PRODUCTION, ISOTOPIC COMPOSITION, AND ATMOSPHERIC FATE OF BIOLOGICALLY PRODUCED NITROUS OXIDE

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■ **Abstract**   The anthropogenic production of greenhouse gases and their consequent effects on global climate have garnered international attention for years. A remaining challenge facing scientists is to unambiguously quantify both sources and sinks of targeted gases. Microbiological metabolism accounts for the largest source of nitrous oxide (N_2O), mostly due to global conversion of land for agriculture and massive usage of nitrogen-based fertilizers. A most powerful method for characterizing the sources of N_2O lies in its multi-isotope signature. This review summarizes mechanisms that lead to biological N_2O production and how discriminate placement of ^{15}N into molecules of N_2O occurs. Through direct measurements and atmospheric modeling, we can now place a constraint on the isotopic composition of biological sources of N_2O and trace its fate in the atmosphere. This powerful interdisciplinary combination of biology and atmospheric chemistry is rapidly advancing the closure of the global N_2O budget.

INTRODUCTION

Nitrous oxide (N_2O) is a potent greenhouse gas and the major source of stratospheric reactive nitrogen species that participate in the catalytic destruction of ozone. It has an atmospheric residence time of 118 ± 25 years (Minschwaner et al. 1998, Olsen et al. 2001). The infrared radiative forcing of N_2O is about 206 times that of CO_2 on a per molecule basis at present atmospheric conditions (IPCC 2001). This is illustrated in Figure 1, which shows the blackbody radiation of an atmosphere at 273 K and the infrared bands of N_2O. The fundamental bands are ν_2, ν_1, and ν_3 at 589, 1285, and 2224 cm^{-1}, respectively; the most important for greenhouse warming of the atmosphere is the ν_1 band at 7.78 μm (Goody & Yung 1989).
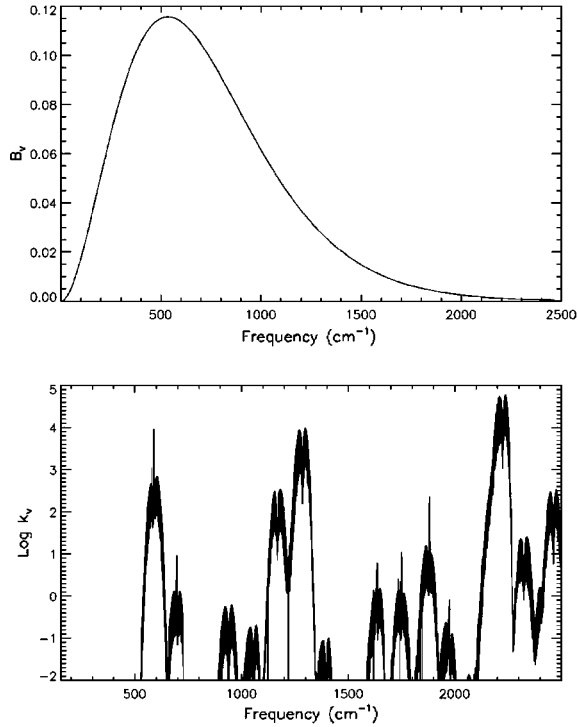
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Figure 1 (*a*) Radiance due to a blackbody at 273 K as a function of wavenumber. The units are in W/(m^2 cm^{-1} sr), where sr is steradian. (*b*) Absorption coefficient for N$_2$O in the infrared. The strongest absorption bands are ν_2, ν_1, and ν_3 at 589, 1285 and 2224 cm^{-1}, respectively. The others are overtone or combination bands. Data taken from the HITRAN (high-resolution transmission molecular absorption database), as described in Goody & Yung (1989).

There has been a steady increase in atmospheric N$_2$O since the Industrial Revolution, as shown in Figure 2 (IPCC 2001). The early data are deduced from gases trapped in air bubbles in polar ice. Over the recent few decades, the concentration of N$_2$O has been accumulating in the atmosphere (see inset of Figure 2) at a rate of 0.6 ppb · year^{-1}, adding to the current concentration of about 314 ppb (parts per billion by volume) (IPCC 2001). The radiative forcing, approximately on a linear scale for small perturbations, is plotted on the right axis. There has been an increase of about 0.15 Wm^{-2} since the Industrial Revolution. For comparison, the radiative forcing due to CO$_2$ over the same period is about 1.4 Wm^{-2}. Although many sources of N$_2$O have been identified, including agricultural soils, oceans, animal waste, biomass burning, fuel combustion, and industry, the combined strength of these sources calculated in 1994 only matched two thirds of the known sinks, which are removal and accumulation in the atmosphere (IPCC 2001). Upon re-evaluation of
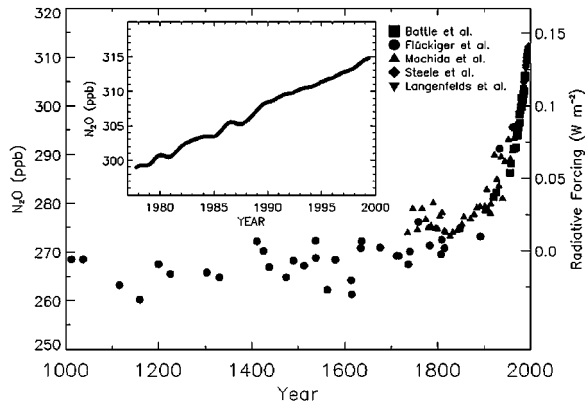
Figure 2 N_2O mixing ratio for the past 1000 years as determined from ice cores, firn, and whole-air samples. Datasets are from Battle et al. (1996), Flückiger et al. (1999), Langenfields et al. (1996), Machida et al. (1995), and Steele et al. (1996). Radiative forcing, approximately on a linear scale, is plotted on the right axis. Deseasonalized global averages are plotted in the inset (Butler et al. 1998). Figure taken from IPCC (2001).

the strength of each source, it was found that the application of nitrogen-based fertilizers to agricultural soils accounted for a much larger source of N_2O than previously thought (Mosier & Kroeze 1998, Nevison & Holland 1997). By 1998, the balance between the total sources and total sinks of N_2O added up to a budget of 16 Tg N · year^{-1} (IPCC 2001). However, large uncertainty remains as to the actual strength of individual sources of N_2O (Table 1).

Increased fertilizer usage over the past several years has stimulated the rates of microbial metabolism, especially those processes involved in the nitrogen cycle (Figure 3). Nitrification and denitrification are the primary metabolic activities leading to N_2O production. However, several physiological and ecological feedbacks can greatly influence the rates of these metabolic pathways. One of the purposes of this review is to examine the diversity of enzymatic, organismal, community, and environmental factors that are simultaneously involved in producing N_2O. Once we achieve an understanding of the complexity of N_2O production by microbial communities, the next goal is to quantify how much N_2O is produced by nitrification and denitrification under a particular set of environmental conditions.

To accomplish this feat, many researchers are attempting to track discrete sources of N_2O accumulating in the atmosphere by using differential isotopic signatures of $^kN^mN^nO$ as produced by specific microbial communities. This concept necessarily relies on enzymatic, organismal, community, and environmental factors that influence the isotopic ratios and intramolecular site-preference of ^{15}N. Here, we review current research on organisms and enzymes within the microbial

TABLE 1 Sources of N_2O (in Tg N year^{-1})

Source	1994[a]	Range	1990[b]	Range
Anthropogenic sources				
Agricultural soils	4.2	0.6–14.8	3.6	2.8–5.7
Biomass burning	0.5	0.2–1.0	0.5	0.2–0.8
Industrial sources	1.3	0.7–1.8	0.7	0.2–1.1
Cattle and feedlots	2.1	0.6–3.1	1.0	0.2–2.0
Subtotal	8.1	2.1–20.7	4.1	1.3–7.7
Natural sources				
Ocean	3.0	1.0–5.0	3.6	2.8–5.7
Atmosphere (NH3 oxidation)	0.6	0.3–1.2	0.6	0.3–1.2
Tropical soils				
Wet forest	3.0	2.2–3.7		
Dry savannas	1.0	0.5–2.0		
Temperate soils				
Forests	1.0	0.1–2.0		
Grasslands	1.0	0.5–2.0		
All soils			6.6	3.3–9.9
Subtotal	9.6	4.6–15.9	10.8	6.4–16.8
Total sources	17.7	6.7–36.6	14.9	7.7–24.5
Imbalance (trend)	3.9	3.1–4.7		
Total sinks (stratospheric)	12.3	9–16		
Implied total sources	16.2			

[a](Kroeze 1999, Mosier et al. 1998).

[b](Olivier et al. 1998).

nitrogen cycle, how isotopic site-preference and fractionation occur, measurements of N_2O isotopologue and isotopomer abundances using spectroscopic techniques, and fate of N_2O isotopologues and isotopomers in the atmosphere (definitions of terms in IUPAC 1997). There are three important isotopologues of N_2O, ^{15}NNO, $N_2{}^{18}O$ and $N_2{}^{17}O$, and two isotopomers, ^{15}NNO and $N^{15}NO$.

The isotopologues and isotopomers of N_2O will greatly advance our understanding of the budgets of these gases, primarily because atmospheric budgets of trace gas species must balance for both the species as a whole and also for individual isotopic analogs. Because most sources and sinks have characteristic fractionation processes, the different isotopic species provide valuable additional constraints in determining the budgets of these gases. The expansion of the database to include isotopic composition obviously increases the information content of the system under study, but it comes with a challenge. The basic physical, chemical, biological, and atmospheric processes must be well understood before isotopic information can be used to place useful constraints on sources and sinks of N_2O.
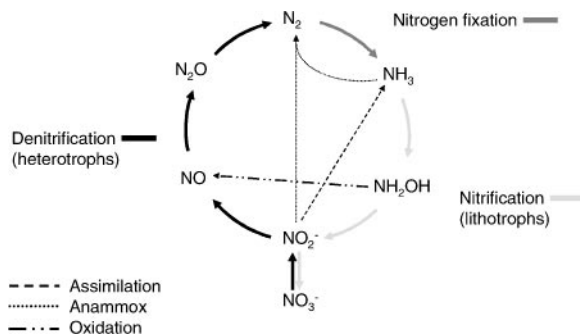
Figure 3   Microbial nitrogen cycle.

