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Direct emission of nitrous oxide from agricultural soils

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Abstract

This analysis is based on published measurements of nitrous oxide (N_2O) emission from fertilized and unfertilized fields. Data was selected in order to evaluate the importance of factors that regulate N_2O production, including soil conditions, type of crop, nitrogen (N) fertilizer type and soil and crop management. Reported N_2O losses from anhydrous ammonia and organic N fertilizers or combinations of organic and synthetic N fertilizers are higher than those for other types of N fertilizer. However, the range of management and environmental conditions represented by the data set is inadequate for use in estimating emission factors for each fertilizer type. The data are appropriate for estimating the order of magnitude of emissions. The longer the period over which measurements are made, the higher the fertilizer-induced emission. Therefore, a simple equation to relate the total annual direct N_2O-N emission (E) from fertilized fields to the N fertilizer applied (F), was based on the measurements covering periods of one year: $E = 1 + 1.25 \times F$, with E and F in kg N ha^{-1} yr^{-1}. This relationship is independent of the type of fertilizer. Although the above regression equation includes considerable uncertainty, it may be appropriate for global estimates.

Introduction

Nitrous oxide (N_2O) plays an important role in the atmospheric radiative balance and in the stratospheric ozone chemistry. A large number of major and minor sources of N_2O emissions and sinks have been identified, yet there is considerable uncertainty about the source and sink strengths. Khalil & Rasmussen (1992) recently presented a global N_2O budget indicating that the uncertainty for most N_2O sources amounts to at least a factor of 2. Part of the uncertainty arises from the paucity of measurements of N_2O fluxes. Another part stems from the difficulty of extrapolating measurements of biogenic fluxes from soils and aquatic sources to larger scales because of their extreme heterogeneity, both in space and time. For abiogenic sources, such as fossil fuel combustion and industrial processes, political, economic and cultural factors are major uncertainties in making extrapolations.

There is considerable uncertainty in the estimates of N_2O emission from soils - a major global source (Watson et al., 1992). Few measurements of N_2O fluxes in agricultural fields have been published recently, despite the concern about the increase in the concentrations of greenhouse gases in the atmosphere. Many flux measurements were carried out between 1980 and 1990. For example, attempts have been made to estimate N_2O emissions caused by synthetic nitrogen (N) fertilizers (Eichner, 1990), and synthetic and organic fertilizers (Bouwman, 1990), based on published values. Recently, Watson et al. (1992) estimated a global annual emission from cultivated fields of 0.03 - 3 Tg N_2O-N (Tg = teragram; $1 Tg = 10^{12} g$).

The direct efflux of N_2O from agricultural fields is possibly only part of the emission caused by N fertilization. Denitrification of N leached from soils may form a potential source of N_2O fluxes from groundwater or from surface waters by degassing. Nitrogen taken up by plants may be consumed by humans or animals. Denitrification of the nitrogen in their excreta may also become a source of N_2O.

Many reviews have been published on N_2O production by nitrification and denitrification (e.g. Firestone & Davidson, 1989). The release of N_2O may be a byproduct of nitrifiers that denitrify nitrite (NO_2^-) under oxygen stress (Poth & Focht, 1985). Under moist and oxygen-depleted conditions, denitrification is generally the major source of N_2O, and both the rate of denitrification and the conditions that influence the ratio of N_2/N_2O determine the N_2O emission (Davidson, 1991). Many factors, summarized below, regulate nitrification and denitrification (Bouwman, 1990).

- Soil moisture and temperature, both of which affect microbial processes
- The amount of mineralizable organic carbon, used as an energy source for denitrifiers
- Soil oxygen availability, which controls denitrification; oxygen supply is mainly determined by the soil water content and the rate of microbial consumption;
- Concentrations of NO_3^- and NH_4^+; obviously the plant roots play a role by consuming nutrients and acting as a source of nutrients and carbon from residues and exudates;
- Soil pH, which influences nitrification and denitrification rates as well as the ratio of N_2/N_2O.

The method proposed by Eichner (1990) to calculate N_2O emission from different fertilizer types was adopted by the IPCC for making country estimates (OECD, 1991). Computer models to simulate N_2O emission from fertilized fields are based on N application and availability, weather conditions, soil properties, soil, crop and water management. The models range from simple mechanistic models (Mosier & Parton, 1985) to more complex process models (Li et al., 1992). These models were developed and validated for the conditions of a single site. Extrapolation of flux measurements should be validated for a wide range of conditions. However, this requires soil data and daily weather data currently not available on the global scale.

In this study published data of N_2O emission in relation to N fertilization were analyzed along with the regulating factors of N_2O production and the flux measurements. On the basis of this analysis and comparison with earlier estimates a method to estimate annual N_2O emission from fertilized fields will be described. Several factors regulating production, consumption and emission of N_2O will be discussed briefly on the basis of the data in the Appendix. Another important aspect that will be discussed is the length of the period covered by the flux measurements and their frequency.

Comparison of experiments

Methods

The data considered include experiments in cropped and unplanted plots with different soils and different types of N fertilizers, ranging from organic to combinations of synthetic and organic fertilizers (Appendix). The flux measurement technique, period covered by the measurements and sampling frequency are indicated for all the experiments (Appendix).

Details on the measurement techniques used can be found in the individual reports listed. Two types of gas collection chambers or enclosures on the soil surface are commonly used to quantify the N_2O flux from the soil to the atmosphere (Appendix). "Open" chambers have forced flow-through air circulation the gas flux from the soil surface can be calculated from concentration difference between incoming and outgoing air. "Closed" chambers have closed-loop air circulation, whereby the flux from the soil surface is calculated from the measured concentration increase inside the chamber. Other techniques in the Appendix include the soil gas gradient method, whereby the gas concentration gradient in the soil profile is used to estimate the flux to the atmosphere, and micrometeorological methods. Generally, in micrometeorological methods the flux between the soil surface and the atmosphere is assumed to be identical to the vertical flux measured at the reference level some distance above the surface, based on the concept that gas transport is accomplished by the eddying motion of the atmosphere which displaces parcels of air from one level to another. Details on the techniques can be found in the individual reports listed. Reviews of the theoretical and practical problems which cause variability in gas flux measurements are presented by Mosier (1989).

Results

Overall emission of N_2O The emission of N_2O is presented as: (i) the total N_2O emission during the period covered by the measurements; (ii) the fertilizer-induced N_2O emission, calculated as the difference in emission between the fertilized and the control plot and presented as a percentage of the fertilizer N applied; (iii) the total N_2O emission as a percentage of the fertilizer applied. The fertilizer-induced N_2O emission varies between 0% and 7% of the N application for 87 experiments for mineral soils as recorded in the Appendix that included a control plot. The total N_2O

emission (not subtracting the emission from the control plots) from 180 experiments for mineral soils recorded in the Appendix ranges between 0% and 8% of the N application.

Period covered by measurements The length of the period over which the measurements were made may influence the amount of N_2O from fertilizers captured. The average fertilizer-induced N_2O emission for all experiments with control plots is 0.6% (±1.1 % standard deviation; *n* = *88*) of the N application based on all experiments for mineral soils (Appendix). The average fertilizer-induced N_2O emission was found to be 0.8 ± 1.2% for experiments > 30 days (*n* = 70), 1.1 ± 1.4% for experiments of > 100 days (*n* = 43) and 1.6 ± 0.4%, for experiments of > 200 days (*n*= 5). This suggests that if N_2O flux measurements are extended over longer periods, more of the N_2O emission induced by N fertilization will be captured. Hence, it is necessary to measure fluxes during prolonged periods to account for all the fertilizer-induced emission.

Frequency of measurements Brumme & Beese (1992) observed that N_2O flux measurements done once per week tend to overestimate the total emission estimate relative to daily observation by 20%. In many studies the frequency of measurements is once per day or once every 2 or 3 days, with the highest frequencies in periods of high fluxes shortly after fertilizer application (Appendix). In some studies the measurements were done only once per week. These differences in frequency of flux measurements may form another source of uncertainty.

Presence and type of crop Many studies included fertilized but unplanted fields (Appendix). Since there is no N uptake by plants, denitrification and associated N_2O emission may be higher than in cropped fields. The mean fertilizer-induced N_2O emission for unplanted fields was found to be 0.9 ± 1.4% of the N application (*n* = *41*), while the mean for fields with crops or grass was 0.4 ± 0.6% (*n* = *47*).

The N_2O emission from ungrazed grassland plots (0.3 ± 0.5%, *n* = *19*) were found to be only slightly lower than that from cropped fields (0.4 ± 0.6%, *n* = *28*) Grasses take up N quickly and completely, and have a longer growing season than crops, which could lead to more N uptake and less denitrification in grasslands than in cropped fields. But the amount of readily oxidizable organic substrate is probably more in grass than annual crops. The data show only a slight difference between grass and crops, possibly because most measurements covered only the spring and summer period and not the full year.

