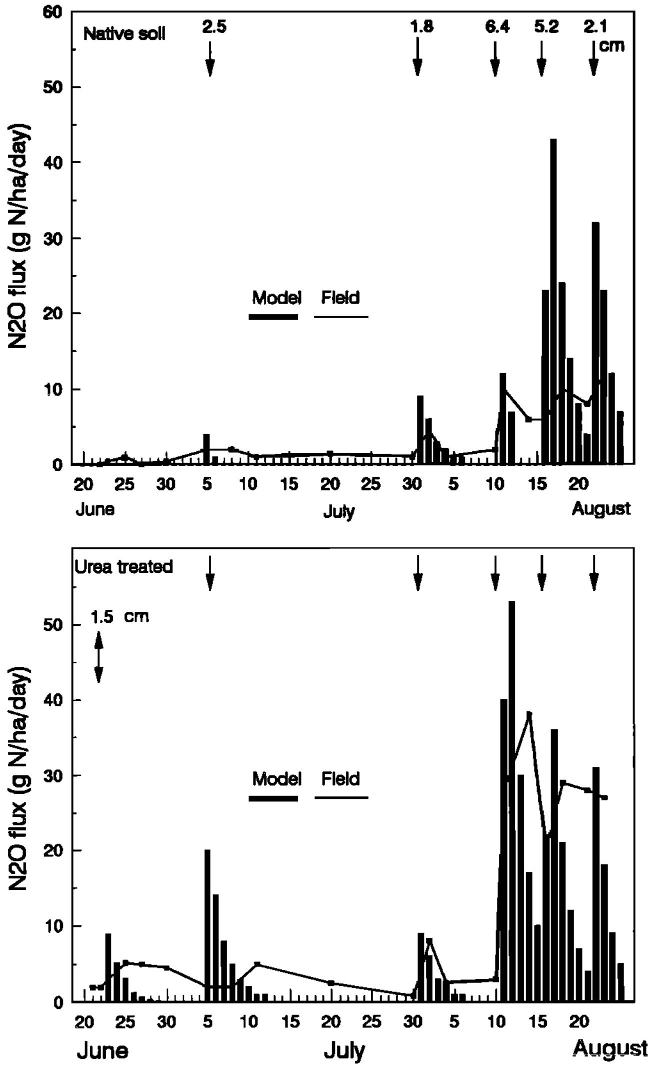

Fig. 1. Comparison of model-simulated N_2O emissions with field-measured N_2O emissions in Colorado in 1979. The bars represent the simulated daily emissions of N_2O from sandy loam soil in Fort Collins County, Colorado, from June 21 to August 22, 1979. The solid squares represent the N_2O emissions measured in the field by *Mosier et al.* [1981]. The single arrows indicate timing of the five rainfall and irrigation events occurring during the sampling period; the numbers above these arrows are the amount of water in centimeters. The double arrow indicates the timing of application of urea equivalent to 450 kg N/ha in 1.5 cm water. In this and the other two denitrification simulations (Figures 2 and 3) the model produces faster and steeper N_2O peaks than are observed in the field following a rain event. This is due to the treatment of gas diffusion in the model (see discussion in text).

were carried out by *Dorr and Munnich* [1987] for a 1-year period in 1979. The average daily emission rates were reported for each month of the year. Soil *p*H is 6.0; total organic C content is 0.02 kg C/kg soil. A climate scenario for the simulation was constructed from 1971 to 1980 mean monthly climate (air temperature and precipitation) for the region [*United States Department of Commerce (USDC)*, 1987]. Briefly, a monthly scenario uses the mean monthly air temperature and an evenly spaced distribution of grade 1 (variable magnitude), grade 2 (19 mm), and grade 3 (6 mm) rainfall events. Grade 3 rainfall events have been found to have no effect on model N_2O fluxes; they do not cause a large enough zone of anaerobic soil. The number of rain events per month in each class depends on the mean monthly precipitation, with the magnitude of the grade 1 rain events varying so the total monthly rain is correct. Annual total precipitation was 58.1 cm, and annual average temperature was 8.9°C. This mean climate scenario will certainly be different from the actual weather at the field site in 1979.

