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Getting lost tracking the carbon footprint of hydropower

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A R T I C L E I N F O

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A B S T R A C T

In the transition to low-carbon electricity, well-quantified estimates of carbon dynamics are needed to ensure that emissions reduction targets are achieved. We review the state of the science on carbon accounting for hydropower reservoirs and identify limitations and future solutions. Nearly all research on reservoir greenhouse-gas (GHG) emissions has focused on individual reservoirs in isolation without considering their position in a freshwater network draining organic matter from upstream watersheds or the coordinated operation of reservoir cascades. Second, carbon inventories have extrapolated from a small, non-probabilistic sample of highly variable measurements of GHG emissions to unsampled reservoirs. A stronger statistical foundation is needed to estimate a global inventory and its uncertainty. Third, attribution to hydropower is based on ranks assigned to reservoir purpose. Instead, the physical influence of hydropower on carbon dynamics could be directly measured. Fourth, current carbon-accounting practices neglect time. A time-varying approach would quantify variation in emissions for electricity portfolios from changes in the fuel mix at different times and account for ancillary services, i.e., the ability to support the grid when variable renewables are not available without using natural gas. Reservoirs also sequester a significant portion of inflowing carbon in sediments and slow the carbon cycle by delaying the return of carbon to the atmosphere for decades to centuries. Together, these refinements would help to illuminate pathways toward meeting energy demand with the longest-possible delay in returning carbon to the atmosphere and without adding ancient sources to the pool of carbon cycling through aquatic ecosystems.

1. Introduction

Fossil fuels extracted from ancient pools of carbon have been added to the active global carbon pool (including the atmosphere and biosphere) and are causing shifts in climate across the globe. To prevent further climate change, a transition to a low-carbon economy is underway. Renewable energy is successfully penetrating the electricity market; on-shore wind and photovoltaic solar in some regions can produce enough to satisfy electricity demand [1]. However, variable renewables do not always provide electricity when it is needed [1]. This mismatch between the timing of supply, combined with a lack of storage, prevents variable renewables from supplying 100% of grid demand [2,3].

Hydropower will play an important role in stabilizing the grid by providing storage and ramping responses (the ability to quickly increase generation) needed to integrate low-carbon energy sources [4]. For example, one recent study showed that as conventional solar photovoltaic generation increased over time, small hydropower plants (<30 MW) provided ramping services at dusk and dawn (between 7 a.m. and 10 a.m. and between 7 p.m. and 10 p.m.) bordering daylight hours when solar generation is possible and electricity demand is high [5]. Hydropower plays a similar role to natural gas, with lower operation cost, flexibility, and dispatchability. Moreover, life-cycle assessments suggest that hydropower has fewer overall negative impacts, with the highest benefits from improved air quality and lower greenhouse-gas (GHG) emissions [6–9]. Nevertheless, growing concerns about GHG emissions have motivated studies to compare the carbon 'footprint' of renewable energy sources that supply the electricity grid [6,10,11].

In this paper, we review the current state of the science for quantifying carbon dynamics in reservoirs and the accounting methodologies used to assign a carbon footprint to hydropower using top-down methods (a portion of reservoir emissions) and bottom-up methods (mechanistic effects on carbon processing associated with generating power). We identify methodological and conceptual challenges with these methods. For each challenge, we offer suggestions for how to

Abbreviations: GHG, greenhouse gas; LCA, life-cycle assessment.

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improve GHG assessments, emphasizing needed improvements to accounting practices and research needed to evaluate the carbon footprint of hydropower within the broader context of growing complementarities among sources of electricity generation in stabilizing the grid (i.e., all MWh are not equal) [12].

2. Background

2.1. Carbon emissions from reservoirs

Man-made reservoirs change the ways that carbon moves through fluvial systems, potentially sequestering some, but also creating conditions that amplify global warming potential by promoting methane production. GHGs contribute to atmospheric warming through both fast responses, including radiative forcing in the atmosphere and thermal response of the ocean mixing layer, and slow responses in the deep ocean [13]. CO_2 has cumulative, but smaller, effects on warming, whereas methane has stronger short-term (decadal scale) warming potential that declines over time but includes a lagged warming response, designated by assigning methane a radiative forcing at least 25-times higher than CO_2 [14]. When accounting for short-term warming effects of methane over a 100-y reservoir life span, nearly 80% of radiative forcing from reservoirs is due to methane emissions [15]. Reservoirs amplify the global warming potential of carbon by transforming CO_2 into methane before returning it to the atmosphere (Fig. 1).