For most experiments it is impossible to determine the contributions of crop, the amount and type of N fertilizer, management practices and weather. However, in some experiments the crop or the combined effect of crop and management clearly determined the N_2O emission, e.g. wetland rice and leguminous crops. Wetland rice in experiments 15 and 36 showed low N_2O fluxes, and the N_2O emission from dryland rice fields was somewhat higher (experiment 23). This may be caused by the low availability of oxygen, which is unfavorable for nitrification. Moreover, low oxygen availability may lead to a low N_2O/N_2 ratio in denitrification products. However, Byrnes et al. (1993) showed that drainage and subsequent reflooding of rice fields may give rise to significant N_2O emission. As measurements during drained phases were not done in experiments 15 and 36, the reported N_2O emissions may be underestimated.

Fields with legumes showed high N_2O emission. As leguminous crops usually receive little or no N fertilizer, these high N_2O emissions may be attributed to N inputs from symbiotic N fixation. The only available data is for alfalfa (2.3-4.2 kg N_2O-N ha^{-1} yr^{-1}, experiment 17), soybeans (0.34-1.97 kg N_2O-N ha^{-1} yr^{-1}, experiment 41) and clover (0-0.07 kg N_2O-N ha^{-1} yr^{-1}, experiment 14). The measurements in the clover fields did not result in high fluxes, perhaps because N fertilizer added in this experiment prevented N fixation. Unfortunately the measurement period was not reported for experiment 14.

Crop residues The data indicate that decomposition and mineralization of crop residues may contribute to N_2O fluxes. The effect of crop residues is illustrated by comparing experiments in Iowa on typic Haplaquolls (experiments 5 and 6). Both the control and the fertilizer treatment of experiment 6 showed much higher N_2O emission than experiment 5. In experiment 5 maize residues were incorporated in the surface layer, while in experiment 6 soybean residues were left on the surface to decompose.

Experiment 20 included plots with rye grown as a cover crop after harvest of the previous crop. The rye was incorporated before planting tobacco and this produced lower N_2O emission than plots with manure or alfalfa residue.

Tillage. Surface application of N fertilizers to plots with minimum or reduced tillage leads to high N_2O emission (experiment 20). This is consistent with experiments 8 and 13, which showed lower N_2O emission from ploughed plots cropped to winter wheat fertilized with NH_4NO_3 than unploughed, directly sown plots.

Source and amount of nitrogen. The variability in N_2O fluxes is extremely high for all N fertilizer types and all application levels (Figure 1). Fluxes ranging between 0 and 30 kg N_2O-N ha^{-1} yr^{-1} were observed in plots with mineral soils. The results for the unfertilized control plots (Appendix) range between -0.6 and 4.2 kg N_2O-N ha^{-1} (average 0.8, standard deviation 1.0 kg N ha^{-1} $n = 55$). The variability may be caused by many different factors, of which the weather conditions and history of fertilization and management may be important ones.

Some forms of N show higher N_2O emissions than other types. Fluxes of N_2O from combinations of organic and synthetic fertilizers are generally high. The experiments listed in the Appendix showed the N content of organic fertilizers as total N, including mineral and organic N. Hence, there is uncertainty in the amount of available N because part of the organic N is not directly available, and volatilization of NH_3 was not accounted for here, just as for synthetic fertilizers.

Emissions from NO_3^- -based fertilizers and combinations of organic and NO_3^- fertilizers from experiment 31 were found relatively high compared to other fertilizer types. Measurements in experiment 31 were carried out immediately after irrigation and rainfall events, and this likely caused an overestimation of both denitrification and N_2O emissions extrapolated over the growing season.

Within the group of synthetic fertilizers, anhydrous ammonia induced the highest N_2O fluxes. This may not, however, be the result of the type of fertilizer, but merely of the mode of application (see below).

Mode of fertilizer application. Some experiments indicated an important effect of the mode of fertilizer application. Most fertilizers were broadcast onto the soil surface and incorporated by tillage. Anhydrous ammonia must be injected as a gas into the soil. This produces highly alkaline zones of high ammonium concentration (various references quoted in Breitenbeck & Bremner, 1986a) that may lead to high N_2O production (Bouwman, 1990). Experiments 4, 5, 6 and 10 showed that deeper injection of anhydrous ammonia lead to higher N_2O emission than shallower injection. Another example of the effect of high pH in experiment 36, in which urea drilled into the soil caused higher N_2O emission than top-dressed urea for the same high N application rate of 180 kg N ha^{-1}.

It is dificult to explain why deeper injection resulted in higher N_2O emission. The N loss by NH_3 volatilization from applied anhydrous ammonia is probably lower for deep than for shallow injection. However, if the ammonia is injected deeper, the transport of the N_2O formed is over a longer distance, which increases possibilities for further N_2O reduction.

Timing of fertilizer application. The data set does not include enough experiments on the effect of timing of the fertilizer application to draw conclusions. Applications in periods when the crop actually takes up nutrients will reduce N losses by denitrification and leaching, thereby also reducing N_2O losses (Mosier, 1993).

Soil type and properties In experiments 4 and 7 different soils were included to measure the effect of different N fertilizers on N_2O emission Unfortunately, the authors did not explain the differences. A possible explanation may be the soil textures, as indicated by experiments 7 and 8. The heavy textured soils showed higher N_2O emission has than the lighter textured ones, possibly because heavy textured soils show stronger anaerobicity, which may extend over longer periods than light textured soils. In contrast, the light textured soils in experiment 4 showed higher emissions than heavier textured soils, possibly due to the dominating role of the weather conditions on the texture effect.

Drained organic soils with no fertilizer additions showed much higher N_2O emissions than mineral soils, up to 100 kg N_2O-N ha^{-1} yr^{-1} (experiments 17 and 43). Mineralization of organic N in organic soils may be as high as 1400 kg N ha^{-1} yr^{-1} (Terry et al., 1981; Appendix). Using these numbers, the observed N_2O emission from the organic soils constitutes a fraction of < 1 to > 10% of the N mineralized (Appendix).

Another soil property that may affect N_2O emission is the soil pH, which may affect nitrification, denitrification and the ratio of N_2/N_2O. Generally, it is thought that N_2O reduction is inhibited at low pH (various references quoted in Bouwman al., 1993). However the same soils modified to different pH gave no measurable differences in N_2O emission (experiment 20). This may be due to adaptation to soil pH of denitrifiers since 1962 when the soils were limed (Parkin et al., 1985).

