Article

# Preindustrial $^{14}CH_4$ indicates greater anthropogenic fossil $CH_4$ emissions

https://doi.org/10.1038/s41586-020-1991-8

Received: 27 May 2019

Accepted: 27 November 2019

Published online: 19 February 2020

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Benjamin Hmiel[1✉], V. V. Petrenko[1], M. N. Dyonisius[1], C. Buizert[2], A. M. Smith[3], P. F. Place[1], C. Harth[4], R. Beaudette[4], Q. Hua[3], B. Yang[3], I. Vimont[5], S. E. Michel[5], J. P. Severinghaus[4], D. Etheridge[7], T. Bromley[8], J. Schmitt[9], X. Faïn[10], R. F. Weiss[4] & E. Dlugokencky[11]

Atmospheric methane ($CH_4$) is a potent greenhouse gas, and its mole fraction has more than doubled since the preindustrial era[1]. Fossil fuel extraction and use are among the largest anthropogenic sources of $CH_4$ emissions, but the precise magnitude of these contributions is a subject of debate[2,3]. Carbon-14 in $CH_4$ ($^{14}CH_4$) can be used to distinguish between fossil ($^{14}$C-free) $CH_4$ emissions and contemporaneous biogenic sources; however, poorly constrained direct $^{14}CH_4$ emissions from nuclear reactors have complicated this approach since the middle of the 20th century[4,5]. Moreover, the partitioning of total fossil $CH_4$ emissions (presently 172 to 195 teragrams $CH_4$ per year)[2,3] between anthropogenic and natural geological sources (such as seeps and mud volcanoes) is under debate; emission inventories suggest that the latter account for about 40 to 60 teragrams $CH_4$ per year[6,7]. Geological emissions were less than 15.4 teragrams $CH_4$ per year at the end of the Pleistocene, about 11,600 years ago[8], but that period is an imperfect analogue for present-day emissions owing to the large terrestrial ice sheet cover, lower sea level and extensive permafrost. Here we use preindustrial-era ice core $^{14}CH_4$ measurements to show that natural geological $CH_4$ emissions to the atmosphere were about 1.6 teragrams $CH_4$ per year, with a maximum of 5.4 teragrams $CH_4$ per year (95 per cent confidence limit)—an order of magnitude lower than the currently used estimates. This result indicates that anthropogenic fossil $CH_4$ emissions are underestimated by about 38 to 58 teragrams $CH_4$ per year, or about 25 to 40 per cent of recent estimates. Our record highlights the human impact on the atmosphere and climate, provides a firm target for inventories of the global $CH_4$ budget, and will help to inform strategies for targeted emission reductions[9,10].

