quite apart from the increased drought risk caused by the greater evaporative demand at higher temperatures.

One approach to model the complexity of these responses is to attempt to encompass knowledge of crop physiology and responses to environmental factors into process-based models[12]. Such models have been extensively applied to predict the impacts of climate change on crop yields and have been tested against experimental data sets in diverse environments, including free-air carbon dioxide-enrichment experiments, which mimic the conditions of climate change on a field scale[13,14]. In a recent study[4], the impacts of climate change on wheat across Europe were assessed using the Sirius wheat simulation model and future climate scenarios based on the projections from the Coupled Model Intercomparison Project phase 3 ensemble of 15 global climate models[15] for the SRES A1B emissions scenario. This study predicted that by 2050 wheat yields in the UK are likely to increase by 11.4% with an uncertainty range between 5.4% and 15.1% representing 10th and 90th percentiles. This increase is attributable to the well-understood positive response to increased carbon dioxide concentration[13,14,16], a factor that was not considered in the generation of the CCRA predictions. However, even these modest increases in predicted yield are highly indefinite, owing to uncertainty about the precise changes in climate and the frequency of extreme events.

As discussed above, extreme temperatures, even of short duration, greatly add to the risks to wheat yields. It is well established, for example, that short periods of high temperatures around flowering can substantially reduce the grain yield for heat-sensitive wheat cultivars, because of reductions in both grain size and grain number[17]. Even under UK conditions, the risk of heat stress around flowering is predicted to increase, which may result in substantial yield losses for heat-sensitive cultivars that are commonly grown in the UK[4]. Although this problem may be amenable to breeding from existing germplasm, the other negative effects of temperature are likely to present major challenges to wheat researchers and breeders. Only continued improvements in wheat varieties and crop management can meet the rapidly increasing demand for wheat and, contrary to the CCRA predictions, increasing temperatures will make this challenge much more difficult. ❐

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COMMENTARY:

Greenhouse-gas emissions from tropical dams

Philip M. Fearnside and Salvador Pueyo

Emissions from tropical hydropower are often underestimated and can exceed those of fossil fuel for decades.

Tropical hydroelectric dams, such as those in Amazonia, emit significant amounts of greenhouse gases, especially methane[1–4]. These emissions have been underestimated or ignored in many global and national greenhouse-gas accounts. If any justification is given for omitting all or part of these emissions, it is usually that they are controversial, uncertain or with no consensus[5]. However, although uncertainty regarding the quantities emitted is substantial[6], dam emissions need to be included in all accounting based on the best available data and calculation methods. Much of the wide variation in the emissions ascribed to tropical dams stems from omissions and errors in accounting, rather than from the physical measurements that are nevertheless also subject to methodological problems.

The fact that substantial emissions are involved can hardly be considered uncertain, having been measured directly at reservoirs such as Balbina in Brazil[2] and Petit Saut in French Guiana[1]. Dam emissions are of two types: reservoir surface or upstream emissions and those from the water that passes through the turbines and spillways (degassing or downstream emissions). Where dam emissions are counted, they often include only the upstream emissions, as in estimates by Centrais Elétricas Brasileiras S.A. (Eletrobrás)[7]. The recent Intergovernmental Panel on Climate Change special report on renewable energy reviews life-cycle assessments for various technologies and, for the typical case (the 50th percentile), ranks hydro as having half the impact or less compared with any other source including solar, wind and ocean energy[5]. The basis in data used for this optimistic classification is unclear from the report.

Carbon that is emitted as carbon dioxide can come from two types of source. First, there are fixed sources that produce a one-time emission, such as the trees killed by flooding the reservoir and the stocks of carbon in the soil (Fig. 1). Second, there are renewable sources such as the carbon that is removed from the atmosphere through photosynthesis by aquatic plants, phytoplankton or algae in the reservoir, trees in the watershed that produce litter that is washed into the reservoir by rainwater, or vegetation in the drawdown zone (the area that is temporarily exposed each time the water level is lowered in the reservoir).

Fixed sources of carbon dioxide should be counted as contributions to global warming, especially the decay of dead trees that are left projecting out of the water in Amazonian reservoirs, but are often omitted. By contrast, carbon dioxide from renewable sources is not a net emission, as this is exactly balanced by the carbon removed from the atmosphere when the biomass is formed (which has not been included in the accounting). All of the methane emissions, however, make a net contribution to global warming. The reservoir's function in transforming renewable carbon into methane gives it the role of a methane factory, continuously removing carbon from the atmosphere as carbon dioxide and returning it as methane, with a much greater impact on global warming[8]. Methane is formed where organic matter decays under anoxic conditions, such as in the sediments at the bottom of a reservoir. The soft vegetation that grows when the drawdown zone is exposed will decay under anoxic conditions at the bottom of the reservoir, releasing methane.