Although methane production (methanogenesis) can occur in the presence of oxygen [16], it is promoted by the supply of recalcitrant carbon and anoxic sediment conditions through the redox cascade [16–18]. Methane can reach the atmosphere through diffusion, ebullition (bubbles), transmission via littoral vegetation, and degassing from dam releases (Fig. 1). Ebullition is often the largest flux of methane to the atmosphere; in a global synthesis, 65% of methane emissions from freshwaters reached the atmosphere via ebullition [15].

2.2. Carbon sequestration in reservoirs

Burial of terrestrial carbon is more efficient in reservoirs than in other depositional environments along the headwaters-to-ocean continuum [19]. On average carbon burial is six-times higher in reservoirs than in lakes, and exceeds carbon emissions in temperate climates [20]. Roughly 40% of carbon stored in inland water bodies is stored in reservoirs [20].

Conditions that promote carbon burial are similar to those that produce methane emissions [21]. For example, shallow reservoirs experience high rates of both methane emission and carbon burial [22,23]. Small agricultural reservoirs have the highest burial rates probably due to eutrophication [20]. In one extreme case, methane emissions reported in a Swiss reservoir were 37% of carbon burial when expressed in terms of radiative forcing [24]. The balance between carbon storage and emission is influenced by a number of factors, including water temperature, sedimentation rate, organic matter inputs, and reservoir morphology (i.e., depth) [21]. As the source of terrestrial carbon, catchment area is also an important influence on burial [23]. High sediment deposition rates and anoxic conditions that prevent mineralization of organic carbon in sediment in temperate reservoirs provide the right environment for carbon burial [19] but also for methanogenesis. However, responses of burial and methane emissions differ under low oxygen or high temperature conditions. Under low oxygen conditions, CO_2 emissions decrease due to restricted carbon mineralization, whereas burial rates increase, with opposite responses under high temperature conditions [21].

2.3. Reservoir morphology influences on carbon dynamics

Morphometric properties of reservoirs influence carbon emission and burial processes (see Table 1). Shallow, eutrophic lakes contribute more to methane emissions than deep reservoirs [17]. However, only the fraction of methane generated by decomposing older carbon represents an increase in net carbon emissions (relative to a pre-reservoir counterfactual) [25]. Higher ebullition is expected from reservoirs with a high ratio of perimeter to area ratio for several reasons. A considerable fraction of methane generated in freshwater sediments is oxidized to CO_2 by methane-oxidizing microbes before reaching the water's surface [22,26]. Methane bubbles are most likely to reach the atmosphere from sediments that are deep enough to provide hydrostatic pressure (>3 m [15]), but shallow enough to reach the water surface without being

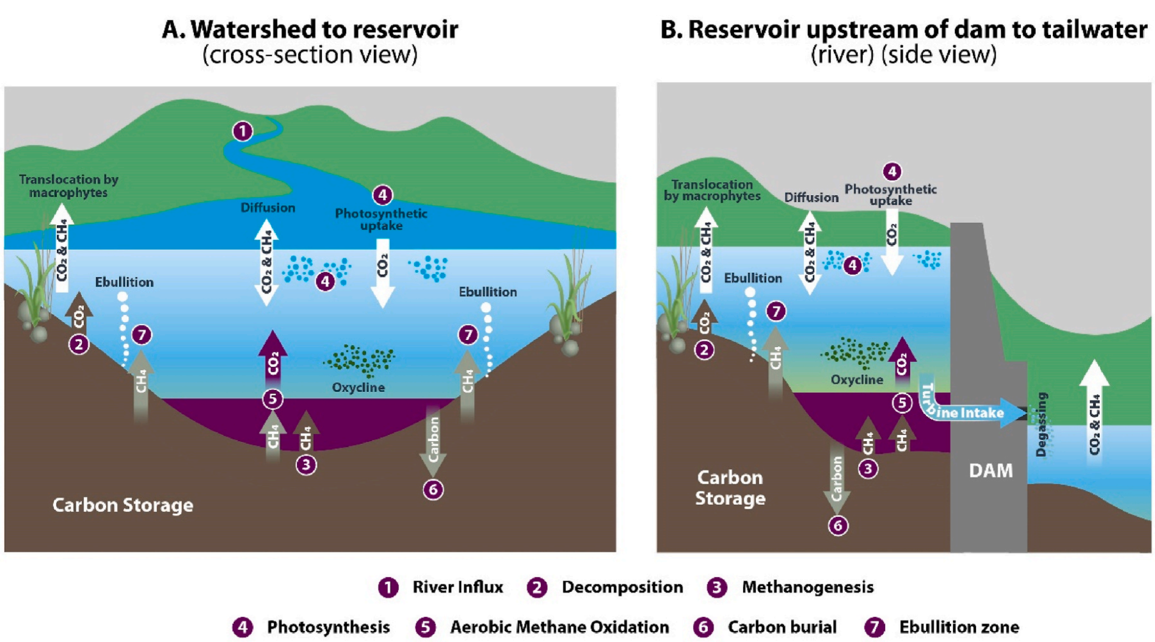
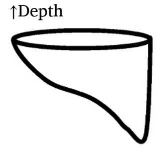
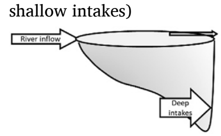
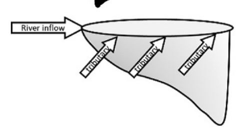