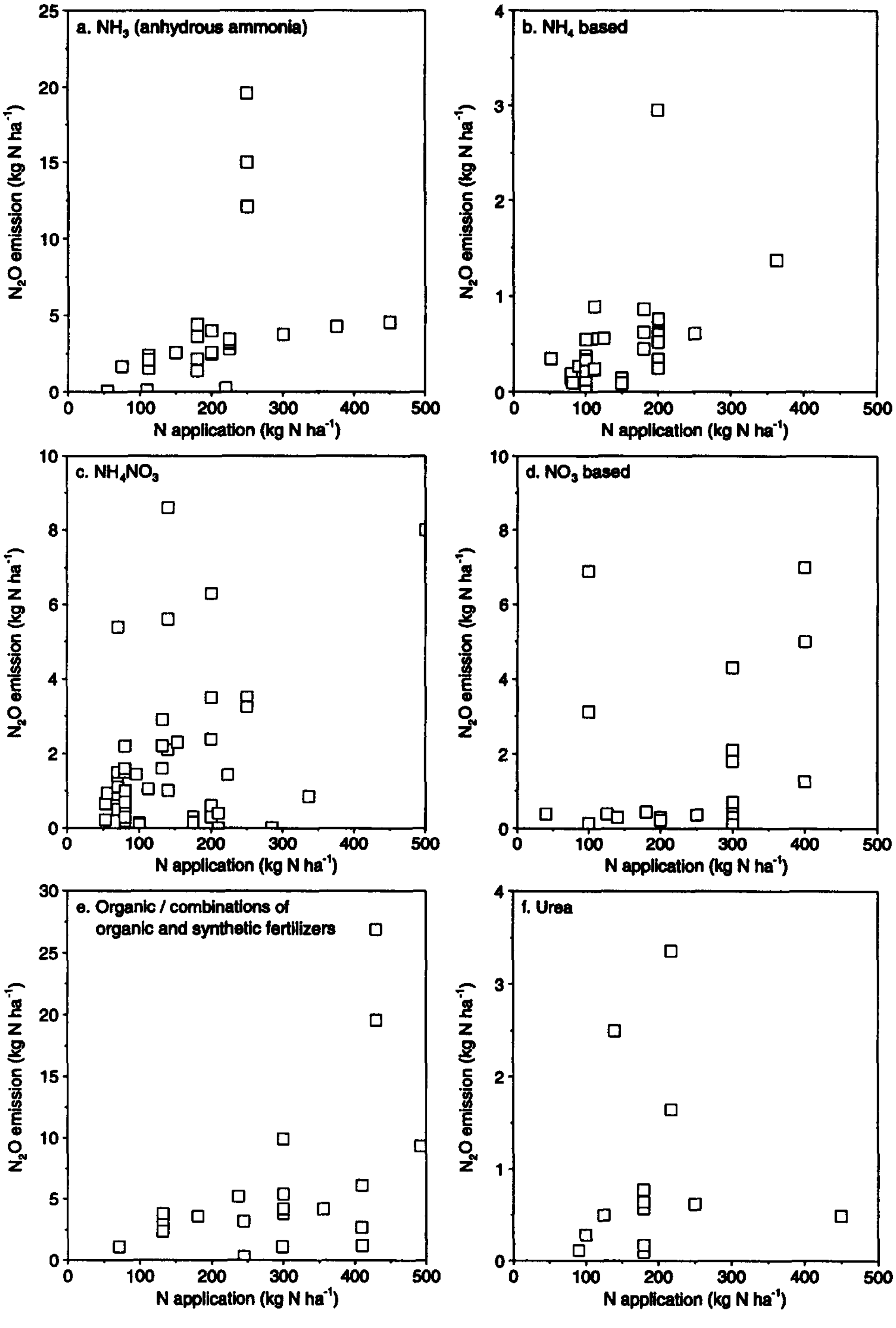

Figure 1. Relation between N fertilizer application and N_2O emission from mineral soils for experiments listed in the Appendix independent of the period covered by the measurements. Data are presented for (*a*) anhydrous ammonia (NH_3); (*b*) ammonium (NH_4)-based fertilizers; (*c*)ammonium nitrate (NH_4NO_3); (*d*) nitrate (NO_3)-based fertilizers; (*e*) organic fertilizers, and combinations of organic and synthetic fertilizers, and (*f*) urea.

Table 1. Average and standard deviation of the fertilizer-induced N_2O emission [a] for different types of N fertilizer reported by Eichner (1990) compared with results from this study

Type	Eichner (1990)[b]			This study		
	Average N (%)	SD	n[c]	Average N (%)	SD	n[c]
Anhydrous ammonia	2.3	2.0	12	1.6	1.6	23
Ammonium nitrate	0.3	0.3	8	0.3	0.3	10
Salts of ammonium	0.1	0.1	17	0.1	0.1	20
urea	0.1	0.0	7	0.3	0.6	14
Saltes of nitrate	0.2	0.5	15	0.2	0.4	16
Organic/combinations of organic and synthetic fertilizers	nd[d]	nd	nd	1.5	0.5	5

[a] The fertilizer-induced emission is calculated as emission from the fertilized plot minus that from the control plot, presented as percentage of N fertilizer application.

[b] Recalculated from the data used by Eichner (1990), including N applications > 250 kg N ha^{-1}. The errors recorded in Eichner's tables in the measurement data from Seiler & Conrad (1981), Conrad et al. (1983) and Christensen (1983) were corrected.

[c] n = number of experiments.

[d] nd = no data.

Soil drainage. Experiment 11 concentrated on drainage of a poorly drained soil with stagnant water. Draining the soil caused a decrease in the N_2O emission. The soils of all the experiments were classified according to soil drainage class based on data given in the reports or on the soil taxonomic class. For example, Paleudalfs are considered well drained, while the name Calciaquolls suggests hydromorphic properties and poor drainage. However, there was no clear relation found between soil drainage and N_2O emission for the experiments listed.

Determining the direct contribution of fertilizer to N_2O emissions

The method presented by Eichner (1990) attempts to estimate fertilizer-induced emission, i.e. the emission from a fertilized plot minus that from a control plot, determined during the measurement period. Eichner (1990) calculated the fertilizer-induced N_2O emission as a percentage of N fertilizer applied for a number of fertilizer types (Table 1). There are a number of uncertainties in this methiod:

- The data sets used by Eichner (1990) and in this study represent only a small number of climactic, soil and management conditions. For example, Eichner based the median and range of N_2O emission induced by anhydrous NH_3 on only a few experiments, mostly carried out in Iowa (experiments 3-7). The highest fertilizer-induced N_2O emission (6.8%, experiment 6) was observed in fields where soybean residues were left on the surface to decompose. This may not be representative of worldwide practices in fields where anhydrous ammonia is applied.
- Addition of observations to the data set of Eichner (1990) can result in changes in the calculated average N_2O losses caused by fertilization. This study included 14 measurements for anhydrous ammonia that were not reviewed by Eichner (1990); the result is a 30% lower fertilizer-induced emission (Table 1). This has important consequences for the estimated emission from the application of anhydrous ammonia, which contributes about 45% to the global N_2O emission from fertilizers based on Eichner's method. The greatest difference is found for urea, where the N_2O emission resulting from this study exceeds the estimate of Eichner (1990) by a factor of 3, brought about by the addition of only 7 measurements.
- Fertilizer-induced N_2O emission does not yield an estimate of the *total* annual emission. Most measurements listed in the Appendix cover the crop season or shorter periods. Most of the N_2O is generally emitted within one month after fertilizer application, after which emissions decline to a "background" level. Although the background emission

may be low its contribution to the annual flux may not be negligible. Moreover, it is very likely that this background emission level is influenced by the fertilization and soil management during previous years. Hence, to estimate the full effect of fertilizers, annual emission estimates should account for this background level.

A simple method is proposed here to calculate the *total annual* N_2O emission from fertilized fields, independent of crop, management, soil conditions and fertilizer type. As noted above, the length of the measurement period seems to be important in determining the total N_2O emission. Figure 1 shows the relationship between N-fertilizer application rate and N_2O emission for all experiments on mineral soils. Clearly, there is no correlation between N application rate and N_2O emission if the duration of measurements is not considered. For experiments with a full year of N_2O flux measurements, the correlation is much better. Data presented in Figure 2 for cropped fields and ungrazed grass plots include a variety of different fertilizers (including synthetic, organic, and combinations of organic and synthetic N fertilizers), weather conditions and soils. The results from experiment 2 were excluded because of reported abnormally low precipitation. The results from leguminous crops (experiments 17 and 41) were also excluded because the input from N fixation was not reported.

Least squares fitting of the data in Figure 2 to a linear function result in equation (1) with an r^2 of 0.8:

$$E = 1 + 0.0125 \times F \qquad (1)$$

here E = emission (kg N_2O-N) and F = fertilizer application rate (kg N ha^{-1} yr^{-1}). This relationship was based on only 20 experiments, with measurements covering a full year; its global applicability is highly uncertain. The *background* emission of 1 kg N_2O-N ha^{-1} yr^{-1} is based on only five estimates for unfertilized plots, with a range of emissions from -0.6 to + 3.2 kg N_2O-N ha^{-1} yr^{-1} (experiments 30 and 19, respectively). It is, however, consistent with the average of the 33 measurements covering more than 100 days in unfertilized control plots of 1.2 ± 1.1 kg N ha^{-1} yr^{-1}.

The *fertilizer-induced N_2O emission* of 1.25% is close to the calculated 1.1% (± 1.4%) fertilizer-induced N_2O emission based on 43 experiments with a duration of measurements of > 100 days where a control plot was included. The 1.25% fertilizer-induced emission is also consistent with Mosier's (1993) estimate of 1% and with the 0.5-2% N_2O emission from fertilizers estimated by Bolle et al. (1986).

Discussion and conclusions

Although the factors that control N_2O production are known, it is impossible to predict their interaction under field conditions on the basis of the available information. These factors greatly affect the N_2O emission generated by fertilizers (Appendix). The processes of nitrification and denitrification, and the controls of the reduction of N_2O to N_2, have specific optimum conditions. Redox, moisture and C sources change during the year and from one year to another, and the importance of the different N_2O producing processes also changes as a consequence. The variability in the data is caused by a variety of factors related to weather and management and their interaction, such as local rainfall and temperature, timing and frequency of irrigation, history, mode and timing of fertilizer application, presence or absence of crops, type of crop and soil management.

Byrnes et al. (1990) concluded that N_2O emissions may be more closely related to soil properties than to the N source. However, the comparison in Table 1 suggests that there may be differences in N_2O emission caused by fertilizer type. With the variability in estimates and the small number of experiments, the addition of a few experiments drastically changed the calculated emission factors, as was shown for anhydrous ammonia and urea. Therefore, the data set is too limited to calculate the N_2O emission specific for each fertilizer type and sufficient new data is not likely to be generated in the coming years. However the available data are adequate to estimate the order of magnitude of emissions.

A simple approach was developed on the basis of a background emission of 1 kg N_2O-N ha^{-1} yr^{-1} plus a fertilizer-induced N_2O emission of 1.25% of the N application. This method has been shown to be independent of fertilizer types, and may not be adequate to estimate emissions for local conditions or specific crops. The absolute range of uncertainty for the fertilizer-induced N_2O emission is 0.25 - 2.25% based on the data set but excluding the extremes (AR Mosier, 1994, personal communication).

