METHANE, Plants and

CLIMATE CHANGE

The surprising recent finding that living plants produce methane does not throw doubt on the cause of global warming. Human activities—not plants—are the source of the surge in this and other greenhouse gases

By Frank Keppler and Thomas Röckmann

What do you do as a scientist when you discover something that clearly contradicts the textbooks? The two of us faced this problem head-on when experiments we were running in 2005 showed that living vegetation produces the greenhouse gas methane. The established view held that only microbes that thrive without oxygen (anaerobic bacteria) can manufacture this gas. But our tests unexpectedly revealed that green plants also make methane—and quite a lot of it.

The first thing we did was look for errors in our experimental design and for every conceivable scenario that could have led us astray. Once we satisfied ourselves that our results were valid, though, we realized we had come across something very special, and we began to think about the consequences of our findings and how to present them to other researchers. Difficult as this discovery had been for us to accept, trying to convince our scientific peers and the public was almost impossible—in large part because we had to explain how such an important source of methane could have been overlooked for decades by the many able investigators studying methane and puzzling over climate change.

Natural Gas

MOST PEOPLE KNOW methane (often written as the chemical formula CH_4) as natural gas. Found in oil fields and coal beds as well as in natural gas fields, it has become an important source of energy and will most likely remain so given the limited reserves of oil on the planet. Approximately 600 million metric tons of it—both anthropogenic (from human activities) and natural—rise into the atmosphere every year. Most of these emissions have been thought to come from the decay of nonfossil organic material as a result of activity by anaerobic bacteria. Wetlands such as swamps, marshes and rice paddies provide the greatest share. Cattle, sheep and termites also make methane, as a by-product of anaerobic microbial digestion in their gut. Forest and savanna fires release methane, as does the combustion of fossil fuels [*see box on page 55*]. Over the years, researchers have gained considerable knowledge about the global methane cycle, and the consensus of the Intergovernmental Panel on Climate Change (IPCC) in 2001 was that the major sources had probably been identified (although the proportion each source contributes was still uncertain).

Nevertheless, some observations were difficult to explain. For instance, large fluctuations of atmospheric methane during the ice ages and warm ages, which have been reconstructed from air bubbles trapped in ice cores, remained a mystery. But no scientist in 2001 would have factored in direct emis-

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sions of methane by plants, because no one suspected that biological production of methane by anything other than microbial anaerobic processes was possible.

Knowing the sources of methane and how much they emit is important because methane is an extremely efficient greenhouse gas. Much more carbon dioxide is spewed into the atmosphere every year, but one kilogram of methane warms the earth 23 times more than a kilogram of carbon dioxide does. As a result of human activities, the concentration of methane in the atmosphere has almost tripled over the past 150 years. Will it continue to increase into the 21st century? Can emissions be reduced? Climate scientists need to answer such questions, and to do so we must know the origin and fate of this important gas.

Startling Findings

THE IDEA OF INVESTIGATING plants as methane emitters grew out of research we had been conducting on chloromethane, a chlorinated gas that destroys ozone and was thought to come mainly from the oceans and forest fires. A few years ago, while working at the Department of Agriculture and Food Science in Northern Ireland, we discovered that aging plants provide most of the chloromethane found in the atmosphere. Because methane, like chloromethane, is released during the burning of biomass, we wondered whether intact plants might also release methane.

To satisfy our curiosity, we collected 30 different kinds of tree leaves and grasses from tropical and temperate regions and placed them in small chambers with typical concentrations of atmospheric oxygen. To our amazement, all of the various kinds of leaves and plant litter produced methane. Usually a gram of dried plant material releases between 0.2 and three nanograms (one billionth of a gram) of methane an hour. These relatively tiny amounts were difficult to monitor, even using our highly sensitive state-of-the-art equipment.

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The task was made still more challenging because we had to differentiate between methane produced by plant tissue and the high background levels normally present in ambient air. We believe this difficulty is what prevented biologists from observing the phenomenon earlier. The secret to our discovery was that we removed the interfering effect of the natural methane background by flushing the chambers with methane-free air before the start of each experiment. We were then able to measure the methane released by plant tissue.