Both the simulated results and the field data show an increase in CO_2 emission with warmer temperatures (Figure 4). The maximum rates were about 35-40 kg C/ha/d in summer and the simulated CO_2 emission rate dropped to zero in winter. The field CO_2 emission rate was very low but measurable in winter. The model underestimates the spring CO_2 fluxes and slightly overestimates summer fluxes but captures the strong seasonal dynamics of microbial activity. Some of the discrepancy may be due to the model's assumption that root respiration is always directly proportional to microbial activity, while spring root growth and associated respiration may cause some deviation.

2.5. *Case 5: CO_2 Emissions From Winter Wheat Field in Missouri*

Measurements of CO_2 emissions from a silty loam soil in a tilled and fertilized winter wheat field in Columbia, Missouri, were carried out by ***Buyanovsky et al.*** [1986] in 1982. The average daily emission rates were reported for each month of the year. Total organic carbon content was 0.012 kg C/kg soil. Wheat was planted in October and harvested by the end of June. Tilling occurred before planting and after harvest. For the simulation the climate scenario was again constructed from long-term (39-year) averages [*United States Department of Agriculture (USDA)*, 1989] and differs from the actual weather in the field in 1982. Annual average precipitation is 101.6 cm, and annual average temperature is 12.8°C at the study area.

The field and simulated CO_2 emission rates show similar seasonal patterns (Figure 5). With the seasonal drop in temperature, autumn emission rates decreased rapidly, but after the wheat was planted (October), CO_2 emission rates increased. This increase was related to increased microbial activity following soil disturbance during planting, probably because of increased aeration and diffusion due to the breakup of a compacted surface crust. The increase in CO_2 emission was significantly higher for the field measurements than the simulated results.

3. DISCUSSION

Overall N_2O fluxes. The simulated emissions of N_2O show the same trends and similar totals to field studies in all cases (Table 4). For three of the four cases (1*b*, 2, and 3) the model underpredicts the total flux by 13-23%, and for the other case (1*a*) it overpredicts by about 75%. Given that the total emissions for the field studies range over 3 orders of magnitude, the deviations of the model simulations are quite small. The model generally captures the timing and intensity of N_2O pulses following rain events. The high peaks and short duration of N_2O emissions in the simulated results could imply that the effective diffusion rates of N_2O in the DNDC model are overestimated. DNDC does not model the diffusion as a gradient-driven flux with diffusion coefficients