The method may be adequate for global analyses. Assuming that the global N fertilizer use of 80 Tg N yr^{-1} in 1990 (FAO, 1991) is applied exclusively to arable fields and that no organic fertilizers are used, the

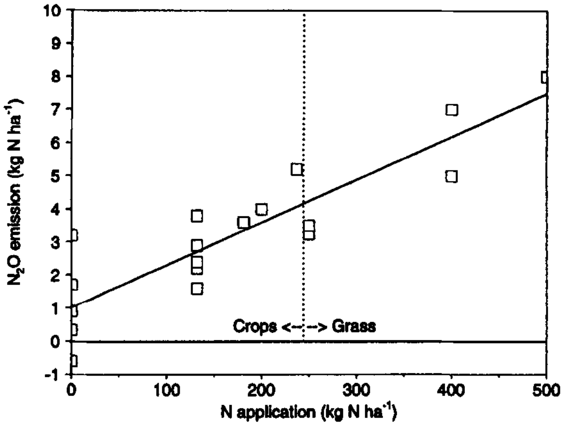

Figure 2. Relationship between N fertilizer application and N_2O emission for experiments on plots with mineral soils for N application rates < 500 kg N ha^{-1} yr^{-1} with a measurement period of one year. Results for experiment 2 and measurements for leguminous crops (Appendix) were excluded. The squares indicate both measurements in cropped fields and ungrazed grasslands.

background emission calculated for the global arable land area of 1440×10^6 ha is 1.4 Tg N_2O-N yr^{-1} and the fertilizer-induced emission is an additional 1 Tg N_2O-N yr^{-1}). Hence, arable lands are a major source in the global N_2O budget of 13-16 Tg yr^{-1}. The fertilizer-induced N_2O emission is about equal to the global N_2O emission from animal excreta (Bouwman et al., 1995). The contribution of global synthetic fertilizer use to the atmospheric increase of N_2O of 4 Tg yr^{-1} is about 25%.

This estimate does not include N_2O emissions from leguminous crops. These crops usually receive little or no N fertilizer. The N_2O emissions from fields with leguminous crops may be considerable. These high N_2O emissions may be attributed to inputs from symbiotic N fixation. The global area of leguminous crops is 145 Mha (FAO, 1991), about 10% of the total arable land. This area does not include legumes grown as green manures not reported by the FAO (1991), and legumes in grasslands and N-fixing grass species. The N inputs from legumes to agricultural systems may be of the same order of magnitude as global synthetic N fertilizer use (Duxbury et al., 1993), indicating the potential importance for the N_2O cycle.

Finally, the above method does not account for the high reported fluxes of N_2O from cultivated drained organic soils and other wetland areas. Although the global area of arable land with organic soil may not be important, this may be a significant local source.

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Appendix

Ref[a]	Location	Soil classification[b]	Texture/other properties	Drainage[c]	Crop/treatment	Fertilizer type[d]	N-Appl. rate (kg N ha^{-1})	N_2O emission (kg N ha^{-1})	Length of exp (days)	Method[e]	Freq[f]	Fertilizer induced N_2O emission (% of N-appl.)[g] I	II	Remarks
Mineral soils														
1	Reading, UK		Loamy sand	w	Unplanted	NO_3	200	0.30	135	c-	d		0.2	Weed free
1	Reading, UK		Clay loam	w	Unplanted	NO_3	200	0.22	135	c-	d		0.1	Weed free
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	117	0.56	63	c-	d/w		0.5	Intensive management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	82	0.10	63	c-	d/w		0.1	Intensive management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	-	0	0.13	105	c-	d/w			Intensive management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	112	0.23	63	c-	d/w		0.2	Intensive management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	52	0.35	63	c-	d/w		0.7	Intensive management; also presented in Hutchinson & Brams (1992)
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	-	0	0.30	63	c-	d/w			Low management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	-	0	0.07	63	c-	d/w			Low management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	-	0	0.08	105	c-	d/w			Low management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	112	0.24	63	c-	d/w		0.2	Low management
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	-	0	0.20	63	c-	d/w			Low management; also presented in Hutchinson & Brams (1992)
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	363	1.37	365	c-	d/w		0.4	Intensive management; sum 365 days
2	Texas, USA	Glossarenic Paleudalfs	Sandy loam, 1.7%C	w	Grass	NH_4	112	0.89	365	c-	d/w		0.8	Low management; sum 365 days
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	-	0	0.33	96	c-	3-7d			
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	urea	125	0.50	96	c-	3-7d	0.1	0.4	
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	urea	250	0.62	96	c-	3-7d	0.1	0.2	
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	NH_4	125	0.56	96	c-	3-7d	0.2	0.4	
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	NH_4	250	0.61	96	c-	3-7d	0.1	0.2	
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	NO_3	125	0.38	96	c-	3-7d	0	0.3	
3	Iowa, USA	Typic Calciaquolls	Clay loam; 4.9%C	p	Unplanted	NO_3	250	0.36	96	c-	3-7d	0	0.1	
4	Iowa, USA	Typic Haplaquolls	Loam; 2.5%C, pH 7.7	p	Unplanted	-	0	0.65	140	c-	3-7d			
4	Iowa, USA	Typic Haplaquolls	Loam; 2.5%C, pH 7.7	p	Unplanted	NH_3	180	4.40	140	c-	3-7d	2.1	2.4	AA injected at 20 cm
4	Iowa, USA	Typic Haplaquolls	Loam; 2.5%C, pH 7.7	p	Unplanted	NH_4 (aq. ammonia)	180	0.86	140	c-	3-7d	0.1	0.5	
4	Iowa, USA	Typic Haplaquolls	Loam; 2.5%C, pH 7.7	p	Unplanted	urea	180	0.77	140	c-	3-7d	0.1	0.4	
4	Iowa, USA	Typic Calciaquolls	Silty clay loam; 4.6%C pH 7.9	p	Unplanted	-	0	0.38	140	c-	3-7d			
4	Iowa, USA	Typic Calciaquolls	Silty clay loam; 4.6%C pH 7.9	p	Unplanted	NH_3	180	1.92	140	c-	3-7d	0.9	1.1	AA injected at 20 cm
4	Iowa, USA	Typic Calciaquolls	Silty clay loam; 4.6%C pH 7.9	p	Unplanted	NH_4 (aq. ammonia)	180	0.45	140	c-	3-7d	0	0.3	
4	Iowa, USA	Typic Calciaquolls	Silty clay loam; 4.6%C pH 7.9	p	Unplanted	urea	180	0.57	140	c-	3-7d	0.1	0.3	
4	Iowa, USA	Typic Calciaquolls	Silty clay loam; 4.6%C pH 7.9	p	Unplanted	NO_3	180	0.44	140	c-	3-7d	0.1	0.2	
4	Iowa, USA	Typic Haplaquolls	Clay loam; 2.7%C pH 6.9	p	Unplanted	-	0	0.51	140	c-	3-7d			
4	Iowa, USA	Typic Haplaquolls	Clay loam; 2.7%C pH 6.9	p	Unplanted	NH_3	180	2.17	140	c-	3-7d	0.9	1.2	AA injected at 20 cm
4	Iowa, USA	Typic Haplaquolls	Clay loam; 2.7%C pH 6.9	p	Unplanted	NH_4 (aq. ammonia)	180	0.62	140	c-	3-7d	0.1	0.3	
4	Iowa, USA	Typic Haplaquolls	Clay loam; 2.7%C pH 6.9	p	Unplanted	urea	180	0.64	140	c-	3-7d	0.1	0.4	
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted; maize residues incorporated	-	0	0.45	116	c-	3-7d			
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted; maize residues incorporated	NH_3	75	1.67	116	c-	3-7d	1.6	2.2	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted; maize residues incorporated	NH_3	150	2.58	116	c-	3-7d	1.4	1.7	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	225	3.17	116	c-	3-7d	1.2	1.4	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted; maize residues incorporated	NH_3	300	3.75	116	c-	3-7d	1.0	1.3	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	375	4.26	116	c-	3-7d	1.0	1.1	AA injected at 20 cm

Appendix (*Continued*).

