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Estimation of Nitrous Oxide Emissions from US Grasslands

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ABSTRACT / Nitrous oxide (N_2O) emissions from temperate grasslands are poorly quantified and may be an important part of the atmospheric N_2O budget. In this study N_2O emissions were simulated for 1052 grassland sites in the United States using the NGAS model of Parton and others (1996) coupled with an organic matter decomposition model. N_2O flux was calculated for each site using soil and land use data obtained from the National Resource Inventory (NRI) database and weather data obtained from NASA. The estimates were regionalized based upon temperature and moisture isotherms. Annual N_2O emissions for each region were based on the grassland area of each region and the mean estimated annual N_2O flux from NRI grassland sites in the region. The regional fluxes ranged from 0.18 to 1.02 kg N_2O N/ha/yr with the mean flux for all regions being 0.28 kg N_2O N/ha/yr. Even though fluxes from the western regions were relatively low, these regions made the largest contribution to total emissions due to their large grassland area. Total US grassland N_2O emissions were estimated to be about 67 Gg N_2O N/yr. Emissions from the Great Plains states, which contain the largest expanse of natural grassland in the United States, were estimated to average 0.24 kg N_2O N/ha/yr. Using the annual flux estimate for the temperate Great Plains, we estimate that temperate grasslands worldwide may potentially produce 0.27 Tg N_2O N/yr. Even though our estimate for global temperate grassland N_2O emissions is less than published estimates for other major temperate and tropical biomes, our results indicate that temperate grasslands are a significant part of both United States and global atmospheric N_2O budgets. This study demonstrates the utility of models for regional N_2O flux estimation although additional data from carefully designed field studies is needed to further validate model results.

Nitrous oxide (N_2O) is a radiatively active atmospheric trace gas implicated in stratospheric ozone destruction (Watson and others 1992). The long atmospheric lifetime of N_2O (120 years) contributes to its large radiative forcing potential, which is, on a molecule-for-molecule basis, about 280–310 times that of CO_2 (Shine and others 1995). In 1990 its atmospheric concentration was about 312 ppbv and has increased in the 1980s at a rate of about 0.8 ppbv/yr (IPPC 1995). N_2O currently accounts for 5%–6% of the radiative forcing caused by long-lived GHG but is becoming increasingly important and may eventually contribute to as much as 10% of the global warming potential (Cicerone 1989).

Although the observed increase in atmospheric N_2O concentration implies that sources of N_2O exceed sinks by 3.9 Tg N/yr, current estimates for total identified sources are less than estimates for known sinks (Prather and others 1995). Concern about the environmental consequences of increased N_2O in the atmosphere and the disparity between observed atmospheric increases and current source and sink estimates has stimulated interest in more accurately quantifying N_2O source strengths.

Even though sources of N_2O are poorly quantified, microbial processes in soil are generally believed to be by far the greatest source. N_2O production in soil is generated from two dissimilar energy-yielding microbial processes, nitrification and denitrification. The denitrification process is regulated by the availability of nitrate (NO_3^-), oxygen, and reduced forms of carbon (Knowles 1982). Nitrification is predominantly regulated by ammonium (NH_4^+) availability (Firestone and Davidson 1989). The substrate for each of these processes is determined by the relative rates of N mineralization and N assimilation by plants and microbes and by diffusional constraints.

On a global basis N_2O emissions from soil in natural or relatively undisturbed ecosystems are the least well

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quantified of the known N_2O sources but are probably at least twice as large as N_2O emissions from anthropogenic sources (IPCC 1995). Soil in humid tropical forests is generally considered the largest natural N_2O emission source followed by wetlands, temperate forests and temperate grasslands (Bowden 1986). Anthropogenic sources of N_2O from fossil fuel and biomass burning contribute 25% of global emissions, whereas, emissions from natural soils contribute 43% of the total yearly emissions of N_2O on a global basis (Bouwman 1990).

Despite the low N_2O emission rates generally associated with temperate grasslands (Mosier and others 1996, Matson and others 1991), they may represent an important part of both the United States and the global N_2O budget due to their large land area. Temperate grasslands cover about 26% (2.4×10^8 ha) of the total US land area (9.2×10^8 ha) (USDA 1996) and cover 12.5×10^9 ha or 8% of the land area globally (Ajtay and others 1979).

