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LITERATURE REVIEW OF GREENHOUSE GAS EMISSIONS FROM BIOGENIC SOURCES

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Emission	Carbon Monoxide	Stationary Sources	14G
Gases	Nitrogen Oxide (N_2O)	Biogenesis	07D
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ABSTRACT

A literature review is presented of estimates of biogenic emissions of five greenhouse gases: CO_2, CH_4, CO, N_2O, and NO_x. Results of the review include data and information from about 170 sources published over the past 10 years. The report's two sections cover greenhouse gases containing (1) carbon and (2) nitrogen. Within each section, emissions estimates are grouped by type of source or sink in a series of tables. First, emission factors are given as a rate in units of mass per unit area per unit time (e.g., kg ha^{-1} yr^{-1}), except for NO_x and N_2O produced by lightning. Second, budget estimates are provided in units of mass per unit of time (e.g., g yr^{-1}). Finally, a few authors provided reservoir estimates in units of mass per land area (e.g., kg m^{-2}); these represent the potential amount of a greenhouse gas that is stored in a specific ecosystem or type of biota. Other data presented in the report are specific to the gas or source and are used to calculate a total budget estimate (e.g., land estimates for CH_4 emitted from rice paddies).

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SECTION 1
INTRODUCTION

This document provides an overview of the quantitative emission estimates for five greenhouse gases: carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), nitrous oxide (N_2O), and oxides of nitrogen (NO_x). The information presented in this document was developed by surveying the literature, and through discussions with researchers who have published recently in this field. It must be emphasized that this report is not a summary of an exhaustive search of all research and studies conducted to date, but rather contains information obtained from readily available sources published over the past ten years. It is intended to provide background information on emission rates, total emissions, types of sources and sinks, and factors that may affect emissions and emission estimates of greenhouse gases. If more detailed information is required on a specific pollutant or source, the reader is encouraged to conduct a more in-depth literature search.

No judgments were made as to the quality or validity of the data presented in this report. The emission factors come from field measurements, laboratory measurements, mass balance calculations, and theoretical calculations. Although the "comments" column in each table provides some indication of the origins of the estimates, the reader is strongly advised to refer to the original reference before using any of the emission factors or budget estimates presented here.

In some cases, summary tables from review articles were used. These are clearly marked in the tables or text, and the primary author and date are stated. The original reference is not cited in the reference list; however, it can be found by referring to the review paper.

Journals published prior to February 1990 were included in the literature survey; most attention was given to major journals concerned with biogeochemical processes. These include Global Biogeochemical Cycles, the Journal of Geophysical Research, the Journal of Atmospheric Chemistry, and Atmospheric Environment.

Three different quantitative estimates are given in the tables. The emission factor is given as a rate, usually in units of mass per area per unit of time (e.g., kg ha^{-1} yr^{-1}). The exception to this is in Table 3-7 which gives estimates of NO_x and N_2O produced by lightning. The emission factor

here is given in terms of mass per lightning stroke or mass per unit of energy (e.g., molecules per joule).

The second estimate used is a budget estimate. The units used are mass per unit time (e.g., g yr^{-1}). The budget estimate is the amount of the gas produced globally over a given span of time by a particular source. Unless otherwise stated, budget estimates should be assumed to be global. In some cases, regional budget estimates are given.

Finally, a few authors gave a reservoir estimate. The units are mass per land area (e.g., kg m^{-2}). This reservoir estimate represents the potential amount of a greenhouse gas that is stored in a specific ecosystem or type of biota. For example, in Table 2-1, reservoir estimates of carbon stored in various ecosystems are cited. This represents the amount of carbon which would be released, primarily as CO_2, if the biomass were burned.

Other numbers presented in these tables are specific to the gas or source and are used to calculate a total budget estimate. Examples are number of animals per unit area for methane emissions from ruminants and land area estimates for methane emitted from rice paddies. These are generally self-explanatory, or are explained in the text for individual gases.

The remainder of this report is divided into two sections covering the major greenhouse gases. Within each section, the emissions estimates are grouped by source (or sink) type. Many sinks can also act as sources. For example, forests are a sink for carbon, but the carbon is released as CO_2, CO, and CH_4 when the biomass is burned or otherwise decomposes. Most of the tables present emission estimates from sources. Those few that deal with sinks are clearly labeled.

SECTION 2
SOURCES AND SINKS OF CARBON COMPOUNDS

The following discussion is intended to provide background information on the sources of carbon compounds that are emitted from biogenic sources. For more detailed information on the studies reviewed, the reader is referred to the original citation and the "Comments/Assumptions/Geographic Area" column of each table.

2.1 CARBON DIOXIDE

Carbon dioxide (CO_2) is emitted from a variety of sources within the terrestrial biota (Table 2-1). Tropical and nontropical forest releases of CO_2 occur due to forest clearing and the resulting decrease in soil organic matter, burning, and decay of cleared vegetation (Detwiler and Hall, 1988). The large range in the budget estimates published vary by vegetation type, rate of land clearing, and localized fluxes. Models of the global carbon budget typically attempt to balance the oceanic uptake of CO_2 (Table 2-2) and terrestrial ecosystem CO_2 uptake with releases of CO_2 from natural and anthropogenic (i.e., fossil fuel combustion) sources (Detwiler and Hall, 1988). Terrestrial ecosystem uptake of CO_2 is also included in Table 2-1 as a reservoir estimate. Estimates of CO_2 emissions are typically expressed in terms of mass of carbon (C).

2.2 METHANE

Biogenic methane (CH_4) fluxes have been measured from rice paddies, wetlands, and tundra, as well as from animal (ruminants), termites, and biomass burning. Atmospheric methane plays an important role in the global radiative budget, but the contributions of individual sources to the total budget estimate are not well understood (Lerner et al., 1988). Methane is produced by microbial activities during the mineralization of organic carbon in anaerobic environments such as water logged soils and the intestines of ruminants (Bolle et al., 1986). Emission estimates from individual methane sources vary greatly due to the limited database from the individual

TABLE 2-1. CO_2 EMITTED FROM TERRESTRIAL BIOTA

Reference	Emission Factor	Reservoir Estimate	Budget Estimate	Comments/Assumptions/Geographic Area
Adams et al. (1977)			400 to 4000 Tg yr^{-1}	Estimated from per capita wood consumption (globally).
Andreae et al. (1988)			Global estimate: 3100 Tg yr^{-1} (Range: 2000 to 4000 Tg yr^{-1}) South American Tropics: 527 Tg yr^{-1}	Based on emission ratios calculated from measurements of biomass-burning plumes.
Bolin (1977)			400 to 1600 Tg yr^{-1}	Global net transfer of carbon to the atmosphere.
Bolin et al. (1979)		Land biota:* 5.9 to 9.8 x 10^5 Tg C Soil humus:* 1.0 to 3.0 x 10^6 Tg C		Chapter reviews previous research on carbon reservoirs and fluxes.
Bramryd (1979)		8.3 x 10^5 Tg C*		Presents global estimate but also lists individual estimates for 14 continental and 5 marine ecosystem types. Good reference for estimated C removal in various countries around the world.
Brunig (1977)			6000 Tg yr^{-1}	Tropical forest clearing only.
Buringh (1984)			Non-agricultural land use: 1167 Tg yr^{-1} Land deterioration: 269 Tg yr^{-1} Fuel wood, fire: 680 Tg yr^{-1}	

*Denotes reservoir estimate, i.e., the amount of carbon stored.

TABLE 2-1. (Continued)

Reference	Emission Factor	Reservoir Estimate	Budget Estimate	Comments/Assumptions/Geographic Area
Buringh (1984) (Continued)			Shifting cultivation: 1134 Tg yr^{-1} Conversion of forest: 922 Tg yr^{-1} Total for world: 4172 Tg yr^{-1}	
Detwiler et al. (1985)	Primary closed forest: 1.5 to 1.8 x 10^5 kg ha^{-1} yr^{-1}		900 to 1200 Tg C yr^{-1} from tropical vegetation	Represents annual release of carbon from tropical vegetation. Study indicates that current models of the oceanic carbon cycle show it is a sink for 1.2 x 10^{15} g yr^{-1}. Thus, global carbon budget may be balanced if there is no significant release from nontropical ecosystems.
	Primary open forest: 3.6 to 5.0 x 10^5 kg ha^{-1} yr^{-1}		1200 to 1500 Tg C yr^{-1} (including release from soils)	
	Secondary closed forest: 5.7 to 6.8 x 10^5 kg ha^{-1} yr^{-1}			
	Secondary open forest: 1.7 to 2.3 x 10^5 kg ha^{-1} yr^{-1}			
	Logged closed: 1.0 to 1.3 x 10^5 kg ha^{-1} yr^{-1}			
Hampicke (1979)			1500 to 4500 Tg C yr^{-1} (range) Average: 2500 Tg yr^{-1}	Global estimate. Author points out that available data are best-reasoned guesses and their accuracy and reliability are low.
Hao et al. (1988)	3.0 x 10^{13} molecules cm^{-2} s^{-1}		1.7 x 10^4 Tg C of CO_2 (Tropical savannas during rainy season)	Measured arithmetic mean of N_2O, CH_4, and CO_2 from undisturbed tropical savanna soils in Venezuela during the dry season. Area of tropical savannas assumed to be 1.5 x 10^7 km^2. Elevated CO_2 fluxes (ninefold increase) decreased with cessation of simulated rainfall.

