The authors criticize us for not using more elaborate tree-growth models that include other influences such as precipitation. However, the fundamental assumption underlying tree-ring-based temperature reconstructions like those we analysed[2] is that annual growth at temperature-limited treeline locations yields an unbiased estimate of temperature changes exclusively.

Anchukaitis *et al.* criticize our tree-growth parameter choices and, in their Supplementary Fig. 1a suggest that they yield an unrealistic prediction of missing twentieth-century tree rings; however, our analysis[1] predicts no missing tree rings for the twentieth century. We agree that our use of 10 °C as a threshold temperature for growth is at the upper end of the accepted 3–10 °C range[3]. This choice yields the closest fit to the observed tree-ring response, but we see qualitatively similar results for a lower temperature threshold value. Using a simple growing degree-day model with a linear response to temperature (Supplementary Fig. 1), which renders moot their other criticisms of our modelling approach, we show that the underestimation of volcanic cooling by tree rings is substantial for threshold values spanning the entire upper half of the 3–10 °C range, even using a conservative assumption of what constitutes a missing ring, that is, a growing season of less than one week. Including the effect of increased diffuse light[4] caused by volcanic aerosols — an important factor neglected by Anchukaitis *et al.* — leads to slightly better agreement between our growth model and existing tree-ring reconstructions[2]. For growth-model assumptions substantially different from those we adopted, however, the effect produces offsetting and spurious warming responses in the first few years following an eruption (Supplementary Fig. 1)

Anchukaitis *et al.* attempt to reconcile the lack of a cooling response to the AD 1258/1259 in the D'Arrigo *et al.*[2] tree-ring reconstruction with the response predicted by climate models by arguing that the radiative forcing might have been smaller than generally assumed. However, our findings are robust, no matter which of the various published volcanic forcing reconstructions or volcanic scaling assumptions[5] was used. We suggest that the lack of any apparent response to the AD 1258/1259 event in the D'Arrigo *et al.*[2] tree-ring reconstruction is indicative of a fundamental problem. Our analysis provides a plausible explanation for why cooling is observed four years later than expected, and is greatly diminished in magnitude. And it explains a similar discrepancy between the tree-ring reconstruction and the cooling associated with the 1815 Tambora eruption, which is constrained by observational data (R. Rohde *et al.*, manuscript in preparation) that confirm the model-estimated cooling and contradict the muted cooling in the tree-ring reconstruction. The authors of ref. 2 (R. D'Arrigo, personal communication) concede there is a threshold for the cooling recorded by tree-ring growth. Thus, the remaining disagreement appears to be over the extent and larger implications of this effect.

Finally, we must stress that we did not argue, as Anchukaitis *et al.* seem to suggest, that tree-rings are uniformly recording the wrong year of the eruption in a way that can be diagnosed just by looking at composite series (for example, their Supplementary Fig. 2C). Instead, we suggest that sufficiently many individual tree-ring records within the composites are likely to have dating errors (due to potential missing or undetected rings following the largest volcanic eruptions) for the cooling signal to become muted and smeared in the large-scale averages. ❐

References

1. Mann, M. E., Fuentes, J. D. & Rutherford, S. *Nature Geosci.* **5,** 202–205 (2012).
2. D'Arrigo, R., Wilson, R. & Jacoby, G. J. *Geophys. Res* **111,** D03103 (2006).
3. MacDonald, G. M., Kremenetski, K. V. & Beilman, D. W. *Phil. Trans. R. Soc. B* **363,** 2285–2299 (2008).
4. Gu, L. *et al. Science* **299,** 2035–2038 (2003).
5. Crowley, T. J. *Science* **289,** 270–277 (2000).

Additional information

Supplementary information accompanies this paper on www.nature.com/naturegeoscience. All code and data used in this comment are available at http://www.meteo.psu.edu/~mann/supplements/TreeVolcano12/Comment/index.html.

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Published online: 25 November 2012

Hydroelectric carbon sequestration

To the Editor — The number of hydroelectric dams has increased rapidly in the past two decades and so, too, has the world's interest in their environmental effects[1]. Hydroelectricity is not free from greenhouse gas emissions[2] and, in particular, methane release from dams has been identified as an important contributor to global warming[3]. However, most greenhouse gas assessments neglect the idea that hydroelectric reservoirs are also large carbon sinks and can sequester organic carbon in their sediments[4]. We argue that the common practice of neglecting carbon burial in hydroelectric reservoirs leads to an erroneous characterization of the effect river damming has on the carbon cycle.