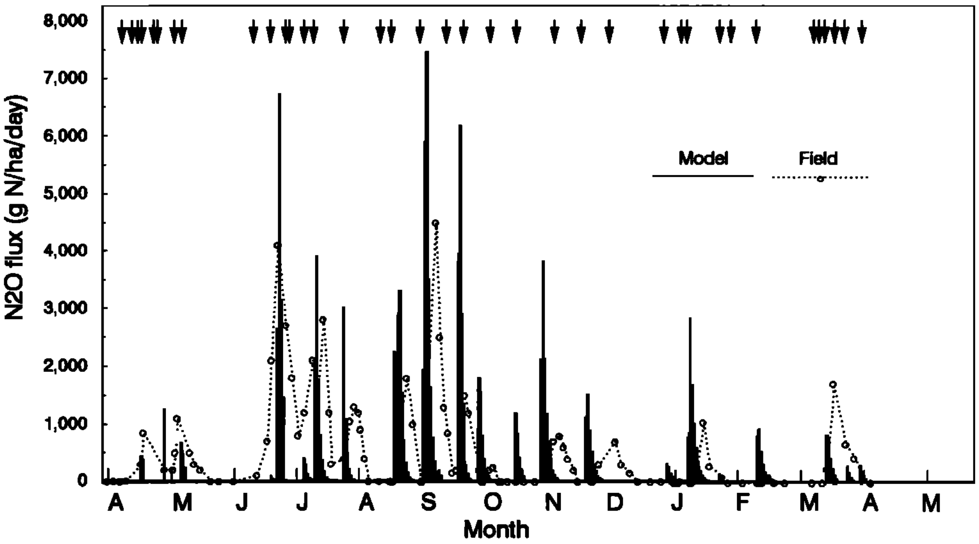

Fig. 2. Comparison of model-simulated N$_2$O emissions with field-measured N$_2$O emissions in Florida. The bars represent the simulated daily emissions of N$_2$O from organic soil (muck) in Belle Glade County, Florida, from April 1979 to May 1980. The circles represent the N$_2$O emissions measured in the field by *Terry et al.* [1981]. The arrows indicate the timing of the 37 rainfall events occurring during the annual sampling period.

TABLE 2. Comparison Between Rainfall Events 18 and 28 in A Fallow Area in Belle Glade County, Florida

Item	Rainfall Event 18	Rainfall Event 28
Date	September 10, 1979	January 26, 1979
Rainfall	11.0 cm	11.6 cm
Temperature	26.5°C	14.7°C
NO$_3^{-a}$	1448.0 kg N/ha	2345.0 kg N/ha
Soluble C^a	54.0 kg C/ha	38.0 kg C/ha
N$_2$O emission	31.8 kg N/ha	8.2 kg N/ha
N$_2$ emission	2.4 kg N/ha	0.3 kg N/ha
CO$_2$ emission	3690.0 kg C/ha	320.0 kg C/ha

[a] Total content in top 15 cm of soil profile.

but rather as an empirical function of N$_2$O production, soil moisture content, and soil clay content [*Li et al.*, this issue]. Field soils have very heterogeneous distributions of pore sizes and tortuosities, which affect both the diffusion of N$_2$O out of the soil and the movements of moisture and oxygen to microsites within soil aggregates, where the microbial activity takes place. The current DNDC model does not account for these details of soil structure. It is also possible that the field studies, with their periodic flux measurements, may themselves be misrepresenting the detailed shape of the N$_2$O pulse, which clearly varies rapidly with time.

Nitrification versus denitrification. In the three unfertilized

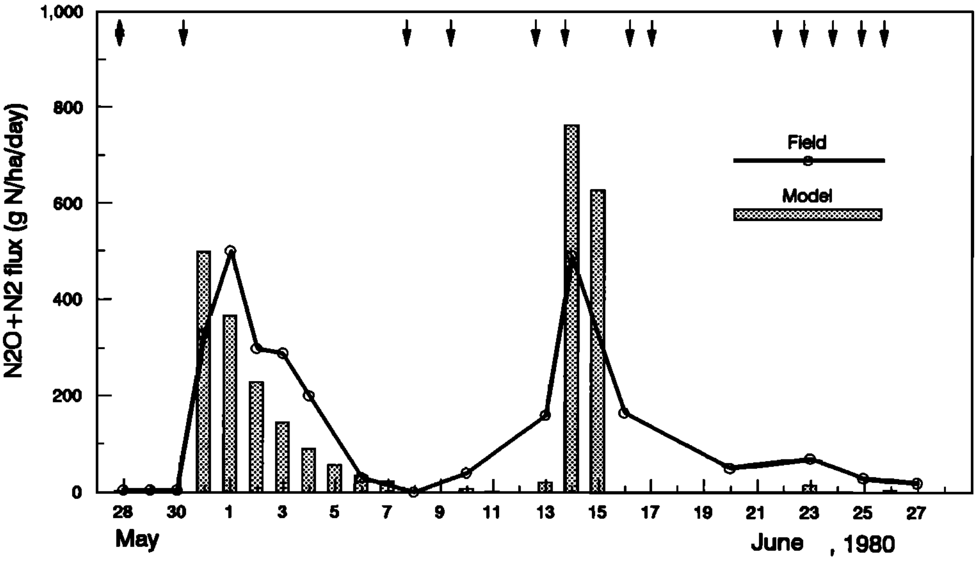

Fig. 3. Comparison of model-simulated N$_2$O+N$_2$ emissions with field-measured N$_2$O+N$_2$ emissions in England in 1980. The bars represent simulated daily total denitrification loss (N$_2$O+N$_2$) from loam soil in a grassland in Berkshire, England, from May 28 to June 27, 1980. Circles represent the denitrification loss measured in field by *Ryden* [1983]. The single arrows indicate timing of the 12 rainfall events occurring during the testing period. The double arrow indicates the timing of the application of 125 kg N/ha as ammonium nitrate.