TABLE 2-1. (Continued)

Reference	Emission Factor	Reservoir Estimate	Budget Estimate	Comments/Assumptions/Geographic Area
Houghton et al. (1983)			1.8 to 4.7 x 10^{15} g yr^{-1} of C	Same data as Woodwell et al. (1983) study listed below. Model calculates net release of C annually by 69 regional ecosystems.
			135 to 228 x 10^{15} g (between 1860 and 1980)	Range of estimates reflects differences among various estimates of forest biomass, soil carbon, and agricultural clearing. Low end of range based on FAO statistics; middle based on population (rate of growth); high end based on Myers (1980). Appendices provide ecosystem data on roundwood production, conversion of natural ecosystems to agriculture or pasture, and deforestation rates.
				Components of net flux in 1980 (10^{15} g)

	Burned	Decay	Regrowth	Soil	Decay	Total
Clearing for agric.	0.38	0.38	0.0	0.54	0.28	1.58
Harvest/Regrowth	0.41	1.79	-1.86	0.29	0.27	0.90
Clearing for pasture	0.10	0.09	0.0	0.04	0.01	0.24
TOTAL	0.89	2.26	-1.86	0.87	0.56	2.72

Houghton et al. (1985)	8.7 x 10^{12} to 2.2 x 10^{14} g$(10^6$ ha$)^{-1}$ yr^{-1}		0.5 to 4.2 x 10^{15} g yr^{-1} of C	Applicable to tropical forests. Range due to different estimates of deforestation rates. FAO assessment of tropical forests provides country-by-country deforestation estimates. The assessment can serve as an independent benchmark from which terrestrial C releases can be calculated.
Keller et al. (1986)	6.6 x 10^{15} g cm^{-2}			Emission factor is for tropical forest soils. Represents average of fluxes measured from undisturbed forest sites in Brazil, Ecuador, and Puerto Rico.
	1,040 g CO_2 m^{-2} yr^{-1}			

TABLE 2-1. (Continued)

Reference	Emission Factor	Reservoir Estimate	Budget Estimate	Comments/Assumptions/Geographic Area
Moore et al. (1981)			1900 to 4300 Tg yr^{-1}	Describes procedure for estimating global CO_2 based on localized fluxes. Indicates major causes of carbon release from natural ecosystems are harvesting of forests and and transformation to agriculture. Study focuses on 10 geographic regions with potentially 12 different ecosystems. Study lists other estimates of annual carbon release (listed also in Hampicke (1979) above).
Schlesinger (1977)	Tropical forest: 405 to 6100 g m^{-2} yr^{-1}	Tropical forest:* ~10 kg m^{-2}		Evaluated C content in soil profile and atmospheric release from soil occurring within nine ecosystem types. Numbers presented for emission factor are mean values.
	Temperate forest: 171 to 1098 g m^{-2} yr^{-1}	Temperate forest:* ~12 kg m^{-2}		
	Boreal forest: 147 to 232 g m^{-2} yr^{-1}	Boreal forest:* ~15 kg m^{-2}		
	Shrubland: 399 to 653 g m^{-2} yr^{-1}	Shrubland:* ~7 kg m^{-2}		
	Tropical savanna: 515 to 785 g m^{-2} yr^{-1}	Tropical savanna:* ~4 kg m^{-2}		
	Temperate grassland: 74 to 452 g m^{-2} yr^{-1}	Temperate grassland:* ~20 kg m^{-2}		
	Tundra and Alpine: 37 to 210 g m^{-2} yr^{-1}	Tundra and Alpine:* ~22 kg m^{-2}		
	Desert scrub: 22 g m^{-2} yr^{-1}	Desert scrub:* ~6 kg m^{-2}		
	Swamp and marsh: 730 to 1350 g m^{-2} yr^{-1}	Swamp and marsh:* ~69 kg m^{-2}		

*Denotes reservoir estimate, i.e., the amount of carbon stored.

TABLE 2-1. (Continued)

Reference	Emission Factor	Reservoir Estimate	Budget Estimate	Comments/Assumptions/Geographic Area
Schlesinger (1984)			799 Tg yr^{-1}	Conversion of forest in tropics. Based on estimates of deforestation for agriculture made by Revelle and Munk (1977).
Stuiver (1978)			1300 Tg C yr^{-1}	Global applicability. Estimate based on C^{12} tree ring measurements.
Wofsy et al. (1988)	Mean daytime: -2.8 kg C ha^{-1} hr^{-1} (uptake by forest soils and canopy) 1.8 kg C ha^{-1} hr^{-1} (mean emission from forest soils) -1.6 kg C ha^{-1} hr^{-1} (mean daytime uptake over wetlands)			CO_2 emissions and uptake from soils studied in the Amazon Basin. Forest is a net source of CO_2 at night and a sink during the day. Cycle is weaker over wetlands.
Woodwell et al. (1978)			0.2 to 1.8 x 10^3 Tg yr^{-1}	Net transfer of carbon to the atmosphere.
Woodwell and Houghton (1977)			0.25 to 10 x 10^4 Tg yr^{-1}	Net transfer of carbon to the atmosphere.
Woodwell et al. (1983)			1800 to 4700 Tg C yr^{-1}	Applicable to entire globe. Summarizes effects of terrestrial biota on the amount of carbon dioxide released. Emission factor represents release in 1980 due to deforestation, particularly in tropics. Study indicates that the increased CO_2 (atmospheric) is not increasing the storage of carbon in earth's forests to offset the release from deforestation.
Wong (1978)			1900 Tg yr^{-1}	Net transfer of carbon to the atmosphere.
Yavitt et al. (1988)	1.0 to 2.6 kg m^{-2} yr^{-1}			Measurements of peatlands in the Appalachian Mountains. Wide range due to temperature variations and chemistry of the peat substrate.

TABLE 2-2. THE OCEAN AS A SINK FOR CO_2

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Anderson et al. (1990)	Released (new production) from over continental shelves: 45 ± 20 g cm^{-2} yr^{-1}	Total for Arctic Ocean: 210 Tg C yr^{-1} Fixed in Arctic river drainage basins: 40 ± 20 Tg C yr^{-1} Fixed over Arctic Continental shelves: 129 ± 65 Tg C yr^{-1}	Assesses transport of CO_2 into Arctic Ocean. Upper layer is an active sink for CO_2, no flux detected in deep water. Five percent of total carbon sequestered by terrestrial ecosystems is estimated to be transported to the Arctic Ocean.
Baes et al. (1985)	0.063 mol m^{-2} μatm^{-1} yr^{-1}	9.3 x 10^4 Tg yr^{-1}	This chapter discusses the uptake of CO_2 by the oceans. The global average exchange rate for CO_2 between the atmosphere and ocean surface is estimated using ocean models. Exchange rate is dependent on atmospheric pCO_2.
Chen and Millero (1979)			Paper discusses the probable increase in oceanic CO_2 as concentrations of CO_2 in the atmosphere increase. Provides physical and chemical computations which indicate oceanic CO_2 has increased by as much as 40 μmol/kg.
Smith (1981)		1800 Tg yr^{-1}	Author estimates approximately 5 x 10^9 tons of carbon are released to atmosphere annually as CO_2 from burning fossil fuel. Of that, approximately 40 percent diffuses across air-sea interface into dissolved CO_2 pool of surface ocean water. Author suggests that marine biota (macrophytes) may act as additional sink for carbon.

TABLE 2-2. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Stuiver (1978)		820 Tg yr^{-1}	Author estimates that approximately half of the CO_2 introduced to the atmosphere is transferred to the oceans. Estimate is based on assuming approximately 1.6 x 10^5 Tg CO_2 was released to atmosphere between 1850 and 1950.

ecosystems, and insufficient size or area estimates for the sources (Bolle et al., 1986) (Tables 2-3 through 2-8).

Rice paddies are a major source of CH_4, with emissions depending on agricultural practices, temperatures, fertilization regimes, time of season, irrigation, soil properties, rice cultivar, and amount of residue left following harvest. Variations in flux estimates are due to ebullition (bubble transport), transport through the plants, and rapid variations in methane emission routes (Cicerone and Oremland, 1988). Methane emissions have increased as the land area available for rice growing increased. Population growth coincided with the introduction of multiple cropping (with irrigation) and with cultivation of new land (Cicerone and Oremland, 1988). In addition, some researchers hypothesize that biological sinks of CH_4, including microorganisms in aerobic soils, may be adversely affected by elevated soil moisture and nitrogen additions, thus reducing the amount of CH_4 taken up (Steudler et al., 1989).

Methane emissions from wetlands vary greatly because of temperatures, soil water levels, and seasonal variations in CH_4 escape routes (Cicerone and Oremland, 1988). Budget estimates for CH_4 from wetlands vary because of land area estimates, with some estimates double those of others (Cicerone and Oremland, 1988).

Tundra methane emissions may be included as unforested bog emissions (Matthews and Fung, 1987), but are provided separately here. Methane production in tundra occurs during summer permafrost thaw periods, and estimates vary due to land area estimates and percent of tundra assumed to be waterlogged (Ehhalt and Schmidt, 1978).

Methane is emitted from ruminants due to intestinal anaerobic digestion of organic carbon. Budget estimates of CH_4 flux vary due to variations in estimates of animal populations, estimates of methane emissions by individual animal species, and emissions due to differing feeds. Table 2-6 also contains some emission factors for CH_4 from human sewage.

Methane emitted from termites has been measured in laboratory and field experiments. The wide range in budget estimates for this source are due to extrapolation disagreements (Cicerone and Oremland, 1988). Termite populations, amount of material consumed by termites, and species variations all must be more closely examined (Cicerone and Oremland, 1988). The last source of CH_4 covered in this document is biomass burning. A wide range

TABLE 2-3. METHANE EMITTED FROM RICE PADDIES

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Baker-Blocker et al. (1977)	260 g m^{-2} yr^{-1}	1.35 x 10^6 km^2	350 Tg yr^{-1}	This estimate may be high because paddy fields are usually drained for part of each year.
Cicerone and Shetter (1981)	42 g m^{-2} yr^{-1}	1.40 x 10^6 km^2	59 Tg yr^{-1}	Emission factor based on field plot studies in California – took into account fertilizer use. Extrapolated across globe using U.N. rice cultivation data and assuming 4-month growing season.
Ehhalt and Schmidt (1978)	206 g m^{-2} yr^{-1}	1.35 x 10^6 km^2	280 Tg yr^{-1}	Extrapolated across globe using U. S. rice cultivation data and assuming 4-month growing season. Based on laboratory studies growing rice plants.
Holzapfel-Pschorn and Seiler (1986)	79 g m^{-2} yr^{-1}	1.45 x 10^6 km^2	120 Tg yr^{-1}	Average of range given in paper: 70 - 170 Tg yr^{-1} based on 1979 land use data. Based on field plot studies. Good discussion on the variation in emissions from different studies. Suggests that different fertilizer use may contribute different amounts of CH_4.
Khalil and Rasmussen (1983)			95 Tg yr^{-1}	Apportioned to 4 geographic regions of the globe based on information on land-use in Time Atlas of the World.
Koyama (1963)		9.2 x 10^5 km^2	190 Tg yr^{-1}	Flux varied by temperature and water depth.
Schutz et al. (1989)	Unfertilized: 0.28 g m^{-2} d^{-1} (33 g m^{-2} yr^{-1}) Organic fertilizer: 0.58 g m^{-2} d^{-1} (68.4 g m^{-2} yr^{-1}) Inorganic fertilizer: 0.16 g m^{-2} d^{-1} (19 g m^{-2} yr^{-1})	1.5 x 10^6 km^2	Average: 100 Tg yr^{-1} Range: 50 to 150 Tg yr^{-1}	Measurements from Italian rice paddies without and with organic and inorganic fertilizers. Range due to seasonal variation and mode of fertilizer application. Inorganic fertilizer (urea or ammonium sulfate) applied at rates of 50 to 200 kg N ha^{-1}.