Although much is known about the biotic and abiotic processes responsible for N_2O production and emission from soil, applying this knowledge to quantifying N_2O flux at regional scales is problematic. The complex interactions between soil type, texture, porosity, pH, N availability, organic carbon content, moisture, and oxygen status and the microorganisms that regulate N_2O production and movement in the soil environment are highly variable both spatially and temporally (Corre and others 1996, Folorunso and Rolston 1984, Schimel and others 1988). Field measurements are few in number and are typically taken from small areas over short time periods, yet to produce regional estimates this data must be integrated up to regional scales and annual or longer cycles.

Most estimation efforts at the regional scale have relied on a few measured estimates multiplied by broad vegetation groups or climate zones. The major limitation of such techniques is ascertaining whether the available measurements are representative of regional N_2O flux (Williams and others 1992, Matson and others 1989). It is unlikely that these techniques can account for the extreme variability of N_2O flux without large numbers of additional measurements that are both costly and time intensive.

Model simulation of the processes responsible for the production of N_2O in the soil environment may be a means to more accurately quantify N_2O emissions at regional scales (Williams and others 1992). A number of simulation models have been developed for estimating denitrification and/or N_2O emissions from soil (Li and others 1992, Bouwman and others 1993). Unfortunately most of these models are unable to predict N_2O emissions on a daily or seasonal basis using readily available input data. Two exceptions are the detailed process-oriented denitrification–decomposition (DNDC) model (Li and others 1992) and the recently developed general model for N_2 and N_2O formation from nitrification and denitrification (NGAS) (Parton and others 1996).

In this study the NGAS model was coupled with an organic matter decomposition model and used to estimate annual N_2O emissions from grassland in the continental United States. Use of the extensive NRI database, which includes specific soil data, allowed the estimation of site-specific N_2O flux from 1052 grassland sites across the United States. Quantification of N_2O emissions from temperate grasslands is important because it can increase the accuracy of our budget calculations and can also serve as a benchmark for determining the effects of ecosystem disturbance due to land conversion and management practices on N_2O emissions. The goals of this study were to estimate N_2O emissions from US grasslands and temperate grasslands worldwide.

Methods

The NGAS model is a hybrid between detailed process-oriented models (Li and others 1992) and simplistic nutrient cycling models (Parton and others 1988). The NGAS model was designed to be incorporated into nitrogen cycling models and used to simulate regional and global trace gas production as a function of climate, soil properties, and management practices. The model was developed using laboratory denitrification gas flux data (Weier and others 1993) and field-observed N_2O flux data from a number of sites in Colorado (Mosier and others 1996).

The main factor driving the NGAS model is the availability of inorganic ammonium (NH_4) for nitrification and denitrification. To simulate daily NH_4^+ availability for nitrification, plant uptake, and denitrification we modified a decomposition model from Li and others (1992) and Molina and others (1983). The model allows for decomposition to occur simultaneously in plant residue, microbial biomass, and humic organic matter pools producing NH_4 for plant uptake, nitrification, and denitrification. Each pool has labile and resistant fractions that decompose at different rates. Each fraction was assigned a first-order decomposition rate for optimal conditions (Li and others 1992). Decomposition was then regulated by reduction factors that retard the decomposition rate based on N-limitations, nonoptimum soil moisture and temperature, and with increasing clay content.

The important processes governing the decomposition section of the model are water addition and movement, nitrification and plant uptake of NH_4, and residue additions. These processes were modeled using basic input data and fundamental water movement equations.

In order to calculate daily water additions to the soil, monthly precipitation was divided into equal amounts corresponding to the number of days each month having precipitation greater than 0.1 inch. These fractions were then added to the soil at equal intervals throughout the month, after subtracting the amount lost to potential evapotransporation (ET). ET was determined as a function of average monthly air temperature using the Thorthwaite formula, adjusted for daylight relative to 12 h (Dunne and Leopold, 1978) and made to decrease linearly from potential ET to zero as soil water content drops from field capacity to the wilting point (Sellers 1965).