5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	450	4.54	116	c-	3-7d	0.9	1.0	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	-	0	0.71	156	c-	3-7d			
5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	112	1.52	156	c-	3-7d	0.7	1.4	AA injected at 10 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	112	2.10	156	c-	3-7d	1.2	1.9	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	112	2.39	156	c-	3-7d	1.5	2.1	AA injected at 30 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	225	2.82	156	c-	3-7d	0.9	1.3	AA injected at 10 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam; 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	225	3.25	156	c-	3-7d	1.1	1.4	AA injected at 20 cm
5	Iowa, USA	Typic Haplaquolls	Clay loam, 3.8%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	225	3.44	156	c-	3-7d	1.2	1.5	AA injected at 30 cm
6	Iowa, USA	Typic Haplaquolls	Clay loam; 3.7%C pH 6.9	p	Unplanted, maize residues incorporated	-	0	0.62	355	c-	3-7d			
6	Iowa, USA	Typic Haplaquolls	Clay loam, 3.7%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	180	3.62	355	c-	3-7d	1.7	2.0	AA injected at 18 cm in fall
6	Iowa, USA	Typic Haplaquolls	Clay loam; 3.7%C pH 6.9	p	Unplanted, maize residues incorporated	-	0	0.43	167	c-	3-7d			
6	Iowa, USA	Typic Haplaquolls	Clay loam, 3.7%C pH 6.9	p	Unplanted, maize residues incorporated	NH_3	180	1.37	167	c-	3-7d	0.5	0.8	AA injected at 18 cm in spring
7	Iowa, USA	Typic Calciaquolls	Silty clay loam, 4.6% C, pH7.9	p	Unplanted, soybean plants left to decompose	-	0	1.70	139	c-	w			
7	Iowa, USA	Typic Calciaquolls	Silty clay loam, 4.6% C, pH7.9	p	Unplanted, soybean plants left to decompose	NH_3	250	15.00	139	c-	w	5.3	6.0	AA injected at 20 cm
7	Iowa, USA	Typic Haplaquolls	Clay loam, 2.7% C, pH6.9	p	Unplanted, soybean plants left to decompose	-	0	2.50	139	c-	w			
7	Iowa, USA	Typic Haplaquolls	Clay loam; 2.7% C, pH6.9	p	Unplanted, soybean plants left to decompose	NH_3	250	19.60	139	c-	w	6.8	7.8	AA injected at 20 cm
7	Iowa, USA	Typic Haplaquolls	Loam, 2.5%, pH7.7	p	Unplanted, soybean plants left to decompose	-	0	2.00	139	c-	w			
7	Iowa, USA	Typic Haplaquolls	Loam, 2.5% C, pH7.7	p	Unplanted, soybean plants left to decompose	NH_3	250	12.10	139	c-	w	4.0	4.8	AA injected at 20 cm
8	Oxon, UK	Typic Haplaquepts	Clay, 3.2-3.9% C	p	Wheat, winter, ploughed	NH_4NO_3	70	0.90	212	c-	w		1.3	Nov '77-June'78
8	Oxon, UK	Typic Haplaquepts	Clay, 3.2-3.9% C	p	Wheat, winter, direct drilled	NH_4NO_3	70	5.40	212	c-	w		7.7	Nov '77-June'78
8	Oxon, UK	Typic Haplaquepts	Clay, 3.2-3.9% C	p	Oilseed rape, ploughed	NH_4NO_3	140	5.60	212	c-	w		4.0	Nov '78-June'79
8	Oxon, UK	Typic Haplaquepts	Clay, 3.2-3.9% C	p	Oilseed rape, direct drilled	NH_4NO_3	140	8.60	212	c-	w		6.1	Nov '78-June'79
8	Oxon, UK	Typic Haplaquepts	Clay loam, 2-2.1% C	p	Wheat, winter, ploughed	NH_4NO_3	70	0.50	212	c-	w		0.7	Nov '77-June'78
8	Oxon, UK	Typic Haplaquepts	Clay loam, 2-2.1% C	p	Wheat, winter, direct drilled	NH_4NO_3	70	1.50	212	c-	w		2.1	Nov '77-June'78
8	Oxon, UK	Typic Haplaquepts	Clay loam, 2-2.1% C	p	Oilseed rape, ploughed	NH_4NO_3	140	1.00	212	c-	w		0.7	Nov '78-June'79
8	Oxon, UK	Typic Haplaquepts	Clay loam, 2-2.1% C	p	Oilseed rape, direct drilled	NH_4NO_3	140	2.10	212	c-	w		1.5	Nov '78-June'79
9	Wisconsin, USA	Typic Hapludalfs		w	Maize	organic/NH_4NO_3/urea	237	5.20	365	c-	7-30 d	2.1	2.2	168/13/56 manure/NH_4NO_3/urea, prev maize residues incorporated
9	Wisconsin, USA	Typic Hapludalfs		w	Maize	organic/NH_4NO_3	181	3.60	365	c-	7-30 d	1.8	2.0	168/13/56 manure/NH_4NO_3/urea, prev maize residues incorporated
9	Wisconsin, USA	Typic Hapludalfs		w	Grass	-	0	0.34	365	c-	7-30 d			
10	Washington, USA	Ultic Haploxerolls	Silt loam	w	Unplanted	-	0	0.03	35	o-	2 d			24 hour cont measurement per 2 days
10	Washington, USA	Ultic Haploxerolls	Silt loam	w	Unplanted	NH_3	55	0.05	35	o-	2 d	0	0.1	AA injected at 15cm
10	Washington, USA	Ultic Haploxerolls	Silt loam	w	Unplanted	NH_3	110	0.10	35	o-	2 d	0.1	0.1	AA injected at 15cm
10	Washington, USA	Ultic Haploxerolls	Silt loam	w	Unplanted	NH_3	220	0.23	35	o-	2 d	0.1	0.1	AA injected at 15cm
11	Oxon, UK	Typic Haplaquepts	Clay, undrained	p	Wheat, winter, direct drilled	NH_4NO_3	53	0.65	30	c l	w		1.2	
11	Oxon, UK	Typic Haplaquepts	Clay, undrained	p	Wheat, winter, direct drilled	–	0	0.07	28	c l	w			
11	Oxon, UK	Typic Haplaquepts	Clay, undrained	p	Wheat, winter, direct drilled	NO_3	100	3.12	31	c l	w		3.1	
11	Oxon, UK	Typic Haplaquepts	Clay, undrained	p	Wheat, winter, direct drilled	-	0	0.07	28	c l	w			
11	Oxon, UK	Typic Haplaquepts	Clay, drained	m	Wheat, winter, direct drilled	NH_4NO_3	96	1.44	30	c l	w		1.5	
11	Oxon, UK	Typic Haplaquepts	Clay, drained	m	Wheat, winter, direct drilled	NH_4NO_3	53	0.22	31	c l	w		0.4	
11	Oxon, UK	Typic Haplaquepts	Clay, drained	m	Wheat, winter, direct drilled	-	0	1.49	31	c l	w			
11	Oxon, UK	Typic Haplaquepts	Clay, drained	m	Wheat, winter, direct drilled	-	0	0.07	30	c l	w			
12	Oxon, UK	Typic Haplaquepts	Clay, undrained	p	Wheat, winter, direct drilled	NH_4NO_3/NO_3	153	2.30	57	c l	2-3 d		1.5	53 kg N as NH_4NO_3, 100 as $Ca(NO_3)_2$