A most powerful method for characterizing the sources of N_2O (and other biogenic trace gases as well) lies in its multi-isotope signature, as demonstrated in the seminal work by Kim & Craig (1993). The measurements made in this study for $\delta^{15}N$ versus $\delta^{18}O$ in N_2O are summarized in Figure 1 of their paper [an updated version is reproduced here as Figure 4; $\delta = (R/R_{standard} - 1) \times 1000$, where R = isotopic ratio (Craig 1961)]. The reference isotopic fractionations of atmospheric N_2 and O_2 are taken to be zero. Average tropospheric N_2O has $\delta^{15}N = 7.0$ and $\delta^{18}O = 20.7$ per mil. In the stratosphere, $\delta^{15}N$ and $\delta^{18}O$ appear to be enriched by as much as 15 and 12 per mil, respectively, relative to tropospheric N_2O. These startling results for stratospheric N_2O were confirmed and extended by Rahn & Wahlen (1997). Referring to Figure 4, the significant results of Kim & Craig (1993) are (a) the major land biospheric sources of N_2O are light in both ^{15}N and ^{18}O, relative to tropospheric N_2O; (b) stratospheric N_2O is enriched in both ^{15}N and ^{18}O, relative to tropospheric N_2O; and (c) there is a large "back flux" of ^{15}N-enriched N_2O from the stratosphere to the troposphere in order to account for the isotopic composition of tropospheric N_2O. A large part of the recent work on N_2O consists of understanding the underlying mechanism of isotopic fractionation in the atmosphere implied by Kim & Craig (1993) (Johnson et al. 2001, Yung & Miller 1997).

MICROBIAL PATHWAYS THAT PRODUCE N_2O

Microbial Nitrogen Transformations and Intramolecular Site Preference of ^{15}N

The requirement for nitrogen in biological molecules necessitates a diversity of mechanisms for assimilating nitrogen into the living cell. The majority of assimilatory mechanisms in bacteria, except the direct fixation of N_2, require the uptake of either ammonia (NH_3) or nitrate (NO_3^-). In addition to assimilation, nitrogenous
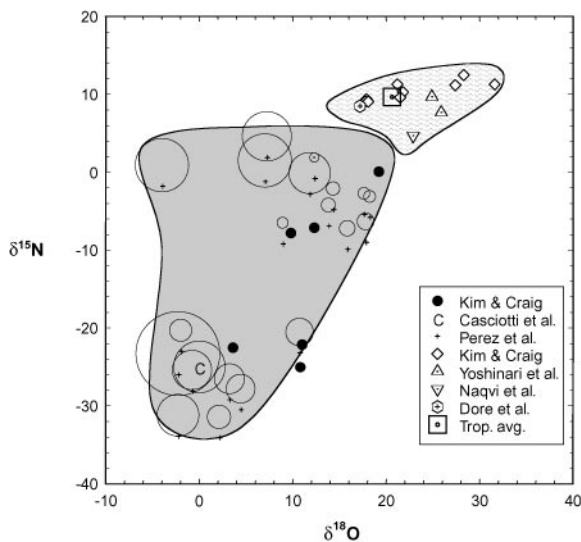
Figure 4 A plot of $\delta^{15}N$ versus $\delta^{18}O$ with highlighted fields representing the range of data found in surface oceans (*gray field*) and terrestrial systems (*textured field*). Symbols representing the work of various authors are defined in the legend. The oceanic results shown from Kim & Craig (1990) are the measured values in the top 1000 m of the subtropical Pacific Ocean. The symbols representing Yoshinari et al. (1997) are the near-surface averages of their data from the Indian Ocean and Arabian Sea. Also from the Arabian Sea is the near-surface average of Naqvi et al. (1998). The subtropical North Pacific end-member value proposed by Dore et al. (1998) is also shown. In the terrestrial field, the open circles associated with the data of Pérez et al. (2000) and Casciotti et al. (1997) are proportional to the relative magnitude of the flux for each of the points. Terrestrial data of Kim & Craig (1993) have no concurrent flux results. The open square is the commonly reported average value of tropospheric N_2O. The $\delta^{15}N$ and $\delta^{18}O$ values are referenced to atmospheric N_2 and O_2, respectively. Taken from Rahn & Wahlen (2000).

compounds are also extremely important for energy generation due to the spectrum of oxidation states from -3 to $+5$ (Table 2). Microbial enzymes have evolved that specialize in shuttling electrons to or from these various molecules, and several are described in Table 3.

Both assimilatory and dissimilatory processes are important for the fractionation and final placement of isotopes within N_2O molecules, although dissimilatory processes have the largest effects. The enzymes in dissimilatory pathways process a large flux of molecules relative to assimilatory pathways, and isotopic discrimination is based predominantly on catalytic rate and number of enzymatic steps (Cleland et al. 1977). In general, enzymes prefer to transform molecules with a smaller molecular weight, such that the end products within a nitrogen transformation pathway will almost always be isotopically lighter than molecules

TABLE 2 Oxidation state of nitrogenous compounds

Compound	Chemical formula	Oxidation state
Ammonia	NH_3	-3
Hydrazine	N_2H_4	-2
Diimine	N_2H_2	-1
Hydroxylamine	NH_2OH	-1
Dinitrogen	N_2	0
Nitrous oxide	N_2O	$+1$
Nitric oxide	NO	$+2$
Nitrite	NO_2^-	$+3$
Nitrogen dioxide	NO_2	$+4$
Nitrate	NO_3^-	$+5$

in prior steps. However, as is evident in Figure 3, there are pathways that contribute to the formation of N_2O and those that consume it. These pathways are in constant competition depending on environmental conditions and can lead to a range of ^{15}N values based on the number and type of enzymatic steps involved. Additionally, some enzymes will allow for the exchange of substrate molecules at the active-site of the enzyme before the conversion of substrate to product is complete. This process will lead to less isotopic discrimination of nitrogen due to the slowed rate of catalysis, as occurs in the process of nitrogen fixation (Beaumont et al. 2000, Hoering & Ford 1960).

The complexity of enzymatic possibilities, processivity of reactions (i.e., rate of exchange), and competition between pathways makes the task of quantifying individual microbial contributions to the budget and isotopic fractionation of N_2O very difficult. The following descriptions explain, in basic terms, the pathways that are found in broad groups of microorganisms, how discrete enzymatic pathways might fractionate ^{15}N leading to a traceable isotopic signature in the N_2O pool, and how environmental factors influence the activities of microbial groups leading to bias in the composition of N_2O isotopologues and isotopomers.

Nitrification

The process of nitrification includes the oxidation of ammonia to nitrate via nitrite (Figure 3). Several groups of microorganisms are involved in nitrification—some use it for their central metabolism, whereas others perform parts of the process fortuitously through co-metabolism (Prosser 1986). The first four groups of bacteria listed in Table 3 all participate in nitrification to varying degrees.

The best characterized microbial pathway for the oxidation of ammonia to nitrite (NO_2^-) is performed by chemolithotrophic bacteria, i.e., they consume only inorganic substrates to generate energy, and in the case of ammonia oxidizers,

TABLE 3 Bacteria in the nitrogen cycle and their enzymes

Bacterial group	Process	Main enzyme[a]	Metabolism[b]	Reference
Chemolithotrophic Ammonia-oxidizers	NH_3 oxidation to NO_2^- via NH_2OH	AMO HAO	dissim.	Wood 1986
	NH_2OH oxidation to NO and N_2O	HAO or nonenzyme	?	Hooper & Terry 1979
	NO_2^- reduction to NO	NIR	?	Hooper 1968
	NO reduction to N_2O	NOR	?	Remde & Conrad 1990
	NO_2^- reduction to N_2	?	?	Bock 1995
Methane oxidizers	NH_3 oxidation to NO_2^- via NH_2OH	MMO P-460	fortuitous	Dalton 1977, Zahn et al. 1994
	NH_2OH oxidation to NO and N_2O	P-460 or nonenzymatic	?	Knowles & Topp 1988
	NO_3^- reduction to NO_2^-	?	assim.	Uncharacterized
	NO_2^- reduction to NH_3	?	assim.	Uncharacterized
	N_2 fixation to NH_3	nitrogenase	assim.	Auman et al. 2001
	NO_2^- reduction to NO	NIR	?	Ye & Thomas 2001
	NO reduction to N_2O	NOR	?	Ye & Thomas 2001
Heterotrophic ammonia-oxidizers	NH3 oxidation to NO_2^- via NH_2OH	AMO HAO	fortuitous	Moir et al. 1996, Wehrfritz et al. 1993
Nitrite oxidizers	NO_2^- oxidation to NO_3^-	nitrite oxidase	dissim.	Prosser 1989
	NO_3^- reduction to NO_2^-, NH_3, and N_2O	nitrite oxidase ?	dissim.	Freitag et al. 1987
	NO oxidation to NO_2^- and NO_3^-	?	?	Freitag & Bock 1990
Dissimilatory denitrifiers	NO_3^- reduction to NO_2^-	NAR, NAP	dissim.	Richardson & Watmough 1999
	NO_2^- reduction to NO	NIR	dissim.	Richardson & Watmough 1999
	NO reduction to N_2O	NOR	dissim.	Richardson & Watmough 1999
		NOS		Richardson & Watmough 1999
	N_2O reduction to N_2	N_2OR	dissim.	Rasmussen et al. 2000
	NO oxidation to NO_3^-	?	?	Baumgartner et al. 1996
	NO_3^- reduction to NH_3	NAR	dissim.	
	via NO_2^-	NAS	assim.	Nakano et al. 1998
Assimilatory denitrifiers	NO_3^- reduction to NO_2^-	NAS	assim.	Lin & Stewart 1998
	NO_2^- reduction to NH_3	sirohaem NIR, hexahaem NIR	assim.	Brittain et al. 1992
Fungal denitrifiers	NO_2^- reduction to NO	Cu-NIR	?	Kobayashi & Shoun 1995
	NO reduction to N_2O	P450nor	?	Kizawa et al. 1991
Nitrogen fixers	N_2 to NH_3	nitrogenase	assim.	Postgate 1998
Anammox	NH_3 and NO_2^- to N_2 via N_2H_4 and NH_2OH	nitrite reductase hydrazine hydrolase hydrazine oxidase	dissim.	Jetten et al. 2001

Enzyme acronyms from cited references.

Assim. = assimilatory, dissim. = dissimilatory, fortuitous = co-metabolic.

they fix inorganic carbon. Ammonia-oxidizing bacteria require molecular oxygen to perform their metabolism and produce hydroxylamine (NH_2OH) as a metabolic intermediate (Wood 1986). Ammonia oxidation by these bacteria is highly stimulated by the addition of nitrogen-based fertilizers to agricultural soils, and the NO_2^- they produce stimulates other processes in the nitrogen cycle, including the production of N_2O (Conrad 1996). Ammonia oxidizers are also capable of producing N_2O under microaerophilic conditions by directly reducing NO_2^-, presumably through the activities of denitrifying enzymes (Goreau et al. 1980, Hooper 1968). This process, known as aerobic or lithotrophic denitrification, has been observed in only a small group of ammonia-oxidizing species (Casciotti & Ward 2001, Colliver & Stephenson 2000). However, the enzymes involved, the phylogenetic breadth, and metabolic purpose remain unknown.

Methane-oxidizing bacteria, or methanotrophs, are closely related evolutionarily to the ammonia oxidizers (Holmes et al. 1995). These bacteria oxidize ammonia to NO_2^- through a co-metabolic process, and thus do not gain energy from it (Dalton 1977). They also reduce NO_2^- to N_2O similarly to ammonia oxidizers, but this metabolism is even less well characterized for the methanotrophs than for the ammonia oxidizers (Knowles & Topp 1988, Yoshinari 1984). The contribution of methanotrophs to the N_2O budget is currently unknown, but may be significant (Mandernack et al. 2000). As shown in Table 3, methanotrophs also process nitrogen through other metabolic processes, including the consumption of NO, which is the substrate for N_2O production (Krämer et al. 1990).

