AP42 Section:	9.2.1
Background Ch	4
Reference:	22
Title:	A. M. Blackmer et al., "Diurnal Variability in Rate of Emission of Nitrous Oxide from Soils," *Soil Science Society of America Journal*, 46:937-942, 1982.

Sect. 4 #22

Diurnal Variability in Rate of Emission of Nitrous Oxide from Soils[1]

A. M. BLACKMER, S. G. ROBBINS, AND J. M. BREMNER[2]

ABSTRACT

Diurnal variability in the rate of emission of nitrous oxide (N_2O) from Iowa soils was studied by using a chamber technique to measure the N_2O emission rates at sites on fertilized and unfertilized soils at 1- or 2-h intervals for periods of from 1 to 5 d. The coefficients of variation for the rates of N_2O emission observed at these sites within 24-h periods ranged from 12 to 66% and averaged 38%. As much as 90% of the diurnal variability observed could be attributed to diurnal N_2O emission patterns related to changes in soil temperature. Observations reported suggest that these patterns were caused largely by changes in the solubility of N_2O in soil water induced by diurnal changes in soil temperature, that the amplitudes of these patterns were determined largely by the amounts of water and N_2O in the surface soil, that the times of minima and maxima in these patterns were determined by the depth at which temperature-induced changes in the solubility of N_2O in water were significant, and that neither the amplitudes nor the times of minima and maxima in these patterns can be predicted solely from soil temperature. Data reported show that there is no short time during a 24-h period that is always satisfactory for assessing the amount of N_2O evolved during that period.

Additional Index Words: spatial variability, soil temperature, solubility of N_2O in water.

Blackmer, A. M., S. G. Robbins, and J. M. Bremner. 1982. Diurnal variability in rate of emission of nitrous oxide from soils. Soil Sci. Soc. Am. J. 46:937–942.

THERE is concern that increased use of N fertilizers to aid world food production may affect our climate by increasing the amount of nitrous oxide (N_2O) evolved from soils to the atmosphere (CAST, 1976; Yung et al., 1976; Crutzen and Ehhalt, 1977; Liu et al., 1977; McElroy et al., 1977; Wang and Sze, 1980). This concern has created a need for reliable estimates of natural and fertilizer-induced emissions of N_2O from soils, but attempts to meet this need have shown that, to develop a satisfactory sampling program for assessment of N_2O emissions from soils in any region, it is necessary to have adequate information concerning spatial and temporal variability in these emissions (see Bremner and Blackmer, 1978; McKenney et al., 1978, 1980; Ryden et al., 1978, 1979; Denmead et al., 1979a, 1979b; Findlay and McKenney, 1979; Hutchinson and Mosier, 1979; Bremner et al., 1980; Matthias et al., 1980).

Several workers have detected marked diurnal variability in the rate of N_2O emission from soil. For example, Ryden et al. (1978) observed pronounced diurnal variability in the rate of emission of N_2O from a soil used for celery production in California, with the peak flux occurring in the early afternoon (see also Ryden et al., 1979). They suggested that this peak arose from the effect of an increase in soil temperature on the activity of denitrifying bacteria or on the rate of diffusion of N_2O from the profile and that it might be related to the daily wind pattern at the sampling site. Denmead et al. (1979b) observed a clearly defined diurnal pattern in the rate of N_2O emission from a grass sward in Australia, with maximum rates occurring in the afternoon and minimum rates near sunrise. They also noted that the diurnal variability in the rate of N_2O emission from this sward seemed closely associated with diurnal variability in the temperature of the topsoil, with very little phase difference.

We report here the results of field studies to assess and account for diurnal variability in the rate of emission of N_2O from Iowa soils. The data presented show that diurnal variability in the rate of N_2O emission from Iowa soils often is markedly out of phase with diurnal variability in the temperature of the surface soil and that there is sometimes a significant negative correlation between the rate of N_2O emission and the temperature of the surface soil.

MATERIALS AND METHODS

The four field studies reported were performed on a field located at the Iowa State University Agronomy Research Center 10 km southwest of Ames. The soil in one area of this field was a Typic Haplaquoll representative of the Webster series. The soil in the other area was a Typic Haplaquoll representative of the Canisteo series. Analyses of composite samples of surface (0–15 cm) soil collected at 12 sites within each of these areas showed that the Webster soil had a pH of 6.7 and contained 2.9% organic C, 30% clay, and 34% sand and that the Canisteo soil had a pH of 7.7 and contained 2.5% organic C, 22% clay, and 40% sand. These analyses were performed as described by Blackmer and Bremner (1977).

