

which some representatives called for a moratorium on the production of further stem-cell lines until these methods work in humans, while others declared that medical science has already gone too far, and must be reined in by laws that criminalize all such attempts. Of course, the attempts to delay or to prevent these kinds of experiment derive from the belief that preimplantation embryos, or entities with little or no potential to form a functioning organism, are human, and have the same rights as born humans. The 'non-implantable entity' is regarded by Hurlbut as a non-viable artefact, but many of his colleagues on the President's Council on Bioethics disagree⁸.

So the crux of the question is when life begins, a debate that cannot be settled by science. In abstract, this would seem to be the realm of philosophy, but if such debates result in moratoria or bans on research, the medical advances that would surely come from such work will be held in abeyance, and patients with a narrow window of opportunity for treatment will be lost. Their lives are the point. Although the efforts cited here^{1,2} will be criticized as a diversion of good science by politics, I believe all of these attempts to advance and translate medical science should be pursued in parallel.

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1. Chung, Y. *et al.* *Nature* **439**, 216–219 (2006).
2. Meissner, A. & Jaenisch, R. *Nature* **439**, 212–215 (2006).
3. Weissman, I. L. *N. Engl. J. Med.* **346**, 1576–1579 (2002).
4. Hwang, W. S. *et al.* *Science* **308**, 1777–1783 (2005).
5. Committee on Science, Engineering, and Public Policy *Scientific and Medical Aspects of Human Reproductive Cloning* (National Academies Press, Washington DC, 2002).
6. Hurlbut, W. *Monitoring Stem Cell Research* 53–108 (President's Council on Bioethics, Washington DC, 2004).
7. Strumpf, D. *et al.* *Development* **132**, 2093–2102 (2005).
8. Hurlbut, W. *Monitoring Stem Cell Research* 90–93 (President's Council on Bioethics, Washington DC, 2004).

GLOBAL CHANGE

A green source of surprise

David C. Lowe

Living terrestrial vegetation emits large amounts of methane into the atmosphere. This unexpected finding, if confirmed, will have an impact on both greenhouse-gas accounting and research into sources of methane.

On page 187 of this issue, Keppler *et al.*¹ report the remarkable discovery that terrestrial plants emit methane into the atmosphere. Their results are startling, for two reasons. First, because the methane emissions they document occur under normal physiological conditions, in the presence of oxygen, rather than through bacterial action in anoxic environments. Second, because the estimated emissions are large, constituting 10–30% of the annual total of methane entering Earth's atmosphere.

In a series of carefully controlled experiments, Keppler and colleagues used gas chromatography and continuous-flow isotope-ratio mass spectrometry to find that methane is emitted from a wide variety of plant species under oxic conditions. Using ¹³C-labelled acetate substrates, they ruled out the possibility that the methane is produced by anoxic microbial activity. Going further, they showed that this vegetative source depends on sunlight and temperature, with emissions approximately doubling for each rise of 10 °C. The details of the methane-production mechanism are not known, but the authors do demonstrate that emissions are related to the quantity of pectin, a cell-bonding agent, that a plant contains.

To estimate the global methane

emissions from vegetation, Keppler *et al.* make two main assumptions: first, that the emission rates they measured are representative values for short-lived biomass; second, that the

emission estimates can be scaled relative to annual net primary productivity, and can distinguish between different types of environment and average daily hours of sunshine, and between differences in the period of vegetation growth. This type of approach, known as a bottom-up calculation, is commonly used to estimate global emissions from various methane sources and is notorious for producing a wide range of estimates (Fig. 1)². Additional constraints are applied to bottom-up estimates using methane isotopic data and inverse modelling techniques, but the errors remain large.

Most methane is lost from the atmosphere by oxidation, and estimates of this process are used in top-down calculations to deduce the amounts thus removed. For the methane budget to be balanced, the two techniques should agree when the atmosphere is near steady state. But this is rarely the case, as shown by Figure 1. The identification of a new source should prompt a re-examination of the global methane budget, and may ultimately help to reconcile the differences between the bottom-up and top-down techniques.

