Methane and megafauna

To the Editor — The drop in atmospheric methane concentrations at the onset of the Younger Dryas cold event ~12,800 yr ago is commonly attributed to decreased methane emissions from wetlands[1]. Smith *et al.*[2] reported calculations of methane emissions from wild herbivores and propose that end-Pleistocene megafaunal extinctions contributed to the methane decline. However, they support their arguments with several claims that are inconsistent with the ice core methane record.

Smith *et al.* claim that the methane decrease at the start of the Younger Dryas was unique compared with other decreases in the ice core record, and therefore suggest that a new mechanism may be required. The methane decrease at the onset of the Younger Dryas in the GISP2 ice core was ~230 ppb over 340 yr, or ~0.7 ppb yr^{-1} (ref. 3) (Fig. 1). Contrary to Smith *et al.*'s assertion, changes at this rate are not particularly rare. The Greenland ice core record shows a large number of abrupt variations in atmospheric methane over the past 125,000 yr, which are closely associated with abrupt temperature change recorded in the isotopic composition of the ice[3–11]. Several of these fluctuations include rapid decreases as fast, or faster, than the Younger Dryas change. During the present interglacial, methane decreased by about 90 ppb over 70 yr (1.3 ppb yr^{-1}) during a cooling event 8,200 yr ago[10] and by 40 ppb over 28 yr (1.5 ppb yr^{-1}) in the late sixteenth century[12]. During the last glacial period, methane fell by 145 ppb over 300 yr (1.0 ppb yr^{-1}) during an event about 84,600 yr ago[11] and by 150 ppb over ~210 yr (0.95 ppb yr^{-1}) about 60,100 yr ago[6]. Measurements at sample spacing needed to adequately resolve these short variations are laborious and not all time periods have been measured in this detail. It is likely that additional measurements will reveal further rapid decreases. Therefore the rate of methane decrease at the onset of the Younger Dryas, although obviously of great interest, does not seem highly unusual when viewed in the context of other abrupt changes in methane levels in the Greenland ice core record.

Smith *et al.* also suggest that the methane decrease owing to megafaunal extinction may have played a role in the Younger Dryas temperature change. However, in every abrupt transition examined, changes