13	Oxon, UK	Typic Haplaquepts	Clay, 3 7% C	p	Wheat, winter, ploughed	NH_4NO_3	70	1 10	242	c l	w		1 6	
13	Oxon, UK	Typic Haplaquepts	Clay, 3 7% C	p	Wheat, winter, direct drilled	NH_4NO_3	70	1 30	242	c l	w		1 9	
13	Oxon, UK	Typic Haplaquepts	Clay, 3 7% C	p	Grass	NH_4NO_3	210	0 40	242	c l	w		0 2	
14	Mainz, Germany	Loess, pararendzina	Sandy clay loam	w	Grass	NO_3	100	0 07	nk	c -	d	0 1		Period not reported
14	Mainz, Germany	Loess, pararendzina	Sandy clay loam	w	Grass	NH_4	100	0 05	nk	c -	d	0 1		
14	Mainz, Germany	Loess, brown soil	Sandy loam	w	Unplanted (beet field, plants removed)	NO_3	100	0 02	nk	c -	d	0		
14	Mainz, Germany	Loess, brown soil	Sandy loam	w	Unplanted (beet field, plants removed)	NH_4	100	0 15	nk	c -	d	0 2		
14	Mainz, Germany	Loess, brown soil	Sandy loam	w	Unplanted (beet field, plants removed)	NH_4	100	0 22	nk	c -	d	0 2		
14	Mainz, Germany	Loess	Sandy clay loam	w	Grass	NO_3	100	0 01	nk	c -	d	0		
14	Mainz, Germany	Loess	Sandy clay loam	w	Grass	NH_4	100	0 03	nk	c -	d	0		
14	Mainz, Germany	Loess	Sandy clay loam	w	Grass	NO_3	100	0 07	nk	c -	d	0 1		
14	Mainz, Germany	Loess	Sandy clay loam	w	Grass	NH_4	100	0 38	nk	c -	d	0 4		
14	Mainz, Germany	Loess	Sandy clay loam	w	Clover	NO_3	100	0	nk	c -	d	0		
14	Mainz, Germany	Loess	Sandy clay loam	w	Clover	NH_4	100	0 07	nk	c -	d	0 1		
14	Mainz, Germany	Loess	Sandy loam	w	Grass	NO_3	100	0 02	nk	c -	d	0		
14	Mainz, Germany	Loess	Sandy loam	w	Grass	NH_4	100	0 07	nk	c -	d	0 1		
14	Mainz, Germany	Loess	Sandy loam	w	Grass	NH_4	100	0 08	nk	c -	d	0 1		
15	Australia		Clay		Rice, wetland	NO_3	40	0 38	18	o -	cont		1 0	
16	New York, USA	Glossoboric Hapludalfs	Silt loam, 1% C, pH 6 9	w	Maize	-	0	0 30	85	c l	d			
16	New York, USA	Glossoboric Hapludalfs	Silt loam, 1% C, pH 6 9	w	Maize	NO_3	140	0 30	85	c l	d	0	0 2	Starter dose of 20 NH_4NO_3
16	New York, USA	Glossoboric Hapludalfs	Silt loam, 1% C, pH 6 9	w	Maize	Urea	140	2 50	85	c l	d	1 6	1 8	Starter dose of 20 NH_4NO_3
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	Organic/NH_4NO_3	132	2 40	365	c -	d		1 8	112/20 organic/NH_4NO_3,1979/80
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	Organic/NH_4NO_3	132	2 90	365	c -	d		2 2	112/20 organic/NH_4NO_3,1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	Organic/NH_4NO_3	132	3 80	365	c -	d		2 9	112/20 organic/NH_4NO_3,1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Timothy weeds	-	0	0 90	365	c -	d			1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Timothy weeds	-	0	1 70	365	c -	d			1979/80
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	NH_4NO_3/urea	132	1 60	365	c -	d		1 2	1979/80
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	NH_4NO_3/urea	132	2 90	365	c -	d		2 2	1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Maize	NH_4NO_3/urea	132	2 20	365	c -	d		1 7	1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Alfalfa	-	0	2 30	365	c -	d			1980/81
17	New York, USA	Glossoboric Hapludalfs	Silt loam	w	Alfalfa	-	0	4 20	365	c -	d			1979/80
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	Organic	1230	3 25	314	g	d/w		0 3	1978-1979
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	-	0	0 45	273	g	d/w			1979-1980
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	NO_3	400	1 25	273	g	d/w		0 3	1979-1980
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	Organic	298	1 10	273	g	d/w		0 4	1979-1980
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	-	0	3 55	314	g	d/w			1978-1979
18	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	NO_3	100	6 90	314	g	d/w		6 9	1978-1979
19	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	NO_3	700	13 40	365	o 2	2-3d/w		1 9	
19	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	Organic	700	3 30	365	o 2	2-3d/w		0 5	
19	Edinburgh, UK	Stagnogley, 4 1% C	Sandy loam over clay loam	p	Grass	-	0	3 20	365	o 2	2-3d/w			
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4 7, 2 16% C	w	Tobacco	NH_4NO_3/straw	80	0 70	253	c -	w		0 9	80 kg N from NH_4NO_3, unknown amount of N from straw incorporated, 1981
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4 7, 2 27% C	w	Tobacco	NH_4NO_3/straw	80	0 30	190	c -	w		0 4	80 kg N from NH_4NO_3, unknown amount of N from incorporated cover crop (rye), 1981

Appendix (*Continued*).

20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 2.31% C	w	Tobacco	Organic/NH_4NO_3	245	0.30	190	c -	w		0.1	80 NH_4NO_3 + 165 kg N ha^{-1} from alfalfa, 1981
20	Wisconsin, USA	Typic Argiudolls	Silt loam pH 4.7, 2.72% C	w	Tobacco	Organic/NH_4NO_3	410	2.70	252	c -	w		0.7	80 NH_4NO_3 + 330 kg N ha^{-1} from manure, 1981
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.7, 1.61% C	w	Tobacco	NH_4NO_3	80	1.00	210	c -	w		1.3	1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 5.1, 1.56% C	w	Tobacco	NH_4NO_3	80	0.90	210	c -	w		1.1	1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 1.56% C	w	Tobacco	NH_4NO_3	80	1.50	206	c -	w		1.9	1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 2.16% C	w	Tobacco	NH_4NO_3/straw	80	2.20	249	c -	w		2.8	80 kg N from NH_4NO_3, unknown amount of N from straw incorporated, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 2.27% C	w	Tobacco	NH_4NO_3/straw	80	1.60	202	c -	w		2.0	80 kg N from NH_4NO_3, unknown amount of N from incorporated cover crop (rye), 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 2.31% C	w	Tobacco	Organic/NH_4NO_3	245	3.20	202	c -	w		1.3	80 NH_4NO_3 + 265 kg N ha^{-1} from alfalfa, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 4.7, 2.72% C	w	Tobacco	Organic/NH_4NO_3	410	6.10	257	c -	w		1.5	80 NH_4NO_3 + 330 kg N ha^{-1} from manure, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 5.8, 2.72% C	w	Barley	Organic/NH_4NO_3	520	1.60	215	c -	w		0.3	80 NH_4NO_3 + 440 kg N ha^{-1} from sludge, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.8, 1.74% C	w	Maize	NH_4NO_3	200	6.30	190	c -	w		3.2	Reduced tillage, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.8, 1.74% C	w	Maize	NH_4NO_3	200	3.50	190	c -	w		1.8	Reduced tillage, 1980
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.7, 1.56% C	w	Vegetables	NH_4NO_3	80	0.20	160	c -	w		0.3	1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 5.1, 1.56% C	w	Vegetables	NH_4NO_3	80	0.20	160	c -	w		0.3	1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam; pH 4.7, 1.56% C	w	Vegetables	NH_4NO_3	80	0.40	160	c -	w		0.5	1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam; pH 4.7, 2.72% C	w	Vegetables	Organic/NH_4NO_3	410	1.20	160	c -	w		0.3	80 NH_4NO_3 + 330 kg N ha^{-1} from manure, 1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 5.8, 2.72% C	w	Barley	Organic/NH_4NO_3	520	0.20	152	c -	w		0.0	80 NH_4NO_3 + 440 kg N ha^{-1} from sludge, 1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.8, 1.81% C	w	Maize	NH_4NO_3	200	0.30	157	c -	w		0.2	Reduced tillage, 1979
20	Wisconsin, USA	Typic Argiudolls	Silt loam, pH 6.8, 1.74% C	w	Maize	NH_4NO_3	200	0.60	157	c -	w		0.3	Reduced tillage, 1979
21	Colorado, USA	Aridic Argiustoll	Clay (montmorillonitic)	w	Maize	NH_3	200	2.60	128	c -/m	w		1.3	Irrigated maize
21	Colorado, USA	Aridic Argiustoll	Clay (montmorillonitic)	w	Maize	NH_3	200	4.00	365	c -/m	w		2.0	Irrigated maize; *flux based on extrapolation*
22	Ontario, Canada	Gray brown Luvisol	Sandy loam	w	Maize	-	0	0.10	80	c -	w			Estimated from Figure 1, p. 434
22	Ontario, Canada	Gray brown Luvisol	Sandy loam	w	Maize	NH_4NO_3	336	0.85	80	c -	w	0.2	0.3	About 3 measurements/month
23	Konosu, Japan	Alluvial soil		w	Rape	NH_4	150	0.09	38	c -	2 h		0.1	Figure 4 (p. 24) shows 2 h intervals of measurement
23	Konosu, Japan	Alluvial soil		w	Wheat	NH_4	80	0.14	186	c -	2 h		0.2	
23	Tsukuba, Japan	Andosols		w	Wheat	NH_4	80	0.19	186	c -	2 h		0.2	
23	Tsukuba, Japan	Andosols		w	Rape	NH_4	100	0.34	56	c -	2 h		0.3	
23	Tsukuba, Japan	Andosols		w	Rape	NH_4	150	0.14	38	c -	2 h		0.1	
23	Tsukuba, Japan	Andosols		w	Carrot	NH_4	200	0.52	116	c -	2 h		0.3	
23	Konosu, Japan	Alluvial soil		w	Carrot	NH_4	200	0.62	116	c -	2 h		0.3	
23	Konosu, Japan	Alluvial soil		w	Rice, dryland	NH_4	100	0.33	120	c -	2 h		0.3	

