Reports

Termites: A Potentially Large Source of Atmospheric Methane, Carbon Dioxide, and Molecular Hydrogen

Abstract. *Termites may emit large quantities of methane, carbon dioxide, and molecular hydrogen into the atmosphere. Global annual emissions calculated from laboratory measurements could reach 1.5 × 10^{14} grams of methane and 5 × 10^{16} grams of carbon dioxide. As much as 2 × 10^{14} grams of molecular hydrogen may also be produced. Field measurements of methane emissions from two termite nests in Guatemala corroborated the laboratory results. The largest emissions should occur in tropical areas disturbed by human activities.*

Methane is an important atmospheric trace gas which affects the chemistry of the troposphere (*1*) and of the stratosphere (*2*). It is also a "greenhouse gas" with the potential to affect the earth's radiation balance (*3*). Major sources of methane emissions into the atmosphere are rice paddy fields, natural wetlands, enteric fermentation processes in ruminants, biomass burning, and leakage from geologic gas reservoirs (*4–8*). All biological methane production occurs in anaerobic environments (*9*). The estimated tropospheric reservoir of methane is 4.8 × 10^{15} g (*6*). The estimated annual global production of methane is 3.5 × 10^{14} g (*6*) to 12.1 × 10^{14} g (*7*). It was suggested recently that the methane content of the atmosphere has been increasing by roughly 2 percent annually (*9*).

Methane has been found in the guts of various xylophagous insects, including scarab beetles (*Oryctes*), wood-eating cockroaches (*Cryptocercus*), and various lower termites (*Reticulitermes*, *Cryptotermes*, *Coptotermes*) (*10, 11*). Termites have the potential to release large quantities of methane into the atmosphere. They occur on about two-thirds of the earth's land surface; they process large amounts of biomass; their digestion is primarily dependent on anaerobic decomposition by symbiotic bacteria in the higher termites (family Termitidae) and by protozoans in the lower termites (all other families); and their digestion efficiency [(carbon ingested − carbon in feces)/(carbon ingested)] is high, usually greater than 60 percent (*12*). In addition, human activities, including clearing of tropical forests and conversion of forests to grazing and agricultural land, tend to increase the density of termites.

We have made laboratory measurements of the emission of CH_4, CO_2, H_2, CO, C_2 to C_{10} hydrocarbons, and reduced sulfur species from *Reticulitermes tibialis* Banks (family Rhinotermitidae), a representative of the lower termites, and *Gnathamitermes perplexus* Banks (family Termitidae), a representative of the higher termites (*13*). In addition, emissions from arboreal nests of an unidentified species of Nasutitermitinae (family Termitidae) were sampled in the field in Guatemala and analyzed for CH_4 and C_2 to C_{10} hydrocarbons (*14*).

Table 1 shows the mean emission rates ($\bar{X}$) and standard errors ($s/\sqrt{n}$) for CH_4, CO_2, and CO from three *Reticulitermes* and two *Gnathamitermes* colonies (*15*); n is the number of days on which samples were analyzed during the 55-day study period. Repetitive samples collected during each sampling day showed little variability (± 10 percent). The variability between days was sometimes much higher. These emission rates are about in the middle of the range of methane production rates reported by Breznak (*11*). This agreement is good considering the differences between the techniques used in the two investigations.

A Student's t-test (*16*) comparing the mean methane emission rates of our *Reticulitermes* and *Gnathamitermes* colonies showed that the difference was not significant at the 5 percent confidence level (t = 1.14). We therefore did not attempt to differentiate between higher and lower termite populations in our global estimate of potential trace gas production. The emission rate data were not directly used since termite consumption rates vary greatly with species and location (*17, 18*). However, since digestion processes are similar among termite species (*12*), we used emission yields (emission mass/carbon ingested) to calculate potential global trace gas production. For our five colonies of termites, 0.77 percent of the carbon ingested was reemitted as CH_4, 84.8 percent as CO_2, and 0.03 percent as CO. The yield in grams of dimethyl disulfide (DMDS) emitted per gram of carbon ingested was 0.005 percent. The standard deviations of the average emission yields of the five nests were 0.49, 40.4, and 0.01 percent for CH_4, CO_2, and CO, respectively (*19*).

These emission yields represent the average conversion efficiencies over the entire experiment. When the termites were first collected and placed in the cultures, their CH_4 yield per carbon ingested was about twice as high. We do not know which efficiency is most representative of field conditions. The CH_4 yield of the Nasutitermitinae nests measured in the field could not be quantified, since the amount of food required to produce the CH_4 in the gas samples collected was not measured. However, based on estimates of the number of individuals per nest (*20*), the CH_4 emission rate was in the same range as that of the species used in the laboratory studies.