The water in a tropical reservoir stratifies thermally, with a warm layer (epilimnion) in the upper 2–10 m where the water is in contact with the air and contains oxygen, and a colder layer (hypolimnion) at the bottom where any oxygen is quickly exhausted and virtually all decay produces methane rather than carbon dioxide. Water passing through the turbines and spillways is drawn from the lower layer (Fig. 2). Downstream gas emissions occur as the water is released under pressure below the dam. Just as bubbles emerge on opening a bottle of soft drink, the release of pressure reduces the solubility of gases, causing bubbles to form (Henry's law)[9]. Later, warming of water in the river below the dam causes further gas to be released.

Downstream emissions have been omitted in a number of global compilations of estimates of dam impacts, such as those led by St Louis[10], Bastviken[11] and Barros[12]. The proportion of upstream and downstream methane emissions depends on the area of the reservoir and the magnitude of the river's flow: upstream emissions are proportional to the reservoir area but downstream emissions are proportional to the streamflow. At Brazil's Balbina, where the reservoir area is unusually large (approximately 3,000 km^2) and the average streamflow unusually small (657 $m^3 s^{-1}$), about half (53%) of the methane emissions occur downstream[13]. At Tucuruí, with approximately the same reservoir area as Balbina but 17 times more streamflow, downstream methane emissions represent 88–93% of the total[3].


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Figure 1 | Dead trees in Brazil's Samuel Reservoir. Above-water decay of this fixed-carbon source releases carbon dioxide.

When downstream emissions have been included, they have often been underestimated by methods that miss a major portion of the release. Because much of the methane is released immediately as the water emerges from the turbines, and even inside the turbines themselves, estimates based on flux measurements by samplers floating on the water surface in the river some distance downstream[14] will inevitably miss much of this emission. The only practical means of avoiding this bias is to calculate the immediate degassing emissions from the difference in methane concentration in the reservoir water at the turbine intake depth and in the water below the dam[8].

A methodological factor that affects all of the concentration-based estimates so far essentially doubles the methane emissions from water passing through the spillways and turbines in typical Amazonian dams. The effect is depth-dependent: the methane concentration in the water at the turbine level (normally near the bottom of the reservoir) is critical and this has traditionally been measured in water that is brought to the surface in a Ruttner bottle, from which a sample is drawn with a syringe and chemically analysed. Any methane that comes out of solution as the bottle is raised to the surface is lost. A sampling device dubbed the Kemenes bottle captures and measures this methane, yielding concentration values at a typical turbine depth of 30 m that are approximately double those of measurements using Ruttner bottles; in the case of Balbina, this results in an average turbine degassing emission calculated from concentration difference (using Kemenes bottles) that is 116% higher than the average based on simultaneous sampling with Ruttner bottles[2].

The importance of emissions released immediately at the turbine outlet is illustrated by the results at Balbina[2]. In this case, the dam's turbine intake includes a funnel-like structure that draws water from 14 to 30 m depth. Considering the methane concentration integrated over the full hypolimnion, the amount released downstream (by immediate bubbling at the turbines and by diffusion in the river farther downstream) would be 2.2 times greater than the downstream diffusion emissions alone if the immediate release is based on Ruttner bottle samples, or 3.4 times more if based on Kemenes bottle samples. If the calculation is based on the location of the turbine intake sill at a depth of 30 m, the corresponding multipliers would be 7.8 and 15.6, respectively. In other words, estimates of downstream emissions based only on fluxes captured by surface chambers in the river below the dam report less than half and possibly as little as one-sixteenth of the actual downstream emissions.

Various mathematical errors have resulted in Brazil's electrical authorities estimating the magnitude of emissions from reservoir surfaces at a level of only one-fourth what it should be (see detailed explanation in ref. 15). Eletrobrás[7] calculated the surface emissions of methane bubbling for each of Brazil's 217 large dams in 2000 by applying a power-law correction to a mean of measured values (in $g\ m^{-2}\ d^{-1}$) for seven reservoirs. The power law is used to capture the effect of infrequent but large events. For example, in the case of earthquakes, many small quakes and only a few main ones occur. By using information on the frequency of quakes measured at different magnitudes, one can calculate the frequency of much larger quakes that are inevitably underrepresented in the available data. The same applies to methane emissions from a reservoir surface, where most measurements will record only modest emissions but a small number of very large emission events do occur. In other words, correcting for these rare events with the power law will inevitably increase the emissions estimate above the simple average of a set of measurements.