Fig. 1. Diagram showing contributions of terrestrial and other upstream sources of carbon to a reservoir (A. left), influx of carbon to the reservoir, and subsequent transformations, fate, and transport of carbon within the reservoir and downstream after passing through the dam (B. right). Note that most CO_2 would have been emitted in a pre-reservoir case, whereas some fraction of methane (CH_4) can be attributed to the presence of the reservoir.

Table 1
Processes that influence carbon dynamics in reservoirs.

Carbon process	Factors that increase rates	Hot moments	Hot spots	Morphometric properties that increase carbon-cycle process rates	Net emissions attributed to reservoir? [25]	Net emissions attributed to hydropower?
Methane Diffusion	Large influx of organic matter promoting methanogenesis Reduced methane oxidation efficiency	Fall turnover for deep reservoirs	Sediment influxes at mainstem and tributary inflows	↑Surface area 	Δ from pre-reservoir ecosystem	Δ in hypoxia due to operations
Methane Ebullition	↑Temperature ↑Perimeter to area ratio Mid-depth: allows methane to accumulate in sediment	Warm periods (hypoxic conditions)	Hypoxic sediments deep enough to form bubbles (hydrostatic pressure) and shallow enough for bubbles to reach the water's surface before oxidation.	↑Perimeter (littoral area) 	Δ from pre-reservoir ecosystem	Δ in methane oxidation between situation without hydropower and operation for hydropower (e.g., sub-daily cycles)
Oxidation of methane	↑Depth: allows methane to convert to CO_2 as it travels through water column	Fall turnover leading to mixing of oxygen throughout water column	Deep areas in the reservoir	↑Depth 	Δ from pre-reservoir ecosystem	Δ in methane oxidation from sub-daily cycles
Degassing	Operation of turbines using hypolimnetic withdrawal	During warm, stratified conditions when deep water has high methane concentrations	Tailwaters below hypolimnetic intakes	↑Fraction of flow from hypolimnetic release (vs spill or shallow intakes) 	No	Yes
Carbon dioxide Diffusion	↑ Temperature ↑ Organic matter inputs ↑ Productivity	Low wind speed	Deep areas in the reservoir	↑Surface area 	Δ from pre-reservoir (flooding of carbon-rich soils)	No, except for CO2 released due to methane oxidation
Csrbon Burial	↑Sedimentation rate (organic matter inputs)	Events with high sediment influxes; stratification; warm, anoxic conditions	Tributaries inflows, river inflows		Δ from pre-reservoir ecosystem	No

oxidized (<6 m [17]). Second, macrophytes in reservoirs with a complex shoreline and abundant shallow littoral area can shunt methane and CO_2 from deeper sediments to the atmosphere via translocation [27]. Finally, shallow water bodies are more likely to experience a high influx of carbon and nutrients relative to water volume leading to eutrophic conditions [28]. The potential for algal growth (and subsequent decomposition leading to anoxia) is high where the photic zone constitutes a large fraction of water volume.

In contrast to ebullition, methane diffusion rates are decoupled from rates of methanogenesis, and likely depend less on reservoir depth than on reservoir area [17] (Table 1). Further, as eutrophication increases and sediment methane production is high, sediment methane oxidation efficiency may be reduced. increasing surface emissions [29]. Both the depth and fetch orientation of a reservoir can also influence eutrophication; shallow reservoirs aligned with the prevailing winds have a higher potential for resuspending phosphorus from sediments.

3. Carbon footprint of hydropower reservoirs

3.1. State of the science

The carbon footprint is one dimension of the 'ecological footprint,' a concept that emerged in the early 1990s with the idea that society can only continue to persist sustainably by maintaining enough 'natural capital' to support the ecosystem services needed [30], including energy. The ecological footprint is measured by the land area (or water volume) needed to sustain resource consumption and waste discharge by the human population [30,31]. Another definition of the carbon footprint consistent with economic input-output analysis is 'all direct and indirect (embodied) GHG emissions caused by a given final demand' [32]. Recent efforts have focused on calculating and comparing carbon footprints among alternative energy sources.