Our curiosity fueled, we undertook similar experiments with living plants [*see box on page 56*], and we found that the rates of methane production increased dramatically, jumping to 10 to 100 times those of leaves detached from plants. By running a series of experiments, we excluded the possibility that bacteria that thrive without oxygen produced the methane. Finally, we were absolutely convinced that living plants release methane in significant quantities. We could provide no immediate answers about the mechanism of how they did this, although we suspect that pectin, a substance in the walls of the plant cells, is involved. We decided that this question would have to await further research, which is currently under way. Because of methane's role in climate change, however, we realized it was crucial to begin to take into account the quantity of gas released into the atmosphere by this newly discovered source.

How much might plants be contributing to the planet's methane totals? It was immediately obvious to us that even though a single leaf or plant made only tiny amounts of methane, these small bits would add up quickly because plants cover a substantial part of the globe. We were nonetheless astounded by the figure generated by our calculations: between 60 million and 240 million metric tons of methane come from plants every year—this constitutes 10 to 40 percent of annual global emissions. Most of it, about two thirds, originates in the vegetation-rich tropics. We knew, of course, that extrapolating global estimates from a limited sample of laboratory measurements was open to error. Still, the final number seemed extremely large—and if it surprised us, it would be heresy to many of our scientific peers.

Fortunately for us, support for our work soon came from an unexpected source. A group of environmental physicists in Heidelberg, Germany, was observing the earth's atmosphere from space. In 2005 the scientists' satellite measurements revealed "clouds" of methane over tropical forests [*see illustration on page 57*]. They reported that their observa-

Overview/*Nature's Surprise*

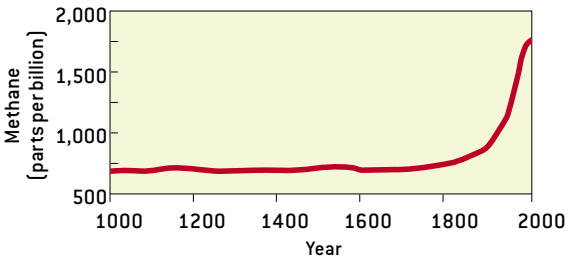
- The established view has been that methane (natural gas) is produced by microbes that thrive without oxygen, but experiments by the authors' team unexpectedly revealed that living plants also manufacture this potent greenhouse gas.
- Although this startling finding can explain many previously puzzling observations, a number of scientists are still skeptical, in particular about the amount of methane that plants generate. Knowing the sources of methane and how much they emit is important because of methane's role in trapping heat.
- An early misinterpretation of the finding suggested that forests might actually be contributing to global warming, but the authors emphasize that plants do not contribute to the recent increase in methane and global warming.

THE TEXTBOOK VIEW

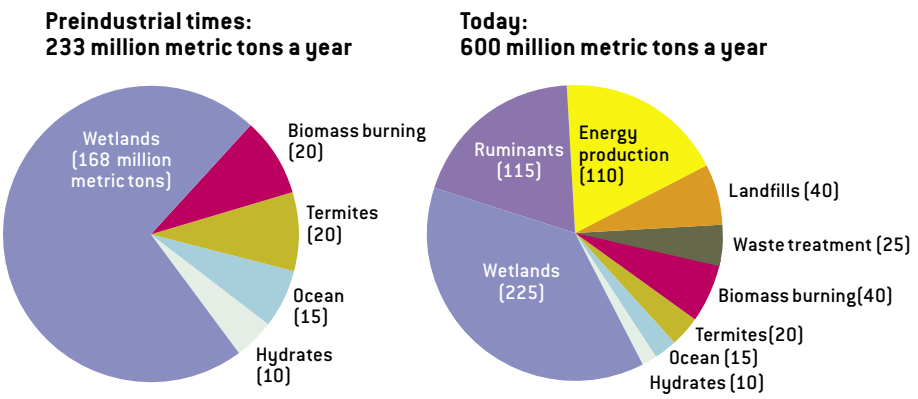
In the past 150 years, methane emissions into the atmosphere have roughly tripled (*graph*), and today some 600 million metric tons are sent into the air annually. That rise is a concern because methane, like carbon dioxide, traps heat in the earth's atmosphere and therefore contributes to global warming.

