

Nitrous Oxide Emission from Soils

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I. Introduction

Nitrous oxide (N₂O) constitutes only 350 parts per billion (ppb) of the atmosphere. Its production by biochemical processes in soils has long been recognized (Delwiche, 1981; Payne, 1981a, b). However, recent

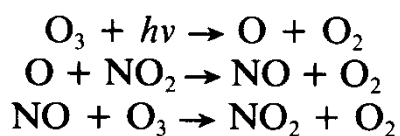
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Contribution from the college of Agricultural and Life Sciences and by the National Science Foundation.

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concern about the involvement of N_2O in promoting destruction of the stratospheric ozone layer, which protects the biosphere from harmful ultraviolet radiation (Crutzen, 1970, 1971, 1974, 1981; Johnston, 1971, 1977; CAST, 1976; McElroy *et al.*, 1977; Liu *et al.*, 1977), and also the concern that the increased N_2O may contribute to the "greenhouse effect" caused by increased CO_2 concentration (Yung *et al.*, 1976), have resulted in extensive research on how N_2O emissions are affected by fertilizer N usage for meeting food, feed, and fiber requirements of the world (Delwiche, 1981; Payne, 1981b; Keeney, 1982; Firestone, 1982; Freney and Simpson, 1983).

Nitrous oxide is the source of various oxides of N that catalyze the destruction of ozone by photochemical reactions (Crutzen, 1981). These can be represented as follows:



This series of reactions results in the net loss of ozone, which can be represented as:



Measurement of N_2O emissions from soils as a result of use of N in inorganic or organic forms is of interest to atmospheric scientists, agronomists, and soil scientists. Atmospheric scientists' concern arises from the effect of N_2O on ozone destruction, while agronomists and soil scientists view N_2O emission as a mechanism of N loss from soils. Additional interest in N_2O measurement as a measure of direct denitrification loss of N has arisen from a recent finding that acetylene blocks the conversion of N_2O to N_2 during denitrification in soils (Balderston *et al.*, 1976; Yoshinari and Knowles, 1976; Yoshinari *et al.*, 1977; M. S. Smith *et al.*, 1978). Although there are problems associated with the use of acetylene to measure N loss through denitrification, this finding has stimulated interest in N_2O emission as a direct measurement of in situ denitrification under field conditions (Tiedje, 1982).

Several recent reviews focus on the processes leading to N_2O emission from soils (Trudinger *et al.*, 1980; Delwiche, 1981; Payne, 1981b; Firestone, 1982). The purpose of this review is to put together the available information on biological and chemical processes in soils that are connected with N_2O production from different soil ecosystems, mechanism of N_2O emission under managed and native soil ecosystems, and the management factors potentially of use in control of N_2O emission in relation to processes contributing to these emissions.

II. Processes Contributing to N_2O Production

While denitrification has been considered the major source of N_2O in soils and waters (CAST, 1976; Delwiche, 1981; Payne, 1981a), it is now

recognized that nitrification may also contribute to N₂O emissions (Bremner and Blackmer, 1981). Nitrous oxide also can be formed by chemical reactions when [NO₂]⁻ or NH₂OH are decomposed in acid soils, producing small amounts of N₂O (Corbet, 1935; Arnold, 1954; Nelson and Bremner, 1970; Bremner and Blackmer, 1980; Nelson, 1982), but these processes likely contribute relatively little to N₂O production in soils as compared to nitrification and denitrification.

A. Nitrification and N₂O Emission

The first indication of N₂O formation during nitrification was obtained by Corbet (1935) with cultures of nitrifiers. He suggested that N₂O was produced by the microorganisms that oxidized [NH₄]⁺ or NH₂OH to [NO₂]⁻. Later studies (Yoshida and Alexander, 1970, 1971) showed that the cells of *Nitrosomonas europaea* produced N₂O during oxidation of [NH₄]⁺ or NH₂OH to [NO₂]⁻. Ritchie and Nicholas (1972, 1974) provided evidence that [NO₂]⁻ was reduced to N₂O by nitrate reductase synthesized by *Nitrosomonas europaea*. It was generally believed that much of the N₂O produced in soils was the result of denitrification of [NO₃]⁻ under anaerobic or microanaerobic conditions. However, recent studies (Blackmer and Bremner, 1977; Bremner and Blackmer, 1978, 1979; Freney *et al.*, 1978, 1979; Goodroad and Keeney, 1984a, 1985; Robertson and Tiedje, 1984; Sahrawat *et al.*, 1985) have shown that N₂O is produced in soils under aerobic conditions in the presence of nitrifiable forms of N and may also represent a major source of marine N₂O (Elkins *et al.*, 1978). Blackmer *et al.* (1980) found that N₂O was evolved when sterilized soils were incubated under aerobic conditions after treatment with cultures of nitrifying microorganisms by *Nitrosomonas*, *Nitrospira*, or *Nitrosolobus* species and (NH₄)₂SO₄ (Table 1). Nitrous oxide was not evolved when the sterilized soils, treated with [NH₄]⁺, were not inoculated with nitrifying microorganisms, indicating that the nitrifiers were capable of producing N₂O in soils.

Bremner and Blackmer (1981), in a summary of the recent literature on N₂O emission associated with nitrification, concluded that N₂O was evolved from well-aerated soils, and that N₂O production was related to the nitrifiable N content and was not affected by the addition of [NO₃]⁻-N. Emissions of N₂O from well-aerated soils treated with [NH₄]⁺-N or urea were greatly retarded by the nitrification inhibitor, nitrapyrin [2-chloro-g-(tri-chloromethyl)pyridine], which retards nitrification of [NH₄]⁺-N.

Field studies of N₂O emission from Iowa soils showed that the amounts of N₂O evolved from plots treated with (NH₄)₂SO₄ or urea markedly exceeded those from plots receiving the same amount of N as Ca(NO₃)₂. The fertilizer-induced emissions of N₂O-N observed during 96 days from plots treated with (NH₄)₂SO₄ (125 to 250 kg N ha⁻¹) constituted only 0.11 to 0.18% of the fertilizer N applied. The amount of

Table 1. Effects of ammonia-oxidizing chemoautotrophic nitrifiers on emission of N₂O from sterilized soil treated with ammonium sulfate^{a,b}

Nitrifier strain used	N ₂ O-N evolved in 21 days (ng g ⁻¹ of soil)
None	< 1
<i>Nitrosomonas europaea</i>	712
<i>Nitrosomonas</i> Tara	30
<i>Nitrosomonas</i> E-K	473
<i>Nitrosolobus</i> AV-3	102
<i>Nitrosolobus</i> Bearden	126
<i>Nitrosopira</i> AV-2	208

^aFrom Blackmer *et al.*, (1980) with permission.

^bSoil samples (30 g) of sterilized storden soil were treated with (NH₄)₂SO₄ (100 mg kg⁻¹ soil) and inoculated with nitrifier specified and incubated (30°C; 0.23 ml water per gram of soil) under air in 1.2-L flasks. Flask atmospheres were renewed after 2, 7, and 14 days.

N₂O emitted from plots receiving Ca(NO₃)₂ did not increase with the amount of N applied and was not appreciably greater than the amounts emitted from control plots (Table 2, Breitenbeck *et al.*, 1980). Bremner *et al.* (1981) studied the effect of anhydrous ammonia (NH₃) fertilization of three Iowa field soils (250 kg N ha⁻¹) on N₂O emissions and found that the emissions of N₂O—N from the fertilized soils in 139 days averaged 15.6 kg ha⁻¹ and ranged from 12.1 to 19.6 kg ha⁻¹. The emissions of N₂O—N from the unfertilized soils averaged 2.0 kg ha⁻¹. The fertilizer-induced N₂O emissions represented 4.0 to 6.8% of the fertilizer N applied (Table 3).

Table 2. Effects of different forms and amounts of fertilizer nitrogen on N₂O evolved from field plots during 96 days^a

Nitrogen fertilizer			
Form	Amount (kg N ha ⁻¹)	Amount of N ₂ O evolved (g N ha ⁻¹)	N ₂ O-N evolved as % of N added
None	—	330	—
Ca(NO ₃) ₂	125	382	0.04
Ca(NO ₃) ₂	250	358	0.01
Urea	125	503	0.14
Urea	250	617	0.12
(NH ₄) ₂ SO ₄	125	557	0.18
(NH ₄) ₂ SO ₄	250	613	0.11

^aFrom Breitenbeck *et al.*, *Geophys. Res. Lett.* 7, 85-88, 1980; copyright by the American Geophysical Union.

Table 3. Effect of anhydrous ammonia fertilization on N₂O emission from soils^a

Soil			Amount of N ₂ O-N evolved			
			96 days		139 days	
Series	Subgroup	Fertilizer treatment ^b	kg ha ⁻¹	% of N applied	kg ha ⁻¹	% of N applied
Harps	Typic Calciaquolls	None	1.6	—	1.7	—
		AA	14.9	5.3	15.0	5.3
Webster	Typic Haplaquolls	None	2.3	—	2.5	—
		AA	19.2	6.8	19.6	6.8
Canisteo	Typic Haplaquolls	None	1.9	—	2.0	—
		AA	12.0	4.0	12.0	4.0
Mean		None	2.0	—	2.0	—
		AA	15.4	5.4	15.6	5.4

^a(Adapted from Bremner *et al.*, *J. Environ. Quality* 10, 1981, 77-80 by permission of the Am. Soc. Agro., Crop Sci. Soc. Am., Soil Sci. Soc. Am.)

^bAA, anhydrous ammonia was applied at the rate of 250 kg N ha⁻¹.

Nitrous oxide emissions exceeded considerably those in similar field studies using Ca(NO₃)₂, urea, or (NH₄)₂SO₄ (for comparison, see results in Tables 2 and 3).

Freney *et al.* (1979) found that N₂O was emitted from soils at water contents ranging from air dry to field capacity. The rate of emission increased with increase in temperature from 4 to 37°C. Nitrous oxide formation resulted from microbiological processes and was prevented by autoclaving and inhibited by HgCl₂ or toluene. Apparently N₂O was formed during nitrification at lower moisture content (see also Bremner and Blackmer, 1978, 1979).

Cochran *et al.* (1981) followed N₂O emission via nitrification from a fallow field fertilized with 0, 55, 110, and 220 kg N ha⁻¹ as NH₃. The daily fluxes of N₂O ranged from 1 to 15 g N ha⁻¹ day⁻¹, with the least from unfertilized plots and maximum from the plots fertilized with 200 kg N. However, even at the highest rate of N application less than 0.1% of the applied N was recovered as N₂O after 5 weeks. Nitrate tended to accumulate in soil fertilized with higher rates of NH₃.