3.2. Challenges with the state of the science

Nearly all research on reservoir GHG emissions has focused on individual reservoirs without considering the broader watershed-scale context. The footprint-based approach used for terrestrial ecosystems is less suitable for freshwater networks, which implicitly assumes that the ecosystem is a closed system; assigning an average emission rate per square km of water surface area implies that emissions scale linearly with the surface area of the water body. However, lakes and reservoirs primarily generate methane from recalcitrant allochthonous carbon of terrestrial origin that they receive from the surrounding watershed via the inflowing river network [25,33].

In reservoir cascades, upstream trapping of organic matter can decrease available allochthonous carbon in downstream reservoirs. For example, Lower Charette Lake in New Mexico drains a large, 560 km^2 watershed, yet it has lower emissions than its drainage area might predict because carbon and nutrients are trapped by Upper Charette Lake [15]. In another example, potential methane production in sediments increased downstream in an oligotrophic reservoir cascade on the Mekong River [34]. However, the estimated downstream increase in methane production in the Mekong River did not result in increased downstream methane emissions (ebullitive or diffusive) [34]. Because terrestrial carbon inputs are so important, tributaries along the cascade can be important sources of sediment input and carbon [35].

Secondly, research suggests that there are longitudinal patterns in biogeochemistry, including carbon dynamics, as depicted in Fig. 2 [36]. The River Continuum Concept [37] proposes a transition from predominantly allochthonous to autochthonous production from headwaters to mid-sized, low-gradient rivers downstream. Consistent with the River Continuum Concept, the methane that 'counts' is from allochthonous sources, whereas downstream increases in eutrophication result in increasing CO_2 emissions. Preferential removal of aromatic compounds occurs upstream shifting the composition of carbon to aliphatic molecules further downstream [38]. Tributary inputs essentially shift this pattern toward an upstream condition. The construction of dams leads to what have been referred to as 'serial discontinuities' in biogeochemistry [38]. Yet, to our knowledge, no field research has examined the incremental changes in carbon trapping and burial and GHG emissions as dams are added or removed.

3.3. Suggested improvements

Carbon accounting for reservoirs can be improved by considering the broader context of the watersheds and upstream waterbodies that they drain. This can be done: 1) by accounting for allochthonous inputs versus surface area, 2) by developing scaling relationships for carbon fluxes to account for river order and watershed geometry, thereby making broad-scale regional assessments possible, and 3) by understanding the effects of upstream waterbodies, for example in reservoir cascades. Thus, one improvement to current accounting practices might be to report emissions relative to estimated influxes of carbon [40], rather than reservoir area [40]. However, we recognize that quantifying carbon influx is much more difficult and complex. Previous empirical modeling has shown dissolved organic carbon (DOC) and erosivity to be useful predictors of both CO_2 and methane emissions [15,41]. Reservoir studies consistently show hotspots of methane generation and emission from areas with high carbon-laden sediment deposition from upstream sources (Fig. 1) [42]. Because DOC and other carbon inputs are not always monitored, surrogates may be available. For example, DOC fluxes can be predicted from watershed area, slope [43], wetland area [44,45] and other watershed attributes [46], combined with flow.

4. Carbon emissions inventories

4.1. State of the science

Global carbon inventories for reservoirs have been developed by assembling GHG emissions data and covariates [41], developing regression models, and then extrapolating to global reservoirs using global data (International Commission on Large Dams, ICOLD), the Global Reservoir and Dam (GRanD) database [47], or HydroLAKES [48]. Global estimates for ICOLD were 48 Tg carbon as CO_2 and 3 Tg carbon as CH_4 [41]. On a per-kWh basis, global emissions based on GRanD were 85 $gCO_2\ kWh^{-1}$ and 3 $gCH_4\ kWh^{-1}$, with multiplicative uncertainty of two (i.e. halved or doubled) [49]. Methane represented approximately 42% of total emissions as global warming potential when using a 100 year time horizon [10]. More recently, global estimates based on very uncertain relationships have been supplanted by bootstrapping of reservoir measurements, including reservoirs used for a range of purposes [15].

Perhaps the most valuable aspect of these analyses is the ability to understand how emissions relate to reservoir attributes. Deemer et al. found that DOC was a good predictor of CO_2 and methane emissions [15]. In models of emissions normalized by electricity generation, including watershed attributes such as land use and terrestrial net primary production as predictors increased the variation explained. Other predictors, including reservoir surface area and area-per-energy have also been included as predictors in regression models. Only one study specifically compared emissions from power and non-power reservoirs [15]. The authors were unable to distinguish emissions from global reservoirs with a listed hydropower capacity from those without documented hydropower generation [15]. However, turbine degassing, which would be unique to hydropower reservoirs, was not measured by these studies [50].