cases (1*a*, 2, and 3) the ratio of N_2O produced during nitrification to that during denitrification in the simulations ranges from 0.003 to 0.013 (Table 5). For sandy loam soil in Colorado the application of a large amount of urea (450 kg N/ha) increased the ratio to 0.058 (case 1b), but the urea-induced nitrification enhancement only lasted for 13 days (see Table 1). If we assume that nitrification reactions mainly occur in the surface soils (< 50 cm), where organic carbon, ammonium, and nitrate are concentrated, the N_2O evolved during nitrification is equal to 0.021 ng/g/d soil in case 1*a* (sandy soil in Colorado); 0.16 ng/g/d in case 1*b* (urea-treated sandy loam in Colorado); 1.3 ng/g/d in case 2 (muck in Florida); and 0.15 ng/g/d in case 3 (loam in England). The simulated results of N_2O evolution during nitrification are generally consistent with but at the low end of the results (0.16-3.1 ng/g soil/day) of *Bremner and Blackmer* [1981], *Minami et al.* [1978], and *Bremner and Blackmer* [1978]. Although application of ammonium-based fertilizers can increase N_2O emission rates in nitrification, the model predicts that the total amount of N_2O evolved in nitrification is still much lower than that in denitrification. In the DNDC model, nitrification-derived N_2O is limited because fertilizer ammonium or urea remains in soils for only 5-6 days before most is converted into nitrate or lost to other sinks (e.g., leaching, volatilization). In contrast, in laboratory incubation studies of the soils of cases 1*a* and 1*b* under a range of soil-water conditions, *Parton et al.* [1988] find that for all but high water contents, nitrification is the dominant N_2O producer. They conclude from this that nitrification must also have been the dominant N_2O source in the field study because they never observed high water contents in the field. Their simulations predict nitrification to be the source of 60-80% of the N_2O emitted annually from shortgrass prairie soils.

TABLE 3. Simulated and Field Tested Denitrification Loss From Loam Soil in Grassland in Berkshire, England

Rate 1980	Rainfall No.	Rainfall Flux,cm	Simulation N_2O[a]	Simulation N_2O[b]	Simulation N_2	Simulation N_2O+N_2	Field N_2O+N_2
May 28			0.0012	0	0	0.0012	0.005
29			0.0006	0	0	0.0006	0.005
30	1	1.8	0.0004	0.498	0	0.498	0.005
31			0.0003	0.367	0	0.367	0.33
June 1			0.0003	0.230	0	0.230	0.50
2			0.0003	0.144	0	0.144	0.30
3			0.0003	0.090	0	0.090	0.29
4			0.0003	0.056	0	0.056	0.20
5			0.0002	0.035	0	0.035	(0.10)[c]
6			0.0002	0.022	0	0.022	0.03
7			0.0002	0	0	0.0002	(0.01)
8	2	0.2	0.0002	0	0	0.0002	0.005
9			0.0002	0	0	0.0002	(0.005)
10	3	0.5	0.0002	0	0.008	0.008	0.05
11			0.0002	0	0.003	0.003	(0.01)
12			0.0003	0	0.001	0.0013	(0.005)
13	4	0.6	0.0003	0.001	0.021	0.0223	0.17
14	5	2.5	0.0003	0.764	0.010	0.774	0.49
15			0.0003	0.627	0.005	0.632	(0.25)
16			0.0003	0	0	0.0003	0.18
17	6	0.3	0.0003	0	0	0.0003	(0.17)
18	7	0.3	0.0003	0	0	0.0003	0.17
19			0.0003	0	0	0.0003	(0.10)
20			0.0003	0	0	0.0003	0.05
21			0.0003	0	0	0.0003	(0.05)
22			0.0003	0	0	0.0003	(0.05)
23	8	0.5	0.0003	0.001	0.015	0.016	0.08
24	9	0.5	0.0003	0	0.002	0.0023	(0.05)
25	10	0.3	0.0003	0	0	0.0003	0.04
26	11	0.7	0.0003	0	0.006	0.006	(0.04)
27	12	0.1	0.0003	0	0	0.0003	0.03
28			0.0003	0	0	0.0003	(0.03)
Total			0.0102	2.835	0.071	2.916	3.80