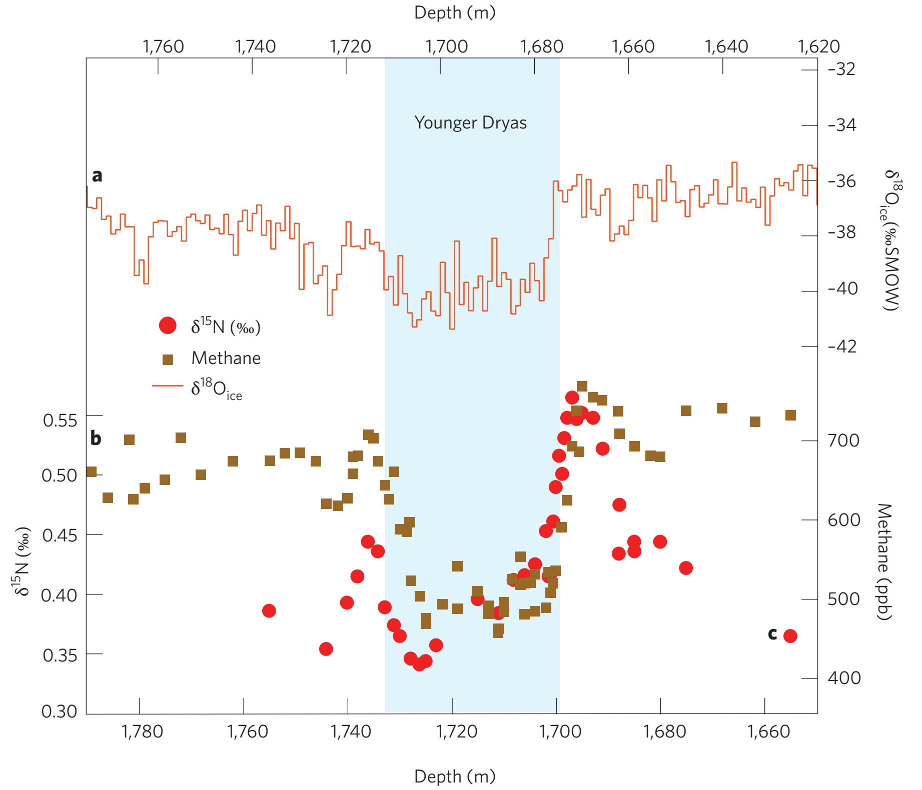

Figure 1 | Proxy records of atmospheric composition and temperature during the Younger Dryas. **a**, The $\delta^{18}O$ of ice[15] reflects the air temperature over Greenland. **b**, Methane concentrations in trapped air (ref. 3 and new results). **c**, Nitrogen isotope ratios in trapped air (ref. 8 and new results) for the Younger Dryas section of the GISP2 ice core. Data are plotted on depth scales, with the top axis offset from the bottom to adjust for the difference between ice- and gas-age timescales owing to trapping of air at depth in the firn column of polar ice sheets. The blue shaded interval is the Younger Dryas cold period. The ~0.1‰ shift of $\delta^{15}N$ of N_2 at 1,734 m reflects the Younger Dryas cooling and is synchronous within data resolution with the associated methane decrease, showing that changes in temperature and methane were simultaneous at this time.

in methane immediately follow or are synchronous with (within data resolution) changes in temperature in Greenland. This supports the hypothesis that abrupt methane variations are driven by changes in climate that influence methane emissions from wetlands[3–5]. For the Younger Dryas cooling specifically, Fig. 1 shows that the start of abrupt cooling at its onset was essentially synchronous with the methane decrease. If the megafaunal extinction caused the methane decrease, then that extinction event would need to closely coincide with cooling in Greenland. The timing of the megafaunal extinction is uncertain, but a recent study concluded that it is highly likely that the extinction event preceded the Younger Dryas[13]. Furthermore, it is unlikely that the methane changes themselves played a large role in the Younger Dryas cooling, because the decrease in greenhouse forcing of a 230 ppb decrease in methane is quite small (direct radiative effect is ~−0.05 W m^{-2} using a common parameterization of radiative forcing[14]).

According to estimates by Smith *et al.*, the megafaunal extinction could have caused a 9.3 Tg yr^{-1} decrease in methane emissions (range 2.3–25.5 Tg yr^{-1}). Explaining the entire methane change at the onset of the Younger Dryas with the demise of the megafauna would require that no other sources changed during the abrupt climate cooling, which seems unlikely. We agree that quantifying the contribution of megafauna to pre-industrial methane variations is important for understanding the biogeochemistry of this gas, and should certainly be pursued further. However, this work must incorporate all of the constraints the ice core record provides. ❐

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Authors' reply – In their comment, Brook and Severinghaus suggest that rates of methane decrease elsewhere in the record are higher than our computations[1] and that it is unlikely that methane concentrations contributed substantially to the temperature decline during the Younger Dryas event.

Fast methane changes have indeed been documented from the ice core records. However, we chose to perform our calculations over an ecologically relevant, standardized 1,000-yr window that corresponds to the duration of the extinction event under consideration. The higher rates reported by Brook and Severinghaus were calculated over varying temporal scales[2–4] and do not include uncertainties. Process rates are not independent of measured time interval[5–7]. To illustrate this, we conducted a logarithmic regression on series of sequential methane values from the GISP2 core. Our analysis yields a highly significant relationship between the perceived rate of methane change and the interval duration ($R^2 = 0.516$, $P < 0.000$, $df = 306$), leading us to conclude that unconstrained temporal comparisons are statistically unsound. Moreover, because resolution decreases with sample age, dating uncertainties for older core samples may exceed the interval over which the rate was computed. We conclude that without better constraints on temporal resolution and the use of equivalent temporal bins, quantitative comparisons are not possible.

Pleistocene carbon cycle fluctuations were probably also modulated by a suite of interlocking mechanisms including clathrate, peatland, yedoma, permafrost, lake ebullition relations and others[8–11]. But the temporal uncertainty of the ice core records complicates the determination of lead–lag relationships between temperature and methane. Furthermore, time constants for the spectrum of known methane geochemical channels range from decades to millennia. Thus, it is difficult to characterize a direct link between methane and temperature decrease, but we feel it cannot be ruled out at this time.

We do agree that it is unlikely that the megafaunal extinction was directly responsible for the entire methane decrease just before the Younger Dryas and did not make this claim. Nonetheless, our computations indicate the extinction of large-bodied herbivores did result in a sizeable decrease in methane inputs to the atmosphere. Interestingly, a recent estimate of the methane emissions by *Bison bison* before European arrival and near extirpation of the herds in the Great Plains of North America was 2.2 Tg CH_4 yr^{-1} (ref. 12). This calculation suggests that our estimate of 9.6 Tg CH_4 yr^{-1} for the 114 large-bodied species extirpated from the Americas is probably quite conservative. Although the role of the megafaunal extinction in the onset of the Younger Dryas is debatable, the human-mediated extinction undoubtedly resulted in measureable impacts on biogeochemical cycles at the end of the last glacial period. ❐

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