Organic carbon in sediments represents carbon dioxide that has been removed from the atmosphere by photosynthesis on land or in water. The fraction of organic carbon that escapes mineralization — that is, the microbial transfer of organic carbon back into carbon dioxide or methane — accumulates and is buried. This process therefore represents a sink for atmospheric carbon. The typically intense inputs of fluvial sediments containing organic carbon and the high trapping efficiency of dams make hydroelectric reservoirs important sites for organic carbon burial[5].

A full assessment of the impact of damming rivers on the carbon budget requires that both carbon burial and emissions before impounding are considered. Burial in a reservoir only represents an effective sink for carbon in cases where, in the absence of the dam, the organic carbon would not have later been buried downstream or in the ocean anyway; or in cases where the buried organic carbon is derived from new production in the reservoir. If these conditions are not met, the burial of land-derived organic carbon in the reservoir is, in part, just a matter of changing the location of storage.

In reservoirs, sediment-deposition rates are high and the ensuing rapid burial means that exposure of the organic carbon particles to oxygen in the overlying water is limited[6]. Moreover, bottom-water oxygen levels are frequently low because stratification hinders the circulation of atmospheric oxygen to these depths. The mineralization of organic carbon is more efficient in oxygenated waters, and therefore the burial of organic carbon in reservoirs is increased relative to rates of burial in the more oxygenated sediments commonly found in floodplain lakes or the ocean[6]. This suggests that in the absence of the dam, a greater fraction of the organic carbon carried by the river would be mineralised and released to the atmosphere as carbon dioxide.

Precise estimation of carbon emission versus burial in hydroelectric reservoirs is, however, complicated by unknown and unconstrained factors that operate over variable timescales. First, when the reservoir is initially filled, terrestrial organic matter that is hard to decompose adds to the reservoir's organic carbon stock representing a type of burial. In a tropical Brazilian reservoir, for example, large tree trunks still emerge from the water surface, 23 years after impounding[7]. Furthermore, some organic carbon in reservoir sediments may come from carbon dioxide fixation by primary producers, such as phytoplankton, originating in the reservoir itself[8]. This process represents an additional carbon sink, but the quantification of its effect requires better estimates of the proportion of locally derived organic carbon compared to that carried from external sources. However, aquatic organic carbon is readily degradable, even in anoxic conditions, so large-scale carbon dioxide fixation by primary producers in the reservoir could ultimately fuel microbes that create methane, a strong greenhouse gas. Moreover, most hydroelectric reservoirs are net heterotrophic[9], meaning that more carbon dioxide is released from the waters than is taken up by photosynthetic organisms. This implies that at least some of the terrestrial organic carbon input is not buried, but decomposed within the reservoir.

Part of the complexity associated with estimating carbon budgets in hydroelectric reservoirs stems from the fact that carbon emission and sediment burial are intimately linked. Increased terrestrial carbon loads (for example, from deforestation or increased precipitation) will elevate both carbon emissions to the atmosphere and burial in the sediment. On the other hand, factors that reduce organic carbon mineralization in sediments, such as a decrease in oxygen or temperature, cause burial to increase[10] with an opposite effect on emission. Consequently, organic carbon burial may alleviate greenhouse gas emissions from reservoirs (Fig. 1). For example, at the highly emitting Lake Wohlen reservoir in Switzerland, organic carbon burial was measured at 4,070 g CO_2-equivalent m^{-2} yr^{-1}, which is 2.7 times higher than its measured greenhouse gas emissions[11]. On a global scale, the estimated rate of organic carbon burial in reservoirs is 1,464 g CO_2-equivalent m^{-2} yr^{-1} (all reservoir types)[5], almost twice their estimated emission rate of 810 g CO_2-equivalent m^{-2} yr^{-1} (hydroelectric reservoirs only)[9]. Although there is no global estimate for organic carbon burial in hydroelectric reservoirs only, it is evident that without burial in hydroelectric reservoirs, greenhouse-gas emissions would likely be even larger.

The importance of organic carbon burial in reservoirs was first discussed at least three decades ago[12], but we have advanced little since then, and the magnitude of the carbon sink created by hydroelectric reservoirs is still unclear. The most commonly reported estimate of organic carbon burial in reservoirs[5] is derived from non-standardized methods, and further measurements in hydroelectric reservoirs seem to be limited to one tropical[8] and one temperate[11]. The lack of organic carbon burial data may stem, in part,