Denitrification Loss, kg N/ha

[a] Produced during nitrification.
[b] Produced during denitrification.
[c] Estimated values in parentheses based on neighbors.

CO_2 fluxes. DNDC calculates CO_2 fluxes by determining the CO_2 produced during decomposition (based on laboratory rates) and then calibrates this to field measurements of total soil flux [*Li et al.*, this issue]. The measured soil flux will include root respiration, which is not modeled. Root respiration is accounted for in the calibration factor, which is the same for all studies, and was determined using data from other field measurements [*Li et al.*, this issue]. Both modeled and measured CO_2 fluxes show a marked seasonal pattern, indicating the strong temperature dependence of both the decomposition processes and the root respiration. The model tends to slightly underestimate spring CO_2 fluxes in both cases (Figures 4 and 5) but captures the seasonal trend

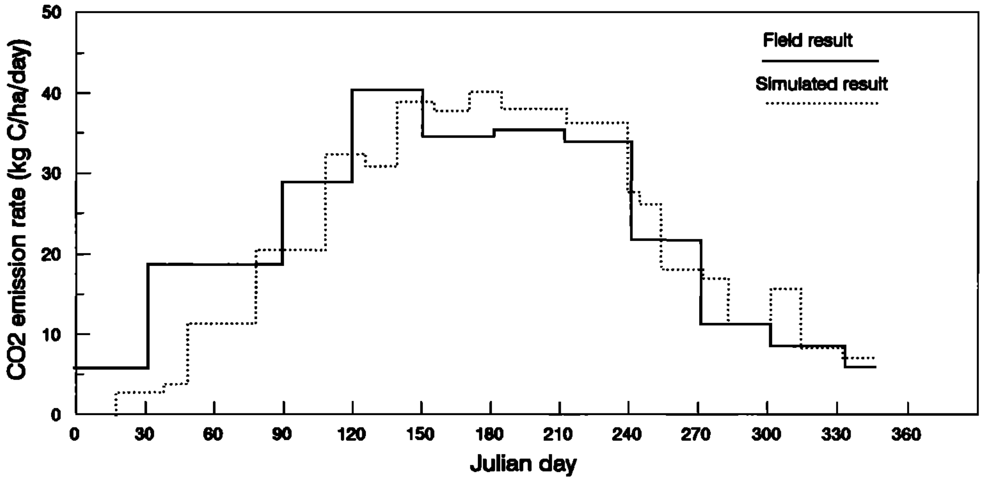

Fig. 4. Simulated and measured CO_2 emissions for a grassland in Heidelberg, Germany. Both CO_2 emission rates show strongly seasonal dependence.