TABLE 2-3. (Continued)

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Schutz et al. (1989) (Continued)	Organic and inorganic fertilizers: 0.28 to 0.60 g m^{-2} d^{-1} (33 to 68 g m^{-2} yr^{-1})			
Seiler and Conrad (1987)			120 Tg yr^{-1}	Uncertainty associated with this estimate is ±40%. The tropics (30°S - 30°N) account for 95% of the rice paddy land area. Estimates are based on 1980 land estimates.
Wang et al. (1988)	3.1 to 2,889 mg m^{2} d^{1}			Rice paddies in Sichuan, China. Measured CH_4 fluxes are largest during seedling stage and just before harvest. Air bubbles were found to transport CH_4 and contributed greatly to total emissions.

TABLE 2-4. METHANE EMITTED FROM WETLANDS

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Baker-Blocker et al. (1977)	260 g m^{-2} yr^{-1}		150 Tg yr^{-1}	Based on extrapolating methane flux from a Michigan wetland to the 4 largest wetland areas in the world, using equations based on temperature functions, and then adding some to get world wide estimate (is ~22 - 30% of the CH_4 in the atmosphere).
Barber et al. (1988)	Mangrove open water: 29.9 ± 10 g m^{-2} yr^{-1}			Diffusive flux estimated by dissolved methane concentrations and wind speed data in wetlands in Florida.
	Urbanized subtropical estuary: 0.96 ± 0.8 g m^{-2} yr^{-1}			
	Densely vegetated sawgrass marsh: 2.9 ± 3.3 g m^{-2} yr^{-1}			
	Sparsely vegetated sawgrass marsh: 32 ± 19 g m^{-2} yr^{-1}			
	Organic-rich forested swamp: 41 ± 30 g m^{-2} yr^{-1}			
	Freshwater lakes: 12 ± 11 g m^{-2} yr^{-1}			
Bartlett et al. (1985)	0.89 g m^{-2} yr^{-1}	3.8 x 10^5 km^2	0.34 Tg yr^{-1}	Includes coastal salt marshes only. Based on field sampling conducted in Virginia.
Bartlett et al. (1988)	Open water lakes: 27 ± 4.7 mg m^{-2} d^{-1} (0.03 to 0.6 Tg yr^{-1})			Amazonia flood plain environments measured. Transport processes were ebullition from sediment, diffusion from sediment to water and air, and transport through roots and stems of aquatic plants. Ebullition accounts for about 49 percent of the flux from open water, 54 percent from flooded forests, and 64 percent from floating mats. Estimated that entire Amazonia flood-plain may supply 12 percent of global CH_4.
	Flooded forests: 192 ± 26.8 mg m^{-2} d^{-1} (1.7 to 12 Tg yr^{-1})			

TABLE 2-4. (Continued)

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Bartlett et al. (1988) (Continued)	Floating grass mats: 230 ± 72.2 mg m^{-2} d^{-1} (1.3 to 8.7 Tg yr^{-1})			
		3.9 x 10^5 km^2	Total: 17 Tg yr^{-1}	
Blake (1984)		2.6 x 10^6 km^2	120 Tg yr^{-1}	
Burke et al. (1988)	0.001 to 2.6 g m^{-2} d^{-1}		0.5 Tg yr^{-1}	Measurements taken from four locations in the Florida Everglades. Concludes that Everglades are weak source of CH_4. Range due to size and spacing of emerging aquatic vegetation.
Chanton and Martens (1988)	19.2 to 20.8 g m^{-2} yr^{-1}			North Carolina, USA. Tidally induced bubble ebullition transports CH_4 to atmosphere.
Chanton et al. (1988)	Marl sawgrass prairie: 5 to 6 mg m^{-2} d^{-1}			Measurements taken in the Florida Everglades. Very little ebullition — CH_4 emitted from plant advection and molecular diffusion from the water column.
Crill et al. (1988a)	27 g m^{-2} d^{-1}			Methane flux measured from an open lake in the Amazon. Ebullition contributed 70 percent to total flux.
Crill et al. (1988b)	11 to 866 mg m^{-2} d^{-1}	3.56 x 10^{12} m^2	70 to 90 Tg yr^{-1}*	Measurements taken from a variety of Minnesota (northern) peatlands during summer months. Methane flux increased with increasing soil temperatures. Estimate of land area taken from Gorham (1988).
Devol et al. (1988)	Total average rate: 390 mg m^{-2} d^{-1}		Entire Amazon floodplain: 10 Tg yr^{-1}	Measured CH_4 flux in the Amazon floodplain in July and August, 1985. Ebullition accounted for 85 percent of total emissions.
	Surfaces covered with aquatic macrophytes: 590 mg m^{-2} d^{-1}			

*For all peatlands north of 40°.

TABLE 2-4. (Continued)

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Devol et al. (1988) (Continued)	Flooded forests: 110 mg m^{-2} d^{-1} Open lakes: 120 mg m^{-2} d^{-1}			
Ehhalt and Schmidt (1978)	400 g m^{-2} yr^{-1}	2.6 x 10^{6} km^{2}	190 to 300 Tg yr^{-1}	
Hao et al. (1988)	1.6 ± 1.2 x 10^{10} molecules CH_4 cm^{-2} s^{-1}			Measured arithmetic mean of N_2O, CH_4, and CO_2 fluxes from undisturbed and disturbed tropical savanna soils in Venezuela during the dry season. Large variation in CH_4 fluxes may have been due to CH_4 escape after insertion of metal frame for measurement. CH_4 fluxes following surface burning and simulated rainfall were within the range of uncertainty. No consumption of CH_4 was noted.
Harriss et al. (1988)	Wet prairies and sawgrass marsh: 61 ± 7 mg m^{-2} d^{-1} Wetland forests: 59 ± 17 mg m^{-2} d^{-1} Saltwater mangroves: 4 ± 0.4 mg m^{-2} d^{-1} Impoundments and disturbed wetlands: 74 ± 10 mg m^{-2} d^{-1}			Measurements of methane flux for wetland ecosystems in South Florida. Variations in regional water budget are important in determining CH_4 flux. Concluded that these sources result in a 26 percent enhancement of CH_4 flux for the region.
Khalil and Rasmussen (1983)			150 Tg yr^{-1}	Apportioned between 4 geographic regions of the globe based on land use information in Time Atlas of the World.
Levine et al. (1990)	5 to 6 g m^{-2} d^{-1}			Southern Florida juncus marsh following burn.
	34.5 g m^{-2} d^{-1}			Southern Florida spartina marsh following burn.

TABLE 2-4. (Continued)

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Lilley and Baross (1988)	Moderately impacted lakes: 1.1 to 2.9 mmol m^{-2} d^{-1}			CH_4 flux from lakes near Mount St. Helens, first summer after eruption.
	Heavily impacted lakes: 17.4 to 25.3 mmol m^{-2} d^{-1}			
Matthews and Fung (1987)	Forested and non-forested bogs: 0.2 g m^{-2} d^{-1}	5.3 x 10^6 km^2	110 Tg yr^{-1}	Wetland sites are divided into 5 major wetland groups. Tropical swamps are estimated to account for ~25% of the wetland emissions, while northern peat-rich bogs are estimated to account for over 60% of the wetland emissions.
	Forested swamps: 0.07 g m^{-2} d^{-1}			
	Non-forested swamps: 0.12 g m^{-2} d^{-1}			
	Alluvial formations: 0.03 g m^{-2} d^{-1}			
Miller and Oremland (1988)	Mean total flux: 416 ± 833 μmol m^{-2} h^{-1}			Searsville Lake, CA. Freshwater lake; ebullition dominates efflux.
	Mean flux: 27 ± 45.2 μmol m^{-2} h^{-1}			Three alkaline, saline lakes (Mono Lake, CA; Soap Lake, WA; and Big Soda Lake, NV). Little ebullition.
Seiler and Conrad (1987)		2.6 x 10^6 km^2	47 Tg yr^{-1}	Uncertainty associated with this estimate is ± 47%. The tropics (30°S - 30°N) account for 80% of the emissions from wetlands. Estimates are based on 1980 land estimates.
Sheppard et al. (1982)			39 Tg yr^{-1}	

TABLE 2-4. (Continued)

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Steudler et al. (1989)	-3.17 mg m^{-2} d^{-1} (Temperate and boreal forest soils)	Temperate forests: 9.3 x 10^{12} m^2 Boreal forests: 11.6 x 10^{12} m^2 Tropical forests: 18.5 x 10^{12} m^2	Temperate and boreal forest soils: -9.3 Tg yr^{-1} Tropical forest soils: -2.5 Tg yr^{-1}	Measured CH_4 consumption by temperate and boreal forest soils. Tropical forest CH_4 consumption estimated from Keller et al. (1986).
Yavitt et al. (1988)	43.2 to 280 g m^2 yr^{-1}			Measurements in peatlands of the Appalachian mountains. Wide range due to temperature variations and chemistry.

TABLE 2-5. METHANE EMITTED FROM TUNDRA

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Brown et al. (1989)			1.7 Gg trapped below 50 cm depth	Measurements taken in an ombrotrophic bog (no groundwater input, only rainfall, very low mineral content) in Canada. Bog acted as a CH_4 reservoir. Conclude that Northern peatlands (>40°N) act as CH_4 reservoirs, and some of the CH_4 will only be released if the peat is disturbed.
King et al. (1989)	30 ± 14 mg m^{-2} d^{-1} (mean flux)			CH_4 flux measured in Alaskan tundra. Field and laboratory measurements are in agreement. Two sites had CH_4 consumption rates of 1.2 and 0.6 mg CH_4 m^{-2} d^{-1}.
Sebacher et. al (1986)	Moist tundra: 0.005 g m^{-2} d^{-1} Waterlogged tundra: 0.12 g m^{-2} d^{-1} Wet meadow: 0.04 g m^{-2} d^{-1} Alpine fen: 0.29 g m^{-2} d^{-1} Boreal marsh: 0.106 g m^{-2} d^{-1} Average annual flux: 11.2 g m^{-2} d^{-1}	4 to 9.5 x 10^6 km^2	45 to 106 Tg yr^{-1}	Study includes arctic and boreal wetlands only. Based on field studies conducted in Alaska (70°N latitude). Emissions are well correlated with water level, and depth of permafrost. The methane flux was found to be poorly correlated with soil temperature. The average annual flux estimate was calculated assuming an average of 100 days/yr of active CH_4 emissions for these northern wetlands.
Whalen and Reeburgh (1988)	Wet meadow tundra: 4.05 g m^{-2} yr^{-1} Tussock and low scrub tundra: 2.45 g m^{-2} yr^{-1}	Wet meadow tundra: 0.88 x 10^{12} m^2 Tussock and low scrub tundra: 6.5 x 10^{12} m^2 Total tundra: 7.34 x 10^{12} m^2	Wet meadow tundra: 3.54 to 4.1 Tg yr^{-1} Tussock and low scrub tundra: 15.8 to 28.8 Tg yr^{-1} Total: 19 to 33 Tg yr^{-1}	Measurements taken in Alaskan tundra. Wet meadow tundra is all nonforested land north of 50°N.