Heterotrophic ammonia-oxidizers, bacteria that consume organic carbon as their primary metabolism, also oxidize ammonia to NO_2^-, but like the methanotrophs, they do not gain energy from it (Killham 1986, Verstraete 1975). It is thought that these bacteria could oxidize as much ammonia as the chemolithotrophic ammonia-oxidizers provided that enough organic carbon is available for energy production (Kuenen & Robertson 1994). Additionally, many heterotrophic nitrifiers reduce NO_2^- to N_2O under microaerophilic conditions using standard denitrifying enzymes (Table 3) (Castignetti et al. 1984). Therefore, the chemolithotrophic ammonia-oxidizers, methanotrophs, and heterotrophic ammonia-oxidizers all occupy the same environmental niche and are all extremely important for N_2O production in aerobic zones (Lipschultz et al. 1981). In addition to the reduction of NO_2^- to NO and N_2O, the oxidation of NH_2OH, a metabolic intermediate of ammonia oxidation, also produces N_2O (Hooper & Terry 1979). However, because NH_2OH is rapidly converted to NO_2^- in the environment, the amount of N_2O from NH_2OH oxidation is presumably insignificant compared to the amount produced through reduction of NO_2^- and NO by denitrifying enzymes (Whittaker et al. 2000).

The other half of nitrification, NO_2^- oxidation to NO_3^-, is performed by a separate group of bacteria known as nitrite oxidizers (Bock & Koops 1991). The NO_3^- produced by this group of bacteria provides much of the substrate for denitrification, a process discussed in the next section, which largely controls the rate of N_2O production in anaerobic environments. The nitrite oxidizers have been highly understudied, but they appear to play an additional role in the direct production

of N_2O (Freitag et al. 1987), and/or in the consumption of NO (Freitag & Bock 1990).

Denitrification

The process of denitrification, the reduction of NO_3^- to N_2 via NO_2^-, NO, and N_2O, is performed by a very diverse group of microorganisms, including archaea and some fungi (Kizawa et al. 1991, Zumft 1992). The enzymatic diversity and ubiquity of this pathway among microbes argue for its central role in energy generation, nitrogen assimilation, and competition in most ecosystems. Denitrifying bacteria can utilize a number of food sources from organic carbon to Fe(II) (Straub et al. 1996) and use the nitrogenous molecules as electron acceptors to complete the task of energy generation. Because denitrification is made up of a sequence of reductive events, this process is thought to occur predominantly in anaerobic environments. The potential for N_2O emission from denitrification increases in water-saturated environments that contain large concentrations of organic carbon and NO_3^- (Baumgärtner & Conrad 1992). High concentrations of NO_3^- inhibit the reduction of N_2O to N_2 and stimulate the reduction of NO to N_2O causing the escape of N_2O from soils to the atmosphere (Gaskell et al. 1981).

There has been a long-standing debate as to whether nitrifying or denitrifying processes contribute the most N_2O from agricultural environments. It appears that the extent of isotopic fractionation from these processes is quite different due to energy conservation and the consumption of N_2O during denitrification (Pérez et al. 2001). As discussed below, this argument will necessitate a closer look at the carbon to nitrogen ratio of soils, available oxygen, temperature, water, and pH.

Other Processes in the Nitrogen Cycle that Influence N_2O Production

Obviously, the direct production of N_2O by microorganisms will have the greatest influence on isotopic fractionation. However, because all aspects of the nitrogen cycle influence the availability of substrates for N_2O production or consumption, indirect processes must also be considered when quantifying the roles of individual microbial groups that participate in N_2O production. In environments that are not heavily influenced by agriculture or industry, N_2 fixation provides much of the ammonia that is subsequently oxidized by the three main groups of ammonia oxidizers discussed above. N_2 fixation provides a ready nitrogen source for assimilation by many types of organisms in natural systems, especially plants, fungi, and bacteria (Postgate 1998). The influence of naturally occurring N_2 fixation on the nitrogen cycle has recently been eclipsed by the wide-spread production and application of ammonia-based fertilizers and atmospheric deposition of ammonia from automobile exhaust and industrial processes (Howarth et al. 1996).

Bacteria that are capable of anaerobically oxidizing ammonia, a process known as anammox, also participate in the nitrogen cycle by transforming NH_3 and NO_2^- to N_2 via hydrazine and hydroxylamine intermediates (Jetten et al. 2001). It is

currently unknown whether this process is globally relevant, but significant rates have been described in marine sediments from continental shelves (Thamdrup & Dalsgaard 2002). Thus, under the right conditions, anammox could compete with denitrification in anaerobic environments by removing substrates that are necessary for producing N_2O.

ENZYME STRUCTURE AS A CAUSE FOR SITE PREFERENCE OF ^{15}N IN N_2O

Differences Between Nitrification and Denitrification

As described above, there are many groups of microorganisms that perform a variety of processes leading to either production or consumption of N_2O in the environment. Our eventual goal is to close the global budget for N_2O by understanding the relative strength of nitrifying versus denitrifying processes. One possibility for quantifying the relative contribution of microbial groups is to find differences in the composition of N_2O isotopomers and isotopologues that they each produce. In other words, is the placement of ^{15}N and extent of ^{15}N fractionation in N_2O molecules different for each microbial process? Several studies have shown that N_2O produced by nitrification is much more depleted in ^{15}N than that produced by denitrification ($-45‰$ to $-66‰$ for nitrification versus $-13‰$ to $-28‰$ for denitrification) (Barford et al. 1999, Pérez et al. 2001, Webster & Hopkins 1996, Yoshida 1988). This observation makes sense due to the conservation of energy during denitrification and the consumption of N_2O, processes that decrease the extent of isotopic fractionation.

A study by Yoshida & Toyoda suggested that we could discriminate among N_2O molecules produced by nitrification, denitrification, and bulk industrial emissions (automobile and factory) by looking at the intramolecular site-preference for ^{15}N within the N_2O molecule (Yoshida & Toyoda 2000). This study proposed that in the $N^{\beta}N^{\alpha}O$ molecule, N_2O produced by microbes will be more fractionated at the N^{α} than at the N^{β} position based on the formation and cleaving of the N^{α}–O bond during ammonia oxidation and N_2O reduction, respectively. Following this logic, environments dominated by nitrification should result in a relatively low ratio of $^{14}N^{15}NO:^{15}N^{14}NO$, whereas denitrification-dominated environments would have a more equalized ratio due to the preferential reduction of $^{15}N^{14}NO$. Although hypothetically sound, the exact opposite effect has been measured for N_2O emitted from fertilized agricultural soils dominated by nitrification, which showed enrichment of ^{15}N at the central N position (Pérez et al. 2001). This observation is supported by the mechanism of the N_2O-producing enzyme as discussed below. Industrial processes were found to cause insignificant fractionation of ^{15}N because they are not catalyzed enzymatically, and can thus be easily distinguished from biological N_2O production (Yoshida & Toyoda 2000).

Few studies have investigated the potential for site discrimination of ^{15}N within N_2O by distinct species of nitrifying versus denitrifying bacteria (Barford et al.

1999; Garber & Hollocher 1982a,b; Webster & Hopkins 1996; Weeg-Aerssens et al. 1988; Yoshida 1988). Furthermore, these studies used model organisms that are not necessarily reflective of the types of bacteria that are most active in the environment (Kowalchuk et al. 1997). In addition to direct studies of model organisms, another way to approach this question is by analyzing differences in enzyme structure among different bacterial groups to predict how ^{15}N site-preference might occur. Both nitrifiers and denitrifiers directly produce N_2O through the presumed activity of at least two enzymes: nitrite reductase, which reduces NO_2^- to NO, and nitric oxide reductase, which reduces NO to N_2O (Richardson & Watmough 1999). We will limit our discussion to these two groups of enzymes because they are directly related to N_2O production.

Nitrite Reductase

Nitrite reductase enzymes are fairly widespread throughout the bacterial kingdom due to the high usage of denitrification as an energy-generating process and for nitrogen assimilation (Brittain et al. 1992). There are two known types of dissimilatory nitrite reductases that reduce NO_2^- to NO, and one known assimilatory enzyme that reduces NO_2^- to NH_3 (Richardson & Watmough 1999). Of the dissimilatory enzymes, the cd_1-cytochrome nitrite reductase is more highly represented in the denitrifying bacteria, whereas the copper nitrite reductase is present in more taxonomically diverse species (Coyne et al. 1989, Hochstein & Tomlinson 1988). Both types of nitrite reductase have been found in the genome of the methanotroph *Methylomonas* sp. strain 16a, the only dual occurrence known, but only the copper enzyme has been found in the chemolithotrophic ammonia-oxidizers (Casciotti & Ward 2001, Ye & Thomas 2001). Based on physiological studies, it remains inconclusive as to whether the nitrite reductase in ammonia oxidizers is actually responsible for dissimilatory nitrite reduction; however, studies are currently underway to resolve this issue (Beaumont et al. 2002).

Figure 5 compares the catalytic mechanism of NO_2^- reduction by the cd_1-cytochrome enzyme (Figure 5*a*) and the copper enzyme (Figure 5*b*) (Cutruzzolà 1999). Although these mechanisms are largely similar, the intermediate steps may be different enough in their relative rate of catalysis to cause differences in isotopic fractionation. NO is a highly toxic product, it inhibits nitrite reductase, and it is shuttled almost instantaneously to nitric oxide reductase upon formation (Averill 1996). In fact, there was a long-standing debate as to whether NO was an independent product from nitrite reductase because it is transformed to N_2O so rapidly under physiological conditions (Zumft 1993). Thus, the rate of NO formation by nitrite reductase and the rate of NO transfer to nitric oxide reductase will largely govern the fractionation of isotopes within N_2O molecules.