Until the authors and their colleagues published their recent discoveries, traditional thinking held that all natural releases of methane resulted from the activity of bacteria that thrive in wet, oxygen-poor environments. Such environments include swamps and rice paddies as well as the digestive systems of termites and ruminants. And analyses of the sources of the gas in the environment (*pie charts*) indicated that the dramatic rise in methane concentrations since the mid-1800s has stemmed from human industrial activities (such as the use of fossil fuels for energy) and increased rice cultivation and breeding of ruminants (because of population growth). The authors' work casts no doubt on the explanation for why methane concentrations in the atmosphere have increased, but estimates of the relative contributions to methane levels from natural sources will have to be revised.

Methane Concentration in the Atmosphere



Methane Emissions



tions could not be explained by simply using the current understanding of the global methane budget. In light of our findings, however, their work made sense: green vegetation was the source of the methane clouds.

Recently further support has come from Paul J. Crutzen, a 1995 Nobel Prize winner, and his colleagues. After our findings were published in January 2006, they reanalyzed measurements made in 1988 of air samples from the Venezuelan savanna and concluded that 30 million to 60 million metric tons of methane could be released from vegetation in these regions. Crutzen said that "looking back to 1988, we could have made the discovery, but accepting the general wisdom that methane can only be produced under anaerobic conditions, we missed the boat."

Despite this support for our work, many scientists are still skeptical about methane emissions from plants, especially about our estimate of how much methane comes from vegetation. A number of our scientific colleagues are therefore recalculating the budget for the plant source, using different methods from ours but applying our emission rates. Of course, we keenly await an independent verification of our laboratory findings.

Solving an Old Puzzle

OUR FINDINGS WOULD EXPLAIN a trend that has puzzled climate scientists for years: fluctuations in methane levels in parallel with changes in global temperatures. Ice cores serve as natural archives that store information about atmospheric composition and climate variability going back almost a million years. Tiny bubbles of air trapped in the ice reveal the relative concentrations of atmospheric gases in the past [*see box on next page*]. We see in the ice cores, for example, that variations of past carbon dioxide levels are closely linked to changes in global temperatures. During ice ages, carbon dioxide concentrations are low; during warm spells, levels increase.

In general, methane concentrations follow the same trend as carbon dioxide, but the reason has been unclear. Scientists have tried to use models of wetlands (the only major natural source of methane previously believed to exist) to reconstruct the curious variations of past methane levels. Yet they found it difficult to reproduce the reported differences in atmospheric methane levels between glacial and interglacial periods.

THE AUTHORS

FRANK KEPPLER and *THOMAS RÖCKMANN* first discovered methane emissions from plants when they were working together at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. Keppler earned a Ph.D. in environmental geochemistry from the University of Heidelberg in 2000. He recently received a European Young Investigator Award (EURYI) to build his own research group at the Max Planck Institute for Chemistry in Mainz. Röckmann received his Ph.D. from the University of Heidelberg. In 2005 he was appointed full professor at the Institute for Marine and Atmospheric Research Utrecht in the Netherlands.