TABLE 2-6. METHANE EMITTED FROM ANIMALS (RUMINANTS)

Reference	Emission Factor	Estimate of Number of Animals	Budget Estimate	Comments/Assumptions/Geographic Area
Crutzen et al. (1986)	In developed countries: 55 kg CH_4 yr^{-1} $animal^{-1}$ In developing countries: 35 kg CH_4 yr^{-1} $animal^{-1}$	Cattle: 1.2×10^9 Buffalo: 1.24×10^8 Sheep: 1.1×10^9 Goats: 4.7×10^8	7.4×10^{13} g yr^{-1}	Includes cattle, wild ruminants and humans. Cattle make up 74% of the emissions. Gives population estimates for various animals, and emission rates/animal species.
Ehhalt (1974)			1.0 to 2.2×10^{14} g yr^{-1}	Multiplied methane release rate per ruminant by estimated animal population.
Khalil and Rasmussen (1983)			1.2×10^{14} g yr^{-1}	(Cattle only) Apportioned among 4 regions of the globe based on land-use data from Time Atlas of the World.
Lerner et al. (1988)	In developing countries: Sheep: 5 kg yr^{-1} $animal^{-1}$ Cattle: 35 kg yr^{-1} $animal^{-1}$ Pigs: 1 kg yr^{-1} $animal^{-1}$ In developed countries: Sheep: 8 kg yr^{-1} $animal^{-1}$ Cattle: 55 kg yr^{-1} $animal^{-1}$ Pigs: 1.5 kg yr^{-1} $animal^{-1}$ Camels: 58 kg yr^{-1} $animal^{-1}$ Water buffalo: 50 kg yr^{-1} $animal^{-1}$ Goats: 5 kg yr^{-1} $animal^{-1}$ Caribou: 15 kg yr^{-1} $animal^{-1}$	Sheep: 7.4×10^8 Cattle: 8.3×10^8 Pigs: 5.9×10^8 Camels: 1.1×10^7 Water Buffalo: 1.0×10^8 Goats: 2.9×10^8 Horses: 4.5×10^7	Sheep: 6.8 Tg yr^{-1} Cattle: 57 Tg yr^{-1} Pigs: 1 Tg yr^{-1} Camels: 1 Tg yr^{-1} Water Buffalo: 6.3 Tg yr^{-1} Goats: 2.3 Tg yr^{-1} Horses: 1 Tg yr^{-1} Total: 75.8 Tg yr^{-1}	Population statistics from 1984 FAO Production Yearbook, United Nations (1985). Emission factors based on estimates of Crutzen (1983), land use data provided by Matthews (1983). Budget estimates also presented by country. Estimate of number of animals includes only countries with the highest populations for each type.
Rust (1981)			78 ± 12 Tg yr^{-1}	
Seiler et al. (1984)			7 to 10 x 10^{13} g yr^{-1}	

TABLE 2-6. (Continued)

Reference	Emission Factor	Estimate of Number of Animals	Budget Estimate	Comments/Assumptions/Geographic Area
Seiler and Conrad (1987)			86 Tg yr^{-1}	Uncertainty associated with this estimate is ±15%. The tropics (30°S - 30°N) account for 40% of the emissions from ruminants. Estimates are based on 1983 animal population.
Sheppard et al. (1982)			90 Tg yr^{-1}	Animals and humans (human sewage).

TABLE 2-7. METHANE EMITTED FROM TERMITES

Reference	Emission Factor	Estimate of Population	Budget Estimate	Comments/Assumptions/Geographic Area
Fraser et al. (1986)	1.0 to 8.0 mg kg^{-1} (termite) hr^{-1} (depending on ecological region)		14 Tg yr^{-1} (Range: 6 to 42 Tg yr^{-1})	Concluded that termites account for less than 15% of global CH_4. Based on lab experiments in Australia and Oregon.
Rasmussen and Khalil (1983)	0.9 μg $termite^{-1}$ d^{-1}	2.4 x 10^{17} individuals	50 Tg yr^{-1} (Range: 10 to 100 Tg yr^{-1})	Studies on termites conducted in glass jars. Estimated this represents less than 15% of total global CH_4es of uncertainty in values of production CH_4/termit. Give ranges of uncertainty in values of production CH_4/termite/yr and in estimation of global population of termites.
Seiler et al. (1984)			3.5 Tg yr^{-1}	Measurements from S. Africa. Constructed large chambers over entire termite nests in the field.
Zimmerman et al. (1982)	0.24 to 0.59 μg $termite^{-1}$ d^{-1} (depending on termite species)	2.4 x 10^{17} individuals	150 Tg yr^{-1}	Based on lab measurements from termite nests in Guatemala. Author suggests that termites may represent up to 40% of total global CH_4. Suggests that emissions from termites are increasing due to human activities (clearing tropical forests, grazing and agriculture land) which provide increased habitat for termites.

TABLE 2-8. METHANE EMITTED FROM BIOMASS BURNING

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Cofer et al. (1988)	0.0041 ± 0.0009 $\Delta CH_4/\Delta CO_2$ (vol/vol)		Los Angeles, CA. Plume samples from intense flaming and mixed fire. CO_2 higher with full flames.
Cofer et al. (1989)	Flaming: 0.36 to 0.76 $\Delta CH_4/\Delta CO_2$ (vol/vol) Mixed: 0.43 to 0.61 $\Delta CH_4/\Delta CO_2$ (vol/vol) Smoldering: 0.87 ± 0.23 $\Delta CH_4/\Delta CO_2$ (vol/vol)		Samples collected by helicopter from burning chaparral in S. California and over a boreal forest fire in Ontario, Canada.
Stevens and Engelkemeir (1988)		45 ± 14 Tg yr^{-1}	Global anthropogenic biomass burning.

exists in the budget estimate and emission factors from this source due to the type of burning, moisture content of the vegetation, and amount of biomass burned each year (Cicerone and Oremland, 1988). The carbon reservoir of the vegetation will be released as CO_2, CH_4, or carbon monoxide (CO), and each compound must be measured.

2.3 CARBON MONOXIDE

Carbon monoxide budget estimates are not well understood, but CO is known to be emitted from biomass burning, oceans, tropical habitats (through biomass burning, vegetation, oxidation of nonmethane hydrocarbons, and soils), and CH_4 oxidation is a major source. Recent experiments show CO is emitted from rice paddies along with CH_4 (Tables 2-9 through 2-13). In addition, soil has been found to act as a sink for CO under some conditions.

Carbon monoxide is produced from biomass burning by releasing stored carbon reservoirs from plant material. While most of the trace gas emissions from biomass burning have focused on the tropics, recent research has attempted to assess the potential impacts of mid-latitude biomass burning (Cofer et al., 1989).

Carbon monoxide is emitted from the oceans through photooxidative processes. Budget estimates vary because of differing surface-sea water supersaturation factors.

Soils can either emit CO or act as sinks, depending primarily on their aeration and moisture content. In soils that are well aerated, CO is oxidized to CO_2 by bacteria (Seiler and Conrad, 1987). Flux estimates for this sink vary due to soil parameters, soil moisture, and temperatures (Seiler and Conrad, 1987). The emission of CO from flooded soils will be discussed in relation to rice paddy CO fluxes.

The tropics are presented separately here as a source of CO because of the large contribution from both terrestrial and aquatic tropical ecosystems. As discussed above, CO is destroyed at the soil surface by microorganisms, and is emitted by plants and photooxidative processes in freshwater and oceans (Seiler and Conrad, 1987). In addition, CO is formed through hydrocarbon oxidation in plants. Crutzen (1983) concludes that the tropics account for two thirds of the global CO budget estimate from these sources.

TABLE 2-9. CO EMITTED FROM BIOMASS BURNING

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Andreae et al. (1988)		Global estimate: 264 Tg yr^{-1} (Range: 120 to 640 Tg yr^{-1}) South American Tropics: 45 Tg yr^{-1}	Based on emission ratios calculated from measurements of biomass-burning plumes.
Cofer et al. (1988)	0.56 ± 0.024 $\Delta CO/\Delta CO_2$ (vol/vol)		Los Angeles, CA. Plume samples from intense and mixed fire. CO_2 higher with full flames.
Cofer et al. (1989)	Flaming: 5.1 to 6.9 $\Delta CO/\Delta CO_2$ (vol/vol) Mixed: 6.0 to 6.9 $\Delta CO/\Delta CO_2$ (vol/vol) Smoldering: 8.2 ± 1.4 $\Delta CO/\Delta CO_2$ (vol/vol)		Samples collected by helicopter from burning chaparral in S. California and over a boreal forest fire in Ontario, Canada.
Crutzen et al. (1979) (1979)		240 to 1660 Tg yr^{-1}	Based on measurements of forest fires in Colorado. Author estimates that CO from biomass burning produces as much CO as that from fossil fuel combustion.
Greenberg et al. (1984)		800 Tg yr^{-1}	Based on measurements taken from tropical biomass burning in Brazil. Fire emissions were sampled from aircraft flying through the plume. Assume that as much as 70% of all biomass burned is in tropical and subtropical areas.
Jaffe (1973)		36 Tg yr^{-1}	Includes agricultural burning only.
Logan et al. (1981)		30 to 140 Tg yr^{-1}	Includes woodburning, forest clearing, and savanna burning. Does not include burning of agricultural wastes.