4.2. Challenges with the state of the science

Global inventories have been attempted multiple times using the same relatively small dataset. To deal with the low sample size, global inventories developed models from a potentially non-representative sample of measurements to extrapolate to the larger set of reservoirs [51]. The addition of more recent measurements in temperate reservoirs calls into question two of the main relationships reported by earlier studies, including decreasing emissions with latitude [15] and lower emissions in older reservoirs [34].

In the conterminous US, no national carbon emission inventory from hydropower reservoirs has yet been attempted, possibly due to the small number of reservoirs sampled and the heterogeneity in sampling of GHG emissions (Fig. 3).

Fewer than 3% of reservoirs in the conterminous US support hydropower (Fig. 4). Furthermore, only 16.7% of waterbodies are reservoirs (ratio of dams in the National Inventory of Dams and National Hydrographic Data), and the majority are small (i.e., farm ponds) whereas hydropower reservoirs tend to be large (Fig. 4). The subset of reservoirs included in studies of GHG emissions [10,41,52,53] occurs across size classes (light pink bars) with overrepresentation of larger

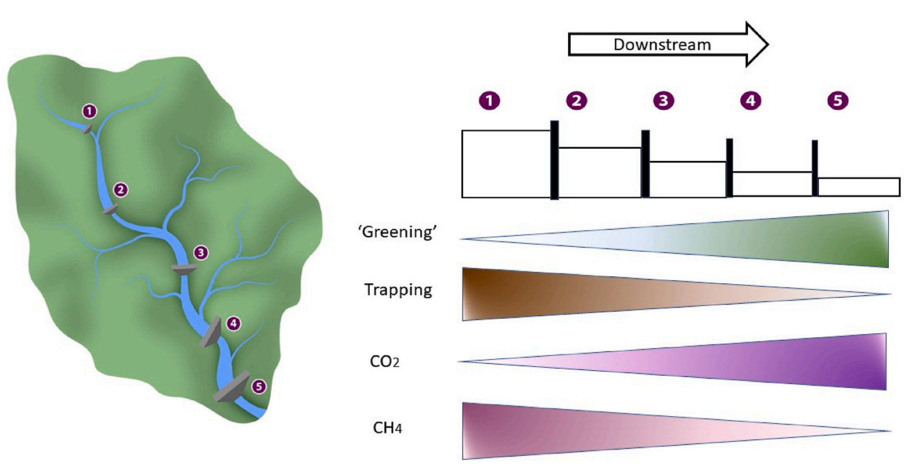


Fig. 2. Illustration of changes in cascades of reservoirs based on a conceptual model [39]; Darker colors denote higher concentrations. The model, shown at right, includes (top) river greening (eutrophication), (middle) sediment trapping and its predicted cumulative effects on greenhouse gas concentrations, (CO_2 and CH_4, bottom) in modified river systems [39] . Note that the effects of tributary inputs of carbon and nutrients, which are also part of the model, are not shown but generally result in increases in all four.