The first study was conducted during 13–14 June 1978 at two sites 4 m apart on an area of Webster soil that had been fertilized with urea (110 kg N/ha) on 6 May 1978 and planted to corn on 8 May 1978. The second study was conducted during 27–28 June 1978 at three sites 5 m apart on an area of fallow Webster soil that had been fertilized with urea (80 kg N/ha) on 22 June 1978. The third study was performed during 7–11 Aug. 1978 at a site on an area of unfertilized fallow Canisteo soil. The fourth study was performed during 17–18 June 1980 at two sites 6 m apart on an area of fallow Canisteo soil that had been fertilized with urea (150 kg N/ha) on 11 June 1980. One of these sites was shaded 4 h before the measurements reported were performed and was kept shaded during these measurements. To shade this site, we supported a sheet of black polyethylene film (4-mil) about 1.5 m above the surface of the site by attaching it to four wooden poles inserted into the soil around the site. Immediately after completion of this study, a surface (0–15 cm) sample of the soil at the unshaded site was collected, crushed to pass through a 2-mm sieve, and used for a laboratory investigation of the effect of temperature on emission of N_2O from this soil. In this investigation, samples of the screened field-moist soil containing the equivalent of 30 g of oven-dry soil were incubated at 10, 20, 30, and 40°C in 1.2-L flasks sealed with ground-glass joints fitted with glass stopcocks, and the amounts of N_2O evolved in 21 h were determined by a sensitive gas chromatographic pro-

[1] Journal Paper no. J-10333 of the Iowa Agric. and Home Econ. Exp. Stn., Ames. Project no. 2096. Presented in part before Div. A-5, Soil Sci. Soc. Am., Fort Collins, Colo., 6 Aug. 1979. This work was supported by a grant (ENV77-23835) from the Natl. Sci. Found. Received 19 Oct. 1981. Approved 18 May 1982.

[2] Assistant Professor, Graduate Research Assistant, and Professor, respectively, Dep. of Agronomy, Iowa State Univ., Ames, IA 50011.

cedure that permits use of the Xe in air as an internal standard (Blackmer and Bremner, 1978).

Where fertilizer was applied in the studies reported, it was broadcast evenly on the soil surface and incorporated by rototilling the soil to a depth of 10 cm.

In each study, the rates of N_2O emission at the sites selected were measured at 1- or 2-h intervals for periods ranging from 1 to 5 d. The method used to measure the rate of N_2O emission was the chamber technique described by Matthias et al. (1980), which involves placement of an insulated cylindrical metal chamber over the soil surface for 15 to 20 min and removal of air samples from the chamber at 5-min intervals for N_2O analysis as described by Blackmer and Bremner (1978). This chamber method has the advantages that it does not significantly disturb the soil under study and does not require that the chamber be placed over the soil surface for more than 15 min. The chamber was removed from the soil surface immediately after each measurement because previous work (Matthias et al., 1980) showed that any type of closed chamber can significantly affect the temperature of the soil and air within it if left in place for more than a short time.

Soil temperature was determined to an accuracy of ±0.15°C by means of Markson (Markson Science Inc., Del Mar, CA 92014) Model 5750 digital thermometers fitted with vinyl-tip thermistor probes. Unless otherwise specified, the temperatures reported were measured at a depth of 2 cm. Soil moisture content was determined by gravimetric determination of weight loss when samples of surface (0–12 cm) soil were dried at 105°C for 24 h. It is reported as a percentage by weight of oven-dry soil. Wind speed was measured at approximately 0.3 m above the soil surface by means of a Robinson 3-cup anemometer.

RESULTS AND DISCUSSION

Figure 1 shows the diurnal variability in the rate of N_2O emission at two sites on a fertilized Webster soil under corn on 13 and 14 June 1978 (study 1). The data reported show a clear diurnal pattern in the rate of N_2O emission, with the maximum rates of N_2O emission occurring in the early evening and the minimum rates of N_2O emission occurring in the late morning.

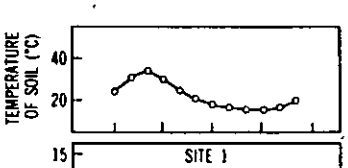

Fig. 1—Results of measurements of N_2O emission rate and soil temperature at two sites 4 m apart on a fertilized Webster soil planted to corn (13–14 June 1978). Temperatures were measured at a depth of 2 cm.

The highest rates of N_2O emission observed at sites 1 and 2 were, respectively, 28 and 12 times the lowest rates observed.

Figure 2 shows the diurnal variability in the rate of N_2O emission at three sites on an unfertilized fallow Webster soil on 27 and 28 June 1978 (study 2). It is evident that there was a clear diurnal pattern in the rate of N_2O emission, with the maximum rates of N_2O emission occurring in the middle of the night and the minimum rates of N_2O emission occurring in the middle of the day. The highest rates of N_2O emission observed at sites 1, 2, and 3 were, respectively, ... 4.7, and 4.7 times the lowest rates observed.