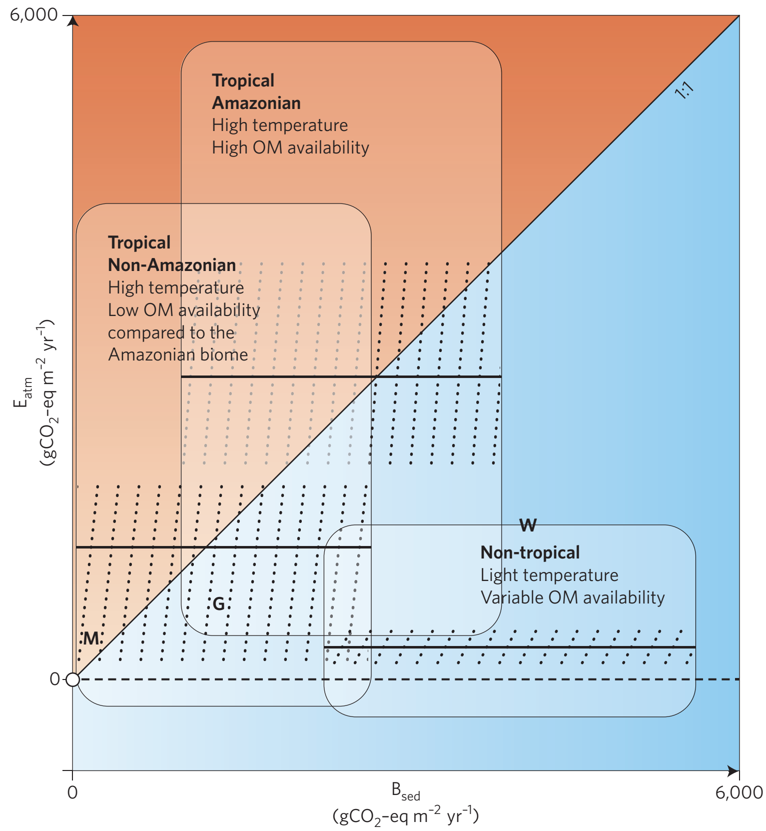

Figure 1 | A conceptual model of the relationship between carbon emission to the atmosphere (E_{atm}) and organic carbon burial (B_{sed}) of hydroelectric reservoirs. Only a small portion of the world's reservoirs is a net sink of atmospheric CO_2 equivalents (here shown as E_{atm}<0)[9]. The range of estimates of organic carbon burial is based on the effect of temperature and organic matter availability on carbon burial. Burial rates exceeding emissions (in blue) are expected in non-tropical regions as a consequence of low mineralization rates. Burial rates in Amazonian reservoirs are thought to be higher than in other tropical regions, where emissions are expected to exceed burial (in red) because of higher organic matter (OM) availability. Dotted lines indicate 75% quartile; horizontal solid lines indicate the median; M, Mascarenhas de Moraes Reservoir, Brazil (ref. 13 and R. Mendonça *et al.*, manuscript in preparation); W, Lake Wohlen, Switzerland[11]; G, global relationship between carbon emission and burial (from hydroelectric[9] and all reservoirs[5], respectively).

from difficulties associated with accurately measuring sediment accumulation rates across entire reservoir basins that experience highly heterogeneous deposition. The evidence so far indicates that in reservoirs in colder regions, carbon burial outweighs emission to the atmosphere, whereas in warm regions such as the Amazonian biome, carbon emissions are probably higher (Fig. 1).

The area covered by hydroelectric reservoirs — currently almost as large as Germany[9] — is steeply increasing due to the world's ever-growing demand for electricity. The net effect of damming rivers on the carbon cycle is, however, still unclear, and requires the combination of pre- and post-flooding assessments. Although assessment of the carbon sink created by hydroelectric reservoirs is not straightforward at present, this sink does constitute an important component of the carbon budget and should not be neglected. ❐

References

1. Wehrli, B. *Nature Geosci.* **4,** 585–586 (2011).
2. St Louis, V. L., Kelly, C. A., Duchemin, E., Rudd, J. W. M. & Rosenberg, D. M. *Bioscience* **50,** 766–775 (2000).
3. Giles, J. *Nature* **444,** 524–525 (2006).
4. Stallard, R. F. *Global Biogeochem. Cycles* **12,** 231–257 (1998).
5. Dean, W. E. & Gorham, E. *Geology* **26,** 535–538 (1998).
6. Sobek, S. *et al. Limnol. Oceanogr.* **54,** 2243–2254 (2009).
7. Fearnside, P. M. & Pueyo, S. *Nature Clim. Change* **2,** 382–384 (2012).
8. Kunz, M. J. *et al. J. Geophys. Res.* **116,** 0148–0227 (2011).
9. Barros, N. *et al. Nature Geosci.* **4,** 593–596 (2011).
10. Gudasz, C. *et al. Nature* **466,** 478–481 (2010).
11. Sobek, S., Delsontro, T., Wongfun, N. & Wehrli, B. *Geophys. Res. Lett.* **39,** 0094–8276 (2012).
12. Mulholland, P. J & Elwood, J. W. *Tellus* **34,** 490–499 (1982).
13. Roland, F. *et al. Aquat. Sci.* **72,** 283–293 (2010).

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