Our estimate of the global ecological significance of termites is shown in Table 2. The ecological impact of termites, as indicated by the ratio of material con-

Table 1. Normalized emission rates per termite; R1, R2, and R3 represent three different colonies of *R. tibialis* Banks and G1 and G2 represent two different colonies of *G. perplexus* Banks.

Colony	CH_4 (μg/day)			CO_2 (mg/day)			CO (μg/day)		
	$\bar{X}$	$s/\sqrt{n}$	n	$\bar{X}$	$s/\sqrt{n}$	n	$\bar{X}$	$s/\sqrt{n}$	n
R1	0.447	0.023	21	0.091	0.005	10	0.006	0.003	11
R2	0.237	0.016	22	0.107	0.010	11	0.018	0.008	10
R3	0.592	0.031	22	0.137	0.010	11	0.060	0.014	10
G1	0.456	0.042	11	0.410	0.026	7	0.091	0.019	7
G2	0.338	0.034	11	0.210	0.023	7	0.053	0.017	7

0036-8075/82/1105-0563$01.00/0

sumed by the termites to net primary productivity (NPP), is greatest for wet savanna, temperate grasslands, cultivated land in underdeveloped countries, and areas that have been cleared and burned. Most of these areas are increasing in size due to human activities. For example, wet savanna is often created as the result of clearing of tropical forest for grazing.

Table 2 also shows that the areas occupied by termites account for 68 percent of the earth's land area and 77 percent of the terrestrial NPP. The world's termite population (2.4×10^{17}) processes material equivalent to 28 percent of the earth's annual NPP and an average of 37 percent of the NPP in areas where they occur. The biomass consumption figures in Table 2 should be considered as rough estimates since the figures used to compute termite consumption were based primarily on data for nonbreeding laboratory cultures. However, the ratios of termite consumption to NPP calculated for this study agree fairly well with values reported in the literature (numbers in parentheses in Table 2).

The last column of Table 2 shows that the potential global production of CH_4 by termites is 1.5×10^{14} g (1.1×10^{14} g of carbon). Values in this column were calculated by multiplying the trace gas emission yield by the total termite consumption (converted to grams of carbon).

Termites are a potentially important source of atmospheric methane; they could account for a large fraction of global emissions (*6, 7*). The ecological areas that should have the largest methane emissions from termites are tropical wet savanna, areas that have been cleared or burned, and cultivated land in developing countries. All these areas have increased due to human activities (see footnotes in Table 2). Using the same calculation procedure for other trace gases yields 4.6×10^{16} g of CO_2 (1.3×10^{16} g of carbon), 10^{13} g of CO (0.4×10^{13} g of carbon), and 7×10^{11} g of DMDS.

The estimated gross amount of CO_2 produced is more than twice the net global input from fossil fuel combustion (5.4×10^{15} g of carbon per year) (*21*). As we noted above, termites process the equivalent of about 28 percent of the earth's NPP. Although CO_2 would probably be released as the result of any decomposition process, termites serve to accelerate carbon cycling.

The emissions of the other trace gases that we measured are small. The emission of 10^{13} g of CO by termites, although comparable to the estimated direct CO emission by plants (*22*), is small compared to the overall production in the environment, 2×10^5 g to 5×10^5 g of CO annually (*6*). Emissions of DMDS are also relatively small and amount to less than 1 percent of the total biogenic sulfur budget (*23*).

The emission of nonmethane C_2 to C_{12} hydrocarbons by the termites studied in the laboratory was insignificant with respect to global hydrocarbon emission from vegetation (*24*). The Nasutitermitinae nests sampled in the field emitted large quantities of hydrocarbons. The primary components were not positively identified; however, they were probably oxygenated monoterpene hydrocarbons. Large hydrocarbon emissions are expected since Nasutitermitinae soldiers are modified for chemical warfare (*25*). The enclosure procedure used during sampling probably stimulated their attack.

Stoichiometrically, the evolution of hydrogen gas from termites is equivalent to approximately 10 percent of their CO_2 production (*26*). Termites could therefore potentially produce about 2×10^{14} g of H_2 per year globally. The gross annual production of H_2 has been estimated as 5×10^{13} g to 11×10^{13} g (*27*). Although an unknown fraction of the H_2 produced by termites may be consumed within the soil, termites could be an important source of atmospheric H_2. Periodic measurements of H_2 emissions from our laboratory termite colonies were made with a radio-frequency analyzer (*28*) and confirm that H_2 gas is emitted from our cultures. We have not yet made enough measurements to allow us to update earlier H_2 emission estimates.