Figure 3 shows the diurnal variability in the rate of N_2O emission at one site on a fertilized fallow Canisteo soil during 7–11 Aug. 1978 (study 3). The data reported show that there was no obvious diurnal pattern in the rate of N_2O emission during this period but that increased rates of N_2O emission were observed in the evenings of 9 and 10 August. It is noteworthy that we observed no clear relationship between the rate of N_2O emission and the average wind speed (see Fig. 3) because Ryden et al. (1978) suggested that diurnal patterns in the rate of N_2O emission from soil might be related to daily wind patterns.

Although the diurnal variability in N_2O emission rate observed in our studies is somewhat similar to that observed in studies in California (Ryden et al., 1978, 1979) and in Australia (Denmead et al., 1979a, 1979b), our results show that there is much more variability in the amplitudes and in the times of minima and maxima of diurnal patterns in the rate of N_2O emission from soils than has previously been reported. In contrast to the work reported here, neither the study in California nor that in Australia revealed situations in which diurnal patterns in the rate of N_2O emission did not occur or were significantly out of phase with diurnal patterns in the temperature of the surface soil.

Both Ryden et al. (1978, 1979) and Denmead et al. (1979a, 1979b) suggested that the diurnal patterns in rate of N_2O emission observed in their work were

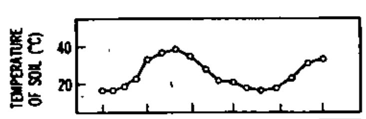

Fig. 2—Results of measurements of N_2O emission rate and soil temperature at three sites 5 m apart on a fertilized fallow Webster soil (27–28 June 1978). Temperatures were measured at a depth of 2 cm.

Fig. 3—Result
fallow Cani

related to
perature o
nisms. Cle
N_2O emiss
to diurnal
by the fiel
showed th
to reduce
a marked
rate of N_2
least some
emission o
uted to th

Fig. 4—Resul
Canisteo soi

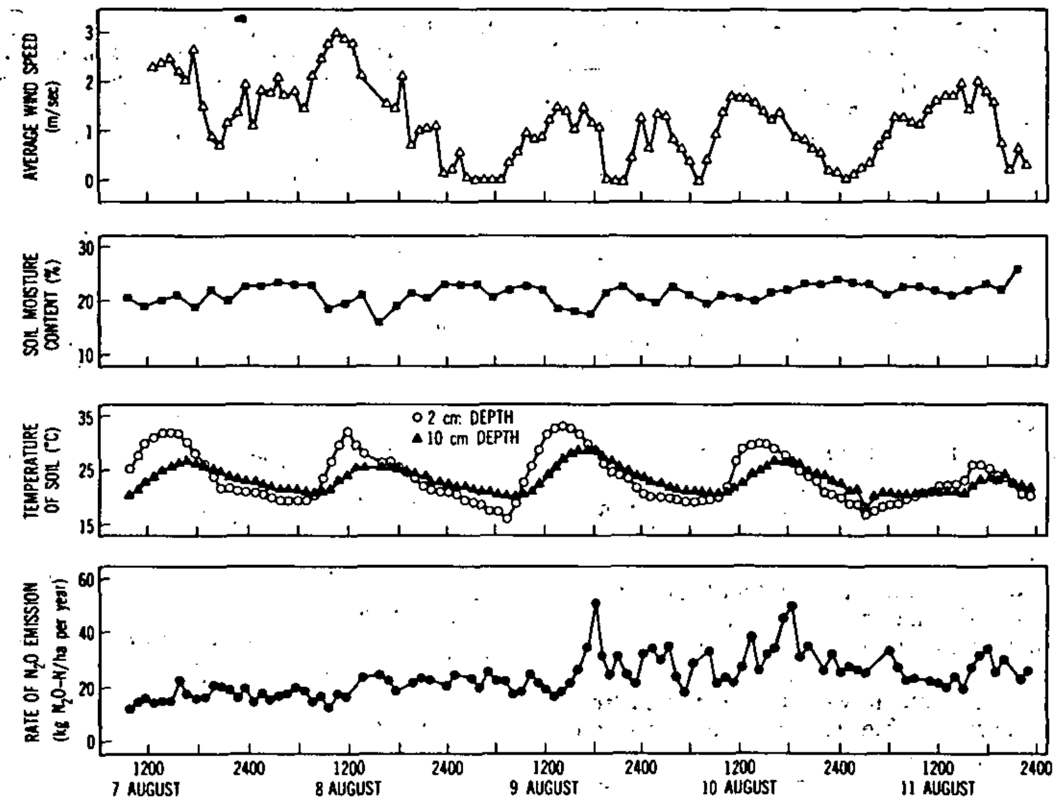

Fig. 3—Results of measurements of N_2O emission rate, soil temperature, soil moisture content, and average wind speed at a site on an unfertilized fallow Canisteo soil (7–11 Aug. 1978).