B. Factors Affecting N₂O Production via Nitrification

Soil and environmental factors that affect nitrification also influence N₂O emissions via the nitrification process. Soil pH, organic matter, water and oxygen status, and the capacity of soils to supply nitrifiable N ([NO₃]⁻¹ production) have greatest influence on N₂O production in soils.

Among the environmental factors, temperature, rainfall (soil water content), and the soil ecosystem and nutrient status affect N₂O emissions.

1. Nitrifier Culture Studies

Nitrous oxide emissions from the cultures of nitrifiers isolated from soils are also influenced by cell density, age of cells, pH, O₂ concentration, temperature, concentration of such elements as phosphate, and the concentration of substrate ([NH₄]⁺ or NH₂OH). Yoshida and Alexander (1970, 1971) found that N₂O emissions by *Nitrosomonas europaea* increased with increasing concentration of substrate ([NH₄]⁺ or NH₂OH), high pH, or an increase in temperature from 0 to 35°C. Cell age and density and phosphate concentration also greatly influenced N₂O evolution. They found that, in addition to *Nitrosomonas* species, several heterotrophic microorganisms, such as *Bacillus subtilis*, *Escherichia coli*, *Aerobacter aerogenes*, *Aspergillus flavus*, and *Penillium atrovenetum*, were capable of forming N₂O from [NO₃]⁻ or [NO₂]⁻.

Goreau *et al.* (1980), in a study with *Nitrosomonas* species isolated from marine environments, found that low O₂ partial pressures (0.005 to 0.2 atm or 0.18 to 7 mg L⁻¹) decreased the rate of [NO₂]⁻ production from 3.6 × 10⁻¹⁰ to 0.5 × 10⁻¹⁰ mmol of [NO₂]⁻ per cell but increased emissions of N₂O from 1 × 10⁻¹² to 4.3 × 10⁻¹² mmol N day⁻¹ per cell. Nitrifying bacteria from the genera *Nitrosomonas*, *Nitrosospira*, *Nitrosolobus*, and *Nitrosococcus* emitted similar quantities of N₂O at 0.2 atm O₂. Nitrite-oxidizing bacteria (*Nitrobacter* species) did not emit measurable quantities of N₂O during growth. Cates (1983) studied the physiological and N substrate factors affecting N₂O–N production by cultures of nitrifiers maintained at pH 7.5 and at 23°C under aerobic conditions (0.2 atm O₂) and reported that the physiological growth stage of the nitrifiers greatly influenced N₂O production. The emission of N₂O–N ranged from 0.2 × 10⁻³ to 23 × 10⁻³ mol per mole of [NH₄]⁺ oxidized. Nitrate level did not affect N₂O emission rates.

Nitrous oxide can be produced by microorganisms other than classical nitrifiers or denitrifiers. Several *Rhizobium* spp. were shown by Zablotowic *et al.* (1978) to be capable of reducing [NO₃]⁻ to N₂O under anoxic conditions, and O'Hara *et al.* (1983) confirmed that N₂O was the dominant gaseous N product. O'Hara *et al.* (1983) found the denitrifying enzymes of *Rhizobium japonicum*, *R. hupini*, and *R. meliloti* to be O₂ sensitive. *Rhizobium*-dependent denitrification may be an important avenue of N loss in certain ecological situations (Daniel *et al.*, 1980; O'Hara *et al.*, 1984). M. S. Smith and Zimmerman (1981) found 209 of 214 soil bacterial isolates capable of producing N₂O from [NO₃]⁻, but only 46 of these were true respiratory denitrifiers. They were unable to evaluate the significance of these nondenitrifying [NO₃]⁻ reducers as a source of soil N₂O but felt they might contribute to N₂O evolution from soil.

Similarly, Bleakley and Tiedje (1982) and Burth *et al.* (1982) have isolated numerous heterotrophic bacteria, yeasts, and fungi capable of producing N_2O . Therefore, it is apparent that N_2O can be produced by nonnitrifiers and nondenitrifiers and that N_2O production involves a complex ecological niche in the soil N cycle.

2. Soil Studies

Bremner and Blackmer (1981) have summarized the factors affecting N_2O emissions during nitrification. Nitrous oxide was emitted from soils under very well-aerated conditions and N_2O emission also was observed from soil samples containing less than 5% water. Nitrous oxide emission rates increased with increase in pH and soil organic matter content and were strongly increased on amendment of soils with nitrifiable sources of inorganic N or plant and organic residues. Increase in soil temperature from 5 to 30°C increased the rate of emission of N_2O from well-aerated soil samples. The temperature effect was far more pronounced when the samples were amended with 200 $\mu\text{g g}^{-1}$ of $[\text{NH}_4]^+-\text{N}$. Nitrous oxide emissions from unamended samples increased from 2 to 5 ng g^{-1} soil with increase in temperature from 5 to 30°C and the $[\text{NH}_4]^+$ -amended samples had $N_2O-\text{N}$ emission increases of from 16 to 242 ng g^{-1} soil in 16 days (Bremner and Blackmer, 1981). Similarly, Freney *et al.* (1979) reported that N_2O emission rates from Australian soils increased with increase in soil temperature from 4 to 37°C. Blackmer *et al.* (1982) found that N_2O emissions from field, moist unamended soil increased with increase in temperature from 10 to 40°C and Q_{10} values, the rate of reaction increase for each 10° increase in temperature, varied from 1.35 to 2.28 (Table 4).

Soil water content also greatly affects N_2O production in soils under aerobic conditions. Freney *et al.* (1979) reported that N_2O emissions

Table 4. Effect of temperature on emission of N_2O from soil^{a,b}

Temperature (°C)	$N_2O-\text{N}$ evolved in 21 hr (ng g^{-1} soil) (s.d.)	Q_{10}
10	8.3 (0.5)	—
20	18.9 (0.8)	2.28
30	37.6 (0.5)	1.99
40	50.9 (3.3)	1.35

^a(Adapted from Blackmer *et al.*, *Soil Sci. Soc. Am. J.*, 46, 1982, 937-942, by permission of Soil Sci. Soc. Am.).

^bSamples of field-moist soil (Typic Hapla-quoll, 23% water) were incubated at the specified temperature for 21 hr.

increased with increase in soil water from air dry to field capacity, and they concluded that production of N_2O was continuous at all moisture contents. Studies reported by Bremner and Blackmer (1981) also indicated that emissions of N_2O increased with increase in soil moisture from 20 to 150% of the water-holding capacity (WHC). It was further observed that emissions of N_2O during 30 days from soils amended with $[\text{NH}_4]^+$ exceeded those from samples amended with $[\text{NO}_3]^-$ when the amended soils were saturated with water to promote denitrification. They also found that air drying of soil samples prior to aerobic incubation greatly increased N_2O emission rates.

The emissions of N_2O from soils are also greatly affected by addition of chemicals that retard nitrification. For example, nitrapyrin, HgCl_2 , toluene, and CS_2 have been reported to retard N_2O emissions associated with nitrification (Freney *et al.*, 1978, 1979; Blackmer *et al.*, 1980; Bremner and Blackmer, 1980, 1981). Acetylene, which is known to inhibit oxidation of $[\text{NH}_4]^+$ by nitrifying microorganisms (Hynes and Knowles, 1978; Walter *et al.*, 1979), is also reported to retard N_2O emissions associated with nitrification in well-aerated soils (Bremner and Blackmer, 1979, 1981; Blackmer *et al.*, 1980; Aulakh *et al.*, 1984b).

Goodroad and Keeney (1984a) investigated N_2O production in aerobically incubated soils as affected by pH, temperature, and water content. Samples of a silt loam collected from plots maintained at pH 4.7, 5.1, or 6.7 were used. It was found that nitrification of added $[\text{NH}_4]^+ - \text{N}$ increased with increase in soil pH (4.7 to 6.7), temperature (10 to 30°C), and water content (10 to 30% v/v). The rate of N_2O emission was proportional to $[\text{NO}_3]^-$ production and on the average 0.1% of the nitrified N was evolved as $\text{N}_2\text{O} - \text{N}$ in 5 days. The ratio of $\text{N}_2\text{O} - \text{N}$ to $[\text{NO}_3]^- - \text{N}$ produced was greatly affected by soil pH and temperature, particularly at 5 kPa soil water potential (Table 5). Addition of nutrients, such as P, and liming materials, such as CaCO_3 , can also affect N_2O evolution from soils in some situations. For example, Minami and Fukushi (1983) found that application of P or CaCO_3 to four Japanese soils increased N_2O emission under aerobic incubation. However, P-induced N_2O emissions were larger than those obtained with CaCO_3 . The addition of CaCO_3 and P enhanced the growth of ammonium oxidizers and accumulation of $[\text{NO}_2]^- - \text{N}$ which probably accounted for enhanced N_2O evolution.

Addition of CaCO_3 to six acid forest soils increased emissions of N_2O during 28 days of aerobic incubation at 30°C under field-moist conditions, but P application had little effect on N_2O emissions (Table 6, Sahrawat *et al.*, 1985). It was found that CaCO_3 addition greatly enhanced ammonification or non- or slowly nitrifying soils and both ammonification and nitrification in nitrifying soils. From 0.03 to 0.3% of the $[\text{NH}_4]^+ - \text{N}$ nitrified was released as $\text{N}_2\text{O} - \text{N}$. Calcium carbonate addition increased the soil pH to the neutral range (6.7 to 7.5) and increased

Table 5. Ratio of N_2O-N to $[NO_3]^{-}-N$ produced in Plano silt loam soils of varying pH at different water contents and temperatures under aerobic incubation for 5 days^{a,b}

		$(N_2O-N/[NO_3]^{-}-N) \times 10^{-3}$								
		pH 4.7			pH 5.1			pH 6.7		
Soil water		10°C	20°C	30°C	10°C	20°C	30°C	10°C	20°C	30°C
	(m^3/m^{-3})									
	0.1	1.5	1.5	1.9	0.7	0.9	0.9	1.0	0.9	1.0
	0.2	1.1	2.0	2.4	0.9	0.8	0.9	0.8	1.0	1.0
	0.3	1.3	1.9	3.3	0.8	1.2	11.5	1.0	6.0	5.7

^aReprinted with permission from *Soil Biol. Biochem.*, 16 L. L. Goodroad and D. R. Keeney, pp. 39-43; copyright 1984 by Pergamon Press, Ltd.

^bSoil samples were treated with 100 mg N as $(NH_4)_2SO_4$ kg^{-1} soil. Soil water potential (kPa) is 1600, 20 and 5; water-filled porosity is 18, 36, and 54% at water content of 0.1, 0.2, and 0.3 $m^3 m^{-3}$, respectively.