TABLE 2-9. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Seiler (1974)		64 Tg yr^{-1} N. Hemisphere: 40 Tg yr^{-1} S. Hemisphere: 20 Tg yr^{-1}	Includes forest fires, bush fires and open burning of agricultural waste. Scaled up to globe based on estimates for the U.S. Assumes U.S. is 25% of global CO emissions from fires.
Volz et al. (1981)		550 Tg yr^{-1}	Calculated from ^{14}CO analysis.

TABLE 2-10. CO EMITTED FROM OCEANS

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Freyer (1979)		35 Tg yr^{-1}	
Linnebom et al. (1973)		22 Tg yr^{-1} N. Hemisphere: 9 Tg yr^{-1} S. Hemisphere: 13 Tg yr^{-1}	Assumes the surface sea-water is supersaturated by an average factor of 28.2.
Liss and Slater (1974)		43 Tg yr^{-1}	Modeling approach. Assumes the surface sea-water is supersaturated by a factor of 23.
Seiler (1974)		100 Tg yr^{-1} N. Hemisphere: 40 Tg yr^{-1} S. Hemisphere: 60 Tg yr^{-1}	
Seiler and Conrad (1987)		100 $\pm$ 90 Tg yr^{-1}	

TABLE 2-11. SOIL AS A SINK FOR CO

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Bartholomew and Alexander (1981)	-1.04×10^{-11} g cm^{-2} s^{-1} (averaged over 12 soil types)	-410 Tg yr^{-1}	Based on measurements from 20 different soil types. World land surface areas and average factors for CO uptake are given for each soil type.
Ingersoll et al. (1974)	-6 to -73×10^{-11} g cm^{-2} s^{-1}	-1400 Tg yr^{-1}	Derived from field studies conducted at 59 sites in N. America and extrapolated to a global estimate.
Seiler (1974)	-1.5×10^{-11} g cm^{-2} s^{-1} (averaged over all soil types)	-450 Tg yr^{-1} N. Hemisphere: -300 Tg yr^{-1} S. Hemisphere: -150 Tg yr^{-1}	Large variation in CO uptake depending on soil temperature and organic content of the soil. Based on field and laboratory estimates in U.S. and Europe.
Seiler and Conrad (1987)		-390 Tg yr^{-1}	CO is oxidized to CO_2 by bacteria in the soil.

TABLE 2-12. CO EMITTED FROM THE TROPICS

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Seiler and Conrad (1987)			Overview and summary of current research. Global and tropical budgets are presented in the report.
		Sources	
		1000 Tg yr^{-1} (±600)	Biomass burning (800 Tg yr^{-1} tropics)
		75 Tg yr^{-1} (± 25)	Vegetation (60 Tg yr^{-1} tropics)
		100 Tg yr^{-1} (± 90)	Ocean (50 Tg yr^{-1} tropics)
		600 Tg yr^{-1} (±300)	CH_4 oxidation (400 Tg yr^{-1} tropics)
		900 Tg yr^{-1} (±500)	Oxidation nonmethane HC (600 Tg yr^{-1} tropics)
		17 Tg yr^{-1} (± 15)	Soil production (10 Tg yr^{-1} tropics)
		Sinks	
		2000 Tg yr^{-1} (±600)	Oxidation by OH (1200 Tg yr^{-1} tropics)
		390 Tg yr^{-1} (±140)	Soil uptake (105 Tg yr^{-1} tropics)
		110 Tg yr^{-1} (± 30)	Flux into stratosphere (80 Tg yr^{-1} tropics)

TABLE 2-13. CO EMITTED FROM RICE PADDIES

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Conrad et al. (1988)			0.1 to 0.5 Tg yr^{-1}	Italian rice paddies studied. CO produced in submerged anoxic soils is released by diffusion through the plants. Based on a calculated CO/CH_4 ratio.

In rice paddies, CO is produced in the anoxic soil and released through the plants and ebullition (Conrad et al., 1988). Carbon monoxide is also produced in the rice plant leaves (Conrad et al., 1988). A budget estimate for CO flux from rice paddies is based on an observed CO/CH_4 ratio. Thus, the wide range in the estimate (0.003 - 0.24 Tg yr^{-1}) is a function of the CH_4 range (Conrad et al. 1988).

SECTION 3
SOURCES OF NITROGEN COMPOUNDS

The discussion below is a summary of the biogenic sources of nitrous oxide (N_2O) and nitrogen oxides (NO_x). For more detailed information on these sources, the reader is encouraged to review the "Comments/Assumptions/ Geographic Area" column on each table and refer to the original study.

3.1 NITROUS OXIDE

Nitrous oxide (N_2O) is emitted following the use of agricultural fertilizers, from soils, and from contaminated aquifers (Tables 3-1 through 3-3).

Nitrous oxide is produced in soils through microbial denitrification and nitrification, and the addition of mineral nitrogen fertilizers causes even higher N_2O releases from soils (Seiler and Conrad, 1981). Nitrous oxide is an intermediate product that is reduced to N_2 in the atmosphere (Seiler and Conrad, 1981). The range of N_2O flux measurements from soils with and without fertilization can be due to denitrification and nitrification rates, soil properties, temperature, type and amount of fertilizer applied, the N_2O/N_2 ratio in soil air, and the exchange rate at the soil-air interface (Seiler and Conrad, 1981). Nitrous oxide flux measured in forest soils was found to vary with soil acidity, season, and biomass burning (Anderson et al., 1988; Schmidt et al., 1988).

The ocean's role in aquatic N_2O cycle is not well documented; recently it has been proposed that the ocean is neither a sink nor a source of N_2O (Ronen et al., 1988). The contamination of ground water aquifers with nitrogen, however, is a potential source of N_2O (Ronen et al., 1988). More research is needed before this source can be accurately quantified as a source of atmospheric N_2O.

3.2 NITROGEN OXIDES

Nitrogen oxides (NO_x) are emitted from soils and through ammonia (NH_3) oxidation. Ammonia may be a significant source of nitrogen oxides in the

TABLE 3-1. N_2O EMITTED FROM FERTILIZER USE

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Anderson and Levine (1987)	0.61 to 2.08 kg N ha^{-1} yr^{-1} (0.79% fertilizer N lost as NO, 1.2% fertilizer N lost as N_2O)		Jamestown, VA. Year-long study, moderately fertilized land. Limited data, therefore % fertilizer lost as NO and N_2O is very uncertain.
Brams et al. (1990)	0.30 kg N ha^{-1} d^{-1}		Late summer, minimum cultivation.
	0.70 kg N ha^{-1} d^{-1}		Fall, minimum cultivation.
	0.08 kg N ha^{-1} d^{-1}		Winter, minimum cultivation.
	0.24 kg N ha^{-1} d^{-1}		Spring, minimum cultivation
	0.20 kg N ha^{-1} d^{-1}		Early summer, minimum cultivation.
	0.56 kg N ha^{-1} d^{-1}		Late summer, maximum cultivation.
	0.10 kg N ha^{-1} d^{-1}		Fall, maximum cultivation.
	0.13 kg N ha^{-1} d^{-1}		Winter, maximum cultivation.
	0.23 kg N ha^{-1} d^{-1}		Spring, maximum cultivation,
	0.35 kg N ha^{-1} d^{-1}		Early summer, maximum cultivation.
Breitenbeck et al. (1980)	$(NH_4)_2SO_4$: 0.11 to 0.18% of N added		Addresses nitrification. Field study of soil in Iowa. Correlates well with lab studies. Study was 96 days; most of N_2O evolved in first 2-3 weeks. Conclude nitrification is primary mechanism of N_2O production. Data possibly applicable to two Canadian soils – Essex Co., S.W. Ontario.
	$CaNO_3$: 0.01 to 0.04% of N added		
	Urea: 0.12 to 0.14% of N added.		
Breitenbeck and Bremner (1986)	90 g N_2O-N $ha^{-1}d^{-1}$ (1.2% of N applied)		Mean rate for 3 soil types following application of anhydrous ammonia (180 kg ha^{-1} fertilizer N). Lower rates were reported for other forms of N fertilizer.

TABLE 3-1. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Mosier et al. (1982)	3.4 g N ha^{-1} d^{-1} 5.9 g N ha^{-1} d^{-1} 6.7 g N ha^{-1} d^{-1} 9.2 g N ha^{-1} d^{-1} 5.3 g N ha^{-1} d^{-1} 7.0 g N ha^{-1} d^{-1} 27.0 g N ha^{-1} d^{-1}		No fertilizer. 56 kg N ha^{-1} applied. 112 kg N ha^{-1} applied. 224 kg N ha^{-1} applied. No fertilizer. 16.7 metric tons of sewage sludge/ha applied. 83.5 metric tons of sewage sludge/ha applied.
Seiler and Conrad (1981)	$NaNO_3$: 0.01% Eolian sand 0.05% Loess Loam 0.01% Loam NH_4Cl: 0.09% Eolian sand 0.07% Loess Loam 0.03% Loess		Rhein/Main - field study.
Slemr et al. (1984)	Unfertilized grass lawn: 1 μg N m^{-2} hr^{-1} Unfertilized cultivated land: 15 μg N m^{-2} hr^{-1} NH_4NO_3 fertilized grass lawn: 850 μg N m^{-2} hr^{-1} (0.075% of N added) Urea fertilized cultivated land: 200 μg N m^{-2} hr^{-1} (0.18% of N added) NH_4NO_3 fertilized cultivated land: 0.04% of N added	From fertilizer use: 0.015 to 2.2 Tg yr^{-1} Total fertilized and unfertilized: 4.5 to 7.7 Tg yr^{-1}	Andalusia, Spain. Propose that 0.01 to 2% fertilizer N is lost as N_2O globally. Higher results may be due to high soil temperatures or soybean residue. Differences between vegetation in loss rate.