Nitric Oxide Reductase

Nitric oxide reductase (NOR) is likely the pivotal enzyme that determines the relative fractionation and site preference of ^{15}N within the N_2O molecule. It is
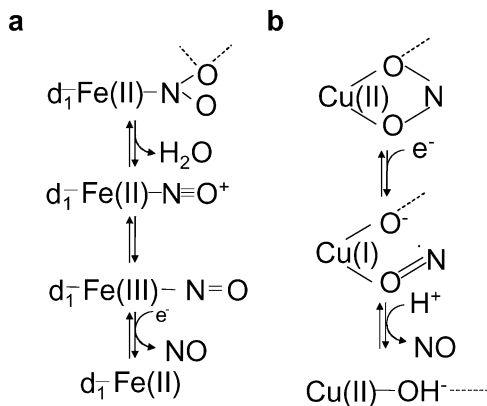
Figure 5 Catalytic mechanism of nitrite reductase—cytochrome cd_1 (*a*) versus copper (*b*) active-site. Redrawn from Cutruzzolà (1999).

also the least well-characterized enzyme within the microbial nitrogen cycle. This enzyme is responsible for bringing two NO molecules together and forming the N=N bond (Hendriks et al. 2000). There are three known classes of NOR enzymes: P-450nor, cNOR, and qNOR. P-450nor is found in denitrifying fungi, cNOR is the most common enzyme found in denitrifying bacteria, and qNOR is most often found in nondenitrifying pathogenic bacteria (Hendriks et al. 2000). Studies of P-450nor, the best-characterized enzyme in this family, have indicated that each NO molecule binds separately to the enzyme before the formation of the N=N bond (Shiro et al. 1995). Sequential binding could hypothetically lead to a preference for initial ^{14}NO binding followed by a slower, less-discriminatory binding of the second NO molecule (Figure 6*b*). Once the second NO binds, this leads to the loss of the O atom from the first NO molecule and release of N_2O (Shiro et al. 1995). This model would lead to greater fractionation at the N^β position than the N^α position (in $N^\beta N^\alpha O$), contradicting the assumption proffered by Yoshida & Toyoda and leading to a higher emission of $^{14}N^{15}NO$ than $^{15}N^{14}NO$ from the microbial environment.
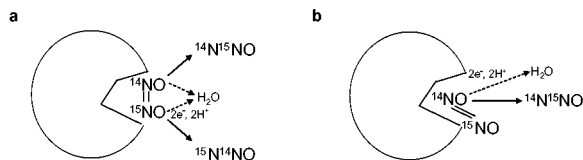
Figure 6 Simultaneous (*a*) versus sequential (*b*) binding of NO to NOR. Formation of predominant N_2O isotopologue(s) indicated for each mechanism: Simultaneous binding leads to equivalent fractionation at N^α and N^β; sequential binding leads to greater fractionation at N^β.

The catalytic mechanism of cNOR remains unclear. There are two possible mechanisms for NO binding and reduction to N_2O; one requires sequential binding of the two NO molecules similarly to that of the P-450nor (Zhao et al. 1995), whereas the other suggests a simultaneous binding of the two NO molecules (Figure 6) (Averill 1996). As illustrated in Figure 6, sequential binding would result in accumulation of ^{14}N at the N^β position, assuming a slower rate of binding by the second NO molecule (and thus with less bias toward the lighter molecule) and loss of the O atom by the first NO molecule to bind. Simultaneous binding would likely result in limited site-preference due to equal positioning of the molecules for loss of the O atom and release of N_2O from the enzyme. Currently, there is scant evidence for sequential binding of NO molecules, but the finding of intramolecular site-preference for ^{15}N in N_2O emitted from fertilized soils suggests that this mechanism does occur (Pérez et al. 2001).

The qNOR enzyme, normally associated with detoxification of NO by pathogenic bacteria, has recently been identified in the genome of *Methylomonas* sp. strain 16a (Ye & Thomas 2001). It is unknown whether qNOR or cNOR is the dominant enzyme in other methanotrophs or chemolithotrophic ammonia-oxidizers, as very little information is available. However, the dominance of qNOR in these bacteria would indicate that their denitrification pathway is present for detoxification rather than for energy generation. Detoxification would likely lead to a greater extent of isotopic fractionation because energy would not have to be conserved at each step in the enzymatic pathway, as is the case for denitrification. Differences in the catalytic mechanism of cNOR and qNOR are unknown, but the different physiological role of these two enzymes in denitrifiers versus nitrifiers may be pivotal in generating isotopic site-preferences.

Obviously, much more work is required to understand how the structure and function of different NOR enzymes within nitrifiers versus denitrifiers may influence the fractionation and site preference of ^{15}N within N_2O molecules. However, if the general enzymatic mechanisms are equivalent among organisms, there would be little difference in enrichment of ^{15}N at either the central or terminal N positions. In this case, only the kinetics and consumption of N_2O as influenced by environmental conditions would discriminate between the pathways.

INFLUENCE OF THE ENVIRONMENT ON NITROGEN TRANSFORMING PATHWAYS

The status of the environment plays an extremely important role along with organism and enzymatic diversity in both the production and amount of isotopic fractionation of N_2O. Among the dominating environmental factors that influence nitrification and denitrification are oxygen availability, which is determined largely by soil moisture; organic carbon versus nitrogen availability; temperature; and pH.

So far, we have divided N_2O production by oxygen availability—nitrification dominates the process in aerobic environments and denitrification dominates in

anaerobic environments. However, there appears to be a continuum in the classes of organisms that lead to N_2O production in particular regions. For example, heterotrophic ammonia-oxidizers express denitrifying enzymes with high activity under aerobic conditions (Anderson et al. 1993, Bell & Ferguson 1991). Denitrification activity in chemolithotrophic ammonia-oxidizers is highest at reduced O_2 tensions (Goreau et al. 1980). The expression of denitrifying enzymes in denitrifying bacteria is only detectable in anaerobically grown cells (Coyne et al. 1990). Based on O_2 availability alone, we now have a situation where different organisms actively denitrify in different regions and, perhaps, at different times. For example, in dryer soils, chemolithotrophic ammonia-oxidizers appear to produce more NO than N_2O, whereas in wet soils, the bulk of N_2O is produced by denitrifiers (Davidson 1993). This situation has been tested by measuring changes in the isotopic composition of emitted N_2O from dry versus wet soils, an indication that the N_2O isotopologue pool changes depending on the strength of nitrifying or denitrifying activities (Pérez et al. 2001).

In addition to O_2 availability, the activities of microbes are also controlled by the availability of nutrients for energy generation. In nitrifying communities, the metabolic activity and population of chemolithotrophic versus heterotrophic ammonia-oxidizers are highly controlled by the carbon to nitrogen ratio (C/N). Chemolithotrophic metabolism dominates in low C/N environments, whereas high C/N stimulates heterotrophic ammonia oxidation (Kuenen & Robertson 1994). Thus, N_2O production in the aerobic to suboxic environment may be controlled by carbon and nitrogen as well as by oxygen availability due to the growth of one population over another. In denitrifying environments, organic carbon and nitrate availability determine whether denitrifiers produce mostly N_2 or N_2O. To further complicate matters, some intermediates in the nitrogen cycle, such as NO_2^- and NO, are highly inhibitory to nitrogen-transforming enzymes, which will influence the population composition and metabolic activity of the community (Averill 1996, Stein & Arp 1998). Thus, a buildup of NO_2^- from ammonia oxidation, which occurs in newly fertilized agricultural fields, may stimulate N_2O production by nitrifiers while inhibiting N_2O production by denitrifiers.

Temperature plays an important but poorly understood role in regulating the flux of N_2O from the environment. In soils, increasing temperatures generally increase the rates of biological activity (Radmer & Kok 1979). This is potentially an extremely important effect because as the mean temperature of Earth increases due to global warming, more greenhouse gases will be released, possibly causing a run-away greenhouse effect (Crutzen 1983). Few studies have shown whether rates of denitrification change in different climatic regions or with imposed changes in temperature, and contradictory results have been described (Powlson et al. 1988, Saad & Conrad 1993). More work is necessary to determine whether temperature is a strong factor in predicting N_2O emissions from the environment.

The pH of the environment may also have an effect on the production of N_2O because NO_2^- chemically decomposes to NO_2 and NO under acidic conditions (Reuss & Smith 1965). The activity of chemolithotrophic ammonia-oxidizers

produces large amounts of acidity, which will influence the pH of their imme-
diate surroundings (Wood 1986). Studies on the effects of pH on the release of
N_2O from soils have indicated that multiple complex interactions that are difficult
to interpret occur between organisms and enzyme populations (Nägele & Conrad
1990). No simple correlations have been found between pH changes and their
effects on N_2O production.

Combinations of environmental, population, and enzymatic effects make quan-
tification of N_2O production by specific bacterial groups very complicated in real-
world systems. We have provided a brief overview of how interactions among all
of these factors work together to produce a pool of N_2O that is likely a combination
of isotopic signatures with bias toward either nitrifying or denitrifying processes.
Environments that are heavily influenced by a few parameters, such as recently
fertilized or irrigated agricultural fields, often have a very strong bias from either
nitrifying or denitrifying processes that can be discerned by relative quantities of
specific N_2O isotopomers and isotopologues (Pérez et al. 2001).

The current challenge for quantifying the global budget of N_2O is to correlate
the biological sources described above with sinks from chemical reactions in the
atmosphere. The remaining portion of this review discusses the predominant sink
of N_2O in the atmosphere, i.e., preferential photolysis of N_2O isotopomers. Addi-
tionally, we present how direct measurements of the isotopic composition of N_2O
from both the biosphere and the stratosphere are furthering the goal of closing the
N_2O budget.

FATE OF N_2O IN THE ATMOSPHERE AND ISOTOPIC FRACTIONATION

Once N_2O is produced and released into the environment, it is removed from the
atmosphere by photodissociation, which accounts for 90% of the total N_2O sink,

$$N_2O + h\nu \rightarrow N_2 + O(^1D). \tag{1}$$
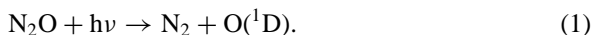
The rest is lost via the photo-oxidation reaction with $O(^1D)$, an excited state of the
O atom derived from photolysis of O_3,

$$N_2O + O(^1D) \rightarrow 2NO \tag{2a}$$

$$\rightarrow N_2 + O_2 \tag{2b}$$

Both Reactions 1 and 2 primarily take place in the stratosphere, resulting in a
mean lifetime of over 100 years for N_2O. Reaction 2a is the major source of odd
nitrogen (NO_x) to the stratosphere and plays a fundamental role in regulating the
ozone layer (e.g., Logan et al. 1978, Wennberg et al. 1994). Figure 7 shows the
distribution of N_2O in the atmosphere for four representative months computed by
the Caltech/JPL two-dimensional (2-D) model of the terrestrial atmosphere (Yung
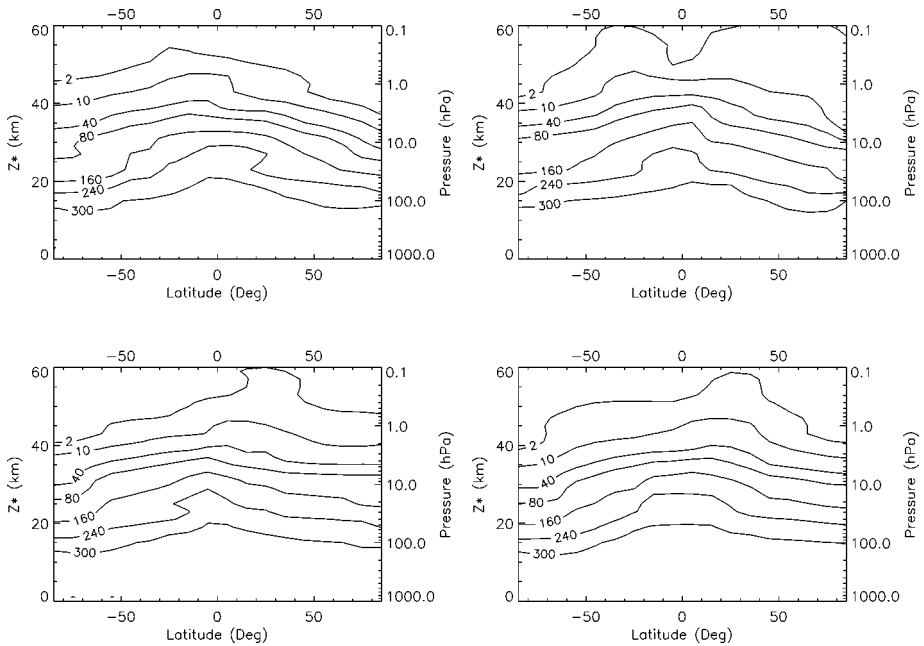& Miller 1997). The surface concentration was set to 300 ppb. N_2O is well mixed