23	Tsukaba, Japan	Andosols		w	Rice, dryland	NH_4	100	0.55	120	c -	2 h		0.6	
23	Mito, Japan	Andosols		w	Rice, dryland	NH_4	90	0.27	139	c -	2 h		0.3	
24	Tsukuba, Japan	Gray lowland soil, 2.5% C		p	carrot	NH_4	200	0.25	116	c -	3-10 d	0.1	0.1	Nitrification inhibitor added
24	Tsukuba, Japan	Gray lowland soil, 2.5% C		p	carrot	NH_4	200	0.60	116	c -	3-10 d	0.3	0.3	
24	Tsukuba, Japan	Gray lowland soil, 2.5% C		p	carrot	-	0	0.08	116	c -	3-10 d			
24	Tsukuba, Japan	Gray lowland soil, 2.5% C		p	carrot	NH_4	200	0.34	116	c -	3-10 d	0.1	0.2	
25	Colorado, USA	Aridic Argiustolls	Clay (montmorillonitic)	w	Maize	NH_4	200	2.50	123	c -/m	d/w		1.3	Irrigated maize, AA injected
26	Colorado, USA	Ustic Torriorthents		w	Barley	Organic (N-mineralized)	356	4.19	153	c -	3 d/w	1.0	1.2	Total N added is 1436 kg
26	Colorado, USA	Ustic Torriorthents		w	Barley	Organic (N-mineralized)	71	1.09	153	c -	3 d/w	0.8	1.5	Total N added is 287 kg
26	Colorado, USA	Ustic Torriorthents		w	Barley	-	0	0.82	153	c -	3 d/w			N-mineralised is 69 kg
26	Colorado, USA	Ustic Torriorthents		w	Barley	NH_4NO_3	224	1.43	153	c -	3 d/w	0.4	0.6	
26	Colorado, USA	Ustic Torriorthents		w	Barley	NH_4NO_3	112	1.04	153	c -	3 d/w	0.5	0.9	
26	Colorado, USA	Ustic Torriorthents		w	Barley	NH_4NO_3	56	0.93	153	c -	3 d/w	0.7	1.7	
26	Colorado, USA	Ustic Torriorthents		w	Barley	-	0	0.52	153	c -	3 d/w			
27	Colorado, USA	Aridic Argiustolls	Clay loam	w	Maize	-	0	2.23	120	c 2	2-4 p d/3 p w			Irrigated maize
27	Colorado, USA	Aridic Argiustolls	Clay loam	w	Maize	NH_4	200	2.95	120	c 2	2-4 p d/3 p.w		1.5	Irrigated maize
27	Colorado, USA	Aridic Argiustolls	Clay loam	w	Barley	-	0	0.45	86	c 2	2-4 p.d/3 p.w			Irrigated barley
27	Colorado, USA	Aridic Argiustolls	Clay loam	w	Barley	NH_4	200	0.76	86	c 2	2-4 p d/3 p w		0.4	Irrigated barley
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3/organic	300	9.90	16	c 2	d/w		3.3	Unknown amount of N from organic fert., controlled soil moisture, summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3/organic	300	5.40	16	c 2	d/w		1.8	Unknown amount of N from organic fert., controlled soil moisture; summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted (ryegrass 4 months before exp.)	NO_3	300	4.30	16	c 2	d/w		1.4	Controlled soil moisture, summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted (ryegrass 4 months before exp.)	NO_3	300	1.80	16	c 2	d/w		0.6	Controlled soil moisture; summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3	300	2.10	16	c 2	d/w		0.7	Controlled soil moisture; summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3	300	0.60	16	c 2	d/w		0.2	Controlled soil moisture, summer exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3/organic	300	4.20	16	c 2	d/w		1.4	Unknown amount of N from organic fert., controlled soil moisture, winter exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3/organic	300	3.80	16	c 2	d/w	1.3		Unknown amount of N from organic fert., controlled soil moisture, winter exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted (ryegrass 4 months before exp.)	NO_3	300	0.70	16	c 2	d/w	0.2		Controlled soil moisture, winter exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted (ryegrass 4 months before exp.)	NO_3	300	0.10	16	c 2	d/w	0		Controlled soil moisture; winter exp
28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3	300	0.40	16	c 2	d/w	0.1		Controlled soil moisture, winter exp

Appendix (*Continued*).

28	California, USA	Typic Xerorthents	Loam	w	Unplanted	NO_3	300	0.20	16	c 2	d/w	0.1		Controlled soil moisture, winter exp
29	Berkshire, UK	Ochraqualfs	loam over clay, 3.5% C	p	Grass	NH_4NO_3	250	3.25	365	o -	d/3 p w	1.3		
30	Berkshire, UK	Ochraqualfs	loam over clay, 3.5% C	p	Grass	-	0	-0.60	365	o 1	2-3 p w			
30	Berkshire, UK	Ochraqualfs	loam over clay, 3.5% C	p	Grass	NH_4NO_3	500	8.00	365	o 1	2-3 p w	1.6		
30	Berkshire, UK	Ochraqualfs	loam over clay, 3.5% C	p	Grass	NH_4NO_3	250	3.50	365	o 1	2-3 p w	1.4		
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NO_3	620	41.80	210	o 1	d/2-3 d	6.7		Lettuce-celery, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NO_3	620	20.20	210	o 1	d/2-3 d	3.3		Lettuce-celery, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NO_3	620	26.40	210	o 1	d/2-3 d	4.3		Lettuce-celery, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	organic/NO_3	430	19.60	210	o 1	d/2-3 d	4.6		144/286 organic/NO_3, artichokes, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	organic/NO_3	430	26.90	210	o 1	d/2-3 d	6.3		144/286 organic/NO_3, artichokes, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NO_3	680	26.80	210	o 1	d/2-3 d	3.9		Cauliflower, irrigated
31	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NO_3	680	29.20	210	o 1	d/2-3 d	4.3		Cauliflower, irrigated
32	California USA	Pachic Haploxerolls	Fine loamy	w	Vegetables	NH_4/urea/NH_3	335	7.68	123	o 1	d/w	2.3		Celery, irrigated, 12-18% of denitrification of 51.2 kg N ha^{-1} as N_2O (p 117)
33	Mainz, Germany	Loess loam	Sandy l -clay loam, 0.8% C, pH 7.4	w	Grass	-	0	0.02	49	c -	d			
33	Mainz, Germany	Loess loam	Sandy l -clay loam, 0.8% C, pH 7.4	w	Grass	NO_3	100	0.07	49	c -	d	0.05	0.1	
33	Mainz, Germany	Loess loam	Sandy l -clay loam, 0.8% C, pH 7.4	w	Grass	NH_4	100	0.09	49	c -	d	0.07	0.1	
33	Mainz, Germany	Aeolian sand	Sand	w	Weeds	-	0	0.13	71	c -	d			
33	Mainz, Germany	Aeolian sand	Sand	w	Weeds	NO_3	100	0.14	71	c -	d	0.01	0.1	
33	Mainz, Germany	Aeolian sand	Sand	w	Weeds	NH_4	100	0.22	71	c -	d	0.09	0.2	
33	Mainz, Germany	Loess	Sandy loam, 2-2.6% C	w	Grass	-	0	0.02	32	c -	d			Authors refer to crop as "meadow"
33	Mainz, Germany	Loess	Sandy loam, 2-2.6% C	w	Grass	NO_3	100	0.03	32	c -	d	0.01	0	Authors refer to crop as "meadow"
33	Mainz, Germany	Loess	Sandy loam, 2-2.6% C	w	Grass	NH_4	100	0.05	32	c -	d	0.03	0	Authors refer to crop as "meadow"
34	Mainz, Germany	Eolian sand	Sand	w	Weeds	-	0	0.04	72	c -	2d/m			Estimated from Figure 2, p 156
34	Mainz, Germany	Eolian sand	Sand	w	Weeds	NH_4	100	0.13	72	c -	2d/m	0.1	0.1	
34	Mainz, Germany	Eolian sand	Sand	w	Weeds	NO_3	100	0.05	72	c -	2d/m	0	0.1	
34	Mainz, Germany	Eolian sand	Sand	w	Weeds	NH_4NO_3	100	0.09	72	c -	2d/m	0.1	0.1	
35	Andalusia, Spain		Loamy sand	w	Grass	-	0	0	10	c -	d			Estimated from Figure 2, p.165
35	Andalusia, Spain		Loamy sand	w	Grass	NH_4NO_3	100	0.08	10	c -	d	0.1	0.1	Estimated from reported % N2O loss; plot received additional 75 kg N earlier in the year
35	Andalusia, Spain		Loamy sand	w	Unplanted, soybean residues incorporated	-	0	0.10	28	c -	d			Estimated from 1.5 × 10^{-1} g N_2O-N loss m^2h^{-1}
35	Andalusia, Spain		Loamy sand	w	Unplanted, soybean residues incorporated	NH_4NO_3	100	0.14	28	c -	d	0	0.1	Estimated from reported 0.04% N_2O-N loss from NH_4NO_3
35	Andalusia, Spain		Loamy sand	w	Unplanted, soybean residues incorporated	Urea	100	0.28	28	c -	d	0.2	0.3	Estimated from reported 0.18% N_2O-N loss from urea
36	Louisiana, USA	Typic Albaqualfs	Silt loam, 0.7% C· pH 6	p	Rice, wetland	-	0	0.07	105	c -	w			
36	Louisiana, USA	Typic Albaqualfs	Silt loam, 0.7% C. pH 6	p	Rice, wetland	Urea	90	0.11	105	c -	w	0	0.1	Urea drilled
36	Louisiana, USA	Typic Albaqualfs	Silt loam, 0.7% C pH 6	p	Rice, wetland	Urea	180	0.17	105	c -	w	0.1	0.1	Urea drilled