Table 6. Effect of phosphorus and CaCO₃ on N₂O-N production during aerobic incubation of six forest soils after 28 days at 30°C^{ab}

Soil	Site		Forest floor type	pH (CaCl ₂)	Organic matter (%)	N ₂ O-N (µg N kg ⁻¹ dry soil)		
	Stand ^c					Control	+P	+CaCO ₃
Histosol Alfisol	Hemlock		Mor	3.9	59	7	3	4
	Sugar maple		Mull	5.1	22	19	29	29
Alfisol	Red oak		Mor	4.3	16	49	48	110
Alfisol	White oak		Mor	4.4	25	36	28	109
Spodosol	White pine		Mor	4.4	42	56	62	96
Entisol	Red pine		Disturbed	4.4	2.4	6	4	25

^aReprinted from Sahrawat *et al.* (1985) by permission of *Forest Sci.*

^bField-moist samples (10 g) from Blackhawk Island, Wisconsin (Pastor *et al.*, 1984) were treated with 1 ml of water, 1 ml of water containing 1000 mg L⁻¹ P (as KH₂PO₄), or 0.2 g (2%) of powdered CaCO₃.

^cHemlock, *Tsuga canadensis* (L.) Carr.; sugar maple, *Acer saccharum* Marsh; red oak, white oak, *Quercus rubra* L., *Q. alba* L.; red pine, white pine, *Pinus resinosa* Ait., *P. strobus* L.

nitrification and N₂O emissions. Adding P and CaCO₃ together did not affect N transformations, including N₂O evolution, compared to CaCO₃ alone.

Keeney *et al.* (1985) showed that CO₂ concentration in the soil atmosphere can affect N₂O evolution associated with nitrification and denitrification. Some results of this study are shown in Table 7. It was found that an increase in CO₂ concentration from 0.3 to 100% increasingly retarded the rate of nitrification in soil. Nitrous oxide production associated with nitrification increased as CO₂ increased from 0.3 to 2.6% and tended to be greater as CO₂ concentration increased to 73%. At 100% CO₂, no N₂O was produced during 7 days of incubation at 25°C. Carbon dioxide, however, did not affect N₂O production or reduction in the saturated, [NO₃]⁻-amended soil nor the rate of N₂O reduction in anaerobic environments. It was concluded that increased CO₂ in arable soils containing large

Table 7. Effect of varying concentrations of CO₂ on N₂O production and on the ratio of N₂O produced to NO₃ produced in soil under aerobic conditions in 7 days^{a,b}

Treatment			CO ₂ 7 days (%)	N ₂ O-N (ng N g ⁻¹)	N ₂ O-N to [NO ₃] ⁻ -N (× 10 ⁻³)
CO ₂ (%)	[NH ₄] ⁺ (μg N g ⁻¹)	[NO ₃] ⁻ (μg N g ⁻¹)			
Air	0	0	3.3	117 ± 2	3.4
22	0	0	25	83 ± 14	4.4
50	0	0	49	154 ± 11	22
73	0	0	70	544 ± 55	181
100	0	0	100	0	—
Air	0	95	3.1	123 ± 10	3.6
23	0	95	25	168 ± 23	7
50	0	95	47	250 ± 28	25
73	0	95	71	716 ± 303	90
100	0	95	100	46,400 ± 1350	—
Air	90	0	3.6	396 ± 126	6
2.6	90	0	6.2	1,120 ± 208	19
5.2	90	0	8.6	972 ± 88	16
11	90	0	14	1,616 ± 637	32
23	90	0	26	1,111 ± 104	28
50	90	0	49	1,034 ± 152	74
73	90	0	71	1,270 ± 562	423
100	90	0	100	0	—

^aReprinted with permission from *Soil Biol. Biochem.*, 17, D. R. Keeney *et al.*, 571-573; copyright 1985, Pergamon Press, Ltd.

^bPlano silt loam (10 g) was incubated at 25°C with 2.5 ml of water or with 2.5 ml of a solution containing either 900 μg NO₃-N (as KNO₃) or 950 μg [NH₄]⁺-N (NH₄)₂SO₄ under the specified CO₂ concentrations.

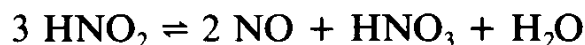
amounts of nitrifiable N could result in increased N₂O production during nitrification. The effect was not large until CO₂ concentration was greater than 50% of the soil atmosphere.

C. Denitrification and N₂O Emission

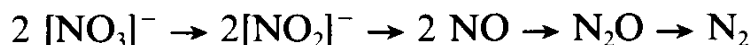
According to the *Glossary of Soil Science* (Soil Science Society of America, 1979), denitrification is "the microbial reduction of [NO₃]⁻ or [NO₂]⁻ to gaseous N as molecular N (N₂) or as an oxide of N" (ps). Several reviews are available (Garcia, 1975a; Delwiche and Bryan, 1976; Focht and Verstraete, 1977; Payne, 1973, 198b; Delwiche, 1981; Knowles, 1981; Firestone, 1982). Additionally, various aspects of N₂O production via denitrification have been covered by several recent reviews (Crutzen, 1981; Ingraham, 1981; Bryan, 1981; Schroeder, 1981; Rolston, 1981; Hahn, 1981; Payne, 1981a, b).

1. Laboratory Studies

Beijernick and Minkman (1910) and Suzuki (1912) reported N₂O to be one of the gases evolved by bacteria in anaerobic cultures and soils. Wijler and Delwiche (1954) studied the gaseous products of denitrification in soils using ¹⁵N-tagged KNO₃. They identified evolution of N₂O, N₂ and NO gases during denitrification. Nitrous oxide was the major product of denitrification and the ratio of N₂O/ to N₂ evolved was affected by soil pH. Above pH 7, N₂O was readily reduced to N₂. However, at pH < 7, the rate of reduction of N₂O to N₂ declined. Evolution of and the relative proportions of N₂O and N₂ were not affected by the applications of organic residues. There was no evidence of any nonenzymatic denitrifications (Van Slyke reaction) taking place. At low soil pH (4.9) NO was produced in amounts equal to that of N₂O evolved. Chemical decomposition of [NO₂]⁻ formed from [NO₃]⁻ was suggested as possible pathway for NO formation (also see Cady and Bartholomew, 1961, 1963):



Subsequent studies have found that numerous facultative heterotrophs can produce N₂O from [NO₃]⁻ and can further reduce N₂O to N₂ (Delwiche, 1959). Payne (1981a, b) has discussed the intermediates formed during denitrification. It is now certain that denitrification involves several enzymatic and chemical reactions and follows the sequence:



Studies with cultures of various denitrifying bacteria (Payne, 1981a, b) indicate that 13 genera include species capable of reducing [NO₃]⁻ to N₂ via [NO₂]⁻, NO, and N₂O. Nitrous oxide production by denitrifying

microorganisms in cultures have been reported by many workers (Najjar and Allen, 1954; Delwiche, 1959; Baalsrud and Baalsrud, 1954; Barbaree and Payne, 1967; Miyata, 1971; Ishaque and Aleem, 1973; Pichinoty *et al.*, 1978; M. S. Smith and Tiedje, 1980; Payne, 1981a, b). Many studies of denitrification in soils have identified N_2O as one of the intermediates, and the ratios of N_2 to N_2O evolved vary greatly (Arnold, 1954; Wijler and Delwiche, 1954; Nommik, 1956; Cooper and Smith, 1963; McGarity and Hauck, 1969; Stefanson, 1973; Burford and Bremner, 1975; Rolston *et al.*, 1976; Letey *et al.*, 1980a, b; Payne 1981a, b).

2. Field Studies

Field studies of N_2O evolution as a mechanism of fertilizer N loss have been summarized by Rolston (1981). The amount of N_2O evolved varied from nil to as high as $8 \text{ kg N ha}^{-1} \text{ day}^{-1}$. The highest emissions were reported in summer from experimental plots maintained in a wet state and treated with manure (Table 8). Much research indicates a range in N_2O emission ranging from <0.01 to $1 \text{ kg N}_2O\text{-N ha}^{-1} \text{ day}^{-1}$ (Burford and Millington, 1968; Burford and Stefanson, 1973; Dowdell and Smith, 1974; Rolston *et al.*, 1976, 1978; Freney *et al.*, 1978; Focht, 1978; McKenney *et al.*, 1978; Ryden *et al.*, 1978, 1979; Findlay and McKenney, 1979; Hutchinson and Mosier 1979, 1981; Ryden, 1981, 1983; C. J. Smith *et al.*, 1981a; Burford *et al.*, 1981; Webster and Dowdell, 1982; Mosier *et al.*, 1982, 1983; Aulakh *et al.*, 1982, 1983a, b; Armstrong, 1983; Goodroad and Keeney, 1984b; Goodroad *et al.*, 1984) depending on N fertilization rate, source of N applied, soil water content, tillage practices, and the prevailing soil temperature.

The fluxes of N_2O reported from organic soils are higher than those reported for mineral soils. For example, Terry *et al.* (1981) reported that $N_2O\text{-N}$ fluxes from cultivated organic soils of south Florida ranged from $0.004 \text{ kg N ha}^{-1} \text{ day}^{-1}$ during the dry periods to $4.5 \text{ kg N ha}^{-1} \text{ day}^{-1}$ following rainfall events. The total $N_2O\text{-N}$ emissions during 1 yr (1979 to 1980) amounted to 165, 97, and 48 kg N ha^{-1} for the fallow, grass cropped, and sugarcane (*Saccharum officinarum* L.) cropped organic soils, respectively (Table 9). Similarly, Duxbury *et al.* (1982) found that the maximum daily $N_2O\text{-N}$ fluxes from cropped mineral soils ranged from 0.19 to $0.63 \text{ kg N ha}^{-1}$ during a 2-yr study compared to 2.9 to 4.6 kg N ha^{-1} for an organic soil during the same period. The annual emission of $N_2O\text{-N}$ from the mineral soils ranged from 0.9 to $0.42 \text{ kg N ha}^{-1}$, whereas for the organic soils they ranged from 7 to 165 kg N ha^{-1} . Goodroad and Keeney (1984b) also found high N_2O emission rates from drained organic soils.

D. Factors Affecting N_2O Production via Denitrification

Factors that affect denitrifications in soils also affect N_2O emissions but the ratio of N_2 to N_2O evolved is sensitive to environmental and soil

Table 8. Denitrification loss of nitrogen in summer as N_2O and N_2 from plots maintained at different soil-water pressure heads^{a,b}

Treatment ^c	Soil water pressure head (cm)	Surface flux		Flux at 60-cm depth ^d		Total (% of fertilizer N)
		N_2O (kg N ha ⁻¹)	N_2 (kg N ha ⁻¹)	$N_2 + N_2O$ (kg N ha ⁻¹)	Total (kg N ha ⁻¹)	
Manure	-15	9.9	198	10	218	73
Manure	-70	5.4	42	0	47	16
Cropped	-15	4.3	30	5.5	40	14
Cropped	-70	1.8	7	0	9	3
Uncropped	-15	2.1	5.7	2.5	10	3
Uncropped	-70	0.6	3.6	0	4	1

^aAdapted from Rolston *et al.*, *Soil Sci. Soc. Am. J.* 42, 1978, 863-869, by permission of Soil Sci. Soc. Am.