related to the effect of diurnal changes in soil temperature on production of N_2O by soil microorganisms. Clear evidence that the diurnal variability in N_2O emission rate observed in our work was related to diurnal variability in soil temperature was provided by the field study reported in Fig. 4 (study 4), which showed that shading of the surface of a Canisteo soil to reduce diurnal changes in soil temperature led to a marked reduction in the diurnal variability in the rate of N_2O emission from this soil. Evidence that at least some of the diurnal variability in the rate of N_2O emission observed in this field study could be attributed to the effect of temperature on production of N_2O by soil microorganisms is reported in Table 1, which shows the results of a laboratory study of the influence of temperature on production of N_2O by soil collected from unshaded site in study 4. However, comparison of the data in Fig. 4 and Table 1 shows that, whereas our field study showed that a 17°C change in the temperature of the soil at the unshaded site was accompanied by a 17-fold change in the rate of N_2O emission at that site (Fig. 4), our laboratory study showed that a 20°C change in the temperature of the soil at this site caused only a 4.5-fold change in the rate of N_2O production. To compensate for the damping of temperature changes that accompanies

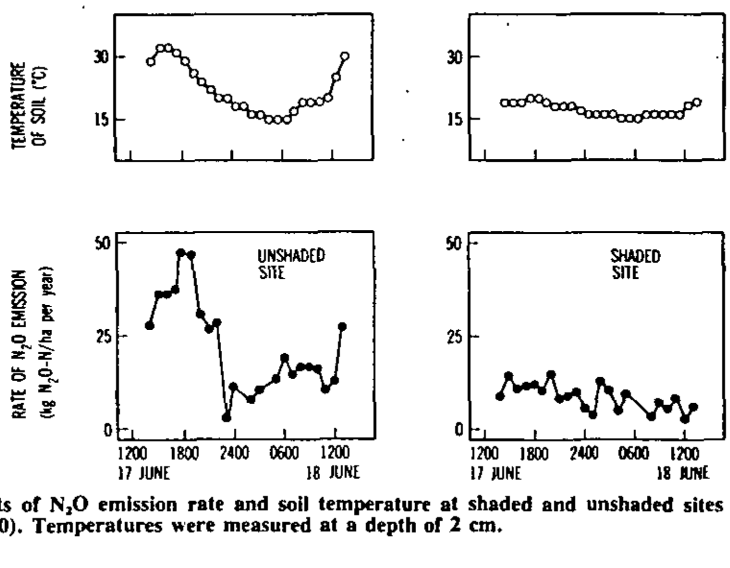

Fig. 4—Results of measurements of N_2O emission rate and soil temperature at shaded and unshaded sites 6 m apart on a fertilized fallow Canisteo soil (17–18 June 1980). Temperatures were measured at a depth of 2 cm.

Table 1—Effect of temperature on emission of N_2O from a Canisteo soil.†

Temperature	Amount of N_2O-N evolved from soil in 21 hours‡	Q_{10}§
°C	ng/g soil	
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

† Samples of field-moist soil (23% moisture) were incubated at 10, 20, 30 and 40°C for 21 h.
‡ Mean and standard deviation (5 replicates).
§ Rate of N_2O emission at temperature specified ÷ rate of N_2O emission at 10°C lower temperature.

increases in depth below the soil surface, R. Horton of our department made calculations (details of his method of calculation will be reported elsewhere) indicating that a 17°C temperature change at a depth of 2 cm should correspond to a mean temperature change of about 13.5°C in the 10-cm layer of soil into which fertilizer was incorporated. Fitting a double sine curve by least squares to the data reported in Fig. 4 resulted in an equation that predicted the ratio of maximum to minimum rates of N_2O emission to be 6. Because this ratio is much larger than would be expected from the work reported in Table 1, we believe that the effect of changes in soil temperature on the rate of N_2O production by soil microorganisms is not adequate to account for the amplitude of the diurnal pattern in the rate of N_2O emission observed in study 4.

It is noteworthy that Denmead et al. (1979b, see Fig. 2) reported a diurnal pattern in the rate of N_2O emission from a grass sward that was characterized by short periods of high rates of N_2O emission between longer periods of low rates of N_2O emission. Calculations from their data show that this pattern could not be attributed solely to the effect of soil temperature on the rate of N_2O production by soil microorganisms even if production of N_2O by soil microorganisms had a Q_{10} of 3.1 as reported by these investigators.