Figure 7 Mixing ratio of N_2O in the atmosphere computed by the Caltech/JPL 2-D model of the terrestrial atmosphere: (*a*) January, (*b*) April, (*c*) July, and (*d*) October. The units are ppb. The surface mixing of N_2O is 300 ppb in the model. The pressure (P) in hPa refers to the left axis. The altitude (Z*) is defined by $Z^* = 6.948712$ km $\times \log_{10}(1000/P)$ and can be regarded as an approximate altitude.

in the troposphere because of its long lifetime. The decrease in mixing ratio in the stratosphere is the result of the aforementioned reactions, and is borne out by measurements (e.g., Gunson et al. 1990). The bulge in the contours in the tropics is due to the upwelling of tropospheric air that is rich in N_2O. The low mixing ratios in the polar stratosphere are due to the downwelling of upper stratospheric air that is depleted in N_2O. The exchange of air between the troposphere and the stratosphere is known as the Brewer-Dobson circulation (Holton et al. 1995). This circulation is strongest in the winter hemisphere, and its effects on N_2O are evident in the north (south) polar stratosphere in January (July). The model results shown in Figure 7 are consistent with measurements obtained by the Upper Atmosphere Research Satellite (UARS) (Kumer et al. 1993). Version 9 of the UARS data for N_2O is currently available at the Goddard DAAC for the period October 25, 1991 to May 5, 1993 from 20 to 50 km. For details, refer to the website http://www.lmsal.com/9120/CLAES/.

Following the discovery of the N_2O isotopic anomaly by Kim & Craig (1993), Johnston et al. (1995) attempted to verify the suggestion that stratospheric

chemistry results in N_2O isotopic fractionation. Yung & Miller (1997) proposed a
wavelength-dependent mechanism for the photolytic fractionation of N_2O based
on subtle shifts in the zero point energy with isotopic substitution. For example,
substituting ^{18}O for ^{16}O results in a calculated zero point energy blue shift for the
heavier isotopologue of -27.5 cm^{-1}. Analogous to determining the kinetic frac-
tionation for a chemical reaction, the photolytic fractionation factor will be equal
to the ratio of the heavy-to-light photolysis rates and thus to the ratio of the cross
sections. For N_2O, the theoretical enrichment factors can be calculated analytically
as a function of wavelength using the spectral function of Selwyn et al. (1977) and
the Yung & Miller (1997) model was able to match, at least qualitatively, the
observed enrichments of both ^{15}N and ^{18}O.

Photolysis experiments investigating the validity of the Yung & Miller (1997)
theory were performed by several different research teams (Rahn et al. 1998,
Röckmann et al. 2000, Turatti et al. 2000, Zhang et al. 2000). The data are clearly
consistent with a simple Rayleigh fractionation model, and the trend of the heavy
isotope enrichment with wavelength was consistent with that predicted by Yung
& Miller (1997). It was observed that enrichments of ^{15}N to ^{18}O yields ratios
were slightly greater than unity at wavelengths close to the effective, or mean,
stratospheric photolysis wavelength of 205 nm. This is nearly identical to the ratio
of the enrichments observed in Rahn & Wahlen (1997) and close to that predicted
in Figure 2 of Yung & Miller (1997); it supports the hypothesis that photolysis is
the principal mechanism responsible for the observed stratospheric enrichments
and that the standard model of stratospheric N_2O chemistry is essentially complete.
Turatti et al. (2000) and Zhang et al. (2000) observed that the fractionation rate
for the $^{14}N^{15}N^{16}O$ isotopomer was greater than the rate for the $^{15}N^{14}N^{16}O$, as
predicted by the Yung & Miller (1997) hypothesis. However, the magnitudes of
the experimentally determined enrichments were all found to be much greater than
that predicted by YM97 Yung & Miller (1997). For example, the ^{18}O fractionation
at 207.6 nm was found to be -46.0 per mil, more than twice that predicted by
Yung & Miller (1997).

Theoretical efforts to extend photodestruction-induced isotopic fractionation to
include other aspects of photolysis have been done by Johnson et al. (2001) and
Blake et al. (2002). Factors other than ZPE that affect isotopic fractionation in-
clude the contribution of vibrationally excited N_2O in the ground electronic state,
the transition dipole moment, and the shape of the ground-state wavefunction. Be-
cause the electronically excited state of N_2O is bent, vibrational excitation of N_2O
in the ground electronic state leads to better Franck-Condon overlap and a larger
contribution to the overall absorption profile. This would lead to a temperature
dependence on isotopomer fractionation. Changes in the vibrational wavefunction
causes the absorption profile to narrow, especially for N_2O in the 200–215-nm
region, the critical region for photolysis in the stratosphere. Johnson et al. (2001),
using time-dependent Hermite propagation, can reproduce the laboratory results
of enrichment for all of the isotopomers with the exception of the $^{15}N^{14}N^{16}O$ iso-
topomer. Blake et al. (2002) have taken a simpler, semi-empirical approach to

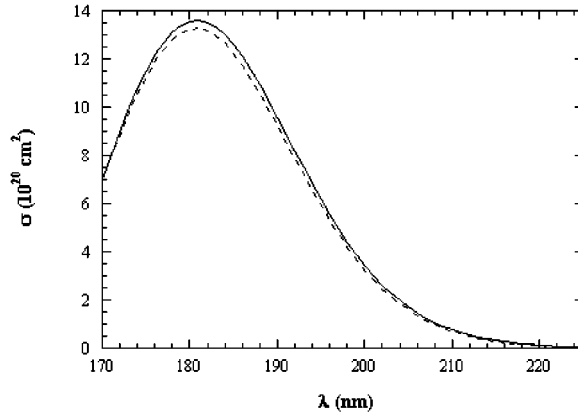**Figure 8**   Absorption cross-sections of N_2O isotopo-
logues in the UV: $^{14}N^{14}N^{16}O$ (*solid line*) and $^{14}N^{15}N^{16}O$
(*dashed line*). The units are 10^{-20} cm^2.

the theoretical calculation of enrichment factors, and the method has been able
to reproduce stratospheric observations of N_2O fractionation in the stratosphere.
Figure 8 shows a comparison for the absorption cross-section for the most abun-
dant isotopologue $^{14}N^{14}N^{16}O$ (*solid line*) and the minor isotopologue $^{14}N^{15}N^{16}O$
(*dashed line*). The heavier isotopomer has a slightly smaller cross-section, re-
sulting in less destruction by photolysis and its enrichment relative to the main
isotopologue.

Although Reaction 2 accounts for only 10% of the overall destruction of N_2O in
the atmosphere (Reaction 1 is the primary sink), in the lower stratosphere (below
22 km) it is actually more important than photolysis. The fractionation in this
reaction has recently been measured by Kaiser & Brenninkmeijer (2002), and can
be expressed as:

$$\alpha = k_5 \text{ (isotopologue)}/k_5\text{(standard)}. \qquad (3)$$

The laboratory measurements give $\alpha_{456} - 1$, $\alpha_{546} - 1$, and $\alpha_{448} - 1$ as -8.87,
-2.22, and -12.38 per mil, respectively, where pqr is a shorthand for an iso-
topologues of N_2O, $^1P N^{1q} N^{1r} O$.

The isotopic fractionation due to Reactions 1–3 were incorporated in a recent
study using the Caltech/JPL 2-D model (Morgan et al. 2002). The results for
January are shown in Figure 9a–d for $\delta^{18}O$, $\delta^{17}O$, $\delta^{15}N^\alpha$, and $\delta^{15}N^\beta$, respectively.
There is little fractionation in the troposphere. The bulk of the isotopic fractionation
takes place in the stratosphere and the δ values can reach as high as 100 per mil
in the upper stratosphere. Model results above 40 km must be taken with caution,
as the mixing ratio of N_2O rapidly approaches zero (see Figure 7). Note that the
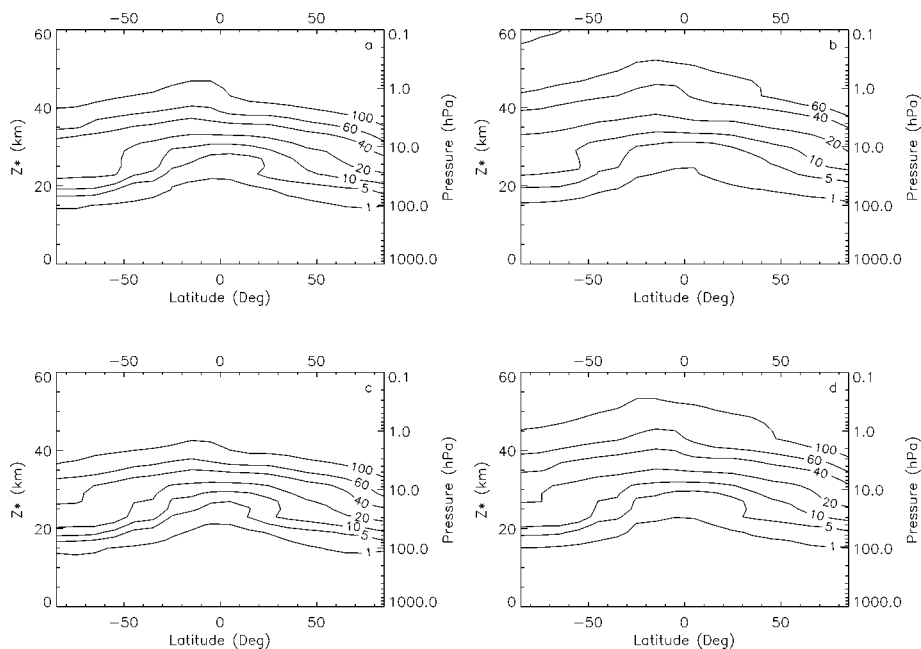destruction of N_2O in the stratosphere results in the enrichment of the heavier

Figure 9 Isotopic fractionation of N_2O due to Reactions 1 and 2 in the atmosphere as computed by the Caltech/JPL 2-D model: (*a*) $\delta^{18}O$, (*b*) $\delta^{17}O$, (*c*) $\delta^{15}N^{\alpha}$, and (*d*) $\delta^{15}N^{\beta}$.

isotopologues. Therefore, the stratosphere is a source of isotopically heavy N_2O, as first pointed out in the insightful analysis of Kim & Craig (1993). The globally and seasonally averaged fractionation due to atmospheric chemistry for $\delta^{18}O$, $\delta^{17}O$, $\delta^{15}N^{\alpha}$, and $\delta^{15}N^{\beta}$ are 14.5, 6.4, 20.0, and 9.8, respectively. If we do not distinguish between $\delta^{15}N^{\alpha}$ and $\delta^{15}N^{\beta}$ (as in a mass spectrometer), we can define a mean $\delta^{15}N = (\delta^{15}N^{\alpha} + \delta^{15}N^{\beta})/2 = 14.9$. The quantitative determination of these fractionation values will now allow an estimation of the mean isotopic composition of the sources of N_2O.