However, the Eletrobrás calculation contains no less than five mathematical errors, including a change of sign from positive to negative[15]. It reduces the reservoir surface estimate by 76% below the simple arithmetic mean, whereas a correct application of the power law to the same data would make the corrected estimate 345% higher than the Eletrobrás estimate[15]. Brazil's hydroelectric reservoirs in 2000 totalled 33×10^3 km^2, an area larger than Belgium. The difference between the Eletrobrás estimate of methane emissions from this surface (0.22×10^6 t yr^{-1}) and our correction of the calculation (0.98×10^6 t yr^{-1}) is equivalent to 7.0×10^6 t of carbon dioxide equivalent carbon per year, or an emission approximately equal to that of greater São Paulo[15] if calculated using a global warming potential of 34 over a 100-year time horizon[16]. The magnitude of the underestimation in the Eletrobrás calculation would be equivalent to 5.2×10^6 t of carbon dioxide equivalent carbon if one uses the lower global warming potential of 25 now adopted by the United Nations Framework Convention on Climate Change (UNFCCC) for the period from 2013 to 2017, but that omits the indirect effects of methane.

The Brazilian Ministry of Mines and Energy's ten-year plan covering the period from 2011 to 2020 calls for the construction of an additional 48 large dams, 30 of which would be in the country's Legal Amazon region[17]. This means building one dam every four months in Amazonia. Dam building is shifting to tropical areas on a global scale, including plans by Eletrobrás to build more than a dozen dams in Peru and other Amazonian countries. Tropical dams (the subject here) emit more greenhouse gases than do dams in other zones[12,18].

Amazonian dams are being promoted, in part, on the basis of a supposed benefit in mitigating global warming[19], including the intention of capturing mitigation funds on a large scale under the Kyoto Protocol's Clean Development Mechanism[19]. Unfortunately, these dams can be expected to have cumulative emissions that exceed those of fossil-fuel generation for periods that can extend for several decades, making them indefensible on the basis of global warming mitigation[20]. In the case of Brazil, much of the country's Amazon forest is under risk from the consequences of global warming on this timescale[21]. The time frame is critical in dealing with global warming: dams produce large emissions in the first few years followed by lower emissions that are sustained indefinitely, whereas generation from fossil fuels produces emissions at a constant rate[22]. The greenhouse-gas debt created by the dam in the first years when emissions are much higher than those from fossil-fuel generation can take decades to pay off after the dam emissions stabilize at a level below those of fossil fuels[4]. The consequences of waiting decades to begin effective reduction of global emissions are grave.

Controlling global warming will require mitigation measures that are sufficient to keep the atmospheric concentration of greenhouse gases below a level defined as dangerous. All emissions must be mitigated, whether or not they are the result of deliberate human actions such as building dams, or their reporting is mandatory at present under UNFCCC guidelines. If any of these emissions are ignored or understated, then the national quotas (assigned amounts) negotiated to reduce emissions will be insufficient and global temperatures will continue to increase, along with all of the impacts that this implies. Among the issues to be faced is that of counting all emissions from dams and including them in national inventories. The emissions from tropical hydropower mean that this is not clean energy and that countries need to commit to making deeper cuts in their anthropogenic greenhouse-gas emissions than they have been willing to consider so far. ❐

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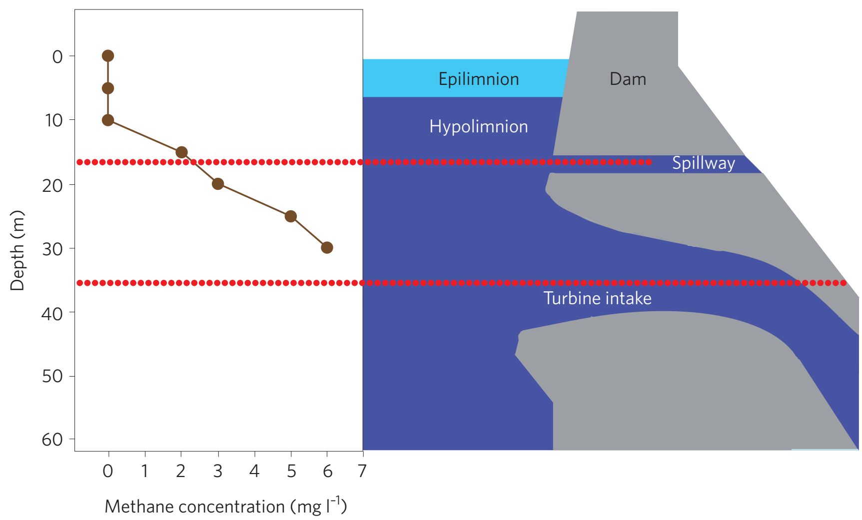

Figure 2 | Methane-rich water is drawn from below the thermocline that divides the water column into a surface layer (epilimnion) and an anoxic bottom layer (hypolimnion). The thermocline prevents cold water at the bottom of the reservoir from reaching the surface. A schematic of Brazil's Tucuruí Dam (right) shows the spillway and turbine depths at the time of a 1989 measurement of methane concentrations by Tundisi (left; data taken from ref. 23). The water level has been raised by a further 2 m since 2002. The release of pressure as the water emerges allows the methane to degas to the atmosphere.

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