^bThe plots were established on a Yolo loam (Typic Xerorthents) soil. The average soil temperature at the 5-cm depth during July (when the study was done) was approximately 23°C.

^cAll treatments received 300 kg N ha⁻¹ as KNO_3 .

^dCalculated from the $^{15}N_2$ and N_2O concentration gradients between the 30- and 60-cm depths and from the average gaseous diffusion coefficient between two depths of 5 cm² hr⁻¹ corresponding to a soil air content of 0.12 cm³ cm⁻³.

Table 9. Effects of cropping on nitrous oxide emissions from Pahokee Muck during 1979 and 1980^a

Period of Study	Treatment					
	Fallow		Grass		Sugarcane	
	Range (kg N ₂ O-N ha ⁻¹)	Total (kg N ₂ O-N ha ⁻¹)	Range (kg N ₂ O-N ha ⁻¹)	Total (kg N ₂ O-N ha ⁻¹)	Range (kg N ₂ O-N ha ⁻¹)	Total (kg N ₂ O-N ha ⁻¹)
May 1979 to April 1980	0.4-60.4	164.9	0.4-58.8	96.8	0.3-26.1	48.4

From Terry *et al.* (1981); reprinted with permission of APCA J.

Table 10. Summary of factors that affect the relative proportion of N₂O to N₂ evolved via the denitrification process^a

Factor	Influence on N ₂ O/N ₂ ratio
Nitrate concentration	Ratio increases with increasing [NO ₃] ⁻
Nitrite concentration	Ratio increases with increasing [NO ₂] ⁻
Oxygen concentration	Ratio increases with increasing O ₂
pH	Ratio increases with pH decrease; pH also enhances the effect of [NO ₃] ⁻
Sulfide	Ratio increases with increasing sulfide
Carbon	Ratio generally decreases with increasing C availability
Redox potential (Eh)	Ratio not affected by Eh changes below 0 mV
Enzyme status	Ratio can be increased or decreased by synthesis of or absence of N ₂ O reducing activity relative to preceding reductases

^aFrom Firestone (1982). Reproduced from Nitrogen in Agricultural Agronomy, Agronomy Monograph No. 22, 1982, pages 289-326. By permission of the American Society of Agronomy.

factors (Table 10). Rolston (1981), Payne (1981b), and Firestone (1982) have discussed factors affecting denitrification and N₂O production in soils. Mosier *et al.* (1983) focused on factors that affected N₂O evolution from cropped and native soils with a view to modeling N₂O emissions in soil.

1. Substrate Concentration and Availability

Presence of NO₃ or [NO₂]⁻ is a prerequisite for N₂O production via denitrification. In a recent review, Mosier *et al.* (1983) analyzed the data obtained from a number of field studies and found that N₂O production via denitrification was correlated with the [NO₃]⁻ content of soil ($r = 0.65$, $n = 136$). They found that N₂O fluxes could be represented by first-order kinetics when the [NO₃]⁻ content of the soils did not exceed 40 μg [NO₃]⁻-N g⁻¹ soil. At higher [NO₃]⁻-N concentration reduction of N₂O to N₂ may be slowed (Blackmer and Bremner, 1978). This conclusion is in accord with the earlier findings that at high [NO₃]⁻-N concentrations the dominant gaseous product of denitrification is N₂O (Nommik, 1956; Cooper and Smith, 1963; Blackmer and Bremner, 1978; Cho and Mills, 1979; Rolston, 1981). However, the effect of [NO₃]⁻ on reduction of N₂O has been found to be less in organic soils and sediments (Terry and Tate, 1980).

Evidence presented by Firestone *et al.* (1980) suggests that [NO₃]⁻

concentration affects the evolution of N_2O and the ratio of N_2 to N_2O , although the total loss of N via denitrification in soils may be independent of $[NO_3]^-$ concentration over a wide range (Wijler and Delwiche, 1954; Nommik, 1956; Bremner and Shaw, 1958).

2. Soil Water Content and Soil Drying

The soil water regime affects denitrification and gaseous products of denitrification directly and also indirectly by affecting the diffusion of O_2 into and through the soil. Nommik (1956) found that the denitrification rate was proportional to the water content of soils, and at the lower water contents the gaseous product of denitrification mainly consisted of N_2O . Molecular nitrogen evolution was favored by strictly anaerobic conditions. Studies by Blackmer and Bremner (1976), Bremner and Blackmer (1979), Freney *et al.* (1978), and Focht *et al.* (1979) suggest that N_2O initially produced when water content is greater than the field capacity is reduced to N_2 , so that N_2O emission rates are lower than N_2 emission rates at field capacity. Mosier *et al.* (1983) reported that soil relative water content (RWC, an index of soil water content at wilting point divided by water content at field capacity minus the water content at wilting point) was related to N_2O emissions in field soils ($r = 0.52$, $n = 136$). Nitrous oxide fluxes were low at $RWC < 0.35$ and increased as RWC increased.

Similarly, studies by Terry *et al.* (1981), Duxbury *et al.* (1982), and Goodroad and Keeney (1984b) found that N_2O fluxes from mineral and organic soils were many times lower during dry periods than shortly after rainfall events when the soils were saturated (Table 11).

Drying or freezing of soil samples prior to anaerobic incubation also increases the rate of denitrification and the evolution of N_2O and N_2 (e.g., McGarity, 1962; Myers and McGarity, 1971; McKenzie and Kurtz, 1976; Patten *et al.*, 1980). Studies by Patten *et al.* (1980) showed that even partial drying of field-moist soils increased the emission of $(N_2O + N_2)-N$ from soils incubated anaerobically after treatment with $[NO_3]^-$. Air-dry storage of soils increased the amounts of $(N_2O + N_2)-N$ evolved when these soils were incubated anaerobically. It was suggested that drying or air-dry storage of soil increased the soil's capacity to denitrify and to evolve gaseous products of denitrification (N_2O and N_2) under anaerobic conditions by enhancing the amount of soil organic matter available to the denitrifiers. C. J. Smith and Patrick (1983) studied the effect of several anaerobic and aerobic cycles on N_2O emission from $(NH_4)_2SO_4$ -amended soil suspensions and found that no N_2O was evolved from continuously anaerobic samples. Continuously aerobic samples produced small amounts of N_2O , whereas alternate anaerobic-aerobic cycles of varying duration increased N_2O emissions several fold (Table 12).

Table 11. Nitrous oxide emissions from cultivated mineral and organic soils during 2 yr of study^a

Crop	N fertilizer or manure treatment ^b	Maximum observed daily N ₂ O kg ha ⁻¹	Annual N ₂ O emissions	
			May 1979–May 1980 (kg ha ⁻¹)	May 1980–May 1981 (kg ha ⁻¹)
<i>Mineral Soils</i>				
Alfalfa	0	0.63	4.2	2.3
Field corn A	130(M)	0.22	2.4	2.9
	130(F)	0.28		2.2
Field corn B	130(M)	0.19		3.8
Timothy weed	0	0.23	1.7	0.9
<i>Organic Soils</i>				
Onions	170	4.5	85	72
Sweet corn	170	2.9	76	152
Sugarcane (Florida)	0	3.1	48	7
St. Augustine grass (Florida)	0	4.6	97	16
None (fallow, Florida)	0	4.5	165	59

^aReprinted by permission from Duxbury *et al.*, *Nature*, 298, 462–464, copyright (c) 1982 Macmillan Journals Limited.

^bField corn sites received 20 kg N ha⁻¹ added as either urea–ammonium nitrate (1:1) fertilizer side dressed 40 days after planting (F) or manure (45 tons ha⁻¹) applied before planting (M). Fertilizer containing NH₄NO₃ was broadcast on the organic soil sites in New York before planting.

Table 12. Effects of continuous aerobic or anaerobic conditions and of alternate anaerobic and aerobic treatments on N₂O emission from soil suspension^{a,b}

Treatment	N ₂ O-N evolved in 56 days (ng N g ⁻¹ dry soil)
Aerobic	790
Anaerobic	0
Alternate anaerobic/aerobic (7/7 days)	7,190
Alternate anaerobic/aerobic (14/14 days)	15,670

^aAdapted with permission from *Soil Biol Biochem.*, 15, C. J. Smith and W. H. Patrick, pp. 693-697; copyright 1983 Pergamon Press, Ltd.

^bSoil samples (400 g) were amended with [NH₄]⁺-N (92 mg N kg⁻¹ dry soil) and ground rice straw (0.5%, w/w) and water was added to form soil: water ratio of 1:5 and pH of 6.2 ± 0.2.

3. Oxygen Supply

The absence of O₂ or its restricted availability in soils or at soil microsites is one prerequisite for denitrification (see Rolston, 1981; Payne, 1981a, b; Firestone, 1982, for reviews). However, the water content of soils also indirectly affects the oxygen content, and hence denitrification, as well as N₂O production by affecting the rate of diffusion of O₂ (Wijler and Delwiche, 1954; Nommik, 1956; Bremner and Shaw, 1958; Pilot and Patrick, 1972; Focht, 1974; Firestone and Tiedje, 1979; Rolston, 1981; Letey *et al.*, 1980a, b; Firestone, 1982; Cho, 1982); K. A. Smith (1980) has developed an excellent model of the extent of anaerobic zones in soil aggregates.

Focht (1974) used a zero-order kinetic model to estimate the production of N₂O and N₂ in soils and stated that aeration affected the ratio of N₂O to N₂ evolved from soils. The rates of denitrification increase with decreased aeration, but the N₂O to N₂ ratio declines because of greater rate of reduction of N₂O to N₂ under anaerobic conditions (also see Letey *et al.*, 1981).

Firestone *et al.* (1980) studied the effects of factors controlling the production of N₂O through biological denitrification by bacteria cultures and soils and found that increased oxygen content enhanced production of N₂O relative to N₂ during denitrification. Under anaerobic conditions, N₂O production initially was also found to increase, but this was followed by N₂O consumption in the system and its conversion to N₂ by nitrous oxide reductase (Letey *et al.*, 1981). C. J. Smith *et al.* (1983) reported that the critical redox potential (Eh) for N₂O reduction and production occurred at +250 mV for pH 6, 7, and 8.5 and at +300 mV for pH 5 for the

soil-water systems. They, as well as Letey *et al.* (1981), have confirmed the theory of Freney *et al.* (1979), that the soil can act as a N₂O sink under anoxic conditions. Letey *et al.* (1981) found that N₂O emissions were higher in soils with fluctuating redox potential established by wetting and drying cycles.