A one-dimensional soil moisture model was used to calculate WFPS for each day of the year. For each 1-h time step, water fluxes were determined by gradients of soil water potential. Unsaturated hydraulic conductivity was calculated for each site using the method of Campbell (1974). Representative values for saturated hydraulic conductivity (K_s) and the water content at saturation (θ_s) for each soil textural class were obtained from Clapp and Hornberger (1978).

Nitrification rates and NO_3^- availability for denitrification and plant uptake were calculated as a function of soil moisture content, soil temperature, and NH_4^+ availability with optimal rates at 35°C and soil pore moisture content of 90%. Plant nitrogen requirements were removed daily over the growing season from soil NH_4^+ and NO_3^- pools based on their relative concentrations. Plant N uptake rates over the growing season were obtained from literature reports of plant growth and N uptake dynamics (Buyanovsky and others 1987).

We calculated the mean biomass of the standing crop at each site using annual precipitation and usable solar incident radiation and a stepwise multiple regression equation generated by Sims and others (1978). All plant residues were assigned a C-to-N ratio of 35. The plant residue pool was gradually released for decomposition one month prior to the end of the growing season to simulate the natural senescence of plant components at the end of the growth phase.

The output from the decomposition submodel feeds directly into the NGAS model, which uses water, pH, temperature, and the mineralization (NH_4 production) of soil organic matter or NH_4 fertilizer input to govern the N_2O flux from nitrification. Thus, the governing equation (Parton and others 1996) can be represented by:

$$N_{N_2O} = N_{H_2O} \cdot N_{pH} \cdot N_t (K_{mx} + N_{mx} \cdot N_{NH_4}) \quad (1)$$

where N_{H_2O}, N_{pH}, and N_t are the effects on the nitrification fraction from water-filled pore space, pH, and temperature, respectively. The variable K_{mx} is the soil organic matter turnover related to nitrification N_2O production (grams N per hectare per day) and the product $N_{mx} \cdot N_{NH_4}$ is the effect of excess levels of NH_4 on the nitrification fraction with N_{mx} being the maximum rate.

The production of N_2O and N_2 from denitrification (D_l) is a function of microbial respiration, soil NO_3 level and water-filled pore space (WFPS) and is represented by equation 2: (Parton and others 1996)

$$D_l = \min [F_d(NO_3), F_d(CO_2)] F_d(WFPS) \quad (2)$$

where F_d is the fraction of denitrification attributed to NO_3 levels from nitrification, CO_2 respiration rates from mineralization of organic matter, and from the effects of WFPS on denitrification, with ''min'' being the minimum of the function.

Parton and others (1996) developed functions for these factors based upon observed data sets that describe the effect of these parameters on nitrification and denitrification. These functions are then used in the model simulation to adjust for changing temporal or spatial conditions. Estimates of denitrification N_2O flux are calculated using a function of total denitrification gas fluxes, soil respiration rate, soil NO_3^- concentration, and WFPS.

For model input parameters we used the US National Resource Inventory (NRI) database, which includes soil characteristics and interpretation, Earth cover, land cover, erosion, land treatment, and vegetative conditions. From this database we extracted data for organic N and C contents, average monthly temperature, textural properties, pH, and moisture contents at field capacity and the wilting point. The data was obtained for 1052 grassland sites in the continental United States and were chosen to limit livestock and fertilized pastures. Precipitation data for these sites was obtained from NASA (1983) from weather stations across the United States. Average long-term weather data were used since we were aggregating temporal and spatial fluxes for regional estimates.