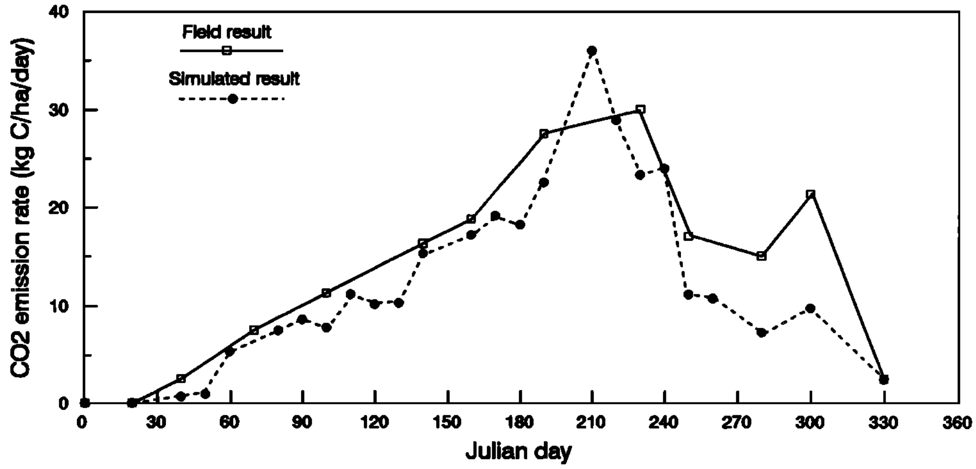

Fig. 5. Simulated and measured CO_2 emissions from winter wheat field in Missouri. The model and field data differ markedly only during September and October. The increase in the CO_2 emission rate in the fall is probably due to cultivation that occurred during the planting of the winter wheat crop.

TABLE 4. Comparison Between Model Simulations and Field Experiments on N_2O Evolution

Case	Soil Type	Duration, Day	N_2O Evolution, kg N/ha	
			Simulation	Field Test
1*a*	sandy loam	61	0.252	0.143[b]
1*b*	urea treated	61	0.421	0.493[b]
2	muck	376	137.0	165.0[c]
3	loam	32	2.92[a]	3.80[ad]

[a] N_2O+N_2.
[b] Mosier et al 1981.
[c] Terry et al 1981.
[d] Ryden 1982.

TABLE 5. Comparison of N_2O Evolved During Nitrification And Denitrification in Model Simulations

Case	Soil Type	Duration, Day	N_2O Evolution, kg N/ha		
			A	B	A/B
1*a*	sandy loam	61	0.0032	0.249	0.013
1*b*	urea treated	61	0.0229	0.396	0.058
2	muck	376	0.422	136.7	0.003
3	loam	32	0.0102	2.835	0.004

A, produced during nitrification; B, produced during denitrification.

and overall magnitude of the fluxes quite well. Some of the differences may be due to the model using a long-term mean climate, while the field results depend on the particular year's weather. Some of the differences may be due to root growth respiration, which will probably have a different seasonal signal than root maintenance respiration [*Johnson*, 1990].

4. CONCLUSIONS AND FURTHER STUDIES

As a mechanistic simulation model, DNDC uses rainfall events as a driving force to conduct monthly to annual biogeochemical simulations of soil carbon and nitrogen cycles. This model structure allows DNDC to account for the main nitrification and denitrification reactions under both aerobic and anaerobic conditions in soils and to integrate these activities with other decomposition processes during dry and wet periods to ascertain total N_2O production and emission. For both N_2O and CO_2 emissions, DNDC behaves consistently with field reports in comprehensive, long-term simulations.

In this study, DNDC simulated N_2O evolution in a wide range of soil types without changing any internal parameters. This implies that the external parameters adequately cover the major factors which influence regional variations in N_2O emissions. Therefore obtaining appropriate climate and soil data becomes critical when applying DNDC to regional or global scales. For a specific area during a specific period of time, as in the five cases simulated in this study, the required external parameters may be available. But for a large region and a long time period, one must determine how to generalize the available data to formulate the required parameters, such as rainfall timing and intensity, soil properties, irrigation, fertilization, and other anthropogenic activities. More general data sources, such as national or international meteorological records and soil surveys, should be considered and compiled into a geographic information system (GIS), to which DNDC could be connected to execute regional analyses.

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S. Frolking, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824.

T. A. Frolking, Department of Geology and Geography, Denison University, Granville, OH 43023.

C. Li, The Bruce Company, 1100 6th Street, N.W., Suite 215, Washington, D. C. 20024.

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