These trace gas emission estimates are not advanced as definitive. The laboratory measurements on which these potential emission estimates are based have an uncertainty of ± 50 percent. There is additional uncertainty in our estimates of the significance of termites in various ecosystems and in the assumption that the termites we used in our experiments are representative of all species. Also, soil microorganisms may consume or modify some of the termite emissions under field conditions. We estimate that all of these uncertainties may cause the actual gas productions to vary from those reported here by a factor of 2. Thus for methane the emissions could range from 0.75×10^{14} to 3.1×10^{14} g.

Table 2. Termite global biomass consumption. Termite densities are discussed in (*33*). Total termite consumption was calculated from table 4.1 of Wood (*17*); one consumption value that was ~ ten times lower than any of the other values was omitted from the calculation.

Ecological region	Area (10^{12} m^2)	NPP (g/m^2-year, dry weight)	Total biomass produced (10^{15} g/year, dry weight)	Termites per square meter	Total termite consumption (10^{15} g, dry weight)	Percent of biomass consumed by termites (calculated)	Annual CH_4 production (10^{12} g)
Tropical wet forest*	4.6	1200	5.5	1000	0.6	12	2.9
Tropical moist forest*	6.1	1500	9.2	4450	3.8	41(30)†	17.3
Tropical dry forest*	7.8	1200	9.4	3163	3.4	36	15.7
Temperate‡	12.0	1250	15.0	600	1.0	7	4.6
Wood/shrub land‡	8.5	700	6.0	431	0.5	9	2.3
Wet savanna§	14.2	1200	17.0	4402	8.7	51(31–47)†	39.9
Dry savanna§	4.3	900	3.9	861	0.5	13(10)†	2.3
Temperate grassland‡	9.0	600	5.4	2139	2.7	50(47)†	12.4
Cultivated land ‖	11.9	650	7.7	2813¶	4.7	60¶	21.6
Desert scrub‡	18.0	90	1.6	229	0.6	38	2.8
Clearing burning**	6.8		9.6	6825	6.5	68	29.8
Total	103.2		90.3	2.4×10^{17}	33.0	37	151.6
Percent of total terrestrial‡	68		77		28		

*See (*29*). †Literature estimate of the percent of biomass consumed by termites in each ecological region (*33*). ‡See (*30*). §Area of wet and dry savannah was calculated by multiplying the ratio of wet to dry savanna (*31*) by the area for savanna in (*30*). Since the area of tropical forest reported in (*30*) has been reduced, part of the reduction has resulted in an increase in cultivated land and part has resulted in an increase in wet savanna (grazing) (*29*). We assumed that half of the tropical forest decrease was converted into each ecological type. Therefore, the area of wet savanna was increased accordingly. ‖ This area was calculated from data in (*32*). It includes the area of cultivated land in undeveloped countries plus half the area removed from Whittaker and Likens' estimate (*30*) of tropical forest. ¶This value for cropland after repeated cultivation was 4966 m^{-2} (*33*). Use of this termite density results in a consumption higher than the NPP of cropland estimated in (*30*). The value used here was calculated from estimates of agricultural residues remaining after harvest and burning (*32*) and termite consumption (*17*). **Only areas in developing countries affected by clearing and burning [derived from (*32*)] were included in this total. The area required for production of industrial and fuel wood in developing countries was estimated by dividing the total production figures in (*32*) by a phytomass estimate of 35 kg/m^2 (*30*).

Although additional fieldwork is needed to narrow the uncertainty, this work indicates that termites have the potential to significantly influence the atmospheric budgets of some important trace gases.

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13. *Reticulitermes tibialis* Banks individuals were collected in Colorado near the National Center for Atmospheric Research by placing 15-cm square pieces of corrugated cardboard under rocks where termites had been observed. Within 1 month each piece of cardboard typically contained 119 to 2000 individuals. *Gnathamitermes perplexus* Banks specimens were collected in Arizona pastures in cow dung and shipped to our laboratory. Because each termite sampling site could have represented a discrete colony, the individuals from each site were kept in a separate culture.

Each culture container was prepared by placing a 4-cm layer of pea gravel in the bottom of a 1-liter glass canning jar. The gravel was followed by a thin layer of glass wool and an 8-cm layer of sand. Each jar was moistened with 150 ml of distilled water. About 0.3 liter of head space remained in each jar. The jars, gravel, and sand were washed with distilled water and baked at 200°C for 15 hours before use. The lids of the jars were modified with 1/8-inch (outer diameter) copper inlet and outlet tubes. The colony of *Reticulitermes* that was analyzed for sulfur emissions was kept in an all-Teflon container prepared as described above and equipped with Teflon inlet and outlet lines. A flow of clean air (produced by an Aadco model 737 pure air generator with a methanizer option) at 10 ml/min was passed through each culture. The jars were placed in a thermostatically controlled water bath maintained at 30°C. The number of termites placed in each jar varied from 119 to 2000. All termites were counted at the beginning and at the end of the experiment. *Reticulitermes* cultures were fed a diet of sweet gum (*Liquidambar styraciflua*) pretreated with the fungus *Gloephyllum trabeum*. The *Gnathamitermes* were fed a diet of cow manure.