Meanwhile, Keppler and colleagues' finding¹ helps to account for observations from space of inexplicably large plumes of methane above tropical forests³. They may also explain the current puzzling decrease in the global growth rate of atmospheric methane^{4,5}. Deforestation has led to a dramatic reduction in the Earth's tropical forested area (more than 12% between 1990 and 2000)¹. Keppler *et al.* calculate a corresponding decrease in methane emissions from tropical plants of between 6 million and 20 million tonnes over the same period. During that decade, the rate of methane accumulation in the atmosphere slowed by about 20 million tonnes per year,

a		
Identified methane sources	Estimates ⁸	Range of estimates ²
Total wetlands	145	92–237
Rice agriculture	60	40–100
Ruminant animals	93	80–115
Termites	20	20–20
Biomass burning	52	23–55
Energy generation	95	75–110
Landfills	50	35–73
Ocean	10	10–15
Hydrates (marine and terrestrial)	5	5–10
Total identified sources	530	500–600

b		
Identified methane sinks	Estimates	Range of estimates
Tropospheric oxidation	507	450–510
Stratospheric loss	40	40–46
Soils	30	10–44
Total identified sinks	577	460–580

Total sources–sinks	–47	–80 to +140
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Figure 1 | Methane sources and sinks. Numbers are millions of tonnes of methane per year. **a**, Estimates⁸ and range of estimates² of annual emissions of methane to the atmosphere from identified sources. **b**, Equivalent figures for methane sinks. The estimates from ref. 8 imply that atmospheric methane is decreasing because identified sources are smaller than the sinks, but this is not confirmed by current measurements of methane in the atmosphere⁵. The ranges in the right-hand column show the extreme values compiled by seven different research groups, as well as estimated total sources and sinks assessed by the Intergovernmental Panel on Climate Change². Note that, for statistical reasons, the sum of the individual source and sink ranges is not the same as the estimated total source and sink ranges. The wide divergence in these figures shows just how ill-defined the methane source inventory and budget are. The new source identified by Keppler *et al.*¹ — methane emitted by vegetation in oxic conditions — is estimated to produce between 63 million and 243 million tonnes per year, but potentially may double count sources listed above.

suggesting that tropical deforestation may have contributed to the decrease.

Methane absorbs solar radiation strongly in infrared wavelengths, and is second only to carbon dioxide in its role in producing an enhanced greenhouse effect and warming the Earth. It also affects the way the atmosphere cleans itself of pollutants, and influences ozone depletion through the production of water vapour in the stratosphere. So methane has been the subject of intense scientific and political scrutiny, and is targeted for emissions controls under the Kyoto Protocol on climate change.

The predominant sources of atmospheric methane are biological. The main ones previously recognized were microbial activity in wetlands (including natural swamps and rice paddy fields) and the eructations of ruminant animals. The dramatic upswing in agriculture required to feed the Earth's growing population has led to huge increases in rice culture and livestock farming in the past 250 years. The result has been large rises in methane emissions from both of these sources.

It was thought that methane production in flooded paddy fields was due to microbial activity in the anoxic environment of the paddy soils. In a 'Kyoto world', in which sources and sinks of greenhouse gases are added and subtracted like the columns in an accountant's report, there are claims that new, 'drier' forms of paddy-field irrigation will lead to reduced methane emissions. But a study of rice plants has shown a strong link between the number and size of leaves on the plant and methane emissions⁶: could the rice plants themselves be as significant a source of methane as the flooded paddy fields?

The implications of Keppler and colleagues' work for the Kyoto Protocol include how reforestation and ruminant animals are treated in methane budgets. Under the Kyoto rules, reforestation since 1990 may be used as a CO₂ sink to offset greenhouse-gas emissions from other sources; we now have the spectre that new forests might increase greenhouse warming through methane emissions rather than decrease it by sequestering CO₂. And in certain countries with large numbers of sheep, cattle and other ruminant livestock, methane constitutes a significant fraction of total greenhouse-gas emissions. In such countries — Ireland and New Zealand, for example — ruminant animals graze on pastures that were originally forested. Given the findings of Keppler *et al.*, it is possible that the forests that once occupied pasture may have produced as much methane as ruminants and grasses on the same land.

The new work will also influence studies of the history of Earth's climate. Indications of past climate are often deduced from analyses of the concentration and isotopic composition of greenhouse gases in tiny air bubbles trapped in polar ice cores. Keppler and colleagues' study shows that, in pre-industrial times, the relative contribution of methane to the

atmosphere by direct emissions from plants could have been much larger than it is today. Measurements of isotopic values in methane derived from Antarctic ice cores show a signal between AD 0 and 1200 that is inconsistent with theories of methane budgets being dominated by wetland sources⁷. A pre-industrial atmosphere containing large contributions of methane derived from vegetation can account for the observed isotopic signal. One of the further avenues of research will centre on the role of methane and vegetation in glacial–interglacial transitions.