TABLE 3-2. N_2O EMITTED FROM SOILS

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Anderson et al. (1988)	Dry and wetted, unburned: NA Dry, burned: <4.8 ng N m^{-2} s^{-1}		Measured N_2O flux following surface burning. The elevated fluxes lasted 6 months post burn. Vegetation burned was typical of a Mediterranean chaparral ecosystem.
Breitenbeck et al. (1980)	8.6 x 10^{9} molecules N_2O cm^{-2} s^{-1}		Iowa, farmland, fallow, June.
Breitenbeck and Bremner (1989)	43.5 to 104.9 µg N g^{-1} soil $(24\ hr)^{-1}$		Inoculated midwestern soil samples with B. japonicum, strain USDA122, an efficient N_2- fixing rhizobia. In one soil, the amount of N_2O-N evolved in 24 hours was 140% higher than the amount evolved in uninoculated soils.
	105.9 to 119.2 µg N g^{-1} soil $(72\ hr)^{-1}$		Inoculated midwestern soil samples with B. japonicum, strain USDA122, an efficient N_2- fixing rhizobia. The amounts of N_2O-N shown evolved after 72 hours.
Bremner et al. (1980)	8.2 x 10^{9} molecules N_2O cm^{-2} s^{-1}		Iowa, soybean field, 1 year.
Duxbury et al. (1982)	6.1 x 10^{9} molecules N_2O cm^{-2} s^{-1}		New York State. Northern hardwood forest, mineral soil over 1 year.
	6.8 x 10^{9} molecules N_2O cm^{-2} s^{-1}		Florida Everglades, organic soil over 1 year.
	1.9 x 10^{10} molecules N_2O cm^{-2} s^{-1}		New York State, alfalfa, fertilized cornfields, mineral soils over 1 year.
Freney et al. (1979)	3.6 x 10^{9} molecules N_2O cm^{-2} s^{-1}		Canberra, Australia, clovergrass, 5 months.
Goreau and DeMello (1985)	3.2 x 10^{11} molecules N_2O cm^{-2} s^{-1}		Clear cut forest.

TABLE 3-2. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Hao et al. (1988)	2.5 x 10^{9} molecules N_2O cm^{-2} s^{-1} (Undisturbed savannah soils) 1.0 x 10^{10} molecules N_2O cm^{-2} s^{-1} (Following 4 days of simulated rainfall)	1.9 x 10^{11} g yr^{-1}	Measured arithmetic mean of N_2O, CH_4, and CO_2 fluxes in undisturbed and disturbed tropical savanna soils in Venezuela during the dry season. No change was observed following surface burning. Budget estimate assumes a 4 month dry season for tropical savannas.
Hutchinson and Mosier (1979)	< 4 kg ha^{-1} yr^{-1}	6 x 10^{9} kg N yr^{-1}	Harvested cropland.
Keller et al. (1983)	Brazil: 2.6 x 10^{10} molecules N_2O cm^{-2} s^{-1} New Hampshire: 1.0 x 10^{9} molecules N_2O cm^{-2} s^{-1}		Annual means. Tropical and northern hardwood forests.
Keller et al. (1986)	1.7 x 10^{10} molecules N_2O cm^{-2} s^{-1}		75 km NE of Manaus, Brazil. Tropical moist forest.
	2.5 x 10^{10} molecules N_2O cm^{-2} s^{-1}		Puerto Rico, dry season, subtropical moist forest.
Keller et al. (1988)	Control site: 1.4 x 10^{10} molecules N_2O cm^{-2} s^{-1} With NO_3^-: 4.5 x 10^{11} molecules N_2O cm^{-2} s^{-1} With NH_4^+: 7.0 x 10^{10} molecules N_2O cm^{-2} s^{-1} With PO_4^{3-}: 2.1 x 10^{10} molecules N_2O cm^{-2} s^{-1}		Measurements from undisturbed Amazon tropical forests soils. Application of ammonium, nitrate, and phosphate fertilizers resulted in increased emissions within 1 day of application. Microbial reduction of NO_3^- shown to be a large source of N_2O in the Amazon. No change in CO_2 flux was found in response to fertilizer.

TABLE 3-2. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Levine et al. (1988)	<2 ng N m^{-2} s^{-1} (pre-burn) 9 to 22 ng N m^{-2} s^{-1} (post-burn)		Measurements taken in a chaparral ecosystem, heavily burned and wetted to simulate rainfall. Pre- and post-burn measurements of soil ammonium and nitrate indicate that soil ammonium (the substrate for nitrification) increased after burning and soil nitrate (the substrate for denitrification) decreased after burning.
Lipschultz et al. (1981)		10 Tg N yr^{-1}	Lab experiment of NO:N_2O ratio from nitrifying bacteria on a liquid medium. Assume N_2O flux ~ calculated photochemical destruction rate.
Livingston et al. (1988)	Mean: 1.3 ng N cm^{-2} h^{-1}		Measurements taken in three types of Amazonian forest ecosystems.
Luizao et al. (1989)	Cleared-and-burned and forested sites: 1.9 kg N ha^{-1} yr^{-1} Pasture sites: 5.7 kg N ha^{-1} yr^{-1}	0.8 to 1.3 Tg yr^{-1}	N_2O flux compared in tropical forest, cleared-and-burned land and pasture land. Estimate of tropical pasture land area is 2 million km^2.
McKenney et al. (1978)	2.9 x 10^9 molecules N_2O cm^{-2} s^{-1}		California, cornfield, June 1977.
	7.1 x 10^9 molecules N_2O cm^{-2} s^{-1}		California, cornfield, fertilized, June 1977.
	1.12 x 10^{10} molecules N_2O cm^{-2} s^{-1}		California, tobacco field, June 1977.
	5.1 x 10^{10} molecules N_2O cm^{-2} s^{-1}		California, tobacco field, fertilized, June 1977.
Mosier et al. (1981)	5.7 x 10^9 molecules N_2O cm^{-2} s^{-1}		Colorado, natural shortgrass prairie, 62 days through June.

TABLE 3-2. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Mosier and Hutchinson (1981)	3.8 g N ha^{-1} d^{-1}		Cornfield, before irrigation.
	520.0 g N ha^{-1} d^{-1}		Cornfield, 1 day after irrigation.
	550.0 g N ha^{-1} d^{-1}		Cornfield, 2 days after irrigation.
	1.3 g N ha^{-1} d^{-1}		Cornfield, 12 days after irrigation.
	30.0 g N ha^{-1} d^{-1}		Cornfield, 1 day after second irrigation.
	0.30 g N ha^{-1} d^{-1}		Sugarbeet field, before irrigation.
	6.5 g N ha^{-1} d^{-1}		Sugarbeet field, 1 day after irrigation.
	8.2 g N ha^{-1} d^{-1}		Sugarbeet field, 2 days after irrigation.
	0.60 g N ha^{-1} d^{-1}		Sugarbeet field, 12 days after irrigation.
	0.66 g N ha^{-1} d^{-1}		Sugarbeet field, 1 day after second irrigation.
Robertson and Tiedje (1988)	Mid-successional forest: <0.034 ng N m^{-2} $month^{-1}$		Measured denitrification (N_2 + N_2O) in rainforest soils of Costa Rica.
	Primary-forest site: 0.11 ng N m^{-2} $month^{-1}$		In the primary forest soils denitrifiers did not respond to nitrate fertilization.
	Early-successional site: 0.16 g N m^{-1} $month^{-1}$		
Ryden (1981)	-2.7 x 10^9 molecules N_2O cm^{-2} s^{-1}		U.K., field fertilizers, perennial ryegrass, Aug - Oct.
Seiler and Conrad (1981)	0.5 to 2.5 μg m^{-2} hr^{-1}		Mainz, Germany – field study. Loess loam, unfertilized.
	1 to 3 μg m^{-2} hr^{-1}		Loess, unfertilized.
	2 to 13 μg m^{-2} hr^{-1}		Eolian soils, unfertilized.
Smith et al. (1983)	3.0 x 10^9 molecules N_2O cm^{-2} s^{-1}		Louisiana, salt brackish and fresh marshes over 2 years.

TABLE 3-2. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Terry et al. (1981)	Dry periods: 4 g N ha^{-1} d^{-1}		Florida Everglades, cultivated organic soils. N_2O emissions increased with increased soil moisture.
	Following rain: 4500 g N ha^{-1} d^{-1}		
	Total Everglades region: 50 to 150 kg ha^{-1} yr^{-1}		
Schmidt et al. (1988)	4 to 8 μg N m^{-2} h^{-1}	0.7 to 1.5 Tg N yr^{-1}*	Temperate forest soils measured throughout central European forests.
		1.5 to 3.0 Tg N yr^{-1}**	

*Land area for temperate forest soils: 21 x 10^6 km^2.

**For a total temperate land area of 41 x 10^6 km^2 (includes grassland and shrubland).

TABLE 3-3. N_2O EMITTED FROM AQUIFERS

Reference	Emission Factor	Estimate of Land Area	Budget Estimate	Comments/Assumptions/Geographic Area
Ronen et al. (1988)	3.4 to 7.8 kg N ha^{-1} y^{-1}	130 x 10^6 km^2	7.2 x 10^8 to 1.5 x 10^9 kg yr^{-1}	Israel. Aquifers contaminated by human and animal wastes, cultivation, and fertilization. Have high N_2O concentrations. Global estimate assumes that1 percent of world's aquifers are contaminated.

atmosphere as it is oxidized by OH to form NO_x (Levine et al., 1984) (Tables 3-4 and 3-5).

Nitrogen oxides, typically nitric oxide (NO), are emitted from nitrification, denitrification, and nitrate respiration by fermenters (Anderson and Levine, 1986). Oxidation of N_2O in the stratosphere is also a source of NO. Biomass burning has a two-fold effect on NO (and N_2O) fluxes because not only does the burning process produce these compounds, but their emission from soils is enhanced for up to six months post-burn (Anderson et al., 1988) (Table 3-6). Anderson et al. (1988) found that aerobic soils produce NO and anaerobic soils produce N_2O, and the soil oxygen content is controlled by soil moisture. Like N_2O, NO_x emissions thus vary because of biomass burning, soil moisture content, use of fertilizers, season, and soil type.

3.3 NITROGEN OXIDES AND NITROUS OXIDE FROM LIGHTNING AND OCEANS

Atmospheric measurements, laboratory experiments, and theoretical calculations are used to estimate the NO_x and N_2O emissions from lightning (Table 3-7). The production of these compounds and the prediction of a budget estimate are dependent on assumptions concerning energy per discharge, number of flashes per second (or number of flashes annually per area), and seasonal and hemispheric variations. Brandvold and Martinez (1988) found that the N_2O/NO_x ratio was not constant in relation to energy, but instead was dependent on discharge conditions. In general, NO is assumed to be produced in greater amounts than NO_2, and NO_x production is greater than N_2O production, but great uncertainty exists in the estimate of total NO_x and N_2O produced from lightning.

The role of the ocean in the nitrogen cycle is also not well understood (Table 3-8). Oxidation of organic matter is a source of aquatic N_2O, but there is no evidence that the ocean acts as a sink (Elkins et al., 1978). The kinetics of the reactions of NO in water are also not well understood (Logan, 1983).