Table 2 shows the mean amplitude of the diurnal variation in soil temperature and the predicted mean ratio of maximum to minimum daily rates of N_2O production at three depths in an Iowa soil for the months of 1978. The data presented show how rapidly temperature variations are damped with increase in depth below the soil surface and the effect this damping should have on the amplitude of diurnal patterns in the rate of N_2O production by soil microorganisms. Because even the highest predicted ratios of maximum to minimum daily rates of N_2O production were only 2.47, 1.51, and 1.13 at depths of 5.7, 10, and 20 cm, respectively, we believe that the data reported in Table 2 support our conclusion that the diurnal patterns in N_2O emission rate observed in our work cannot be attributed solely to the effect of temperature on the rate of N_2O production by soil microorganisms. In regard to this conclusion, it should be noted that later in this paper we present evidence that some of the diurnal patterns in N_2O emission rate observed in our studies should be related to temperature changes at depths significantly below the soil surface. It also should be noted that we consider it highly unlikely that significant N_2O production occurred in the surface

Table 2—Mean amplitude of diurnal variation in soil temperature and predicted mean ratio of maximum to minimum daily rates of N_2O production at three depths in an Iowa soil for the months of 1978.

Month	Mean amplitude of diurnal variation in soil temperature†			Predicted mean ratio of maximum to minimum daily rates of N_2O production‡		
	At 5.7 cm	At 10 cm	At 20 cm	At 5.7 cm	At 10 cm	At 20 cm
	°C					
January	3.3	1.0	0.5	1.36	1.09	1.05
February	0.6	0.3	0.3	1.05	1.03	1.03
March	4.0	1.6	0.4	1.41	1.15	1.04
April	9.2	4.1	1.2	2.11	1.40	1.10
May	10.1	4.3	1.5	2.15	1.40	1.12
June	10.7	4.6	1.7	2.17	1.40	1.14
July	10.2	4.3	1.5	2.08	1.38	1.12
August	12.6	5.6	1.7	2.47	1.51	1.13
September	11.1	5.1	1.7	2.26	1.45	1.13
October	10.0	4.1	1.6	2.11	1.38	1.13
November	4.9	2.2	1.1	1.50	1.20	1.09
December	0.6	0.1	0.1	1.05	1.01	1.01

† Monthly mean of differences between maximum and minimum soil temperatures observed each day at various depths in a fallow Webster soil (NOAA, 1978).
‡ Calculated by use of the integrated form of the Arrhenius equation (Segel, 1975). Rates of N_2O production shown for 10 and 30°C in Table 1 were used to calculate the energy of activation for N_2O production, and this value was then used to calculate the ratio of maximum to minimum rates of N_2O production from the monthly means of daily maximum and minimum soil temperatures.

1 or 2 cm of soil in our field studies because this layer of soil was sufficiently dry to inhibit production of N_2O by soil microorganisms.

We have made calculations suggesting that the diurnal patterns in N_2O emission rate observed in our work can be explained by temperature-induced changes in the solubility of N_2O in soil water if it is assumed that, when these patterns were observed, the concentrations of N_2O in the atmospheres of the surface soils examined were significantly higher than the atmospheric concentration of N_2O. For example, we calculated that a 35-cm layer of surface soil in study 1 contained 1×10^6 kg water per ha. By assuming that the gravimetric solubility coefficient for N_2O in this water was 0.0402 mol kg^{-1} atm^{-1} at 10°C and 0.0349 mol kg^{-1} atm^{-1} at 14°C (see Weiss and Price, 1980), we calculated that this layer of soil would release about 0.044, 0.44, and 2.2 g N_2O-N/ha if the soil temperature increased from 10 to 14°C and the concentration of N_2O in the atmosphere of this layer remained constant at 0.3, 3.0, and 15 ppm (v/v), respectively. If the N_2O evolved from soil water at these three N_2O concentrations were released at a constant rate over a period of 6 h (ca. the period of time during which soil temperature showed an increase in study 1), the rate of N_2O emission would be about 0.06, 0.6, and 3 kg N_2O-N/ha per year, respectively. Temperature-induced changes in the solubility of N_2O in soil water should cause the rate of N_2O emission to be higher than the rate of N_2O production when the soil is warming and to be lower than the rate of N_2O production when the soil is cooling. If the 24-h mean rate of N_2O emission observed in study 1 (4.7 kg N_2O-N/ha per year) were increased by 3 kg N_2O-N/ha per year when the soil is warming and decreased by this amount when the soil is cooling, the rate of N_2O emission during the warming period would be 4.5

Table 3—Correlation coefficients for relationships between soil temperature (2-cm depth) at various sites and rate of N_2O emission from these sites following various lag periods between measurement of soil temperature and measurement of rate of N_2O emission.