MEASURING N_2O ISOTOPOLOGUES AND ISOTOPOMERS TO QUANTIFY INDIVIDUAL SOURCES AND SINKS OF N_2O

Given the large uncertainties in estimates for sources of N_2O, as shown in Table 1, it is natural to ask whether the isotopic composition of the sources can pose useful constraints. As pointed out earlier, the combination of quantifying the isotopic composition of atmospheric N_2O along with the modeling of isotopic fractionation due to reactions in the atmosphere allows us to estimate the isotopic composition of the source. The results are summarized in Figure 10, in which the mean atmospheric
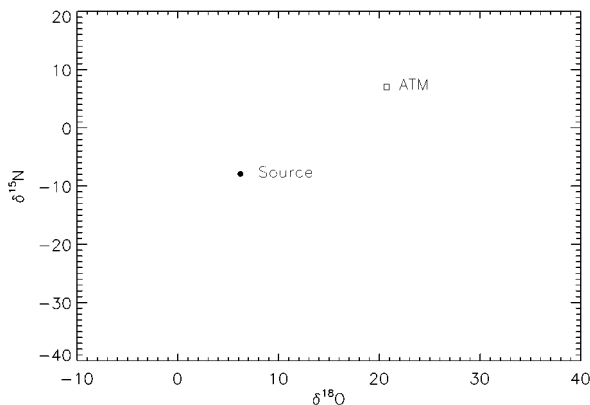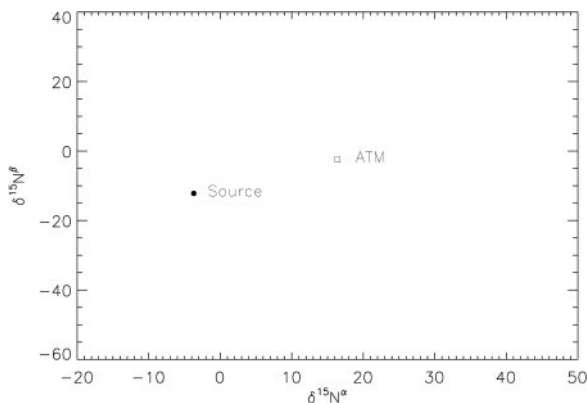
Figure 10   Isotopic composition of N_2O: Square = average of atmospheric composition, dot = average of all sources.

isotopic composition is given by the square and the mean source is given by the dark dot. The source must be lighter than the atmosphere because of the enrichment of the heavy isotopes in the destruction processes in the stratosphere. Thus, the best estimate for the average isotopic composition of N_2O is given by $\delta^{18}O = 7$ per mil and $\delta^{15}N = -7.5$ per mil. Referring to Figure 4, the above results imply that the ocean could not be a major source of N_2O. Additional information is available if we distinguish between $\delta^{15}N^\alpha$ and $\delta^{15}N^\beta$. Figure 11 summarizes recent measurements of $\delta^{15}N^\alpha$ and $\delta^{15}N^\beta$.
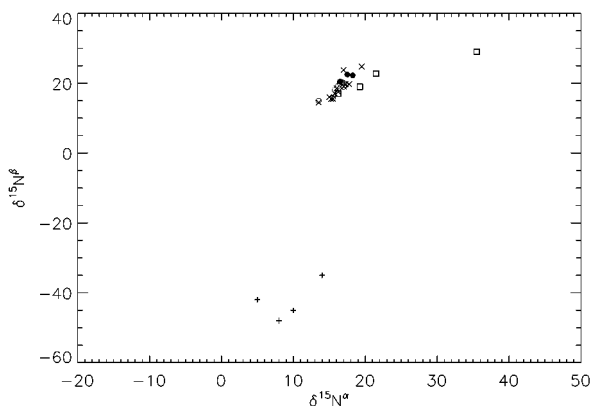
Figure 11   Isotopic composition of positional N_2O in the troposphere, stratosphere, soil, and ocean. ● from Yoshinari et al. 1997; ○, × from Yoshida & Toyoda 2000; and + from Pérez et al. 2001.

Figure 12 Isotopic composition of positional N_2O: Square = average of atmospheric composition, dot = average of all sources.

The average atmospheric and the implied source composition are shown in Figure 12. The characteristic values of $\delta^{15}N^\alpha$ and $\delta^{15}N^\beta$ should provide powerful further constraints on the sources. For example, the average source must have a small positive $\delta^{15}N^\alpha$ but a large negative $\delta^{15}N^\beta$. Isotopic measurements of N_2O from fertilized agricultural soils are consistent with this constraint (Pérez et al. 2001). In a perceptive analysis, Rahn & Wahlen (2000) pointed out that the isotopic budget evolved with time, implying that N_2O is generated from a biological source. Their simple model predicted a decrease in $\delta^{18}O$ and $\delta^{15}N$ of about 1.6 and 1.8 per mil, respectively, since the Industrial Revolution. Preliminary results from ice cores appear to support this simple model (T. Röckmann, unpublished data).

CONCLUDING REMARKS

Judging from the current datasets for global sources of N_2O (Table 1), biological processes contribute by far the most N_2O to the atmosphere relative to purely industrial sources. Additions of nitrogen to the environment, especially in agricultural and wet soils, greatly stimulate the microbial nitrogen cycle leading to large-scale production and emission of nitrogen oxide intermediates (based on gas production per unit area). This review has presented the current understanding of how microorganisms produce N_2O and the various biological and environmental factors that control nitrogen cycling processes. We are now closer than ever to understanding how different microorganisms produce different ratios of N_2O isotopologues and isotopomers. It is also evident that further study must be accomplished from enzymological to landscape ecology scales to fully appreciate and quantify discrete sources of N_2O.

A most-powerful method for characterizing the sources of N_2O lies in its multi-isotope signature. It is now known that (*a*) the major land biospheric sources of N_2O are light in both ^{15}N and ^{18}O, relative to tropospheric N_2O; (*b*) stratospheric loss of N_2O results in enriching both ^{15}N and ^{18}O; and (*c*) there is a large "back flux" of heavy N_2O from the stratosphere to the troposphere. Therefore, if we could compute (*c*) accurately in an atmospheric model, we could have a constraint on the isotopic composition of the biological source. By assigning production of specific isotopomers and isotopologes of N_2O to different microbial groups, and by quantifying the rates of photolysis of specific N_2O pools, we are determining the conditions for N_2O production in the biosphere and tracing its fate in the atmosphere.

The combination of knowledge from both biological and atmospheric sciences is rapidly leading to a tightened global budget for N_2O. The information from this collaboration will greatly improve international efforts to stem the continued accumulation N_2O to the atmosphere by expanding and encompassing the scientific view from molecular to global levels.

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LITERATURE CITED

Anderson IC, Poth M, Homstead J, Burdige D. 1993. A comparison of NO and N_2O production by the autotrophic nitrifier *Nitrosomonas europaea* and the heterotrophic nitrifier *Alcaligenes faecalis*. *Appl. Environ. Microbiol.* 59:3525–33

Auman AJ, Speake CC, Lidstrom ME. 2001. *nifH* sequences and nitrogen fixation in Type I and Type II methanotrophs. *Appl. Environ. Microbiol.* 67:4009–16

Averill BA. 1996. Dissimilatory nitrite and nitric oxide reductases. *Chem. Rev.* 96:2951–64

Barford CC, Montoya JP, Altabet MA, Mitchell R. 1999. Steady-state nitrogen isotope effects of N_2 and N_2O production of *Paracoccus denitrificans*. *Appl. Environ. Microbiol.* 65:989–94

Battle M, Bender M, Sowers T, Tans PP, Butler JH, et al. 1996. Atmospheric gas concentrations over the past century measured in air from firn at South Pole. *Nature* 383:231–35

Baumgärtner M, Conrad R. 1992. Role of nitrate and nitrite for production and consumption of nitric oxide during denitrification in soil. *FEMS Microb. Ecol.* 101: 59-65

Baumgärtner M, Koschorreck M, Conrad R. 1996. Oxidative consumption of nitric oxide by heterotrophic bacteria in soil. *FEMS Microbiol. Ecol.* 19:165–70

Beaumont HJE, Hommes NG, Sayavedra-Soto LA, Arp DJ, Arciero DM, et al. 2002. Nitrite reductase of *Nitrosomonas europaea* is not essential for production of gaseous nitrogen oxides and confers tolerance to nitrite. *J. Bacteriol.* 184:2557–60

Beaumont VI, Jahnke LL, Des Marais DJ. 2000. Nitrogen isotopic fractionation in the synthesis of photosynthetic pigments in

Rhodobacter capsulatus and *Anabaena cylindrica. Org. Geochem.* 31:1075–85

Bell LC, Ferguson SJ. 1991. Nitric oxide and nitrous oxide reductases are active under aerobic conditions in cells of *Thiosphaera pantotropha. Biochem. J.* 273:423–27

Blake GA, Liang NC, Morgan CG, Yung YL. 2002. Photolytic fractionation of stratospheric nitrous oxide. *EOS Trans. Am. Geophys. Union* 83:48

Bock E. 1995. Nitrogen loss caused by denitrifying *Nitrosomonas* cells using ammonium or hydrogen as electron donors and nitrite as electron acceptor. *Arch. Microbiol.* 163:16–20

Bock E, Koops H-P. 1991. The genus *Nitrobacter* and related genera. In *The Prokaryotes*, ed. K-H Schleifer, pp. 2302–9. New York: Springer-Verlag

Brittain T, Blackmore R, Greenwood C, Thomson AJ. 1992. Bacterial nitrite-reducing enzymes. *Eur. J. Biochem.* 209:793–802

Butler JH, Montzka SA, Clarke AD, Lobert JM, Elkins JW. 1998. Nitrous oxide and halocompounds. In *Climate Monitoring and Diagnostics Laboratory Summary Report No. 24, 1996–1997*, eds. DJ Hofmann, JT Peterson and RM Rosson, pp. 91–121. Boulder, CO: NOAA

Casciotti K, Rahn T, Wahlen M. 1997. Stable isotopes of N and O in nitrous oxide emissions from fertilized soils. *EOS Trans. Am. Geophys. Union* 78:F58 (Fall Meet. Suppl.)