Two years were simulated to allow residue, microbial biomass, humic, and inorganic pools to equilibrate. Annual N_2O flux estimates for the second year were used for subsequent regional analysis. Annual N_2O emissions were calculated on a state-by-state basis by multiplying the grassland area (USDA 1996) of each state by the mean estimate for all NRI grassland sites in

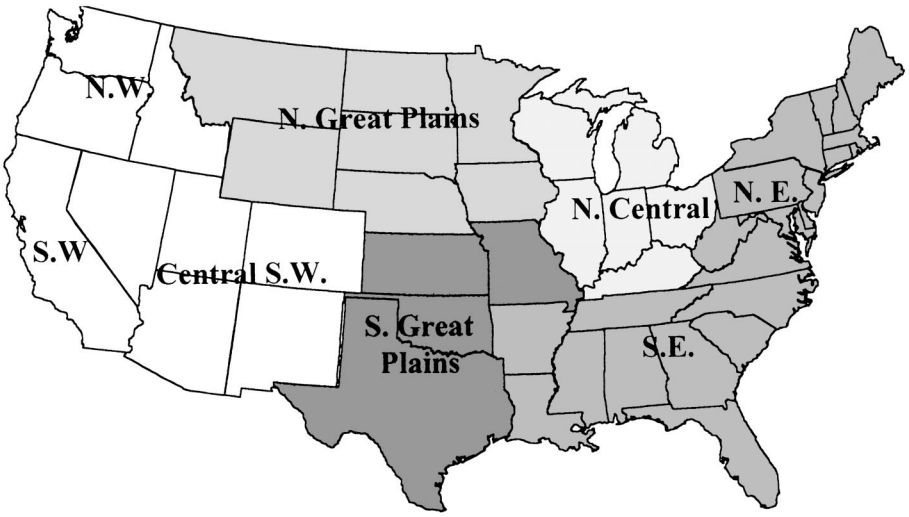

Figure 1. Regions of the United States used to model N_2O flux from grasslands.

the state. States were then grouped into regions based on climate and soil type similarity (Figure 1).

Results and Discussion

Model Comparisons

Model estimates were compared to N_2O flux measurements from US grasslands reported in the literature. Modeled mean flux estimates were very similar to estimates from two studies in Colorado and Wyoming, Mosier and others (1996) and Matson and others (1991), respectively. However, other comparisons using studies with few measured data and general climate attributes showed differences between measured and modeled values.

Mosier and others (1996) measured N_2O flux each week over six years from shortgrass prairie sites in Colorado that encompass a broad range of soil types and slope positions. This is the longest and most intensively sampled study we are aware of and therefore should reflect the seasonal and interannual variability of N_2O flux in this region. The modeled mean flux estimate of 0.17 kg N_2O N/ha/yr is well within the range of 0.1–0.2 N_2O N/ha/yr measured by these authors.

Matson and others (1991) recognized that nitrogen cycling, and therefore N_2O flux characteristics, varies among plant communities within shrub–steppe ecosystems. These authors measured N_2O flux from a number of different vegetation associations and soil types in Wyoming shrub–steppe ecosystems over two years. Weighting the values by the areal extent of each vegetation association, they calculated a regional N_2O flux estimate of 0.21 N_2O N/ha/yr. The mean flux predicted by the model for the Wyoming region was 0.20 N_2O N/ha/yr.

These studies are similar in that both were designed to account for variation in regional vegetation and/or soil characteristics and both collected a relatively large number of samples at frequent intervals.

Estimates from studies that were not designed to account for interregional variability (Goodroad and Keeney 1984, Mummey and others 1997) were generally dissimilar to modeled mean fluxes. For the Wisconsin study of Goodroad and Keeney (1984), the measured flux was 0.1 N_2O N/ha/yr whereas the modeled flux was 0.28 N_2O N/ha/yr. For the semiarid shrubland study of Mummey and others (1997), the measured value was 0.15 N_2O N/ha/yr and the modeled estimate was 0.26 N_2O N/ha/yr.

These results indicate that the model predicts N_2O emissions from grasslands with reasonable accuracy when soil and environmental characteristics are accurately measured or known. Since, the relationships between the variables that control N_2O production and emission from the soil are probably universal and the model is driven by these relationships, then with specific input data the model should be able to estimate N_2O on a regional basis.