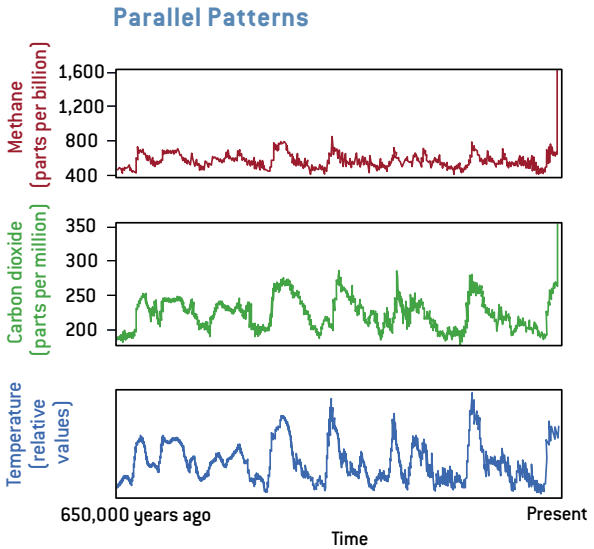
LAURIE GRACE AND JANA BRENNING

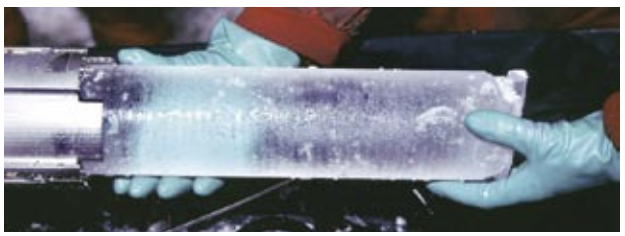
THE NEW VIEW

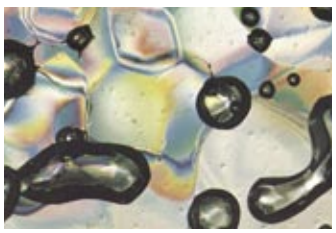
The authors' team scrutinized the gases emitted by plant debris and by living plants. To their surprise, the scientists found that both plant debris and growing vegetation produce methane. This important source of emissions had been overlooked until the team performed experiments in chambers that had been flushed of methane, which allowed the researchers to measure the minute amounts of the gas that plants give off.

The new view could explain puzzling fluctuations in methane levels that mirror changes in levels of carbon dioxide and in global temperatures (*graphs*). Scientists have tracked these changes by studying ice cores, in which trapped bubbles preserve information about the composition of the atmosphere going back almost a million years; concentrations of deuterium in the ice provide information about temperature. High atmospheric carbon dioxide concentrations and rising temperatures most likely led to a large increase in vegetation, which could have been accompanied by correspondingly large releases of methane.

AUTHORS' EXPERIMENT detected minuscule quantities of methane produced by living vegetation (*rye grass in photograph*).







ICE CORE (*far left*) contains bubbles that reveal the composition of the ancient atmosphere. The gas bubbles in the micrograph of a thin cut (*left*) are dark in color and one to three millimeters across.

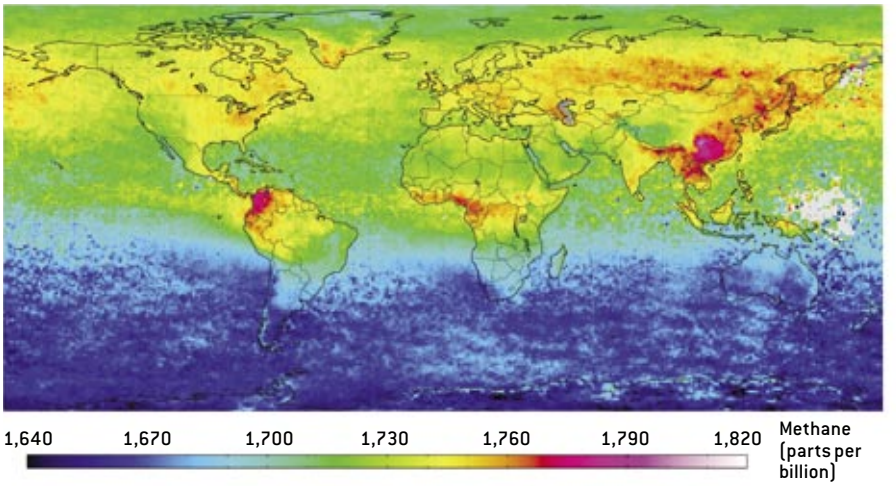
Another explanation that has been suggested involves the gas in a form known as methane hydrates [see "Flammable Ice," by Erwin Suess, Gerhard Bohrmann, Jens Greinert and Erwin Lausch; SCIENTIFIC AMERICAN, November 1999]. These develop at high pressure, such as that found on the ocean floor. An unknown but possibly very large quantity of methane is trapped in this form in ocean sediments. The sudden release of large volumes of methane from these sediments into the atmosphere has been suggested as a possible cause for rapid global warming events in the earth's distant past. Yet recent results from polar ice core studies show that marine methane hydrates were stable at least over the past 40,000 years, indicating that they were not involved in the abrupt increases of atmospheric methane during the last glacial cycle.

We know that terrestrial vegetation is very sensitive to environmental changes, and thus the total amount of vegetation on the planet varies as the climate cools down and warms up during glacial cycles. In light of our findings, such variations should now be seriously considered as a possible cause of declines in methane levels during glacial periods and rises during the interglacials. During the last glacial maximum—around 21,000 years ago—the plant growth of the Amazon forests was only half as extensive as today, and tropical vegetation might thus have released much less methane. Since that time, global surface temperature and carbon dioxide concentrations have risen, leading to enhanced plant growth and, we would expect, to more and more methane released from vegetation.