Blanks were prepared and treated in an identical manner except that no termites were added. Some blanks included cow manure, others included fungus-treated wood. When the termites were removed from some jars that had been occupied for periods of a few weeks to 6 months, methane emissions were reduced to zero. Conversely, no methane uptake could be detected from any of the blanks. This indicates that methane-oxidizing bacteria were not present or that their activity was too low to affect methane concentrations during this experiment.

Termite food consumption was calculated from the weight loss of the food placed in each culture. Food was dried at 70°C for approximately 12 hours before it was weighed. Termites consume their dead; therefore, the estimated weight of the dead termites was added to the weight of the food consumed to calculate emission yields. We used 0.45 as the ratio of the carbon in the food to the food dry weight (*32*).
14. The field enclosure method used was similar to that described for vegetation by P. R. Zimmerman, in *Final Report EPA-450/4-79-004* (Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, N.C., March 1979).
15. Measurements were collected from three *Reticulitermes* and two *Gnathamitermes* colonies. Some gas samples were removed with a 10-ml gas-tight syringe (Precision Sampling Co.). For others, the exhaust line of the jar was connected directly to the sampling loop of a six-port sampling valve (Carle, model MK-2). The samples were analyzed chromatographically for CH_4, CO, and CO_2 by the method described by Rasmussen and Khalil (*9*); for C_2 to C_{10} hydrocarbons by the method of P. R. Zimmerman [*EPA 904/9-77-028, appendix C* (Environmental Protection Agency Region IV Air and Hazardous Materials Division, Atlanta, 1979)] and for reduced sulfur compounds by the method of S. O. Farwell *et al.* [*Anal. Chem.* **51**, 609 (1976)].
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19. An average emission yield was calculated for each of the five colonies. The standard deviation reported here represents the dispersion among these five data points. The DMDS conversion efficiency reported is the average of two samples collected from one colony; therefore, no standard deviation was calculated.
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33. Termite densities are from T. G. Woods and W. A. Sands [in (*18*), pp. 245–292]. Woods and Sands estimate O_2 consumption for termites in various ecosystems from termite densities and body sizes and from this calculate energy flows and biomass consumption. Our global estimates of biomass consumption, termite densities, and CO_2 evolution result in a calculated O_2 consumption per termite that is in good agreement with their experimental data.
34. We thank F. M. Weesner, who developed methods for collecting and handling the termites and provided us with some of the *R. tibialis* and with valuable advice. We thank R. B. Zimmerman for collecting the *G. perplexus*. L. E. Heidt, B. Bonsang, and J. Shetter performed some of the analyses and provided technical assistance. We appreciate R. Cicerone's assistance and advice. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

17 August 1981; revised 9 July 1982

Tin and Methyltin Species in Seawater: Concentrations and Fluxes

Abstract. *The concentrations of tin and methyltin species in rivers, an estuary, and the surface and deep ocean generally are less than 50 picomoles of tin per liter. Estuarine profiles and river concentrations suggest that the dissolved riverine input of tin is only a minor source of this element to the oceans. Oceanic concentrations of inorganic tin decrease both with distance from land and with increasing depth from the surface, an indication of atmospheric transport to the surface ocean. Most of the contemporaneous eolian influx of tin to the oceans is anthropogenic. The vertical structure of tin concentrations in the northwestern Atlantic can be explained in terms of a model based on eolian input, advective processes, and removal of tin by particulate scavenging.*

Although a considerable body of knowledge exists on the geochemistry of tin in rocks and ores (*1*), the cycle of this element through weathering, transport from the continents to the sea by rivers and the atmosphere, oceanic circulation, and removal from seawater to marine sediments remains unknown, largely because of analytical problems. Meaningful determinations of tin concentrations in natural waters have been obtained only recently (*2–4*) after development of sufficiently sensitive analytical techniques and successful prevention of sample contamination. Three geochemical characteristics make tin an element of unique interest. (i) Its mobilization by man, as evidenced by an annual production of about 240×10^9 g, exceeds tenfold the natural rate of mobilization of tin by erosion. (ii) Tin is one of the three most highly enriched metals (after lead and tellurium) in atmospheric particulate matter as compared to the earth's crust (*5*). (iii) Tin can be biomethylated in the environment to organometallic species comparable in their toxicity to methylmercury (*2–4, 6*).

0036-8075/82/1105-0565$01.00/0