This paper¹ will undoubtedly unleash controversy, not the least of which will be political. But there are many scientific questions to be addressed. How could such a potentially large methane source have been overlooked? And what kind of mechanism could produce a highly reduced gas such as methane in an oxic environment? There will be a lively scramble

among researchers for the answers to these and other questions. ■

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1. Keppler, F., Hamilton, J. T. G., Brass, M. & Röckmann, T. *Nature* **439**, 187–191 (2006).
2. Prather, M. & Ehhalt, D. in *Climate Change 2001: The Scientific Basis* (eds Houghton, J. T. *et al.*) 239–287 (Cambridge Univ. Press, 2001).
3. Frankenberg, C., Meirink, J. F., van Weele, M., Platt, U. & Wagner, T. *Science* **308**, 1010–1014 (2005).
4. Dlugokencky, E. J., Masarie, K. A., Lang, P. M. & Tans, P. P. *Nature* **393**, 447–450 (1998).
5. Dlugokencky, E. J. *et al. Geophys. Res. Lett.* **30**, doi:10.1029/2003GL018126 (2003).
6. Gogoi, N., Baruah, K. K., Gogoi, B. & Gupta, P. K. *Chemosphere* **59**, 1677–1684 (2005).
7. Ferretti, D. *et al. Science* **309**, 1714–1717 (2005).
8. Mikaloff Fletcher, S. E., Tans, P. P., Bruhwiler, L. M., Miller, J. B. & Heimann, M. *Glob. Biogeochem. Cycles* **18**, doi:10.1029/2004GB002223 (2004).

BEHAVIOUR

Smells, brains and hormones

Gordon M. Shepherd

Contrary to the traditional view, the main olfactory pathway can mediate responses to pheromones as well as to common odours. Recent studies show that pheromone-activated hormonal systems extend widely within the brain.

Pheromones are powerful species-specific chemical signals that organize a wide range of the social conduct of animals, such as mating behaviour, social dominance, aggression, and bonding of a mother with her young. A common belief is that in mammals pheromones are detected only by a specialized sensor in the nose known as the vomeronasal organ, and that the main olfactory epithelium, which lines the nasal cavity, is responsible only for sensing common odours (Fig. 1, overleaf). A long line of under-appreciated work has suggested that this view is too restrictive. Three papers^{1–3} apply the *coup de grâce*, indicating that we need to rethink entirely how pheromones control hormonal responses, not only in mammals generally, but in humans in particular.

In mammals, female mating and reproductive behaviour are controlled by a group of neurons in the hypothalamus, the brain's chief hormonal, or endocrine, control centre. These particular neurons secrete 'luteinizing hormone-releasing hormone' (LHRH; also known as gonadotrophin-releasing hormone, or GnRH) into the hypothalamic–pituitary system to control gonadal and steroidal functions^{4,5}. As they report in *Cell*, Yoon *et al.*¹ and Boehm *et al.*² have developed ingenious methods to trace the brain systems that connect to these neurons.

Yoon *et al.*¹ used a fluorescent virus that is transported only backwards across the junctions

(synapses) between neurons; that is, it will follow the path of a neuronal input to its point of origin. They genetically engineered mice to express a factor specifically in the LHRH neurons that would allow the uptake of the virus into only these cells. So, when the virus is injected into the hypothalamus of the mice, its progress can be traced backwards from the LHRH cells over at least two synapses along the circuits related to these neurons.

The cells that first take up the virus are in the expected hypothalamic areas. However, tracing backwards, labelling occurred in many brain regions, indicating a complex system of mainly olfactory regions and somatosensory areas (dealing with sensations in the body). In the olfactory brain regions, fluorescence was found in the olfactory cortex, the main olfactory bulb, and even out into the main olfactory epithelium. Contrary to predictions from the traditional view, none was seen in the 'accessory' pheromone pathway that originates in the vomeronasal organ. Moreover, behavioural experiments showed that chemosensory modulation of activity in LHRH neurons is primarily through the main olfactory pathway. The results extend previous indications (summarized in ref. 3) that the main olfactory pathway triggers generalized mating behaviour, whereas the vomeronasal pathway mediates specific male and female cues.

Boehm *et al.*² took a different approach. They