Casciotti KL, Ward BB. 2001. Dissimilatory nitrite reductase genes from autotrophic ammonia-oxidizing bacteria. *Appl. Environ. Microbiol.* 67:2213–21

Castignetti D, Yanong R, Gramzinski R. 1984. Heterotrophic nitrification among denitrifiers. *Appl. Environ. Microbiol.* 47:620–23

Cleland WW, O'Leary MH, Northrop DB, eds. 1977. *Isotope Effects on Enzyme-Catalyzed Reactions: Proceedings of the Sixth Annual Harry Steenbock Symposium.* Baltimore, MD: Univ. Park Press

Colliver BB, Stephenson T. 2000. Production of nitrogen oxide and dinitrogen oxide by autotrophic nitrifiers. *Biotech. Adv.* 18:219–32

Conrad R. 1996. Soil microorganisms as controllers of atmospheric trace gases (H_2, CO, CH_4, OCS, N_2O, and NO). *Microbiol. Rev.* 60:609–40

Coyne MS, Arunakumari A, Averill BA, Tiedje JM. 1989. Immunological identification and distribution of dissimilatory heme cd_1 and nonheme copper nitrite reductases in denitrifying bacteria. *Appl. Environ. Microbiol.* 55:2924–31

Coyne MS, Arunakumari A, Pankratz HS, Tiedje JM. 1990. Localization of the cytochrome cd_1 and copper nitrite reductases in denitrifying bacteria. *J. Bacteriol.* 172:2558–62

Craig H. 1961. Standard for reporting concentrations for deuterium and oxygen-18 in natural waters. *Science* 133:1833–34

Crutzen PJ. 1983. Atmospheric interactions. Homogeneous gas reactions of C, N, and S containing compounds. In *The Major Biogeochemical Cycles and their Interactions, SCOPE 21*, ed. RB Cook, pp. 67–114. New York: Wiley

Cutruzzolà F. 1999. Bacterial nitric oxide synthesis. *Biochim. Biophys. Acta* 1411:231–49

Dalton H. 1977. Ammonia oxidation by the methane oxidising bacterium *Methylococcus capsulatus* strain Bath. *Arch. Microbiol.* 114:273–79

Davidson EA. 1993. Soil water content and the ratio of nitrous oxide and nitric oxide emitted from soil. In *Biogeochemistry of Global Change Radiatively Active Trace Gases: Selected Papers from the Tenth International Symposium on Environmental Biogeochemistry, San Francisco, August 19–24, 1991*, ed. RS Oremland, pp. 369–86. New York: Chapman Hall

Dore JE, Popp BN, Karl DM, Sansone FJ. 1998. A large source of atmospheric nitrous oxide from subtropical North Pacific surface waters. *Nature* 396:63–66

Flückiger J, Dällenbach A, Blunier T, Stauffer B, Stocker TF, et al. 1999. Variations in atmospheric N_2O concentration during abrupt climatic changes. *Science* 285:227–30

Freitag A, Bock E. 1990. Energy conservation

in *Nitrobacter*. *FEMS Microbiol. Lett.* 66: 157–62

Freitag A, Rudert M, Bock E. 1987. Growth of *Nitrobacter* by dissimilatoric nitrate reduction. *FEMS Microbiol. Lett.* 48:105–9

Garber EAE, Hollocher TC. 1982a. ^{15}N, ^{18}O tracer studies on the activation of nitrite by denitrifying bacteria. *J. Biol. Chem.* 257: 8091–97

Garber EAE, Hollocher TC. 1982b. Positional isotopic equivalence of nitrogen in N_2O produced by the denitrifying bacterium *Pseudomonas stutzeri*. *J. Biol. Chem.* 257:4705–8

Gaskell JF, Blackmer AM, Bremner JM. 1981. Comparison of effects of nitrate, nitrite, and nitric oxide on reduction of nitrous oxide to dinitrogen by soil microorganisms. *Soil Sci. Soc. Am. J.* 45:1124–27

Goody RM, Yung YL. 1989. *Atmospheric Radiation: Theoretical Basis*. New York: Oxford Univ. Press

Goreau TJ, Kaplan WA, Wofsy SC, McElroy MB, Valois FW, Watson SW. 1980. Production of NO_2^- and N_2O by nitrifying bacteria at reduced concentrations of oxygen. *Appl. Environ. Microbiol.* 40:526–32

Gunson MR, Farmer CB, Norton RH, Zander R, Rinsland CP, et al. 1990. Measurements of CH_4, N_2O, CO, H_2O, and O_3 in the middle atmosphere by the atmospheric trace molecule spectroscopy experiment on SPACELAB-3. *J. Geophys. Res.-Atmos.* 95(D9):13867–82

Hendriks J, Oubrie A, Castresana J, Urbani A, Gemeinhardt S, Saraste M. 2000. Nitric oxide reductases in bacteria. *Biochim. Biophys. Acta* 1459:266–73

Hochstein LI, Tomlinson GA. 1988. The enzymes associated with denitrification. *Annu. Rev. Microbiol.* 42:231–61

Hoering TC, Ford HT. 1960. The isotope effect in the fixation of nitrogen by *Azotobacter*. *J. Am. Chem. Soc.* 82:376–78

Holmes AJ, Costello A, Lidstrom ME, Murrell JC. 1995. Evidence that particulate methane monooxygenase and ammonia monooxygenase may be related. *FEMS Microbiol. Lett.* 132:203–8

Holton JR, Haynes PH, McIntyre ME, Douglass

AR, Rood RB, Pfister L. 1995. Stratosphere-troposphere exchange. *Rev. Geophys.* 33: 403–39

Hooper AB. 1968. A nitrite-reducing enzyme from *Nitrosomonas europaea*. Preliminary characterization with hydroxylamine as electron donor. *Biochim. Biophys. Acta* 162:49–65

Hooper AB, Terry KR. 1979. Hydroxylamine oxidoreductase of *Nitrosomonas*, production of nitric oxide from hydroxylamine. *Biochim. Biophys. Acta.* 571:12–20

Howarth RW, Billen G, Swaney D, Townsend A, Jaworski N, et al. 1996. Regional nitrogen budgets and riverine N&P fluxes for the drainages to the North Atlantic Ocean: natural and human influences. *Biogeochemistry* 35:75–139

IPCC. 2001. *Climate Change 2001: The Scientific Basis*. Cambridge, UK: Cambridge Univ. Press

IUPAC. 1997. *Compendium of Chemical Terminology, 2nd Edition*. Boston: Blackwell Sci.

Jetten MSM, Wagner M, Fuerst J, van Loosdrecht M, Kuenen G, Strous M. 2001. Microbiology and application of the anaerobic ammonium oxidation ('anammox') process. *Curr. Opin. Biotech.* 12:283–88

Johnson MS, Billing GD, Gruodis A, Janssen MHM. 2001. Photolysis of nitrous oxide isotopomers studied by time-dependent hermite propagation. *J. Phys. Chem. A* 105:8672–80

Johnston JC, Cliff SS, Thiemens MH. 1995. Measurement of multioxygen isotopic (δ-O^{18} and δ-O^{17}) fractionation factors in the stratospheric sink reactions of nitrous oxide. *J. Geophys. Res.-Atmos.* 100(D8):16801–4

Killham K. 1986. Heterotrophic nitrification. In *Nitrification*, ed. JI Prosser, pp. 117–26. Oxford: IRL

Kim K-R, Craig H. 1990. Two-isotope characterization of N_2O in the Pacific Ocean and constraints on its origin in deep water. *Nature* 347:58–61

Kim K-R, Craig H. 1993. Nitrogen-15 and oxygen-18 characteristics of nitrous oxide: a global perspective. *Science* 262:1855–57

Kizawa H, Tomura D, Oda M, Fukamizu A,

Hoshino T, et al. 1991. Nucleotide sequence of the unique nitrate nitrite-inducible cytochrome P-450 cDNA from *Fusarium oxysporum*. *J. Biol. Chem.* 266:10632–37

Knowles R, Topp E. 1988. Some factors affecting nitrification and the production of nitrous oxide by the methanotrophic bacterium *Methylosinus trichosporium* OB3b. In *Current Perpectives in Environmental Biogeochemistry*, ed. P Nannipieri, pp. 383–93. Rome: Consiglione delle Richerche-I.P.R.A.

Kobayashi M, Shoun H. 1995. The copper-containing dissimilatory nitrite reductase involved in the denitrifying system of the fungus *Fusarium oxysporum*. *J. Biol. Chem.* 270:4146–51

Kowalchuk GA, Stephen JR, DeBoer W, Prosser JI, Embley TM, Woldendorp JW. 1997. Analysis of ammonia-oxidizing bacteria of the β subdivision of the class *Proteobacteria* in coastal sand dunes by denaturing gradient gel electrophoresis and sequencing of PCR-amplified 16S ribosomal DNA fragments. *Appl. Environ. Microbiol.* 63:1489–97

Krämer M, Baumgärtner M, Bender M, Conrad R. 1990. Consumption of NO by methanotrophic bacteria in pure culture and in soil. *FEMS Microbiol. Ecol.* 73:345–50

Kroeze C. 1999. Closing the global N_2O budget: a retrospective analysis 1500–1994. *Global Biogeochem. Cycles* 13:1–8

Kuenen JG, Robertson LA. 1994. Combined nitrification-denitrification processes. *FEMS Microbiol. Rev.* 15:109–17

Kumer JB, Mergenthaler JL, Roche AE. 1993. CLAES CH_4, N_2O, and CCl_2F_2 global data. *Geophys. Res. Lett.* 20:1239–42

Langenfields RL, Fraser PJ, Francey RJ, Steele LP, Porter LW, Allison CE. 1996. The cape grim air archive: the first seventeen years. In *Baseline Atmospheric Program Australia, 1994–95*, eds. RJ Francey, AL Dick and N Derek, pp. 53–70. Melbourne: Bur. Meteorol./CSIRO Div. Atmos. Res.

