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. ❐

References


1. Chappellaz, J. *et al. Nature* **366,** 443–445 (1993).
2. Smith, F. A., Elliott, S. M. & Lyons, S. K. *Nature Geosci.* **3,** 374–375 (2010).
3. Brook, E. J., Harder, S., Severinghaus, J., Steig, E. J. & Sucher, C. M. *Glob. Biogeochem. Cycles* **14,** 559–572 (2000).
4. Chappellaz, J. A., Fung, I. Y. & Thompson, A. M. *Tellus B* **45,** 228–241 (1993).
5. Brook, E. J., Sowers, T. & Orchardo, J. *Science* **273,** 1087–1091 (1996).
6. Huber, C. *et al. Earth Planet. Sci. Lett.* **243,** 504–519 (2006).
7. EPICA Members *Nature* **444,** 195–198 (2006).
8. Severinghaus, J. P., Sowers, T., Brook, E. J., Alley, R. B. & Bender, M. L. *Nature* **391,** 141–146 (1998).
9. Severinghaus, J. P. & Brook E. J. *Science* **286,** 930–934 (1999).
10. Kobashi, T., Severinghaus, J. P., Brook, E. J., Barnola, J-M. & Grachev, A. *Quat. Sci. Rev.* **26,** 1212–1222 (2007).
11. Grachev, A. M., Brook, E. J. & Severinghaus, J. P. *Geophys. Res. Lett.* **34,** L20703 (2007).
12. Meure, C. M. *et al. Geophys. Res. Lett.* **33,** L14810 (2006).
13. Buck, C. E. & Bard, E. *Quat. Sci. Rev.* **26,** 2031–2035 (2009).
14. Ramaswamy, V. *et al.* in *IPCC Climate Change 2001: The Scientific Basis* (eds Houghton, J. T. *et al.*) 349–416 (Cambridge Univ. Press, 2001).
15. Grootes, P. M. & Stuiver, M. *Quat. Res.* **53,** 277–284 (2000).



Edward J. Brook[1]* and Jeffrey P. Severinghaus[2]
[1]Department of Geosciences, Oregon State University, Corvallis, Oregon 97331, USA, [2]Scripps Institution of Oceanography, University of California, San Diego, California 92093, USA.
*e-mail: brooke@geo.oregonstate.edu


**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. ❐

References


1. Smith, F. A., Elliott, S. M. & Lyons, S. K. *Nature Geosci.* **3,** 374–375 (2010).
2. MacFarling Meure, C. *et al. Geophys. Res. Lett.* **33**, L14810 (2006).
3. Grachev, A., Brook, E. J. & Severinghaus, J. P. *Geophys. Res. Lett.* **34,** L20703 (2007).
4. Kobashi, T., Severinghaus, J. P., Brook, E. J., Barnola, J-M. & Grachev, A. *Quat. Sci. Rev.* **26,** 1212–1222 (2007).
5. Gardner, T. W., Jorgensen, D. W., Shuman, C. & Lemieux, C. R. *Geology* **15,** 259–261 (1987).
6. Gingerich, P. D. *Science* **222,** 159–161 (1983).
7. Gingerich, P. D. *Am. J. Sci.* **293A,** 453–478 (1993).
8. Christensen, T. R. *et al. Geophys. Res. Lett.* **31,** L04501 (2004).
9. Walter, K. M., Zimov, S. A., Chanton, J. P., Verbyla, D. & Chapin, F. S. *Nature* **443,** 71–75 (2006).
10. Walter, K. M., Edwards, M. E., Grosse, G., Zimov, S. A. & Chapin, F. S. *Science* **318,** 633–635 (2007).
11. Shakhova, N. *et al. Science* **327**, 1246–2150 (2010).
12. Kelliher, F. M. & Clark, H. *Agr. Forest Meteorol.* **150,** 473–477 (2010).



Felisa A. Smith[1]*, Scott M. Elliott[2] and S. Kathleen Lyons[3]
[1]Department of Biology, University of New Mexico, Albuquerque, New Mexico 87131, USA, [2]Climate, Ocean, Sea Ice Modeling Team, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA, [3]Department of Paleobiology, National Museum of Natural History, Smithsonian Institution, Washington DC 20013, USA.
*e-mail: fasmith@unm.edu




© 2011 Macmillan Publishers Limited. All rights reserved