Site	Correlation coefficient (r) 0-h lag	2-h lag	4-h lag	6-h lag	8-h lag	10-h lag	12-h lag
1 (study 1)	0.54	0.83	0.93	0.79	0.40	0.22	0.06
2 (study 1)	0.64	0.95	0.87	0.69	0.68	0.54	0.32
1 (study 2)	−0.85	−0.60	−0.25	0.17	0.65	0.89	0.92
2 (study 2)	−0.73	−0.32	0.03	0.40	0.72	0.93	0.60
3 (study 2)	−0.57	−0.13	0.46	0.80	0.85	0.90	0.86
1 (study 3)	0.00	0.20	0.28	0.23	0.04	−0.14	−0.24
US† (study 4)	0.76	0.83	0.62	0.20	−0.36	−0.59	−0.42

† US = unshaded site.

Table 4—Results of measurements of N_2O emission rate performed at 1- or 2-h intervals at various sites, and coefficients of variation (C.V.) of these measurements.

Site	Period of measurement	N_2O emission rate Range	Mean	C.V.
		kg N_2O-N/ha per year		%
1 (study 1)	1100 13 June–1100 14 June 1978†	0.4–11.2	4.7	66
2 (study 1)	1100 13 June–1100 14 June 1978†	0.5–6.1	2.6	62
1 (study 2)	1100 27 June–1100 28 June 1978†	5.1–16.9	11.8	34
2 (study 2)	0930 27 June–0930 28 June 1978†	3.1–14.5	8.4	48
3 (study 2)	1200 27 June–1200 28 June 1978†	3.1–14.6	10.4	35
1 (study 3)	1200 7 Aug.–1200 8 Aug. 1978‡	13.1–23.6	17.7	13
1 (study 3)	1200 8 Aug.–1200 9 Aug. 1978‡	17.2–26.5	22.3	12
1 (study 3)	1200 9 Aug.–1200 10 Aug. 1978‡	17.4–51.5	27.7	27
1 (study 3)	1200 10 Aug.–1200 11 Aug. 1978‡	22.6–50.6	30.9	24
US§ (study 4)	1400 17 June–1400 18 June 1980‡	2.8–47.0	22.5	56
	Mean		15.9	38

† Measurements were performed at 2-h intervals.
‡ Measurements were performed at 1-h intervals.
§ US = unshaded site.

times the rate of N_2O emission during the cooling period. This simple example is not offered as proof that the diurnal patterns in N_2O emission rate observed in study 1 were caused by temperature-induced changes in the solubility of N_2O in water, but as a numerical illustration of how temperature-induced changes in the solubility of N_2O in soil water offer a reasonable explanation of the observed diurnal patterns in N_2O emission rate if it is assumed that the concentration of N_2O in the soil atmosphere was significantly greater than the concentration of this gas in air. This seems a reasonable assumption because many investigations have indicated that the N_2O concentration in soil atmospheres frequently is much greater than the N_2O concentration in air (Burford and Millington, 1968; Burford and Stefanson, 1973; Flühler et al., 1976; Focht, 1978).

The calculations discussed indicate that, when the concentration of N_2O in a surface soil is similar to the concentration of this gas in air, temperature-induced changes in the solubility of N_2O in soil water should not produce significant diurnal patterns in the rate of N_2O emission from soil. They therefore provide an explanation as to why we did not observe a clear diurnal pattern in the rate of N_2O emission in study 3 because this study was conducted during a period of low rainfall, and the surface soil was so well aerated that accumulation of N_2O should not have occurred.

Figures 1 through 4 present clear evidence that the times of minima and maxima in diurnal patterns in the rate of N_2O emission from soils cannot be predicted solely from soil temperature. This is not surprising because daily minima and maxima in soil temperature occur progressively later with increasing depth in the soil, and the time required for N_2O to diffuse to the soil surface should increase with increasing depth of the source of N_2O. Therefore, when the N_2O emitted originates below the depth at which soil temperature measurements are made, a phase lag should be expected between the diurnal pattern in the rate of N_2O emission and the diurnal pattern in soil temperature, and the duration of this lag should increase as the depth of N_2O production increases. Data presented in Table 3 show that, if an appropriate lag is selected, 72 to 90% of the diurnal variability in the rate of N_2O emission observed in our work at sites showing clear diurnal patterns in N_2O emission rate could be related to variations in the surface soil temperature. It should be noted, however, that the most appropriate lag cannot be predicted solely from soil temperature, and that, when soil temperature and rate of N_2O emission were measured at the same time (i.e., 0-h lag in Table 3), we observed poor, and frequently negative, correlations between soil temperature and rate of N_2O emission.