4. Carbon Supply

It has long been recognized that availability of C enhances the loss of [NO₃]⁻ or [NO₂]⁻ through denitrification (Rolston, 1981; Payne, 1981a, b; Firestone, 1982). Studies by Wijler and Delwiche (1954), Nommik (1956), and M. S. Smith and Tiedje (1979) showed that C supply decreased the ratio of N₂O to N₂ evolved during denitrification in soils.

The total fluxes of N₂O-N have been reported to be many times higher in organic soils with higher contents of soil organic matter and are also affected by cropping (Tables 11 and 12; Terry *et al.*, 1981; Duxbury *et al.*, 1982). Burford and Bremmer (1975) and Patten *et al.* (1980) found that N₂O or N₂ production in a number of Iowa soils was positively correlated with total organic C, water-soluble C, and mineralizable C (as measured by CO₂ production). The highest correlations ($r = 0.98$ and 0.99) were reported between the amounts of (N₂ + N₂O)-N evolved and the amounts of CO₂ produced during anaerobic incubation of soils treated with [NO₃]⁻ (Patten *et al.*, 1980).

The availability of C as an electron donor influences N₂O production in soils but the relationship is not direct. Often, changes in C availability are associated with factors that may affect N₂O production (Firestone, 1982; Koskinen and Keeney, 1982). Carbon supplied by application of organic residues increases not only N₂O production in soils but also the rate of N₂O reduction to N₂ (Wijler and Delwiche, 1954; Nommik, 1956; Firestone *et al.*, 1980; Letey *et al.*, 1980a, b, 1981). The rhizosphere of a plant may be a better source of energy for denitrification (Garcia, 1975b; Rolston, 1981; Firestone, 1982). However, the effect of the rhizosphere on N₂O production is not established. It is speculated that N₂O production may be greater in the rhizosphere zone to start with until nitrous oxide reductase is synthesized or repressed by anoxic conditions. This should decrease N₂O fluxes and increase N₂ production.

The depth within the soil profile where denitrification occurs also affects the N₂O mole fraction evolved. If denitrification occurs very near to the soil surface, N₂O produced can readily diffuse into the atmosphere, whereas if denitrification occurs deeper in the profile there is more possibility that the N₂O produced will be further reduced to N₂. Thus, the mole fraction of N₂O [(N₂O-N)/(N₂O + N₂)-N] evolved is larger when denitrification occurs very close to the surface and smaller when the site of denitrification is deeper in the soil profile (Rolston, 1981).

5. Temperature

Temperature greatly influences denitrification rates in soils (Bremner, 1978; Broadbent and Clark, 1965; Rolston, 1981; Knowles, 1981; Payne, 1981a, b; Firestone, 1982). In earlier studies on the effects of temperature on denitrification, Nommik (1956) and Bremner and Shaw (1958) indicated that temperature was very important in controlling the rate of denitrification in soils and the temperature optimum for denitrification was suggested to be between 60 and 70°C. Nommik (1956) also noted that amounts of gaseous products formed were greatly influenced by temperature. He showed that while the rate of (N₂O + N₂)-N evolved from anaerobic soils treated with [NO₃]⁻ increased with the increase in temperature from 3 to 65°C, evolution of N₂O became an increasingly

Table 13. Amounts of N₂ and N₂O evolved from nitrate-amended soil incubated under He at different temperatures^{a,b}

Temperature (°C)	Form of N (µg N per 50 g soil)	Time (hr)		
		24	48	96
7	N ₂	26	42	86
	N ₂ O	98	145	209
15	N ₂	49	84	163
	N ₂ O	71	127	195
25	N ₂	88	337	664
	N ₂ O	255	361	299
40	N ₂	145	295	1117
	N ₂ O	749	2247	2659
50	N ₂	953	7816	7609
	N ₂ O	4274	158	0
60	N ₂	8884	8726	8159
	N ₂ O	0	0	0
65	N ₂	8850	8553	7739
	N ₂ O	0	0	0
67	N ₂	8956	8142	8707
	N ₂ O	0	0	0
70	N ₂	262	695	851
	N ₂ O	3084	4171	5786
75	No N ₂ or N ₂ O evolved			

^aAdapted from Keeney *et al. Soil Sci. Soc. Am. J.* 43, 1979, 1124-1128, by permission of Soil Sci. Soc. Am.

^bPlano silt from (Typic Argiudoll) soil samples (50 g) were treated with 6 ml of water containing 5 mg [NO₃]-N [as Ca(NO₃)₂] and incubated under He after adjusting soil water content to 40% (w/w) at the specified temperatures.

smaller component of gaseous N evolved and also that N_2O persisted for shorter times with increasing temperature.

Focht (1974) and Focht and Verstraete (1977), on the other hand, suggested that temperature had little effect on the gaseous composition of denitrification products. Focht (1974) did not include temperature in the zero-order kinetic model suggested for studying N_2O and N_2 production through denitrification. Bailey (1976) found, as did Nommik (1956), that greater proportions of N_2O were evolved at lower temperatures (6 to 8°C, 15°C) than at higher (30°C).

Keeney *et al.* (1979) examined the relative proportion of N_2O and N_2 evolved from a $[NO_3]^-$ -amended silt loam during anaerobic incubation (under He atmosphere) in the temperature range of 7 to 75°C (Table 13). They found that the denitrification rate increased with temperature above 15°C, with an apparent temperature optimum of 60 to 67°C. Nitrous oxide evolution in relation to total ($N_2O + N_2$)-N declined with time but was still 44 to 50% of the gas produced at 16 days at 7 and 15°C. Nitrous oxide comprised up to 88% of the gas produced at 40°C and after 2 days. However, at 50°C, most of the gas was N_2O after 1 day but at 50 to 70°C, N_2O had disappeared by 1 day. Denitrification was found to be occurring at 70°C but at a reduced rate. Nitrous oxide represented more than 85% of the N evolved at 70°C. Denitrification did not occur at 75°C. It was suggested that the commonly stated temperature optima for denitrification might be too high for true biological denitrification because of the dominance of temperature-dependent chemical reactions at temperatures higher than 50°C.

As suggested by Bailey (1976) and Keeney *et al.* (1979), temperature effects on N_2O production in soils may be complicated by accumulation of $[NO_2]^-$, which could be involved in chemodenitrification. Also in response to temperature, differential organic matter mineralization may change the redox potential, which further complicates prediction of N_2O production (Keeney *et al.*, 1979).

6. pH

Soil pH is an important factor in controlling the rate of denitrification. It is generally accepted that the optimal pH range for denitrification is between 7.0 and 8.0. Although denitrification occurs in soils over a wide range of pH, it is often reported that the denitrification rate is slow below pH 6 (Broadbent and Clark, 1965; Delwiche and Bryan, 1976; Focht and Verstraete, 1977; Rolston, 1981; Payne, 1981a, b; Knowles, 1981; Delwiche, 1981; Firestone, 1982).

It is now accepted that as the soil pH declines below 6.0, the evolution of N_2O relative to N_2 increases (Rolston, 1981; Knowles, 1981; Payne, 1981a, b; Firestone, 1982). For example, Wijler and Delwiche (1954) and Nommik (1956) found that production of N_2O relative to N_2 was much higher in soils with pH lower than 6.0, and this was because reduction of

N_2O was inhibited at low pH. These results have been confirmed by subsequent research (Hauck and Melsted; Cady and Bartholomew, 1960; Matsubara and Mori, 1968; Focht, 1974; Firestone *et al.*, 1980; Koskinen and Keeney, 1982).

Firestone *et al.* (1980) found that pH 4.9 or 6.5 had little effect on the ratio of N_2O to N_2 evolved at very low levels of $[\text{NO}_3]^-$ ($<0.5 \mu\text{g g}^{-1}$) but that the pH effect was large at $10 \mu\text{g g}^{-1}$, indicating an interaction between pH and $[\text{NO}_3]^-$ substrate levels on the gaseous products of denitrification.

Koskinen and Keeney (1982) studied the effect of soil pH on the rate and products of denitrification in a soil that had been maintained at various pH levels in the field for 18 yrs. This avoided additions of salts to manipulate soil pH, which might have caused perturbations in the native microflora. It was found that N_2O comprised 83% of the gaseous N products for pH 4.6 and 5.4 when 90% of the $[\text{NO}_3]^-$ -N ($100 \mu\text{g g}^{-1}$ of $[\text{NO}_3]^-$ added) had been denitrified. At pH 6.9, N_2 was the dominant product of denitrification, even after the first day of incubation. They also reported production of NO in soils with pH 4.6 and 5.4 that was consistent with the findings of Wijler and Dewiche (1954), who reported that considerable amounts of NO were evolved as a result of denitrification in soils at pH 4.9.

However, as suggested by Koskinen and Keeney (1982), it is difficult to evaluate the absolute effect of pH on the relative production of gaseous products of denitrification because of involvement of $[\text{NO}_2]^-$ and soil pH interactions that may affect production of N_2O and N_2 . It is recognized that in more acid soils, chemical reactions of $[\text{NO}_2]^-$ -N can also contribute to gaseous N production (Bollag *et al.*, 1973; Nelson, 1982).

7. Other Factors

In addition to the above-discussed environmental, substrate, and soil factors that affect N_2O emissions from soils, there are other factors that affect N_2O production which cannot be ascribed easily to any individual effect but are best explained by considering the total ecosystem. A combination of several environmental, soil, and agricultural practices, and perhaps plant factors, interact to influence such biological processes as mineralization, nitrification, and denitrification, which affect N_2O emissions.

For example, research by Aulakh *et al.* (1982) in Canadian prairies showed that gaseous N loss as $(\text{N}_2\text{O} + \text{N}_2)$ -N was two to five times higher from summer-fallowed plots than from cropped plots. In a 2-yr study of various management practices on gaseous loss of N, Aulakh *et al.* (1983b) found that incorporation of legume residue followed by partial fallow decreased the gaseous loss of N compared to summer fallow. It was also found that soil moisture, mean air temperature, and inorganic N concentrations collectively accounted for 37 to 66% of the variations in

N₂O fluxes. The contribution of lower soil horizons to gaseous N loss was negligible.

Regarding the possible effect of ecosystems on N₂O fluxes, Goodroad and Keeney (1984b) observed major differences in N₂O emissions from forest soils. For example, it was found in a 2-yr study that significantly more N₂O was released from coniferous forest floors than from deciduous forest floors (Table 14). Differences in soil pH and N cycling processes might have contributed to these differences in N₂O fluxes. Usually low-N grassland ecosystems have been reported to emit small amounts of N₂O as compared to managed ecosystems (Mosier *et al.*, 1983; Goodroad and Keeney, 1984b).