TABLE 3-4. NO_x EMITTED FROM SOILS

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Anderson and Levine (1987)	0.53 kg N ha^{-1} yr^{-1}		NO. Jamestown, VA. Year-long study.
Anderson et al. (1988)	Dry, unburned: 9.7 ng N m^{-2} s^{-1} Wetted (1 day), unburned: 21.4 ng N m^{-2} s^{-1} Wetted (7-11 days), unburned: NA* Wetted (180 days), unburned: 1.1 ng N m^{-2} s^{-1} Dry, burned: 13.3 ng N m^{-2} s^{-1} Burned and wetted (1 day): 60.7 ng N m^{-2} s^{-1} Burned and wetted (7-11 days): 23.7 ng N m^{-2} s^{-1} Burned and wetted (180 days): 22.3 ng N m^{-2} s^{-1}		Measured NO flux following surface burning. The elevated fluxes lasted six months post burn. Vegetation was typical of a Mediteranean chaparral ecosystem.
Baulch et al. (1982)		0 to 15 Tg N yr^{-1}	

*NA = Not measured.

TABLE 3-4. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Delany et al. (1985)	Daily average: 7×10^{-12} kg N m^{-2} s^{-1} Range: -9.3 to 28.0×10^{-12} kg N m^{-2} s^{-1}		Crested wheat grass.
Ehhalt and Drummond (1982)		5.5 Tg N yr^{-1} (1 to 10 Tg N yr^{-1})	
Galbally and Roy (1978)	0.5 to 1.1 kg N ha^{-1} yr^{-1}	10 Tg N yr^{-1}	12 flux measurements, no correction for seasonal or diurnal variability. Ungrazed and grazed grasslands.
Galbally and Roy (1981)	Grazed pasture (range): 1 to 50 $\times 10^{-12}$ kg N m^{-2} s^{-1} Grazed pasture (average): 3.5×10^{-12} kg N m^{-2} s^{-1} Ungrazed pasture (average): 1.6×10^{-12} kg N m^{-2} s^{-1}		
Galbally et al. (1987)	0.2 to 1.0 ng N m^{-2} s^{-1}		Fertilized rice field.
Johansson (1984)	Median: 0.3×10^{-12} kg N m^{-2} s^{-1} Range: 0.1 - 0.8 $\times 10^{-12}$ kg N m^{-2} s^{-1}		Unfertilized forest soil.
Galbally and Johansson (1989)	3 to 11 $\times 10^{-9}$ g N m^{-2} s^{-1}		NO. Model calculation prepared for comparison with NO flux presented by Johansson and Granat (1984) (2 to 17 $\times 10^{-9}$ g N m^{-2} s^{-1}).

TABLE 3-4. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Johansson and Granat (1984)	Fertilized grass: 0.6 kg N ha^{-1} yr^{-1} Unfertilized barley: 0.2 kg N ha^{-1} yr^{-1}		NO. Sweden: April-July, September.
Johansson and Sanhueza (1988)	7 month rainy season: 0.2 to 1.2 g N m^{-2}		NO. Measurements taken from a woodland savanna of Venezuela. Annual estimate obtained by combining rainy season estimate with dry season measurement in Johansson et al. (1988). Savanna, Ecuador.
Johansson et al. (1988)	Dry season, undisturbed: 8 ng N m^{-2} s^{-1} Dry season, burned: 25 ng N m^{-2} s^{-1} Dry season, total (5 mo.): 100 mg N m^{-2} yr^{-1} Simulated rain (wet season, 7 mo.): 200 mg N m^{-2} yr^{-1} Wet and dry savannah total: 0.4 to 0.5 g N m^{-2} yr^{-1} Cloud forest, undisturbed: < 0.2 to 2 ng N m^{-2} s^{-1}		NO. Measured in the Venezuelan savannah and cloud forest during the dry season and with simulated rainfall and burning. No change was seen with the addition of water to the cloudforest soil. An additional 100 mg N m^{-2} yr^{-1} are emitted with the fire plume for biomass burning in the total savannah emission estimate.
Kaplan et al. (1988)	9.2 x 10^{-12} to 16 x 10^{-12} kg N m^{-2} s^{-1}		NO. Measured emission rates and O_3 deposition in the Amazon Region.

TABLE 3-4. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Levine et al. (1984)		10 Tg N yr^{-1}	NO. Assume soil nitrification is at least 5 x 10^{12} g(N) yr^{-1} of N_2O and using measured NO:N_2O ratio = 2 in media at low oxygen. Also assume all produced is released to atmosphere.
Levine et al. (1988)	> 40 ng N m^{-2} s^{-1}		NO. Measurements taken in a chaparral ecosystem, heavily burned and wetted to simulate rainfall. Increase of 2 to 3 over preburn wetted measurements.
Levine et al. (1990)	0.34 ± 0.14 ng N m^{-2} s^{-1} 0.22 ± 0.11 ng N m^{-2} s^{-1} 1.80 ± 0.68 ng N m^{-2} s^{-1} 0.68 ± 0.29 ng N m^{-2} s^{-1} 0.43 ± 0.00 ng N m^{-2} s^{-1} 0.04 ± 0.01 ng N m^{-2} s^{-1}		Southern Florida; brackish marsh following burn.
	0.14 ± 0.038 ng N m^{-2} s^{-1} 0.13 ± 0.04 ng N m^{-2} s^{-1} 0.10 ± 0.01 ng N m^{-2} s^{-1} 0.90 ± 0.035 ng N m^{-2} s^{-1}		Southern Florida; brackish marsh before burn.
	1.290 ± 0.5 ng N m^{-2} s^{-1} 0.800 ± 0.04 ng N m^{-2} s^{-1} 0.387 ± 0.01 ng N m^{-2} s^{-1} 0.530 ± 0.02 ng N m^{-2} s^{-1} 0.380 ± 0.01 ng N m^{-2} s^{-1} 0.370 ± 0.01 ng N m^{-2} s^{-1} 0.392 ± 0.01 ng N m^{-2} s^{-1}		Southern Florida; following burn.
	0.858 ± 0.04 ng N m^{-2} s^{-1} 0.262 ± 0.005 ng N m^{-2} s^{-1} 0.115 ± 0.001 ng N m^{-2} s^{-1} 0.254 ± 0.005 ng N m^{-2} s^{-1} 0.230 ± 0.005 ng N m^{-2} s^{-1} 0.249 ± 0.005 ng N m^{-2} s^{-1}		Southern Florida; following flooding and burn.
	0.058 ± 0.001 ng N m^{-2} s^{-1}		Southern Florida; unburned.
Lipschultz et al. (1981)		14 Tg N yr^{-1}	Lab experiments of NO:N_2O ratio from nitrifying bacteria on a liquid medium.

TABLE 3-4. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Logan (1983)		8 Tg N yr^{-1}	Observation by one group in Australian growing season. Primarily NO.
		10 Tg N yr^{-1}	Assuming NO and N_2O production by nitrifying bacteria are equal and using N_2O number.
National Academy of Sciences (1984)		1 to 10 Tg N yr^{-1}	NO.
Slemr and Seiler (1984)	Average: 2.2×10^{-12} kg N m^{-2} s^{-1} Range: -5.8 to 14.2×10^{-12} kg N m^{-2} s^{-1}		Bare, unfertilized soil, Finthen.
Stedman and Shetter (1983)		10 Tg N yr^{-1} (5 to 20 Tg yr^{-1})	NO.
Wesley et al. (1989)	Moist unsaturated soils: 1.4 to 4.2 ng m^{-2} s^{-1}		NO. NE Illinois, measured 8 meters above lush grass.
Williams et al. (1987)	3 ng N m^{-2} s^{-1}		Ungrazed grassland.
Williams et al. (1988)	Cleared forest, NO average: 1.20 ng N m^{-2} s^{-1} Cleared forest, NO_2 0.077 ng N m^{-2} s^{-1} Wheat field, NO average: 1.2 ng N m^{-2} s^{-1} Wheat field, NO_2 average: 0.0071 ng N m^{-2} s^{-1} Corn field, NO average: 94 ng N m^{-2} s^{-1}		Measurements taken in central Pennsylvania. Strong correlation found between temperature and NO emission for all sites and soil types. Soil moisture and pesticides also have potential influence.

TABLE 3-4. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Williams et al. (1988) (Continued)	Corn field, NO_2 average: 3.8 ng N m^{-2} s^{-1}		
Wofsy et al. (1988)	1 ng N m^{-2} s^{-1}		Amazon Forest, wet season.

TABLE 3-5. NO_x EMITTED FROM NH_3 OXIDATION

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Ehhalt and Drummond (1982)		3.1 Tg N yr^{-1} (1.2 to 4.9 Tg yr^{-1})	NO.
Levine et al. (1984)		15 Tg N yr^{-1}	Estimate of upper limit source strength based on NH_3 lifetime against OH destruction (40 d.) and rainout (10 d.) ~ 20% will react with OH. Assume all NH_3 oxidized by OH ----> NOx and 80 x 10^{12} g(N) yr^{-1} NH_3 production in N. Hemisphere.
Logan (1983)		1 to 10 Tg N yr^{-1}	Mechanism unclear, one product (NH_4) may be a sink. Based on rate of reaction NH_3 with OH, [NH_3] distribution and [OH] distribution in the troposphere.
National Academy of Sciences (1984)		$\leq$ 5 Tg N yr^{-1}	NO.
Stedman and Shetter (1983)		1 Tg N yr^{-1} (0.5 to 2 Tg yr^{-1})	NO.

TABLE 3-6. NO_x and N_2O EMITTED FROM BIOMASS BURNING

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Andreae et al. (1988)		Global estimate: 7.6 Tg N yr^{-1} (Range: 1.5 to 16.3 Tg N yr^{-1})	Based on emission ratios calculated from measurements of biomass-burning plumes.
		South American Tropics: 1.3 Tg N yr^{-1}	
Baulch et al. (1982)		10 to 40 Tg N yr^{-1}	
Cofer et al. (1988)	0.0018 ± 0.00010 $\Delta N_2O/\Delta CO_2$		Los Angeles, CA. Plume samples collected from intense flaming and mixed fire. CO_2 higher with full flames (vol/vol).
Cofer et al. (1989)	Flaming: 0.014 to 0.019 $\Delta N_2O/\Delta CO_2$		Samples collected by helicopter from burning chaparral in S. California and over a boreal forest fire in Ontario, Canada (vol/vol).
	Mixed: 0.019 to 0.021 $\Delta N_2O/\Delta CO_2$		
	Smoldering: 0.039 ± 0.008 $\Delta N_2O/\Delta CO_2$		
Crutzen et al. (1979)		50 Tg N yr^{-1} (20 to 100 Tg range)	Upper limit NO_x, based on N content, average maximum global N/C ratio = 1.5 - 2.5%.
		14 Tg N yr^{-1} as NO_x	Based on the measured ratios of the trace gas to CO_2 under various conditions. NO_x/CO_2 = 0.47% average ratio.
		200 Tg N_2O yr^{-1}	Based on the N_2O/CO_2 = 0.22% average ratio.
		~13 Tg N_2O yr^{-1}	Based on maximum observed N_2O/CO_2 = 0.4%, average global.