36	Louisiana, USA	Typic Albaqualfs	Silt loam, 0.7% C pH 6	p	Rice, wetland	Urea	90	0.11	105	c -	w	0	0.1	Urea top dressed
36	Louisiana, USA	Typic Albaqualfs	Silt loam, 0.7% C pH 6	p	Rice, wetland	Urea	180	0.09	105	c -	w	0	0.1	Urea top dressed
37	UK		Clay loam, 4% C	p	Grass	NO_3	400	7.00	365	c -	2p d./w	1.5	1.8	Mean of reported emission of 6.0-8.0 kg N ha^{-1}
37	UK		Silt loam, 2.3% C	w	Grass	NO_3	400	5.00	365	c -	2p d./w	1.0	1.3	Mean of reported emission of 4.0-6.0 kg N ha^{-1}
37	UK		Silt loam, 2.3% C	w	Grass	-	0	0.90	365	c -	2p d./w			Mean of reported emission of 0.8-1.0 kg N ha^{-1}
38	Denmark		Sandy loam, 1.9%C, pH 5.3	w	Grass	NH_4NO_3	200	2.38	100	o -	h	0.9	1.2	Two applications
38	Denmark		Sandy loam, 1.9%C, pH 5.3	w	Grass	Organic	492	9.35	100	o -	h	1.8	1.9	Two applications, cow slurry, 50% of N inorganic
38	Denmark		Sandy loam, 1.9%C, pH 5.3	w	Grass	-	0	0.67	100	o -	h			
39	Scotland		Loam, pH 6.6, 4.4%C	w	barley, winter, ploughed	NH_4NO_3	210	0.01	8	c -	d		0	
39	Scotland		Loam, pH 6.6; 4.4%C	w	barley, winter, ploughed	NH_4NO_3	285	0.01	8	c -	nk		0	
39	Scotland		Loam, pH 6.6, 4.4%C	w	barley, winter, direct drilled	NH_4NO_3	210	0.01	8	c -	nk		0	
39	Scotland		Loam; pH 6.6, 4.4%C	w	barley, winter, direct drilled	NH_4NO_3	285	0.01	8	c -	nk		0	
39	Scotland		Loam; pH 6.5, 3.3%C	w	barley, winter, ploughed	NH_4NO_3	210	0.01	8	c -	nk		0	
39	Scotland		Loam, pH 6.5, 3.3%C	w	barley, winter, ploughed	NH_4NO_3	285	0	8	c -	nk		0	
39	Scotland		Loam, pH 6.5, 3.3%C	w	barley, winter, direct drilled	NH_4NO_3	210	0.01	8	c -	nk		0	
39	Scotland		Loam, pH 6.5, 3.3%C	w	barley, winter, direct drilled	NH_4NO_3	285	0.01	8	c -	nk		0	
40	Colorado, USA	Aridic Argiustolls	Clay loam, 1.1%C, pH 7.2	w	Maize	-	0	0.12	97	c -	3 p w			Irrigated 1989
40	Colorado, USA	Aridic Argiustolls	Clay loam, 1.1%C, pH 7.2	w	Maize	Urea	218	3.36	97	c -	3 p w	1.5	1.5	Irrigated 1989
40	Colorado, USA	Aridic Argiustolls	Clay loam, 1.1%C, pH 7.2	w	Maize	-	0	0.11	97	c -	3 p w			Irrigated 1990
40	Colorado, USA	Aridic Argiustolls	Clay loam, 1.1%C, pH 7.2	w	Maize	Urea	218	1.65	97	c -	3 p w	0.7	0.8	Irrigated 1990
41	Iowa, USA		Sandy loam, 0.9%C, pH 7.9	p	Soybeans	-	0	0.34	365	c -	3d/21d			
41	Iowa, USA		Silty clay loam, 5.4%C, pH 7.5	p	Soybeans	-	0	0.65	365	c -	3d/21d			
41	Iowa, USA	Typic Calciaquolls	Clay loam, 3.6%C, pH 8.1	p	Soybeans	-	0	1.35	365	c -	3d/21d			
41	Iowa, USA		Sandy loam, 1.3%C, pH 6.7	p	Soybeans	-	0	1.05	365	c -	3d/21d			
41	Iowa, USA	Typic Haplaquolls	Loam, 2.9%C, pH 6.9	p	Soybeans	-	0	1.97	365	c -	3d/21d			
41	Iowa, USA		Loam, 2.5%C, pH 6.5	p	Soybeans	-	0	1.87	365	c -	3d/21d			
42	New York, USA				Wheat	-	0	0.09	46	nk	nk			
42	New York, USA				Wheat	NH_4NO_3	175	0.30	46	nk	nk	0.1	0.2	
42	New York, USA				Wheat	NH_4NO_3	175	0.16	46	nk	nk	0	0.1	
44	Colorado, USA	Ustollic Haplargids	Fine sandy loam	w	Grass	-	0	0.14	62	c -	3d			
44	Colorado, USA	Ustollic Haplargids	Fine sandy loam	w	Grass	Urine	450	0.49	62	c -	3d	0.1	0.1	
17	Florida, USA		Organic	w	Onions	NH_4NO_3	170	85	365	c -	d		50	
17	Florida, USA		Organic	w	Onions	NH_4NO_3	170	72	365	c -	d		42	
17	Florida, USA		Organic	w	Maize	NH_4NO_3	170	76	365	c -	d		45	
17	Florida, USA		Organic	w	Maize	NH_4NO_3	170	152	365	c -	d		89	
17	Florida, USA		Organic	w	Sugarcane	-	0	48	365	c -	d			

Appendix (*Continued*).

17	Florida, USA		Organic	w	Sugarcane	-	0	7	365	c -	d			
17	Florida, USA		Organic	w	Grass	-	0	97	365	c -	d			
17	Florida, USA		Organic	w	Grass	-	0	16	365	c -	d			
17	Florida, USA		Organic	w	Unplanted	-	0	165	365	c -	d			
17	Florida, USA		Organic	w	Unplanted	-	0	59	365	c -	d			
43	Florida, USA	Euic lithic Medisaprists	Organic	p	Unplanted	-	0	165	365	c -	3d			Estimated N-mineralization 1200-1400 $kg N ha^{-1} yr^{-1}$
43	Florida, USA	Euic lithic Medisaprists	Organic	p	Grass	-	0	97	365	c -	3d			Estimated N-mineralization 1200-1400 $kg N ha^{-1} yr^{-1}$
43	Florida, USA	Euic lithic Medisaprists	Organic	p	Sugarcane	-	0	48	365	c -	3d			Estimated N-mineralization 1200-1400 $kg N ha^{-1} yr^{-1}$

nk = not reported.

[a] 1, Armstrong (1983); 2, Brams et al. (1990); 3, Breitenbeck et al. (1980); 4, Breitenbeck & Bremner (1986a); 5, Breitenbeck & Bremner (1986b); 6, Bremner et al (1981a); 7, Bremner et al (1981b); 8, Burford et al. (1981); 9, Cates & Keeney (1987); 10, Cochran et al. (1980); 11, Colbourn & Harper (1987); 12, Colbourn et al (1984a); 13, Colbourn et al. (1984b); 14, Conrad et al. (1983); 15, Denmead et al. (1979); 16, Duxbury & McConnaughey (1986); 17, Duxbury et al. (1982); 18, Eggington & Smith (1986a); 19, Eggington & Smith (1986b); 20, Goodroad et al. (1984); 21, Hutchinson & Mosier (1979); 22, McKenney et al (1980); 23, Minami (1987); 24, Minami (1990); 25, Mosier & Hutchinson (1981); 26, Mosier et al. (1982); 27, Mosier et al. (1986); 28, Rolston et al (1978); 29, Ryden (1981); 30, Ryden (1983); 31, Ryden & Lund (1980); 32, Ryden et al (1979); 33, Seiler & Conrad (1981); 34, Conrad & Seiler (1980); 35, Slemr et al. (1984); 36, Smith et al. (1982); 37, Webster & Dowdell (1982); 38, Christensen (1983); 39, Arah et al. (1991); 40, Bronson et al. (1992); 41, Bremner et al. (1980); 42, Duxbury (personal communication), quoted in Eichner (1990); 43, Terry et al. (1981); 44, Mosier et al. (1981).

[b] Reported soil classification according to USDA (1975) or general description.

[c] w - well drained; m - moderately well drained; p - poorly drained.

[d] NH_3 - anhydrous ammonia; NH_4 - salts of ammonia; NO_3 - salts of nitrate; NH_4NO_3 - ammonium nitrate; organic - various forms of organic fertilizers.

[e] c - closed chamber method; o - open chamber method; g - soil N_2O gradient method, based on N_2O gas concentration gradient in the soil profile to estimate the flux to the atmosphere; m - micrometeorological method; 1 - N_2 and N_2O measured (with/without C_2H_2 inhibition), only N_2O is recorded here; 2 - ^{15}N labelling; -= N_2O measured (no C_2H_2 inhibition).

[f] Freq. - frequency of sampling; d - once per day, w - once per week; m - once per month; 3-7 d - once per 3-7 days, 2 p.d or 2p.w - twice per day/week, cont - continuous, d/w or other combinations indicate higher frequency at high and lower frequency at low flux rates.

[g] I - flux from fertilized plot minus flux from unfertilized control plot, presented as % of N-application; II - flux from fertilized plot presented as % of N-application.