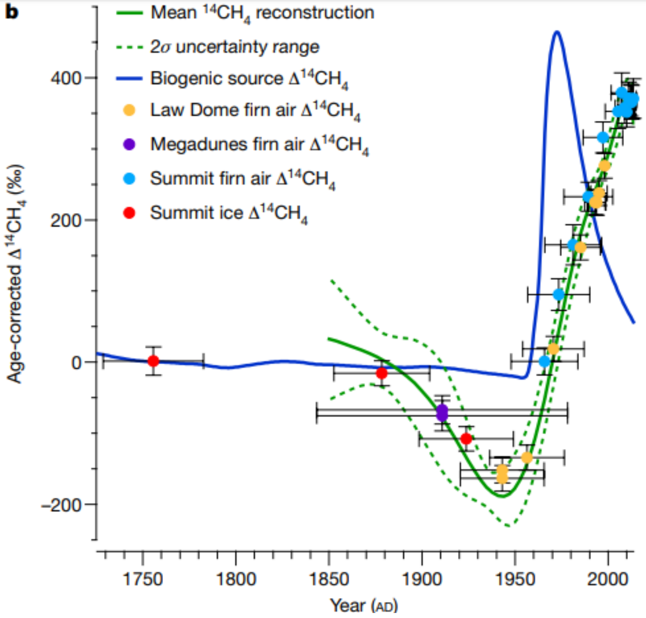


**Fig. 1 | Reconstruction of atmospheric $^{14}CH_4$ from firn air and ice core data.** **a**, Global $CH_4$ mole fraction, [$CH_4$], reconstructed from ice core, firn air and atmospheric measurements[1]. ppb, parts per billion. **b**, Reconstructed history of atmospheric $\Delta^{14}CH_4$ from firn air and ice core samples (this study). Dotted lines represent the 95% confidence range based on all calculated $^{14}CH_4$ histories using three different inversion methods (Supplementary Information section 9). Ice core and firn air $\Delta^{14}CH_4$ measurements are shown at the mean age of the modelled air age distribution. Vertical error bars on the $\Delta^{14}CH_4$ data from each site represent the 2$\sigma$ uncertainty for each sample after corrections (Supplementary Information Tables 2, 6), and horizontal error bars represent $\pm 2\Delta$, where $\Delta$ is the spectral width of the sample-air age distribution[20]. We also plot the $^{14}CH_4$ signature of the contemporaneous biogenic source (blue; Supplementary Information section 10). Our time series begins in 1850 because the age distributions of the collected ice core samples have poor coverage of air from ~1780 to 1850 (Supplementary Information section 10, Supplementary Fig. 3B).

SCIENTIFIC REPORTS
natureresearch

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# A novel cellular structure in the retina of insectivorous birds

Luke P. Tyrrell[1*], Leandro B. C. Teixeira[2], Richard R. Dubielzig[2], Diana Pita[3], Patrice Baumhardt[3], Bret A. Moore[4] & Esteban Fernández-Juricic[3]

**The keen visual systems of birds have been relatively well-studied. The foundations of avian vision rest on their cone and rod photoreceptors. Most birds use four cone photoreceptor types for color vision, a fifth cone for achromatic tasks, and a rod for dim-light vision. The cones, along with their oil droplets, and rods are conserved across birds – with the exception of a few shifts in spectral sensitivity – despite taxonomic, behavioral and ecological differences. Here, however, we describe a novel photoreceptor organelle in a group of New World flycatchers (*Empidonax* spp.) in which the traditional oil droplet is replaced with a complex of electron-dense megamitochondria surrounded by hundreds of small, orange oil droplets. The photoreceptors with this organelle were unevenly distributed across the retina, being present in the central region (including in the fovea), but absent from the retinal periphery and the *area temporalis* of these insectivorous birds. Of the many bird species with their photoreceptors characterized, only the two flycatchers described here (*E. virescens and E. minimus*) possess this unusual retinal structure. We discuss the potential functional significance of this unique sub-cellular structure, which might provide an additional visual channel for these small predatory songbirds.**

With potentially large quantities of energy available to the flycatchers' MMOD-complex photoreceptor, it is likely capable of more rapid response rates[26–28]. Rapid photoreceptor response rates may yield higher temporal visual resolution and spatio-temporal tracking of motion[29–31], which would ultimately give flycatchers a photoreceptor potentially specialized in motion detection and motion tracking. This specialization can be particularly useful for flycatchers because they use a sit-and-wait hunting strategy[32] that requires considerable motion-tracking as individuals sit almost motionless while their flying prey (flies, mosquitos, etc.) move at high speeds[33]. Therefore, flycatchers must detect and track the absolute velocity of their prey rather than the slower, relative velocity required by predators that actively chase prey (e.g., swifts and swallows). *Empidonax* flycatchers often hunt against blue or green backgrounds. The filtering effect of the orange oil droplets may even shield the potentially motion-sensitive MMOD-complex photoreceptors from the motion of green leaves blowing in the wind, isolating the motion of the insect. It is likely that the photoreceptor with the MMOD-complex would serve a photoreceptive function. Diurnal birds have retinas with dense photoreceptor arrays that have little or no gap between adjacent photoreceptors. Non-photoreceptive cells inserted into the photoreceptor array would take up valuable 'real estate' and would reduce visual acuity, seemingly unnecessarily, although exceptions to this line of thinking are possible.