US Grassland N_2O Emissions

Model estimates for mean annual N_2O N flux, temperature, and precipitation for grasslands in each region are presented in Table 1. These results show that the spatial distribution of N_2O flux is very similar to climate patterns. Mean annual precipitation, temperature, and N_2O flux estimates generally increase from the northern Great Plains region to the SE region. The

Table 1. Regional mean annual temperature, precipitation, and modeled N_2O flux for grassland sites in the United States

Region	Mean annual temperature (°C)	Annual precipitation (cm)	N_2O N (kg/ha/yr)
South East	18.3	117	1.02
North East	11.1	99.1	0.41
N. Central	11.3	91.9	0.28
Southern Great Plains	18.8	69.9	0.42
North West	11.8	53.5	0.19
Northern Great Plains	9.9	48.8	0.21
South West	16.8	34.0	0.31
Central Southwest	17.2	33.0	0.18

Table 2. Grassland area and total N_2O emission for each region

Region	Grassland area (ha $\times 10^6$)[a]	N_2O N (kg $\times 10^6$)
South East	7.5	7.6
North East	3.8	1.6
North Central	2.1	0.6
Southern Great Plains	56.3	23.5
North West	20.4	3.9
Northern Great Plains	61.3	13.1
South West	9.9	3.1
Central Southwest	77.4	14.0
Total	239	67.4

[a]Adapted from USDA (1996).

highest flux estimates are for states in the southeastern region having a subtropical climate along the Gulf Coast (E. Texas, Louisiana, Mississippi, Alabama, and Florida), where both moisture and temperature characteristics are favorable for N_2O production year round. Low mean annual precipitation coupled with high mean annual temperature results in N_2O production being moisture-limited for much of the year in the southwest–central region.

Total grassland area and N_2O N emission estimates for each region are presented in Table 2. We estimate that the 238×10^6 ha of grassland in the continental United States produce 67.2 Gg N_2O N/yr. Although fluxes from the western regions are relatively low, they have the largest grassland areas and therefore make the largest contribution to emissions. Even though the grassland area of the Gulf Coast states (Florida, Mississippi, Alabama, Louisiana) comprises only about 2% of the total grassland area (4.64×10^6 ha), the high N_2O flux per hectare of grassland in these states makes their contribution disproportionately large (5.95 Gg N_2O N/yr, 8.8% of total emissions).

Total N_2O N emissions from agriculture, fossil fuel consumption, and industrial processes are estimated to be about 0.26 Tg/yr (EPA 1994). Therefore, in the United States, grasslands may emit 26% as much N_2O to the atmosphere as anthropogenic emission sources. These results suggest that N_2O emissions from grassland in the United States may be an important part of the US atmospheric budget.

Global Grassland N_2O Emissions

Natural grasslands can be defined as areas in which herbaceous plant cover is the dominant climax community (Coupland 1992a). Natural grasslands occur along a climatic gradient between desert and forest and share many common features, such as climates with periodic droughts, frequent fires, and level to gently rolling topography (Ripley 1992). Land management practices such as forest clearing and fire suppression has altered the spatial distribution of grass-dominated lands in the United States to include areas that were not historically grassland. Grass-dominated areas in which trees have been removed, but that will revert back to forest vegetation if undisturbed, and areas in which woody species are the dominant overstory, such as desert scrublands, do not meet the grassland definition. Therefore, the total grassland area used to calculate US grassland emissions may not be representative of all grasslands; however, the large area of the temperate Great Plains grasslands may be more suitable for global analysis.

The grasslands of the Great Plains states (Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas) cover 2.23×10^8 ha or 19% of global temperate grassland (Bouwman 1990, Mosier and others 1997) and comprise the largest area in the United States that meets the natural grassland criteria (Coupland 1992b). Moisture conditions in these states encompass the conditions found throughout the majority of temperate grasslands worldwide and vary from near-arid at the southwestern extension to humid along the eastern border with coniferous and deciduous forests. We used the modeled emission for the grasslands of the Great Plains of 0.24 kg N_2O N/ha/yr to estimate global temperate grassland N_2O flux.