Other factors, such as preincubation conditions (anaerobic and aerobic) and time of preincubation, also greatly affect N₂O evolution (Tiedje *et al.*, 1979; Letey *et al.*, 1980a, b). Letey *et al.* (1980a, b) found that little N₂O was evolved when the soil had been preincubated for 7 days under saturated conditions. There were relatively higher rates of N₂O evolution during the initial stages of incubation when the soil had been preincubated under air-dry or moist conditions. Nitrous oxide evolution decreased to nil with time. The ratio of N₂O to N₂ evolved was high initially and decreased rapidly with time mainly because of reduction of N₂O to N₂.

E. Other Processes Contributing to N₂O Production

In addition to biological reactions, chemodenitrification, in which volatile loss of N results from chemical reactions of [NO₂]⁻ with organic reducing compounds, may contribute to production of N₂ and N₂O (Bremner and Blackmer, 1980; Nelson, 1982; Mosier *et al.*, 1983; Pang and Cho, 1984). Mosier *et al.* (1983) outlined five N₂O-producing processes and stated that nitrification and denitrification were the most important. However, in addition to chemodenitrification they listed dissimilatory [NO₃]⁻ reduction to [NH₄]⁺ and assimilatory [NO₃]⁻ reduction (where N is incorporated into cell biomass) as processes that might contribute to N₂O evolution. Chemodenitrification may be of importance at times in soils with neutral to alkaline reaction where [NO₂]⁻ accumulation is a problem. However, research on N₂O emission from soils clearly establishes the importance of denitrification and nitrification as the main processes for N₂O production.

III. Mechanisms of N₂O Production in Soils

A. Chemical Reactions

Alternatively, the unidentified compound produced by oxidation of [NH₄]⁺ or reduction of [NO₂]⁻ may chemically react with organic

Table 14. Nitrous oxide emissions from University of Wisconsin Arboretum sites^a

Site	(ng N ₂ O-N m ⁻² S ⁻¹)			Sampling dates	Total emissions (kg N ₂ O-N ha ⁻¹)
	Mean	Spatial S.D. ^b	Temporal S.D. ^b		
1979					
<i>Forests</i>					
Deciduous	1.5	1.7	3.8	11 June-5 Nov.	0.19
Coniferous	7.7	9.5	18.1	11 June-5 Nov.	0.99
<i>Prairie</i>					
Burned	0.6	1.6	1.9	11 June-5 Nov.	0.09
Unburned	0.7	1.0	2.3	11 June-5 Nov.	0.10
<i>Organic soils</i>					
Drained marsh	18.0	13.8	45.8	11 June-5 Nov.	2.3
Undrained marsh	0.2	0.6	0.6	23 July-15 Nov.	0.02
Wet meadow	8.5	7.7	14.8	11 June-5 Nov.	1.1
1980					
<i>Forests</i>					
Deciduous	4.3	2.6	5.9	28 March-10 Nov.	0.80
Coniferous	10.1	4.9	8.5	28 March-10 Nov.	2.1
<i>Prairie</i>					
Burned	0.6	0.2	0.5	9 April-10 Nov.	0.11
Unburned	0.6	0.2	0.5	9 April-10 Nov.	0.10
<i>Organic soils</i>					
Drained marsh	41.3	35.4	134.7	28 March-10 Nov.	7.4
Undrained marsh	0.3	0.3	0.7	9 April-10 Nov.	0.06
Wet meadow	8.5	11.1	22.3	24 April-10 Nov.	1.4

^aReproduced from Goodroad and Keeney *J. Environ. Qual.* 13, 1984, 448-452, by permission of the Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am.

^bStandard deviations (S.D.) are pooled estimates between sample chambers (spatial) or between sampling dates (temporal).

materials to form N_2O as does $[NO_2]^-$. Accumulation of $[NO_2]^-$ is reported to occur in both acid and alkaline soils following application of alkaline-producing fertilizers, especially at high pH or at microsites where the fertilizer band is situated. Numerous factors, including low temperature, low soil buffering capacity, type and rate of fertilizer N, rate of nitrification, and soil pH, affect $[NO_2]^-$ accumulation in soils (Chalk and Smith, 1983). Arnold (1954) and Wijler and Delwiche (1954) suggested that a Van Slyke-type chemical reaction may be responsible for production of N_2O through reaction of $[NO_2]^-$ with NH_2OH :



Several subsequent reports also suggest that N_2O and N_2 are produced during chemical decomposition of hydroxylamine in soils (Bremner and Blackmer, 1980; Nelson, 1982; Chalk and Smith, 1983). Similarly, production of N gases, such as N_2 and N_2O , has been reported following the reaction of $[NO_2]^-$ with soil organic components. Discussions of the mechanism of N_2O formation via chemodenitrification are given in the reviews by Nelson (1982), Chalk and Smith (1983), and Hauck (1983).

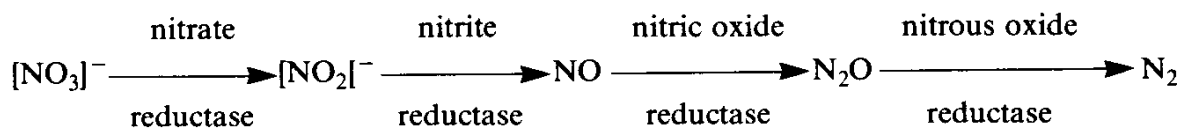
B. Biological Reactions

Bremner and Blackmer (1980, 1981) have discussed the various factors affecting N_2O production in soils. It becomes evident from the cases they present that *Nitrosomonas* species have the capacity to produce nitrite reductase that reduces $[NO_2]^-$ to N_2O under anaerobic conditions or aerobically during concurrent oxidation of $[NH_4]^+$ to $[NO_2]^-$.

Work by Ritchie and Nicholas (1972, 1974) established that the conversion of $[NO_2]^-$ to N_2O (Yoshida and Alexander, 1970, 1971) by cells of *Nitrosomonas europaea* involves the production of an intermediate compound, nitroxyl, that dimerizes to form hyponitrous acid. Nitrous oxide production results from the decomposition of hyponitrous acid.

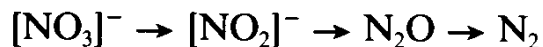
According to Bremner and Blackmer (1981), the mechanism of N_2O production during nitrification of $[NH_4]^+$ by *Nitrosomonas* spp. involves production of $[NO_2]^-$ -N via NH_2OH and probably an unidentified compound. Nitrite is acted upon by nitrite reductase, resulting in evolution of N_2O .

Evidence presented by Payne (1973, 1981a, b), Ingraham (1981), Bryan (1981), Firestone (1982), and McKenney *et al.* (1982) suggests that the pathways of N_2O production employ the following route:



However, there is still uncertainty about NO being an intermediate (Bryan, 1981; McKenney *et al.*, 1982) in the overall denitrification

mechanism. The processes and mechanisms leading to N_2O and N_2 production are clearly established. The well-accepted pathway for N_2O and N_2 production is:



M. S. Smith and Tiedje (1979) suggested that there were two distinct phases of denitrification in soil. In phase I, the initial rate of denitrification was attributed to the activity of the preexisting denitrifying enzyme systems. This phase was little affected by C amendments and lasted for 1 to 3 hrs. Nitrous oxide concentrations reached measurable levels after 15 min and remained in easily measurable amounts during the rest of the phase I time. Chloramphenicol, an inhibitor of protein enzyme synthesis, did not decrease the rate of denitrification (N_2 and N_2O production) during phase I. Phase II of denitrification in soils was attained after 4 to 8 h of anaerobic incubation, and chloramphenicol inhibited the rate of denitrification in this phase. The rate of denitrification was linear because of a lack of significant growth of denitrifiers. Whereas phase I denitrification was found to be affected by the aeration state of the sample, phase II was not affected. It was suggested that although the denitrifying enzymes were present in relatively dry soils, they were not repressed until O_2 inhibition was eliminated. Evidence presented indicated that most of the N is lost through denitrification during the brief period of a few hours following an irrigation or a rainfall event. Further, the phase I denitrification rate was more likely to be related directly to field denitrification rates.

IV. Control of N_2O Emission from Soils

As discussed earlier, a range of soils and environmental factors affect N_2O emissions from soils via nitrification and denitrification processes. In addition to these factors, the production of N_2O is also greatly affected by soil, crop, and fertilizer N management practices (Mosier *et al.*, 1983). Studies have also shown that the cropping systems and the fertilization practices affect N_2O emissions from soils (Rolston, 1981; Mosier *et al.*, 1983). Some of the factors affecting N_2O production relating to soil ecosystems and management and native soil conditions are briefly covered here.

A. Effects of Management and Native Conditions on N_2O Emissions from Different Soil Ecosystems

Mosier *et al.* (1982) presented evidence to show that the source and rate of fertilizer N affect N_2O production in soils. In a field study of N_2O emissions from soil fertilized with 0, 56, 112, and 224 kg N ha^{-1} as

NH_4NO_3 , it was found that N_2O emissions increased with the rate of N application. However, the increases in N_2O emissions with N rates were small and $\text{N}_2\text{O}-\text{N}$ accounted for only about 0.4 to 1.5% of the fertilizer added (Mosier *et al.*, 1982). Similar results have been reported by many other researchers, indicating that the overall contribution of fertilizer N to N_2O production is rather small (Hutchinson and Mosier, 1979; Denmead *et al.*, 1979; McKenney *et al.*, 1978, 1980; Rolston *et al.*, 1980; Mosier and Hutchinson, 1981; Rolston, 1981; Cochran *et al.*, 1981; Seiler and Conrad, 1981; C. J. Smith *et al.*, 1981; Rice and Smith, 1982; Aulakh *et al.*, 1982, 1983a, b; Armstrong, 1983) with the possible exception of organic soils (Terry *et al.*, 1981; Duxbury *et al.*, 1982; Mosier *et al.*, 1983) and vegetable crops heavily fertilized under irrigated conditions (Rolston, 1981; Rolston *et al.*, 1982).

Similarly, the source of fertilizer N also influences the fluxes of N_2O emissions from soils. For example, it has been observed that the N_2O emissions are larger from soils fertilized with anhydrous NH_3 than from those fertilized with $[\text{NO}_3]^-$ or $[\text{NH}_4]^+$ sources (Breitenbeck *et al.*, 1980; Bremner *et al.*, 1981; Cochran *et al.*, 1981; Mosier *et al.*, 1983).

Mosier *et al.* (1983) formulated a linear regression model of N_2O flux from soils describing the effect of fertilizer N rate on N_2O emissions, which can be represented by the following equation:

$$FN_2O = 3.88 + 0.024 Ft$$

Where FN_2O is the N_2O flux expressed as $\text{g N ha}^{-1} \text{ day}^{-1}$ and Ft is the applied fertilizer expressed as kg N ha^{-1} .