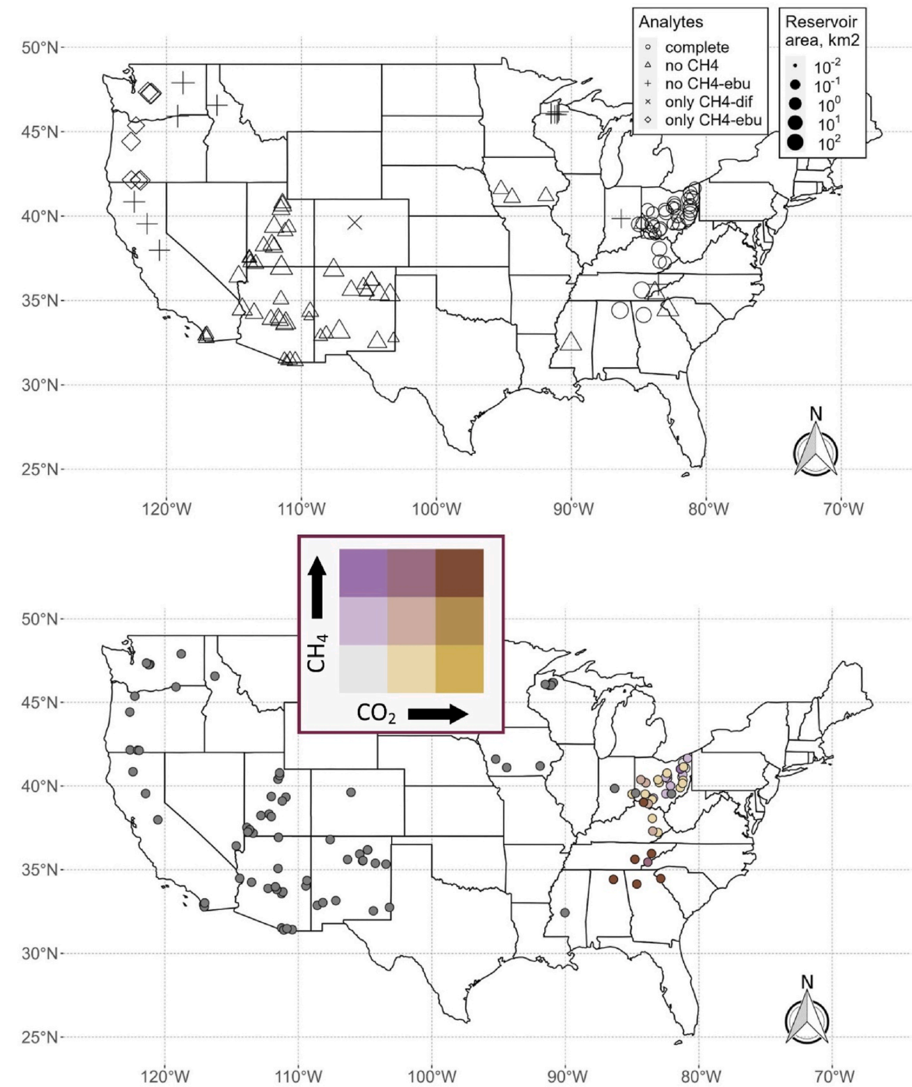


Fig. 3. Top: Area of reservoirs with measurements of some or all forms of carbon emissions included in a compilation of studies by Deemer et al. [15] or the USEPA study in Ohio and Kentucky [52] Bottom: Bivariate plot showing geographic variability in measured emissions (low, medium, and high).

reservoirs.

Both in the US and globally, available emissions data have been collected by various methods (including different fluxes, and covariates missing from different subsets of reservoirs) and with different seasonal or spatial coverage. To illustrate this, we evaluated spatial and temporal heterogeneity in data collected from reservoirs in the conterminous US by Deemer et al. [15]. These measurements represent a heterogeneous collection of flux measurements, often taken only during one season (Fig. 5). Similarly, measurements were often taken from relatively few locations within a reservoir, resulting in non-systematic spatial coverage (Fig. 6). Only a few studies are based on samples that span an entire year. Studies that include all fluxes were taken only in summer (Fig. 6). Most studies included CO_2, and many of those that measured methane measured only diffusive emissions (Figs. 5 and 6). When modelling, this heterogeneity in data collection has been addressed by including indicator variables to denote missing fluxes, which assumes that ebullition is a fixed proportion of the total methane flux. Studies measuring degassing from turbines are very rare, and little is known about how these relate to project attributes.

4.3. Suggested improvements

With time, the number of GHG emissions estimates will expand to represent a larger, more representative portion of the conterminous US than is currently shown by the map in Fig. 5. Probabilistic surveys to measure GHG emissions from reservoirs ensure that scaling up to produce regional inventories has a proper statistical foundation and that uncertainty associated with the extrapolation is reported. In the US, a geographically representative synoptic survey of GHG emissions from reservoirs is underway, but collection of comprehensive temporal data has not, to our knowledge, been planned. The problem of measuring only CO_2 and not methane will be resolved in future as more studies include measurement of methane ebullition.

From the modeling perspective, carbon-cycle data focused specifically on quantifying the hydropower footprint is needed to reduce uncertainty in net emissions from reservoirs due to hydropower. For example, few studies have measured degassing emissions associated with turbines. Because reservoirs used to develop relationships were not representative of the population of reservoirs, it is important to report uncertainties associated with extrapolating emission estimates to the larger population. Ideally, data should be collected consistently from probabilistic surveys of reservoirs and reference pre-dam ecosystems with adequate spatial and seasonal coverage, although we recognize that this can be very difficult in practice. Where model-based methods are used to extrapolate to a larger population of reservoirs, prediction uncertainties associated with models should be reported.