Similar climate scenarios may have occurred during other periods of the earth's history, particularly at mass extinction events, such as the Permian-Triassic boundary (250 million years ago) and the Triassic-Jurassic boundary (200 million years ago). Extremely high atmospheric carbon dioxide concentrations as well as rising temperatures could have resulted in a dramatic increase in vegetation biomass. Such global

FRANK KEPPLER AND THE MAX PLANCK INSTITUTE FOR NUCLEAR PHYSICS IN HEIDELBERG (*lab photograph*); ADAPTED FROM "TINY BUBBLES TELL ALL," BY EDWARD J. BROOK, IN *SCIENCE*, VOL. 310, NOVEMBER 25, 2005, USED WITH PERMISSION FROM AAAS (*graphs*); AFP/GETTY IMAGES (*ice core*); W. BERNER *University of Bern* (*micrograph*)

warming periods could have been accompanied by a massive release of methane from vegetation and by more heating. Though speculative, the assumption that emissions may have been as much as 10 times higher than at present is not totally unreasonable. If this is so, methane emissions from vegetation, in addition to emissions of the gas from wetlands and perhaps from the seafloor, could be envisaged as a driving force in historic climate change.



SATELLITE IMAGES of the earth's atmosphere provided support for the authors' controversial finding. In 2005 environmental physicists observed clouds of methane over tropical forests. Although the standard model of methane production cannot explain this observation, the authors' discovery made sense of the curious clouds: the abundant green vegetation of the tropics was emitting the methane.

Media Misinterpretations

WHEN YOU SEE A REPORT on your scientific work on the BBC World News immediately following news about bird flu and the situation in Iraq, on the very day your work has first been published, you realize that you have found something with great societal relevance. This realization was reinforced the next day as our research appeared in newspapers around the world, often in front-page headlines.

Unfortunately, extensive media coverage can lead to exaggerations, and in our case it resulted in the misinterpretation of our results. In particular, many reports claimed that plants may be responsible for global warming; in one instance, we saw the headline "Global Warming—Blame the Forests" on the front page of a reputable newspaper.

When you then receive many e-mails and phone calls from individuals asking whether they should cut down all the trees in their garden to fight global warming, you realize that something has gone badly wrong in the communication to the public. We felt compelled to issue another press release to address the misinterpretations.

In our second press release we emphasized that if our finding is true, plants have been emitting methane into the atmosphere for hundreds of millions of years. Those emissions have contributed to the natural greenhouse effect, without which life as we know it would not be possible. Plants are not responsible, however, for the dramatic increase in methane concentrations since the start of industrialization. This surge was brought about by human activities.

Our discovery also led to intense speculation that methane emissions by plants could diminish or even outweigh the carbon storage effect of reforestation programs. If that were correct, it would have important implications for countries attempting to implement the Kyoto Protocol to minimize global carbon emissions, because, under the protocol, tree-planting programs can be used in national carbon dioxide mitigation strategies. But our calculations show that the climatic benefits gained by establishing new forests to absorb carbon dioxide would far exceed the relatively small negative effect of adding more methane to the atmosphere (which may reduce the overall carbon uptake of the trees by 4 percent at most). The potential for reducing global warming by planting trees is most definitely positive.

In the heat of this debate, people forgot a crucial fact: plants are the green lung of our planet—they provide the oxygen that makes life as we know it possible. They perform many other beneficial tasks as well. As just two crucial examples, they provide a natural environment that fosters biodiversity, and they control the tropical water cycle. The problem is not the plants; it is the global large-scale burning of fossil fuels.

A more legitimate concern is whether the methane produced by vegetation can have an impact on climate in the near future. Although plants are not responsible for the massive increase of methane in the atmosphere since preindustrial times, they do tend to grow faster. As we can expect methane emissions from vegetation to increase with temperature, this would lead to even more warming. This vicious cycle would be a natural phenomenon except for its speed, which is accelerated mainly by anthropogenic activities such as burning fossil fuels. The large plant feedback to global climate change that most likely happened in the past, however, is probably unlikely today because so many forests have been cut down.

Although it is too early to say exactly how our revelation might influence predictions for climate change in the more distant future, it is clear that all new assessments should consider emissions of methane by plants. SA

MORE TO EXPLORE

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