Bouwman (1990) estimated that worldwide temperate grasslands cover 1.15×10^9 ha[2]. If we assume that the distribution of climate patterns and other variables that drive N_2O emissions in temperate grasslands worldwide is similar to the Great Plains, we can use the product of the modeled Great Plains N_2O N flux and the global temperate grassland area data of Bouwman (1990) to estimate a global temperate grassland emis-

Table 3. N_2O emission estimates from some of the worlds major biomes

Biome	Area (10^6 km^2)	N_2O N (Tg/yr)	Reference
Temperate forest	21	1–2.5	Bowden (1986)
Temperate forest	21	0.7–1.5	Schmidt and others (1988)
Temperate forest	21	0.01	Bowden and others (1990)
Wet tropical forest	15	2.4	Matson and Vitousek (1990)
Drought-deciduous tropical forest	10	0.4–1.3	Vitousek and others (1989)
Temperate grassland	12	0.27	This study

sion of 0.27 Tg N_2O N/yr. Globally, total anthropogenic emission of N_2O N is estimated to be between 3 and 7 Tg/yr (IPPC 1995). Therefore, temperate grasslands may produce between 4% and 9% as much N_2O as current anthropogenic sources.

N_2O emission estimates for the major temperate and tropical biomes are listed in Table 3. Although the uncertainty associated with these estimates is great, they suggest that undisturbed temperate grasslands may produce less N_2O than other major biomes in temperate and tropical regions. However, temperate grasslands have been extensively developed and are some of the major livestock- and crop-producing areas of the world. Thus future emissions from grasslands may need to include specific management practices such as crop and livestock production.

It is well documented that when grassland is converted to cropland, N_2O emissions generally increase (e.g., Duxbury and others 1982, Mosier and others 1997). Fertilizer N use and the enhanced organic matter decomposition and soil erosion associated with conventional agriculture results in gaseous losses of both carbon and nitrogen, including N_2O, to the atmosphere (Lal and others 1995).

Livestock affect the chemical, physical, and biological properties of soil that influence N_2O emission, through excretion of urine and feces, and treading (Flessa and others 1996). These authors recently estimated that 1.18 Tg N_2O N is evolved to the atmosphere from cattle and buffalo excreta worldwide each year. This estimate is over four times greater than our estimate for temperate grassland N_2O emissions. Although much of the N_2O emissions from this source are from manure application to cultivated lands, a large amount must be evolved from temperate grasslands.

Anthropogenic N_2O emissions from temperate grasslands may therefore be considerable. Further research is needed to determine the effects of cultivation, livestock excreta and other anthropogenic influences on total N_2O emissions from temperate grasslands.

Literature Cited

Ajtay, G. L., P. Ketner, and P. Duvigneeaud. 1979. Terrestrial primary production and phytomass. Pages 129–181 *in* B. Bolin, E. T. Degens, S. Kempe, and P. Ketner (eds.), The global carbon cycle. Wiley, Chichester, UK.

Bouwman, A. F. 1990. Exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. Pages 61–127 *in* A. F. Bouwman (ed.), Soils and the greenhouse effect. John Wiley & Sons, New York.

Bouwman, A. F., I. Fung, E. Matthews, and J. John. 1993. Global analysis of the potential for N_2O production in natural soils. *Global Biogeochemical Cycles* 7:557–597.

Bowden, W. B. 1986. Gaseous nitrogen emissions from undisturbed terrestrial ecosystems: An assessment of their impacts on local and global nitrogen budgets. *Biogeochemistry* 2:249–279.

Bowden, D. B., P. A. Steudler, and J. M. Melillo. 1990. Annual nitrous oxide fluxes from temperate forest soils in the northeastern United States. *Journal of Geophysical Research* 95:13,997–14,005.

Buyanovsky, G. A., C. L. Kucera, and G. H. Wagner. 1987. Comparative analyses of carbon dynamics in native and cultivated ecosystems. *Ecology* 68:2023–2031.

Campbell, G. S. 1974. A simple method for determining unsaturated conductivity from moisture retention data. *Soil Science* 117:311–314.

Cicerone, R. J. 1989. Analysis of sources and sinks of atmospheric nitrous oxide (N_2O). *Journal of Geophysical Research* 94:18265–18271.