The emissions of N_2O from soils have been characterized by a large efflux of N_2O for a short time following fertilizer N application, followed by declining rates approaching baseline levels, irrespective of the amounts of N applied. The period characterized by a large efflux of N_2O is reported to vary from 5 to 6 weeks when most of the N_2O emissions occur (Breitenbeck *et al.*, 1980; McKenney *et al.*, 1980; Bremner *et al.*, 1981; Mosier *et al.*, 1983).

Research summarized by Mosier *et al.* (1983) indicates that the amounts of N_2O evolved from the native grasslands were similar to amounts emitted from unfertilized cropped soils. The total amounts of $\text{N}_2\text{O}-\text{N}$ emitted from these ecosystems annually amounted to about 1 kg N ha^{-1} and its source was apparently atmospheric deposition of N, which was about 10 kg N ha^{-1} annually.

Recent studies in Canada have shown that such management practices as summer fallowing, green manuring, and tillage affect the gaseous loss of N_2 and N_2O (Aulakh *et al.*, 1982, 1983a, b, 1984a).

1. Agricultural Soils

Recent field studies of N_2O emissions from agricultural soils fertilized with chemical fertilizers or organic manures have been summarized by

Rolston (1981), Mosier *et al.* (1983), Ryden and Rolston (1983), and Goodroad *et al.* (1984). It becomes evident that N₂O emissions from arable soils are greatly influenced by fertilizer management practices. The form and rate of fertilizer applications influence N₂O emissions (Hutchinson and Mosier, 1979; McKeeney *et al.*, 1978, 1980; Breitenbeck *et al.*, 1980; Bremner *et al.*, 1981; Cochran *et al.*, 1981; Seiler and Conrad, 1981; Mosier and Hutchinson, 1981; Mosier *et al.*, 1982, 1983). Also tillage and crop cover management (Aulakh *et al.*, 1982, 1983a, b) and irrigation and rainfall events that affect the water content of soils also affect N₂O emissions (Burford *et al.*, 1981; Rolston, 1981; Ryden, 1983; Ryden and Rolston, 1983; Goodroad *et al.*, 1984).

It has generally been found that the total N₂O emissions from agricultural soils fertilized with N are greatly influenced by the moisture regime. In dry regions with low rainfall activity, the annual emissions have been reported to be low and usually range from about 1 to 16 kg N₂O–N ha⁻¹ (McKeeney *et al.*, 1978, 1980; Hutchinson and Mosier, 1979; Burford *et al.*, 1981; Aulakh *et al.*, 1982, 1983b). Nitrous oxide emission from N-fertilized and irrigated soils are reported to be of higher magnitude and can be as high as 20 to 42 kg N ha⁻¹ (Ryden and Lund, 1980). Also, N₂O emissions from cropped or uncropped cultivated organic soils are larger than those from mineral soils (Terry *et al.*, 1981; Duxbury *et al.*, 1982).

Goodroad *et al.* (1984) measured the N₂O emissions from Wisconsin agricultural soils for two consecutive years and found that the total emissions were highest in the manure-amended and reduced tillage treatment (Table 15). Highest rate of N₂O emissions were often observed at the time of soil thaw. Soil pH (4.7, 5.1 and 6.7) had little effect on the emissions. The total emissions (in kg N₂O–N ha⁻¹) in 1980 under different treatments were: reduced tillage corn, 3.5 to 6.3; sludge, 1.6; manure, 6.1; alfalfa (*Medicago sativa*), 3.2; rye (*Secale cereale* L.), 1.6; straw, 2.2. These values are in the range of those reported in the literature from other arable agricultural soils (Mosier *et al.*, 1983).

Evidence presented by Mosier *et al.* (1983) suggests that the N₂O fluxes from the N-fertilized and irrigated fields in Colorado are larger than those from similar unfertilized sites under the same irrigation regimes. However, the N₂O–N emissions accounted for only 0.6 to 1.5% of the total N added.

With other agricultural soils, emissions of N₂O were highest from the vegetable cropland (Ryden and Lund, 1980) and drained organic soils used for cropping or left fallow (Duxbury *et al.*, 1982). However, their contribution to the overall global fluxes of N₂O may be small because of the small area covered by these soils.

Studies of N₂O emissions from agricultural arable soils so far reported, including both short-term and long-term measurements, suggest that generally less than 2.0% of the applied fertilizer N is lost as N₂O–N.

Table 15. Nitrous oxide emissions from agricultural soils in Wisconsin^a

Site	(ng N ₂ O-N m ⁻² s ⁻¹)			Total emissions ^c (kg N ₂ O-N ha ⁻¹)
	Mean	Spatial S.D. ^b	Temporal S.D. ^b	
1979				
<i>Reduced tillage corn</i>				
In the row	4.4	5.8	7.8	0.6
Between the rows	2.4	2.8	5.2	0.3
<i>Organic amendments</i>				
Sludge	1.9	1.0	2.2	0.2
Manure	8.6	10.7	19.8	1.2
<i>Lime</i>				
pH 4.7	2.8	1.4	3.8	0.4
pH 5.1	1.7	0.9	2.7	0.2
pH 6.7	1.6	1.4	2.7	0.2
1980				
<i>Reduced tillage corn</i>				
In the row	21.5	23.7	30.8	3.5
Between the rows	38.7	59.3	142.7	1.6
<i>Organic amendments</i>				
Sludge	9.3	7.3	20.1	1.6
Manure	27.7	48.1	79.1	6.1
<i>Lime</i>				
pH 4.7	8.4	10.1	15.7	1.5
pH 5.1	5.2	3.7	9.2	0.9
pH 6.7	5.6	6.0	8.2	1.0

^aAdapted from Goodroad *et al.* *J. Environ. Qual.* 13, 1984, 557-561, by permission of the Am. Soc. Agron., Crop Sci. Soc. Am., Soil Sci. Soc. Am.

^bStandard deviations (S.D.) are pooled estimates between sample chambers (spatial) and between sampling dates (temporal).

^cValues obtained by summing the products of the daily emissions and time period in days over actual dates sampled.

Nitrous oxide emission rates are usually characterized by large temporal and spatial variability because of complex interactions between physical and biochemical factors that affect production and emission of N_2O from soils.

2. Forest Soils

There is lack of data on N_2O flux from forest soils ecosystems. A recent study by Goodroad and Keeney (1984b) suggested that there were large differences in N_2O emissions among various forest covers and that N_2O flux from replanted forest was on the same order of magnitude as that in agricultural systems (Table 14). It was also found that significantly more N_2O was emitted from coniferous than from deciduous forest floors. Perhaps N added through precipitation could be the source for these emissions. The average daily flux of $\text{N}_2\text{O}-\text{N}$ from deciduous and coniferous forest floors were found to be 1.2 and 5.8 $\text{g ha}^{-1} \text{ day}^{-1}$, respectively, and were 0.180 and 0.860 $\text{kg N}_2\text{O}-\text{N}$ for the year. A recent study by Melillo *et al.* (1983) showed that N_2O emissions were highest from the forest floor of a 2-yr-old hardwood stand. Although the pH of the forest floors ranged from 3.5 to 3.9, there was considerable apparent denitrification loss of N as N_2O . The denitrification potential as measured by the acetylene blockage technique was highly correlated with the $[\text{NO}_3]^- - \text{N}$ content. The results suggested that recently cut forest systems have the potential to emit N_2O in amounts similar to those reported from agricultural soils.

Because forests occupy a significant area of land, their overall contribution to the global $\text{N}_2\text{O}-\text{N}$ flux may be important, and there is need to obtain more data on N_2O emissions from forest soil ecosystems.

3. Prairies

Schultz *et al.* (1970) and Burford and Hall (1977) reported that the $\text{N}_2\text{O}-\text{N}$ flux from unfertilized grasslands was small and ranged from 0.1 to 0.8 $\text{mg N m}^{-2} \text{ day}^{-1}$. Burford and Hall (1977) found that fertilization of the grass sward increased the daily flux (range of 0.2 to 2 $\text{mg N}_2\text{O}-\text{N m}^{-2}$). Rolston *et al.* (1978) reported that N_2O emission rates from grass swards were the highest when they were heavily fertilized with organic manures and the soil water content was high. The N_2O flux in their study from grass sward ranged from 40 to 800 $\text{mg N m}^{-2} \text{ day}^{-1}$. Ryden (1981), on the other hand, indicated that the daily N_2O flux from a British grassland soil fertilized with inorganic fertilizer N ranged from nil to 21 mg N m^{-2} . Soils very low in $[\text{NO}_3]^- - \text{N}$ were found to act as sinks for atmospheric N_2O .

Mosier *et al.* (1981) studied N_2O emissions from a native short grass prairie and found that the daily flux averaged 2.3 $\text{g N ha}^{-1} \text{ day}^{-1}$ during

summer. They found that fertilization of soils with urea to simulate grazing animal urine deposition increased the N_2O emission rates by a factor of three over the untreated soils. However, $\text{N}_2\text{O}-\text{N}$ accounted for only 0.6% of the added N. They concluded that although N_2O emissions from the native grasslands were small, they were significantly larger than results obtained from uncultivated soils. Their estimate indicated that about 10% of total N input in the grasslands from biological N_2 fixation and atmospheric depositions was lost as N_2O . Sherlock and Goh (1983) noted that urine stimulated N_2O production in a grazed pasture relative to urea or $[\text{NH}_4]^+$. Large emissions of $\text{N}_2\text{O}-\text{N}$ (up to $0.6 \text{ g ha}^{-1} \text{ day}^{-1}$) occurred from sheep urine patches.

Denmead *et al.* (1979) measured N_2O emission from an unfertilized grass sward over 5 months and found that the emissions were largest in spring and increased with increase in the soil water and $[\text{NO}_3]^-$ contents. Nitrous oxide emission rates showed a diurnal cycle in response to soil surface temperatures. Peak emission rates occurred in the afternoon, with a minimum near sunrise. Average daily N_2O emissions from soils with soil water less than field capacity ranged from 0.6 to 2.5 mg N m^{-2} .

Christensen (1983) found that the N_2O flux from untreated soils under permanent grass during 5 months averaged $0.58 \text{ mg N m}^{-2} \text{ day}^{-1}$. Application of cow dung slurry caused a surge in N_2O flux that increased up to 40-fold compared to untreated grassland. On the other hand, applications of NH_4NO_3 caused up to a five-fold increase in the N_2O flux during the same period (Table 16). These results, along with those reported by Rolston *et al.* (1978), suggest that grassland heavily fertilized with organic N has a greatly increased rate of N_2O emission.