TABLE 3-6. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area			
			Burned and/or cleared area (10^6 hectare)	Total Biomass cleared (100 Tg dry matter)	Annually burned biomass (100 Tg dry matter)	
Crutzen et al. (1979) (Continued)			21 - 62	31 - 92	9 - 25	-Burning due to shifting agriculture
			8.8 - 15.1	20 - 33	5.5 - 8.8	-Deforestation due to population increase and colonization
			600	12.2 - 23.8	4.8 - 19	-Burning of savanna and bushland
			3.0 - 5.0	10.5 - 17.5	1.5 - 2.6	-Wild fires in temperate forests
			2.0 - 3.0	1.2 - 1.8	0.1 - 0.2	-Prescribed fires in temperate forests
			1.0 - 1.5	2.5 - 3.8	0.4 - 0.6	-Wild fires in boreal forests
			17 - 21			-Burning of agriculture wastes

TABLE 3-6. (Continued)

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Ehhalt and Drummond (1982)		11.2 Tg N yr^{-1} (5.6 to 16.4 Tg N yr^{-1})	NO.
Logan (1983)		12.5 Tg N yr^{-1} (0.25 to 18.75 Tg yr^{-1} range)	Based on estimate of 25% of global NO_x results from this source.
National Academy of Sciences (1984)		1 to 10 Tg N yr^{-1}	NO.
Stedman and Shetter (1983)		5 Tg N yr^{-1}	NO.

TABLE 3-7. NO_x AND N_2O EMITTED FROM LIGHTNING

Reference	Emission Factor	Budget Estimate	Flash Density/ Flash Frequency/ Energy Deposited*	Comments/Assumptions/Geographic Area
Baulch et al. (1982)		3 to 4 Tg N yr^{-1}		NO.
Brandvold and Martinez (1988)	1.0 ± 0.2 x 10^{-7} moles NO_x $joule^{-1}$			NO_x (NO + NO_2). Between 0.005 and 0.1 joules, NO, production was linear with electrical discharge energy. N_2O/NO_x ratio not constant in relation to energy, depends instead on the discharge conditions.
Chameides et al. (1977)	3 to 7 x 10^{16} molecules NO_x $joule^{-1}$	30 to 40 Tg N yr^{-1}	1.6 x 10^{-7} joules cm^{-2} s^{-1}	Theoretical calculations; global production range using lab experiments corresponds.
Chameides (1979)	8 to 17 x 10^{16} molecules NO_x $joule^{-1}$	35 to 90 Tg N yr^{-1}	1.6 x 10^{-7} joules cm^{-2} s^{-1}	Theoretical calculations.
Dawson (1980)		3 Tg N yr^{-1}		Theoretically calculated, used revised parameters for lightning.
Donohue et al. (1977)		1.4 x 10^6 kg N_2O yr^{-1}		
Drapcho et al. (1983)	40 x 10^{25} molecules NO_x $stroke^{-1}$	30 Tg N yr^{-1}	100 flashes s^{-1}	Atmospheric measurements.
Ehhalt and Drummond (1982)		5 Tg N yr^{-1} (2 to 8 Tg N yr^{-1})		NO.
Franzblau and Popp (1989)	3 x 10^{27} molecules NO_x $flash^{-1}$	100 Tg N yr^{-1}	100 flashes s^{-1}	NO_x. Atmospheric measurements.

*Average value of 5 strokes $flash^{-1}$ often assumed (Logan, 1983).

TABLE 3-7. (Continued)

Reference	Emission Factor	Budget Estimate	Flash Density/ Flash Frequency/ Energy Deposited*	Comments/Assumptions/Geographic Area
Golde (1977)			Germany: 4.0 x 10^{-6} flashes min^{-1} km^{-2} UK: 0.5 - 11.5 x 10^{-6} flashes min^{-1} km^{-2} USSR: 14.0 x 10^{-6} flashes min^{-1} km^{-2} Australia: 6.0 x 10^{-6} flashes min^{-1} km^{-2} Switzerland: 20.0 x 10^{-6} flashes min^{-1} km^{-2} Singapore: 60.0 x 10^{-6} flashes min^{-1} km^{-2} Sweden: 4.5 x 10^{-6} flashes min^{-1} km^{-2} Thailand: 44.7 x 10^{-6} flashes min^{-1} km^{-2}	
Hill et al. (1980)		4.4 Tg N yr^{-1}		Theoretically calculated, used revised parameters for lightning.
Hill et al. (1984)	1 x 10^{24} molecules N_2O yr^{-1}	2.0 x 10^{6} kg N_2O yr^{-1}		Independent of any assumptions of typical dissipation energy/stroke, assume 3 strokes/flash, 300 flashes/ second.
	5 x 10^{29} to 1 x 10^{31} molecules N_2O yr^{-1}	3.6 x 10^{4} to 7.2 x 10^{5} kg N_2O yr^{-1}		Assumes power dissipation of typical corona = 5.56 x 10^{6} W, total number storms = 2400, total energy = 1.75 x 10^{14} joules yr^{-1}.

*Average value of 5 strokes $flash^{-1}$ often assumed (Logan, 1983).

TABLE 3-7. (Continued)

Reference	Emission Factor	Budget Estimate	Flash Density/ Flash Frequency/ Energy Deposited*	Comments/Assumptions/Geographic Area
Levine et al. (1979)	4×10^{17} molecules N_2O joule^{-1} Global production rate: 6×10^{5} molecules N_2O cm^{-2} s^{-1} (3.5×10^{9} g N yr^{-1}		1.5×10^{-7} joules cm^{-2} s^{-1}	N_2O. Lab experiment: 10^{5} - 10^{6} joules/m. Extrapolated to global contribution, but based on average global dissipation.
Levine et al. (1981)	$5 \pm 2 \times 10^{16}$ molecules NO joule^{-1}	1.8 ± 0.7 Tg N yr^{-1}	1×10^{-8} joules cm^{-2} s^{-1}	NO. Lab experiment used revised parameters for lightning that result in a lower global dissipation energy. Lightning frequency ~70% greater in N. Hemisphere than S. Hemisphere.
Livingston and Krider (1978)			Florida: 365.0×10^{-6} flashes min^{-1} km^{-2} S. Africa: 38.6×10^{-6} flashes min^{-1} km^{-2}	Numbers are total flash densities.
Logan (1983)		8 Tg N yr^{-1} (2 to 20 Tg range)		NO_x. Uses empirical to modify other published values. Range should accommodate uncertainties in both production rate per flash and the global frequency of lightning.
Martinez and Ohline (1988)	2.4×10^{-9} moles NO_x discharge^{-1} (0.02 joules discharge^{-1}) 3.4×10^{-9} moles NO_x discharge^{-1} (0.03 joules discharge^{-1})			

*Average value of 5 strokes flash^{-1} often assumed (Logan, 1983).

TABLE 3-7. (Continued)

Reference	Emission Factor	Budget Estimate	Flash Density/ Flash Frequency/ Energy Deposited*	Comments/Assumptions/Geographic Area
Martinez and Ohline (1988) (Continued)	4.7×10^{-9} moles NO_x discharge^{-1} (0.04 joules discharge^{-1})			
	9×10^{-9} moles NO_x discharge^{-1} (0.08 joules discharge^{-1})			
National Academy of Sciences (1984)		2 to 20 Tg N yr^{-1}		
Noxon (1976)	$10 \text{ to } 20 \times 10^{25}$ molecules NO_x stroke^{-1}	7 Tg N yr^{-1}		Atmospheric measurements. 100 flashes/ sec used by Dawson (1980) to calculate global production.
Peyrous and Lapeyre (1982)	$1.6 \text{ to } 2.6 \times 10^{16}$ molecules joule^{-1}	9.25 to 15.5 Tg N yr^{-1}	1.57×10^{-7} joules cm^{-2} s^{-1}	Laboratory experiments. Original paper reported annual production in grams of NO_x and grams NO; converted to annual fixation rate.
Stedman and Shetter (1983)		3 Tg N yr^{-1} (1.5 to 6 Tg N yr^{-1})		NO.
Tuck (1976)	1.1×10^{25} molecules NO_x stroke^{-1}	4 Tg N yr^{-1}	6×10^{8} joules cm^{-2} s^{-1}; 500 strokes s^{-1}	Theoretical calculations. Global estimate calculated by Levine et al.
Turman and Edgar (1982)			40 to 120 flashes s^{-1} Seasonal variation ~10%	Uses Defense Meteorol. Satellite Program data. More detailed information on a bimonthly basis, August - June. Limitations of data are imposed by the sensor design.

*Average value of 5 strokes flash^{-1} often assumed (Logan, 1983).

TABLE 3-8. NO_x and N_2O EMITTED FROM OCEANS

Reference	Emission Factor	Budget Estimate	Comments/Assumptions/Geographic Area
Cohen and Gordon (1979)		4 to 10 Tg N yr^{-1} (6 to 10 Tg N_2O yr^{-1})	N_2O. Used a marine N cycle from a global model to estimate N_2O; Compared estimates to measured N_2O at sea surface. Assumed a mineralization rate of 2000 Tg N yr^{-1} as an estimate of oxidative production of nitrate in the ocean, and an average value of 0.2% for the N_2O/NO_3 ratio. Data lacking for southern oceans.
Logan (1983)		0.5 Tg N yr^{-1}	NO_x. Author states that kinetics of reactions of NO in water not well understood. Number based on one group's flux estimate.
McElroy et al. (1976)		0.09 Tg N yr^{-1} max. from marine sources	N_2O. Central Pacific, Peru, Chesapeake Bay and various ponds and rivers. Assume C:N = 6.6 for marine biosphere.

SECTION 4
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