Clapp, R. B., and G. M. Hornberger. 1978. Empirical equations for some soil hydraulic properties. *Water Resources Research* 14:601–604.

Corre, M. D., C. van Kessel, and D. J. Pennock. 1996. Landscape and seasonal patterns of nitrous oxide emissions in a semiarid region. *Soil Science Society of America Journal* 60:1806–1815.

Coupland, R. T. 1992a. Approach and generalizations. Pages 1–6 *in* R. T. Coupland (ed.), Ecosystems of the world, natural grasslands, introduction and Western Hemisphere. Elsevier, New York.

Coupland, R. T. 1992b. Overview of the grasslands of North America. Pages 147–150 *in* R. T. Coupland (ed.), Ecosystems of the world, natural grasslands, introduction and Western Hemisphere. Elsevier, New York.

Dunne, T., and L. Leopold. 1978. Water in environmental planning, W. H. Freeman, New York.

Duxbury, J. M., D. R. Bouldlin, R. E. Terry, and R. L. Tate. 1982. Emissions of nitrous oxide from soils. *Nature* 298:462–464.

EPA. 1994. Inventory of US greenhouse gas emissions and sinks: 1990–1993. US Environmental Protection Agency, Office of Policy, Planning and Evaluation. Washington, DC.

Firestone, M. K., and E. A. Davidson. 1989. Microbiological basis of NO and N_2O production and consumption in soil. Pages 7–21 *in* M. O. Andreae and D. S. Schimel (eds.), Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons, New York.

Flessa, H., P. Dorsch, F. Beese, H. Konig, and A. F. Bouwman. 1996. Influence of cattle wastes on nitrous oxide and methane fluxes in pasture land. *Journal of Environmental Quality* 25:1366–1370.

Folorunso, O. A., and D. E. Rolston. 1984. Spatial variability of field-measured denitrification gas fluxes. *Soil Science Society of America Journal* 48:1214–1219.

Goodroad, L. L., and D. R. Keeney. 1984. Nitrous oxide emission from forest, marsh, and prairie ecosystems. *Journal of Environmental Quality* 13:448–452.

IPCC. 1995. Technical summary. Pages 9–49 *in* J. T. Houghton, L. G. Meira Filho, B. A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), Climate change 1995, the science of climate change. Cambridge University Press, New York.

Knowles, R. 1982. Denitrification. *Microbiological Reviews* 46: 43–70.

Lal, R., J. Kimble, and B. A. Stewart. 1995. World soils as a source or sink for radiatively-active gases. *In* R. Lal, J. Kimble, E. Levine, and B. A. Stewart (eds.), Soil management and greenhouse effect. Lewis Publishers, Boca Raton, Florida.

Li, C., S. Frolking, and T. A. Frolking. 1992. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. *Journal of Geophysical. Research* 97: 9759–9776.

Matson, P. A., and P. M. Vitousek. 1990. Ecosystem approach to a global nitrous oxide budget. *Bioscience* 40:667–672.

Matson, P. A., P. M. Vitousek, and D. S. Schimel. 1989. Regional extrapolation of trace gas flux based on soils and ecosystems. Pages 109–119 *in* M. O. Andreae and D. S. Schimel (eds.), Exchange of trace gases between terrestrial ecosystems and the atmosphere. John Wiley & Sons, Chichester, UK.

Matson, P. A., C. Volkmann, K. Coppinger, and W. A. Reiners. 1991. Annual nitrous oxide flux and soil nitrogen characteristics in sagebrush steppe ecosystems. *Biogeochemistry* 14:1–12.

Molina, J. A. E., C. E. Clapp, M. J. Shaffer, F. W. Chichester, and W. E. Larson. 1983. NCSOIL, a model of nitrogen and carbon transformations in soil; description, calibration, and behavior. *Soil Science Society of America Journal* 47:85–91.

Mosier, A. R., W. J. Parton, D. W. Valentine, D. S. Ojima, D. S. Schimel, and J. A. Delgado. 1996. CH_4 and N_2O fluxes in the Colorado shortgrass steppe: 1. Impact of landscape and nitrogen addition. *Global Biogeochemical Cycles* 10:387–399.