Figures 1 through 4 show that the amplitudes of diurnal patterns in the rate of N_2O emission cannot be predicted solely from soil temperature. If diurnal patterns in the rate of N_2O emission are largely caused by the influence of diurnal changes in soil temperature on production of N_2O by soil microorganisms, then the amplitude of diurnal patterns in the rate of N_2O emission should decrease markedly with increase in depth of N_2O production because the amplitude of diurnal changes in soil temperature decreases with increase in soil depth (see Table 2). However, if diurnal patterns in the rate of N_2O emission are largely caused by temperature-induced changes in the solubility of N_2O in soil water, then the amplitude of diurnal patterns in the rate of N_2O emission need not decrease with the depth at which the N_2O originates because the amount of N_2O released from the water depends on the concentration of N_2O in the soil, which can increase markedly with increase in soil depth, and on the diurnal change in soil temperature. Because the amount of water in a soil influences (i) the rate of N_2O diffusion in the soil, (ii) the amount of N_2O dissolved in the soil water, (iii) the rate of N_2O production by soil microorganisms, (iv) the rate of reduction of N_2O to N_2 by soil microorganisms, and (v) the amplitude of the diurnal change in temperature that occurs at any given depth in the soil, it is obvious that, although the water content must influence the amplitude of the diurnal pattern in the rate of N_2O emission from soil, there should be no simple relationship between soil water content and the amplitude of the diurnal pattern in the rate of N_2O emission.

Table 4 shows the means, ranges, and coefficients of variation for measurements of N_2O emission rate made at 1- or 2-h intervals within 24-h periods in studies 1 through 4. The data reported show that the coefficients of variation for these measurements ranged

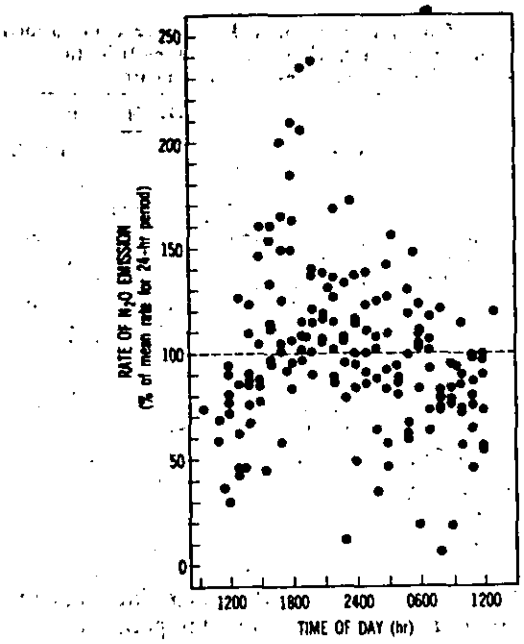

Fig. 5—Results of measurements of N_2O emission rate performed at various times within 24-h periods at unshaded sites in studies 1 through 4. The periods of measurement are indicated in Table 4.

from 12 to 27% when no clear diurnal patterns in the rate of N_2O emission were observed (study 3) and from 34 to 66% when diurnal patterns were evident (studies 1, 2, and 4).

Diurnal variability in the rate of N_2O emission from soil poses a serious problem in field research to assess N_2O emissions from soils because it has been assumed in such research that the amount of N_2O evolved in a 24-h period can be assessed reasonably accurately by measuring the rate of N_2O emission for a short time during this period. Ryden et al. (1978) suggested that this measurement should be performed during the midmorning or mid- to late afternoon to avoid the peak N_2O flux they observed in the early afternoon. However, our studies of diurnal variability in the rate of N_2O emission from Iowa soils indicate that there is no short time during a 24-h period that is always satisfactory for assessing the amount of N_2O evolved during that period. This is illustrated by Fig. 5, which shows the results of measurements of N_2O emission rate performed at 1- or 2-h intervals within 24-h periods at unshaded sites in studies 1 through 4.

Although the work reported shows that diurnal variability in the rate of N_2O emission can be a serious problem in assessment of N_2O emissions from soils, we have evidence from field studies to be reported in another publication that spatial variability in the rate of N_2O emission from Iowa soils poses an even greater problem in assessment of N_2O emissions from these soils.

ACKNOWLEDGMENT

We thank Azeem Ahsan, Todd Carter, Nina Champagne, Boak Desmond, Scott Gatter, Tony Ptak, and Bill Rickard for valuable technical assistance.