Christensen (1983) reported that the N_2O flux often showed marked diurnal fluctuations, which were not solely associated with change in temperature but were also likely related to grass root activity and photosynthetic rates. A study by Blackmer *et al.* (1982) also showed that diurnal variability in rate of emissions of N_2O from Iowa soils was often not related to diurnal variability in soil temperature but was related to the solubility of N_2O in water induced by temperature change. The N_2O flux from the unfertilized grassland ranged from 0.5 to $1.4 \text{ mg N m}^{-2} \text{ day}^{-1}$ and increased up to $50 \text{ mg N m}^{-2} \text{ day}^{-1}$ when they were fertilized with organic N (Christensen, 1983).

Goodroad and Keeney (1984b) measured N_2O flux from Wisconsin prairies for 2 yr and found that the total $\text{N}_2\text{O}-\text{N}$ emissions ranged from 0.09 to $0.11 \text{ kg N ha}^{-1}$. Nitrous oxide emissions were similar from burned and unburned prairies (Table 14). Seasonal patterns of N_2O emissions were markedly influenced by changes in soil temperature and soil water content. The average daily N_2O flux from uncultivated tall grass prairies amounted to $0.5 \text{ g N}_2\text{O}-\text{N ha}^{-1}$ and was not significantly affected by removal of plant residues by burning.

Table 16. Cow slurry and ammonium nitrate-induced N₂O flux from soil under permanent grass^{a,b}

Fertilizer/Slurry			
Treatment	Rate (g N m ⁻²)	Sampling date	N ₂ O-N flux (mg N m ⁻²)
None	—	1 May-10 July	43
	—	10 July-6 August	24
NH ₄ NO ₃	10.0	1 May-10 July	132
	10.0	10 July-6 August	106
Slurry ^c	10.3/11.1	1 May-10 July	165
	15.9/11.9	10 July-6 August	770

^aReprinted with permission from *Soil Biol. Biochem.*, 15, S. Christensen, pp. 531-536; copyright 1983 Pergamon Press Ltd.

^bCow slurry and NH₄NO₃ were added to the plots on 30 April and 10 July 1981.

^cSlurry was added on inorganic N/organic N basis.

4. Wetlands

Denmead *et al.* (1979) measured N₂O flux from a flooded rice field in New South Wales. The soils had about 40 kg NO₃-N ha⁻¹ in the surface soils at the start of the experiment. Measurements were made continuously for 18 days after the field was flooded. Nitrous oxide fluxes showed a diurnal cycle in response to temperature of the paddy flood water. Between the second and 19th day of flooding, about 27 kg [NO₃]⁻-N ha⁻¹ was lost from the flood water. However, N₂O-N evolved was only 0.38 kg ha⁻¹ and represented only about 1.4% of the apparent [NO₃]⁻ loss. In another small-bay experiment in which NaNO₃ was added, N₂O production accounted for only 0.8% of the [NO₃]⁻-N lost.

Similarly, a study of N₂O flux from a flooded rice paddy in the Philippines fertilized with (NH₄)₂SO₄ (80 kg N ha⁻¹) showed that N₂O emissions amounted to only 0.1% of the N applied (Frey *et al.*, 1981). Smith, C. J. *et al.* (1982) measured the rate of N₂O emissions from a flooded rice field in Louisiana fertilized with urea (0, 90, and 180 g N ha⁻¹). Urea application increased the flux of N₂O-N, but the emissions were low and ranged from 90 to 197 g N ha⁻¹ over 105 days. Nitrous oxide fluxes were found to be correlated with the content of exchangeable [NH₄]⁺-N in soil and ([NO₃]⁻ + [NO₂]⁻)-N in the flood water. The average N₂O-N emissions from the unfertilized soil totaled 74 g N ha⁻¹, indicating that the fertilizer-induced emissions of N₂O represented only a very small proportion of the urea N applied (0.01 to 0.05%).

This brief discussion of the available information regarding N₂O emissions from flooded rice paddies clearly suggests that the N₂O emissions from these systems are very low and that fertilizer-induced N₂O emissions are also small, usually accounting for less than 1.4% of the fertilizer N.

B. Ecological Factors Affecting N₂O Emissions

It is evident that a large number of soil and environmental factors affect N₂O emission from soils. These include a number of physical and biochemical processes that directly or indirectly affect N₂O production or emission from soil.

In addition to these factors, the ecosystem as a whole likely has a profound effect on N₂O emissions. For example, recent studies have shown that there is a marked difference in N₂O emissions rate from different forest soil ecosystems representing different plant communities (Goodroad and Keeney, 1984b). There may be at least three factors that are affecting these emissions: (1) soil pH may be an important factor in controlling production of substrate for N₂O production via denitrification and nitrification. Perhaps immobilization of mineral N may be another factor controlling net availability of mineral N for nitrification and subsequent denitrification. (2) Deficiency of nutrients, such as P, may be implicated in N mineralization and nitrification, which affect N₂O emissions. (3) The possibility of some toxic substances being produced in a soil ecosystem, which then affects, nitrification and N mineralization, also needs investigation, because these "inhibitory substances" may be important in controlling the population of nitrifiers and denitrifiers involved in N₂O production.

All these ecological factors that may be affecting N₂O production in soils are speculative, for lack of supporting data, but may provide a good starting point for research to identify factors that affect N₂O emissions in different ecosystems.

C. Use of Chemicals to Control N₂O Emissions

Recent laboratory (Bremner and Blackmer, 1978; C. J. Smith and Chalk, 1980; Blackmer *et al.*, 1980; Aulakh *et al.*, 1984b) and field (Bremner *et al.* 1981; Magalhaes *et al.*, 1984) studies have shown that nitrapyrin reduces the rate of N₂O emission associated with the nitrification in soils. Field results showing the effect of nitrapyrin on anhydrous ammonia-induced N₂O emissions are given in Table 17, which clearly shows that nitrapyrin is effective in reducing N₂O emissions from both fall and spring applications of anhydrous ammonia. However, nitrapyrin has been

Table 17. Effects of nitrapyrin on N₂O emission from soil fertilized with anhydrous ammonia in fall or spring^a

Treatment ^b	Amount of N ₂ O-N evolved (kg N ha ⁻¹) in 167 days	
	Fall application	Spring application
None	0.16	0.43
AA	1.55	1.37
AA + NP	1.04	0.55

^aFrom Bremner *et al.*, *Geophys Res. Lett.* 8, 353-356, 1981, copyright by the American Geophysical Union.

^bAA, anhydrous ammonia (180 kg N ha⁻¹); NP, nitrapyrin (0.56 kg ha⁻¹). Treatments were performed on 9 October, 1979 for the fall application and on 15 April, 1980 for the spring application.

found to have little direct effect on N₂O production via denitrification of [NO₃]⁻-N (Bremner and Blackmer, 1980, 1981). This opens up a new avenue for the use of nitrification inhibitors to control N₂O emissions from soils.

There is a need to develop chemicals that can control N₂O emissions associated not only with nitrification but also with denitrification. A better understanding of the enzyme system involved in N₂O production should aid in developing chemicals that can block the specific enzymatic system which is responsible for N₂O production.

V. Summary

We have reviewed current literature on the processes that contribute to N₂O emissions from soils. It would appear that denitrification is the dominant source of N₂O evolution from soils. However, it is now well recognized that nitrification can release significant amounts of N₂O in some situations. Chemodenitrification as a mechanism of N₂O production in soils is well established under laboratory conditions. However, it is not possible at the present time to speculate how much nitrification and chemodenitrification contribute to the overall N₂O emissions from soils under field conditions. It is rather difficult to delineate the contributions of denitrification and nitrification to N₂O evolution from soils in the field because of the occurrence of anaerobic microsites in apparently aerobic soils, particularly ones with considerable native organic matter or carbon added externally as plant residues or manures.

The mechanism of N₂O production via nitrification of [NH₄]⁺-N to [NO₂]⁻-N is not clearly understood. It is clear, however, that N₂O can be

formed from $[\text{NO}_2]^-$ via denitrification under anaerobic conditions or during oxidation of $[\text{NH}_4]^+$ to $[\text{NO}_2]^-$ under aerobic conditions. It is also not clearly understood whether N_2O is formed by chemical decomposition of hydroxylamine during nitrification or as a result of reaction between hydroxylamine and $[\text{NO}_2]^-$. It is clear, however that $[\text{NO}_2]^-$ accumulates in soils in situations where biological oxidation of $[\text{NO}_2]^-$ by *Nitrobacter* is at low ebb. There is a need to understand the significance of chemodenitrification in the field when alkaline-hydrolyzing fertilizers are band applied.

Research on N_2O emissions from native and managed ecosystems suggests that significant amounts of emissions occur under wet conditions from agricultural soils, particularly those fertilized with organic manures or having a high content of organic matter. The daily flux of $\text{N}_2\text{O}-\text{N}$ can vary from as low as <0.01 to as high as 8 kg N ha^{-1} . The high fluxes of $\text{N}_2\text{O}-\text{N}$ are not common in agricultural soils, with the exceptions of cultivated organic soils. Limited studies on forest soils suggest that fluxes of N_2O from these systems may be of an order of magnitude similar to those obtained from agricultural soils. Nitrous oxide emissions are greatly affected by the kind of forest stand and differences in N cycling processes. The potential for larger emissions of N_2O exists in recently cut forests.

The fluxes of N_2O from grasslands are quite variable and are affected by fertilization and other management practices. They range from 0.1 to $800 \text{ mg N m}^{-2} \text{ day}^{-1}$. Mosier *et al.* (1981) reported an average daily flux of $2.3 \text{ g N ha}^{-1} \text{ day}^{-1}$ from a native short grass prairie in summer. They estimate that about 10% of total N inputs in the grasslands from biological N_2 fixation and atmospheric deposition is lost as N_2O annually. Nitrous oxide fluxes reported from flooded rice paddies are relatively small compared to other ecosystems. The fertilizer-induced N_2O emissions are also usually small from flooded rice soils. It would appear that under the anaerobic conditions found in flooded soils, the gaseous product of denitrification is dominantly N_2 , because N_2O is readily reduced to N_2 under these conditions. These soils may act as sinks rather than sources for N_2O .

The best way of reducing N_2O emissions from soils is by increasing the efficiency of N in crop production. Nitrification inhibitors are capable of reducing N_2O production via nitrification or by chemodenitrification by slowing $[\text{NO}_2]^-$ accumulation. Development of chemicals that can retard denitrification and associated N_2O production will interest agronomists, soil scientists, and environmentalists.

Finally, modeling efforts are now needed to take stock of N_2O emissions from soils used for production of food, feed, and fiber crops with the available data sets as well as to learn about the kind of data sets needed for the modeling exercise prerequisite to prediction of global N_2O emissions.

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