Mosier, A. R., W. J. Parton, D. W. Valentine, D. S. Ojima, D. S. Schimel, and O. Heinemeyer. 1997. CH_4 and N_2O fluxes in the Colorado shortgrass steppe 2. Long-term impact of land use change. *Global Biogeochemical Cycles* 11:29–42.

Mummey, D. L., J. L. Smith, and H. Bolton, Jr. 1997. Small-scale spatial and temporal variability of N_2O flux from a shrub-steppe ecosystem. *Soil Biology and Biochemistry* 29:1699–1706.

NASA. 1983. Climate normals for the U.S. (base: 1951–1980). National Climatic Center, Environmental Data and Environmental Data Information Service, National Oceanic and Atmospheric Administration, Gale Research Company, Detroit, Michigan.

Parton, W. J., A. R. Mosier, and D. S. Schimel. 1988. Rates and pathways of nitrous oxide production in a shortgrass steppe. *Biogeochemistry* 6:45–48.

Parton, W. J., A. R. Mosier, D. S. Ojima, D. W. Valentine, D. S. Schimel, K. Weier, and A. E. Kulmala. 1996. Generalized model for N_2 and N_2O production from nitrification and denitrification. *Global Biogeochemical Cycles* 10:401–412.

Prather, M., R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, and X. Zhou. 1995. Other trace gasses and atmospheric chemistry. Pages 73–126 *in* J. T. Houghton, L. G. Meira Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haites, N. Harris, and K. Maskell. (eds.), Climate change 1994. Cambridge University Press, Cambridge.

Ripley, E. A. 1992. Grassland Climate. Pages 7–24 *in* R. T. Coupland (ed.), Ecosystems of the world, natural grasslands, introduction and Western Hemisphere. Elsevier, New York.

Schimel, D. S., S. Simkins, T. Rosswall, A. R. Mosier, and W. J. Parton. 1988. Scale and measurement of nitrogen-gas fluxes from terrestrial ecosystems. Pages 179–193 *in* T. Rosswall, R. G. Woodmansee, and P. G. Risser (eds.), Scales and global change, Scientific Committee on Problems of the Environment (SCOPE). John Wiley & Sons, New York.

Schmidt, J., W. Seiler, and R. Conrad. 1988. Emission of nitrous oxide from temperate forest soils into the atmosphere. *Journal of Atmospheric Chemistry* 6:95–115.

Sellers, W. D. 1965. Physical climatology. University of Chicago Press, Chicago.

Shine, K. P., Y. Fouquart, V. Ramaswamy, S. Solomon, and J. Srinivasan. 1995. Radiative forcing. *In* J. T. Houghton, L. G. Meiro Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haites, N. Harris, and K. Maskell (eds.), Climate change 1994, impacts, adaptations and mitigation of climate change: scientific technical analysis. Cambridge University Press, Cambridge.

Sims, P. L., J. S. Singh, and W. K. Lauenroth. 1978. The structure and function of ten western North American grasslands. *Journal of Ecology* 66:251–285.

USDA. 1996. Agricultural Statistics 1995–96. United States Department of Agriculture. United States Government Printing Office, Washington, DC.

Vitousek, P., P. Matson, C. Volkmann, J. M. Maass, and G. Garcia. 1989. Nitrous oxide flux from dry tropical forests. *Global Biogeochemical Cycles* 3:375–382.

Watson, R. T., L. G. Meiro Filho, E. Sanhuenza, and A. Janetos. 1992. Pages 25–46 *in* J. T. Houghton, B. A. Callander, and S. K. Varney (eds.). Climate change 1992. The supplimentary report to the IPCC scientific assessment, Cambridge University Press, New York.

Weier, K. L., J. W. Doran, J. F. Power, and D. T. Walters. 1993. Denitrification and the dinitrogen/nitrous oxide ration as effected by soil water, available carbon, and nitrate. *Soil Science Society of America Journal* 57:66–72.

Williams, E. J., G. L. Hutchinson, and F. C. Fehsenfeld. 1992. No_x and N_2O emissions from soil. *Global Biogeochemical Cycles* 6:351–388.