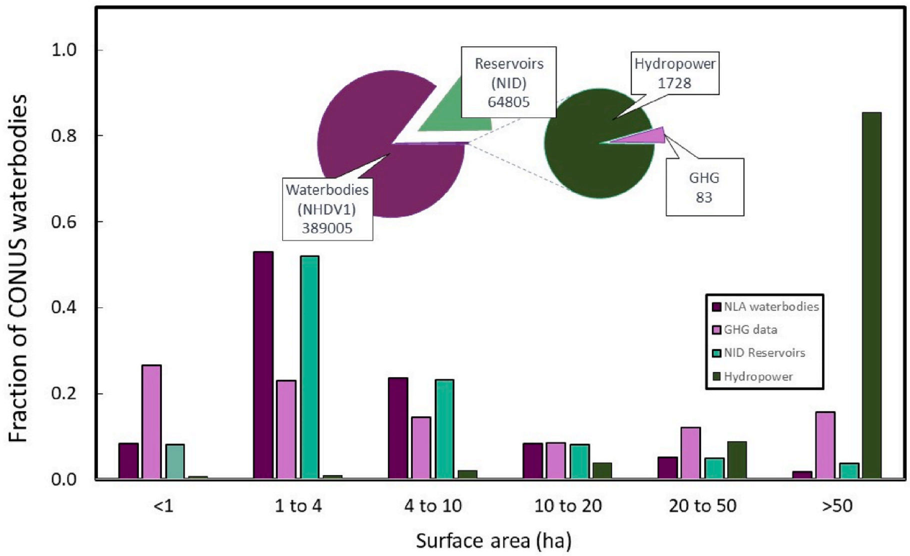


Fig. 4. Comparison of size distributions of waterbodies (lakes, ponds, and reservoirs) in the conterminous US based on a the 1:100,000 National Hydrographic Data version 1 [54,55] compared to reservoirs in the National Inventory of Dams, hydropower reservoirs, and reservoirs with GHG measurements included in a global synthesis [15].