REFERENCES

1. Blackmer, A. M., and J. M. Bremner. 1977. Nitrogen isotope discrimination in denitrification of nitrate in soils. Soil Biol. Biochem. 9:73–77.
2. Blackmer, A. M., and J. M. Bremner. 1978. Determination of nitrous oxide in air. Agron. Abstr. p. 137.
3. Bremner, J. M., and A. M. Blackmer. 1978. Natural and fertilizer-induced emissions of nitrous oxide from soils. Progr. Rep. to the Natl. Sci. Found. (grant ENV77-23835). Natl. Sci. Found., Washington, DC.
4. Bremner, J. M., S. G. Robbins, and A. M. Blackmer. 1980. Seasonal variability in emission of nitrous oxide from soil. Geophys. Res. Lett. 7:641–644.
5. Burford, J. R., and R. J. Millington. 1968. Nitrous oxide in the atmosphere of a red-brown earth. 9th Int. Congr. Soil Sci. Trans. (Adelaide) 2:505–511.
6. Burford, J. R., and R. C. Stefanson. 1973. Measurement of gaseous losses of nitrogen from soils. Soil Biol. Biochem. 5:133–141.
7. Council for Agricultural Science and Technology (CAST). 1976. Effect of increased nitrogen fixation on stratospheric ozone. CAST Rep. no. 53. Iowa State Univ., Ames.
8. Crutzen, P. J., and D. H. Ehhalt. 1977. Effects of nitrogen fertilizers and combustion on the stratospheric ozone layer. Ambio 6:112–117.
9. Denmead, O. T., J. R. Freney, and J. R. Simpson. 1979a. Nitrous oxide emission during denitrification in a flooded field. Soil Sci. Soc. Am. J. 43:716–719.
10. Denmead, O. T., J. R. Freney, and J. R. Simpson. 1979b. Studies of nitrous oxide emission from a grass sward. Soil Sci. Soc. Am. J. 43:726–728.
11. Findlay, W. I., and D. J. McKenney. 1979. Direct measurement of nitrous oxide flux from soil. Can. J. Soil Sci. 59:413–421.
12. Flühler, H., M. S. Ardakani, T. E. Szuszkiewicz, and L. H. Stolzy. 1976. Field-measured nitrous oxide concentrations, redox potentials, oxygen diffusion rates, and oxygen partial pressures in relation to denitrification. Soil. Sci. 122:107–114.
13. Focht, D. D. 1978. Methods for analysis of denitrification in soils. p. 433–490. *In* D. R. Nielsen and J. G. MacDonald (ed.) Nitrogen in the environment, Vol. 2. Academic Press, New York.
14. Hutchinson, G. L., and A. R. Mosier. 1979. Nitrous oxide emissions from an irrigated cornfield. Science 205:1125–1127.
15. Liu, S. C., R. J. Cicerone, T. M. Donahue, and W. L. Chameides. 1977. Sources and sinks of atmospheric N_2O and possible ozone reduction due to industrial fixed nitrogen fertilizers. Tellus 29:251–263.
16. Matthias, A. D., A. M. Blackmer, and J. M. Bremner. 1980. A simple chamber technique for field measurement of emissions of nitrous oxide from soils. J. Environ. Qual. 9:251–256.
17. McElroy, M. B., S. C. Wofsy, and Y. L. Yung. 1977. The nitrogen cycle: perturbations due to man and their impact on atmospheric N_2O and O_3. Philos. Trans. R. Soc. London Ser. B. 277:159–181.
18. McKenney, D. J., K. F. Shuttleworth, and W. I. Findlay. 1980. Nitrous oxide evolution rates from fertilized soil: effects of applied nitrogen. Can. J. Soil Sci. 60:429–438.
19. McKenney, D. J., D. L. Wade, and W. I. Findlay. 1978. Rates of N_2O evolution from N-fertilized soil. Geophys. Res. Lett. 5:777–780.
20. NOAA. 1978. National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center, Asheville, N.C.
21. Ryden, J. C., L. J. Lund, and D. D. Focht. 1978. Direct in-field measurement of nitrous oxide flux from soil. Soil Sci. Soc. Am. J. 42:731–738.
22. Ryden, J. C., L. J. Lund, J. Letey, and D. D. Focht. 1979. Direct measurement of denitrification loss from soils: II. Development and application of field methods. Soil Sci. Soc. Am. J. 43:110–118.
23. Segel, I. H. 1975. Enzyme kinetics. John Wiley & Sons, Inc., New York.
24. Wang, W. C., and N. D. Sze. 1980. Coupled effects of atmospheric N_2O and O_3 on the earth's climate. Nature (London) 286:589–590.
25. Weiss, R. F., and B. A. Price. 1980. Nitrous oxide solubility in water and seawater. Mar. Chem. 8:347–359.
26. Yung, Y. L., W. C. Wang, and A. A. Lacis. 1976. Greenhouse effect due to atmospheric nitrous oxide. Geophys. Res. Lett. 3:619–621.