Lin JT, Stewart V. 1998. Nitrate assimilation by bacteria. *Adv. Microb. Physiol.* 39:1–30

Lipschultz F, Zafiriou OC, Wofsy SC, McElroy MB, Valois FW, Watson SW. 1981. Production of NO and N_2O by soil nitrifying bacteria. *Nature* 294:641–43

Logan JA, Prather MJ, Wofsy SC, McElroy MB. 1978. Global budgets for carbon-monoxide and nitrogen-oxides. *EOS Trans. Am. Geophys. Union* 59:1076

Machida T, Nakazawa T, Fujii Y, Aoki S, Watanabe O. 1995. Increase in the atmospheric nitrous oxide concentration during the last 250 years. *Geophys. Res. Lett.* 22:2921–24

Mandernack KW, Kinney CA, Coleman D, Huang Y-S, Freeman KH, Bogner J. 2000. The biogeochemical controls of N_2O production and emission in landfill cover soils: the role of methanotrophs in the nitrogen cycle. *Environ. Microbiol.* 2:298–309

Minschwaner KR, Carver RW, Briegleb BP, Roche AE. 1998. Infrared radiative forcing and atmospheric lifetimes of trace species based on observations from UARS. *J. Geophys. Res.* 103:23243–53

Moir JWB, Crossman LC, Sprio S, Richardson DJ. 1996. The purification of ammonia monooxygenase from *Paracoccus denitrificans*. *FEBS Lett.* 387:71–74

Morgan CG, Yung YL, Allen MA, Blake GA, Liang NC. 2002. Isotopic fractionation of atmospheric nitrous oxide. *EOS Trans. Am. Geophys. Union* 83:47

Mosier AR, Kroeze C. 1998. A new approach to estimate emissions of nitrous oxide from agriculture and its implications to the global N_2O budget. *Glob. Change Newsl.* 34:8–14

Mosier AR, Kroeze C, Nevison CD, Oenema O, Seitzinger S, van Cleemput O. 1998. Closing the global N2O budget: nitrous oxide emissions through the agricultural nitrogen cycle-OECD/IPCC/IEA phase II development of IPCC guidelines for national greenhouse gas inventory methodology. *Nutr. Cycl. Agroecosyst.* 52:225–48

Nägele W, Conrad R. 1990. Influence of pH on the release of NO and N_2O from fertilized and unfertilized soil. *Biol. Fertil. Soils* 10:139–44

Nakano MM, Hoffmann T, Zhu Y, Jahn D. 1998.

Nitrogen and oxygen regulation of *Bacillus subtilis nasDEF* encoding NADH-dependent nitrite reductase by TnrA and ResDE. *J. Bacteriol.* 180:5344–50

Naqvi SWA, Yoshinari T, Jayakumar DA, Altabet MA, Narvekar PV, et al. 1998. Budgetary and biogeochemical implications of N_2O isotope signatures in the Arabian Sea. *Nature* 394:462–64

Nevison C, Holland E. 1997. A reexamination of the impact of anthropogenically fixed nitrogen on atmospheric N_2O and the stratospheric O_3 layer. *Geophys. Res. Lett.* 102:25519–36

Olivier JGJ, Bouwman AF, van der Hoek KW, Berdowski JJM. 1998. Global air emission inventories for anthropogenic sources of NOx, NH_3, and N_2O in 1990. *Environ. Poll.* 102:135–48

Olsen S, McLinden C, Prather M. 2001. Stratospheric N2O-NOy system: testing uncertainties in a three-dimensional framework. *J. Geophys. Res.-Atmos.* 106(D22):28771–84

Pérez T, Trumbore SE, Tyler SC, Davidson EA, Keller M, de Camargo PB. 2000. Isotopic variability of N_2O emissions from tropical forest soils. *Glob. Biogeochem. Cycl.* 14:525–35

Pérez T, Trumbore SE, Tyler SC, Matson PA, Ortiz-Monasterio I, et al. 2001. Identifying the agricultural imprint on the global N_2O budget using stable isotopes. *J. Geophys. Res.* 106:9869–78

Postgate JR. 1998. *Nitrogen Fixation*. New York: Cambridge Univ. Press

Powlson DS, Saffigna PG, Kragt-Cottaar M. 1988. Denitrification at sub-optimal temperatures in soils from different climatic zones. *Soil Biol. Biochem.* 20:719–23

Prosser JI, ed. 1986. *Nitrification*, Vols. 20. Washington, DC: IRL. 219 pp.

Prosser JI. 1989. Autotrophic nitrification in bacteria. *Adv. Microb. Physiol.* 30:125–77

Radmer RJ, Kok B. 1979. Rate-temperature curves as an unambiguous indicator of biological activity in soil. *Appl. Environ. Microbiol.* 38:224–28

Rahn T, Wahlen M. 1997. Stable isotope enrichment in stratospheric nitrous oxide. *Science* 278:1776–78

Rahn T, Wahlen M. 2000. A reassessment of the global isotopic budget of atmospheric nitrous oxide. *Glob. Biogeochem. Cycl.* 14:537–43

Rahn T, Zhang H, Wahlen M, Blake GA. 1998. Stable isotope fractionation during ultraviolet photolysis of N_2O. *Geophys. Res. Lett.* 25:4489–92

Rasmussen T, Berks BC, Sanders-Loehr J, Dooley DM, Zumft WG, Thomson AJ. 2000. The catalytic center in nitrous oxide reductase, Cu-z, is a copper-sulfide cluster. *Biochem.* 39:12753–56

Remde A, Conrad R. 1990. Production of nitric oxide in *Nitrosomonas europaea* by reduction of nitrite. *Arch. Microbiol.* 154:187–91

Reuss JO, Smith RL. 1965. Chemical reaction of nitrites in acid soils. *Soil Sci. Soc. Am. Proc.* 29:267–70

Richardson DJ, Watmough NJ. 1999. Inorganic nitrogen metabolism in bacteria. *Curr. Opin. Chem. Biol.* 3:207–19

Röckmann TC, Brenninkmeijer AM, Wollenhaupt M, Crowley JN, Crutzen PJ. 2000. Measurement of the isotopic fractionation of $^{15}N^{14}N^{16}O$, $^{14}N^{15}N^{16}O$, and $^{14}N^{14}N^{18}O$ in the UV photolysis of nitrous oxide. *Geophys. Res. Lett.* 27:1399–402

Saad OALO, Conrad R. 1993. Temperature dependence of nitrification, denitrification, and turnover of nitric oxide in different soils. *Biol. Fertil. Soils* 15:21–27

Selwyn G, Podolske JR, Johnston HS. 1977. Nitrous oxide ultraviolet absorption spectrum at stratospheric temperatures. *Geophys. Res. Lett.* 4:427–30

Shiro Y, Fujii M, Iizuka T, Adachi S, Tsukamoto K, et al. 1995. Spectroscopic and kinetic studies on reaction of cytochrome P450nor with nitric oxide. *J. Biol. Chem.* 270:1617–23

Steele LP, Langenfields RL, Lucarelli MP, Fraser PJ, Cooper LN, et al. 1996. Atmospheric methane, carbon dioxide, carbon monoxide, hydrogen, and nitrous oxide from Cape Grim air samples analysed by gas chromatography. In *Baseline Atmospheric Program Australia, 1994-95*, ed. N Derek, pp. 107–10.

Melbourne: Bur. Meteorol./CSIRO Div. Atmos. Res.

Stein LY, Arp DJ. 1998. Loss of ammonia monooxygenase activity in *Nitrosomonas europaea* upon exposure to nitrite. *Appl. Environ. Microbiol.* 64:4098–102

Straub KL, Benz M, Schink B, Widdel F. 1996. Anaerobic, nitrate-dependent microbial oxidation of ferrous iron. *Appl. Environ. Microbiol.* 62:1458–60

Thamdrup B, Dalsgaard T. 2002. Production of N_2 through anaerobic ammonium oxidation coupled to nitrite reduction in marine sediments. *Appl. Environ. Microbiol.* 68:1312–18

Turatti F, Griffith DWT, Wilson SR, Esler MB, Rahn T, et al. 2000. Positionally dependent 15N factors in the UV photolysis of N_2O determined by high resolution FTIR spectroscopy. *Geophys. Res. Lett.* 27:2489–92

Verstraete W. 1975. Heterotrophic nitrification in soils and aqueous media. *Izvest. Akad. Nauk SSSR Ser. Biol.* 4:541–58

Webster EA, Hopkins DW. 1996. Nitrogen and oxygen isotope ratios of nitrous oxide emitted from soil and produced by nitrifying and denitrifying bacteria. *Biol. Fertil. Soils* 22:326–30

Weeg-Aerssens E, Tiedje JM, Averill BA. 1988. Evidence from isotope labeling studies for a sequential mechanism for dissimilatory nitrite reduction. *J. Am. Chem. Soc.* 110:6851–56

Wehrfritz J-M, Reilly A, Spiro S, Richardson DJ. 1993. Purification of hydroxylamine oxidase from *Thiosphaera pantotropha*: Identification of electron acceptors that couple heterotrophic nitrification to aerobic denitrification. *FEBS Lett.* 335:246–50

Wennberg PO, Cohen RC, Stimpfle RM, Koplow JP, Anderson JG, et al. 1994. Removal of stratospheric O_3 by radicals—*in situ* measurements of OH, HO_2, NO, NO_2, ClO, and BrO. *Science* 266:398–404

Whittaker M, Bergmann D, Arciero D, Hooper AB. 2000. Electron transfer during the oxidation of ammonia by the chemolithotrophic bacterium *Nitrosomonas europaea*. *Biochim. Biophys. Acta* 1459:346–55

Wood PM. 1986. Nitrification as a bacterial energy source. In *Nitrification*, ed. JI Prosser, pp. 39–62. Oxford, UK: Soc. Gen. Microbiol, IRL

Ye RW, Thomas SM. 2001. Microbial nitrogen cycles: physiology, genomics and applications. *Curr. Opin. Microbiol.* 4:307–12

Yoshida N. 1988. ^{15}N-depleted N_2O as a product of nitrification. *Nature* 335:528–29

Yoshida N, Toyoda S. 2000. Constraining the atmospheric N2O budget from intramolecular site preference in N2O isotopomers. *Nature* 405:330–34

Yoshinari T. 1984. Nitrite and nitrous oxide production by Methylosinus trichosporium. *Can. J. Microbiol.* 31:139–44

Yoshinari T, Altabet MA, Naqvi SWA, Codispoti L, Jayakumar A, et al. 1997. Nitrogen and oxygen isotopic compositions of N_2O from suboxic waters of the eastern tropical North Pacific and the Arabian Sea—Measurement by continuous-flow isotope-ratio monitoring. *Mar. Chem.* 56:253–64

Yung YL, Miller CE. 1997. Isotopic fractionation of stratospheric nitrous oxide. *Science* 278:1778–80

Zahn JA, Duncan C, DiSpirito AA. 1994. Oxidation of hydroxylamine by cytochrome P-460 of the obligate methylotroph *Methylococcus capsulatus* Bath. *J. Bacteriol.* 176:5879–87

Zhang H, Wennberg PO, Wu VH, Blake GA. 2000. Fractionation of $^{14}N^{15}N^{16}O$ and $^{15}N^{14}N^{16}O$ during photolysis at 213 nm. *Geophys. Res. Lett.* 27:2481–84

Zhao XJ, Sampath V, Caughey WS. 1995. Cytochrome-c-oxidase catalysis of the reduction of nitric-oxide to nitrous-oxide. *Biochem. Biophys. Res. Comm.* 212:1054-60

Zumft WG. 1992. The denitrifying prokaryotes. In *The Prokaryotes*, ed. M Dworkin, pp. 554–82. New York: Springer Verlag

Zumft WG. 1993. The biological role of nitric oxide in bacteria. *Arch. Microbiol.* 160:253–64

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