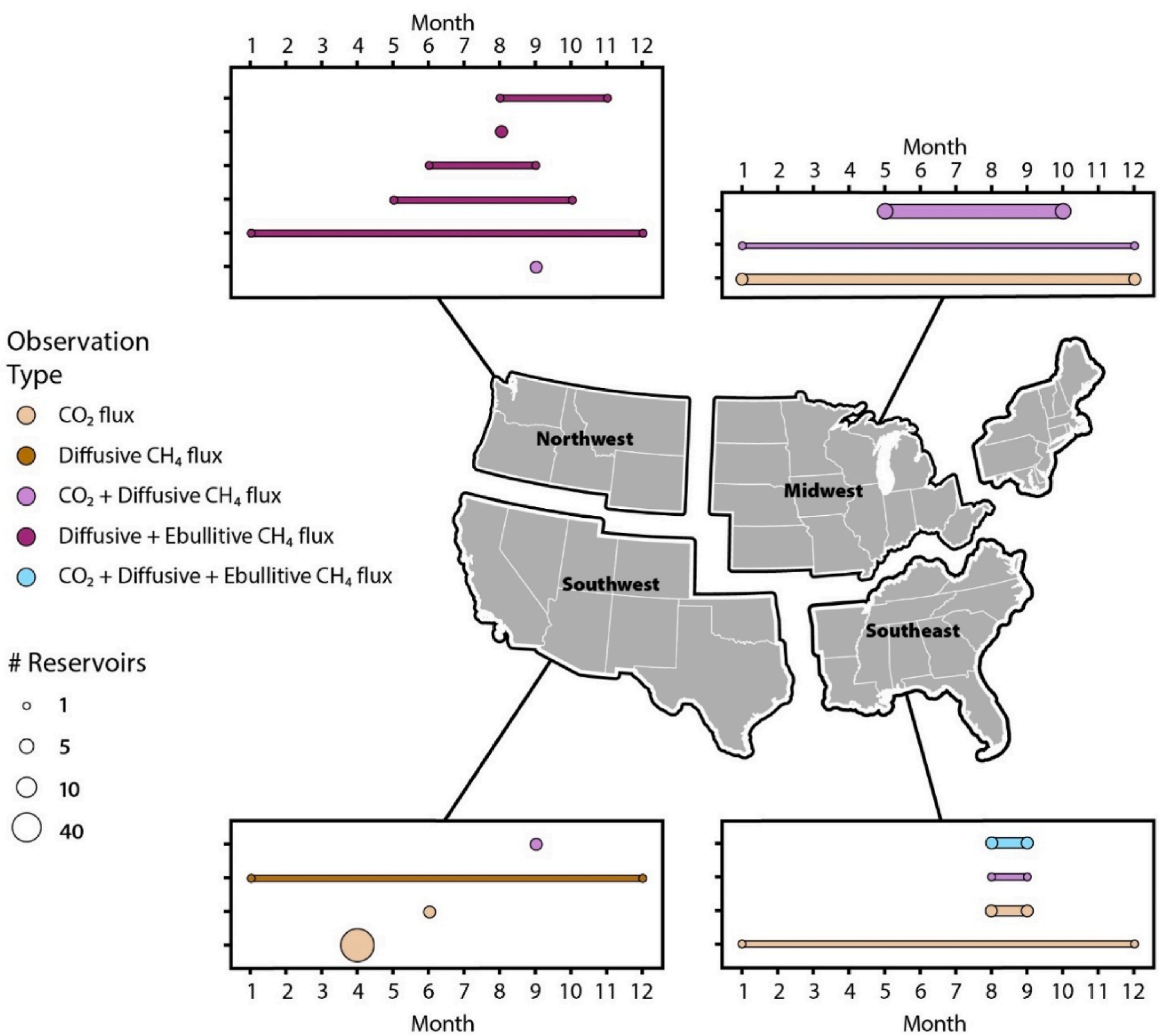


Fig. 5. Seasonal and geographic coverage of greenhouse-gas emissions measured from reservoirs in the conterminous US, reported in Deemer et al. (2016). The width of horizontal bars indicates the number of reservoirs sampled. Measured emissions can include three types of flux (diffusive CO_2, diffusive CH_4, ebullitive CH_4).

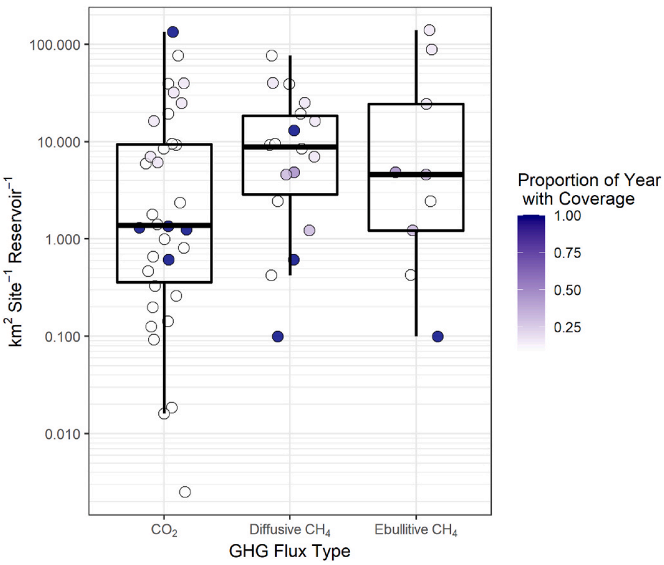


Fig. 6. The distribution of area per sample location (y-axis) and the proportion of year sampled for each flux for studies reported by Deemer et al. (2016). In some cases, the reservoir area represented by a single sample exceeds 100 km^2.

5. Time scales in carbon accounting

5.1. State of the science

Carbon accounting for reservoirs focuses on carbon emissions, whereas terrestrial accounting focuses on carbon sequestration. Global warming potential is one time-related quantity considered in evaluating GHG emissions.

5.2. Challenges with the state of the science

Current approaches to calculating carbon footprints for reservoirs do not appropriately factor in the temporal scales relevant to carbon cycling.

Time scales for storing carbon in sections of river between reservoirs are greater (decades to centuries) in cold, temperate regions and in freshwater networks with complex braided channels [56]. In the Missouri River, USA, tree-ring and ^{14}C dating of oak logs in stream and floodplains showed a median residence time of 3515 years (mean = 1960 years) with few samples younger than 150 years [57]. Likely residence times in co-located reservoirs are even longer because the influx rates of wood are higher (continuous hydrologic connection) and exposure to oxygen is low once logs become waterlogged and sink. Although modern reservoirs are not old enough yet, aging of late-Pleistocene fossils in lakes revealed burial of a mass forest die-off 155–130 thousand years ago [58].

Secondly, current approaches do not account for future changes in carbon dynamics. Under future climate conditions, the role of reservoirs may shift relative to other ecosystems. Warmer climate conditions may increase mineralization rates for buried carbon, decreasing the ratio of buried to emitted carbon. However, increased eutrophication will likely increase the prevalence of anoxia, increasing carbon storage rates. Furthermore, the increased frequency of land disturbance by wildfire and floods will likely reduce terrestrial storage and increase storage in aquatic systems. Carbon sequestered in freshwater networks, if considered at all in global models, is typically counted as part of the 'terrestrial' sink, which has exaggerated terrestrial storage [56,59].

5.3. Suggested improvements

Sequestered carbon should be credited in aquatic ecosystems as it is in terrestrial ones. Two arguments raised for not considering carbon sequestration in reservoirs are: 1) absent a dam, carbon would be transported to the ocean, followed by sequestration in ocean sediments, and 2) the lifetime of a reservoir is finite and that sediments would be exposed to the atmosphere following dam removal. However, if the objective is to compare across energy sources, it is appropriate to account for time delays in reaching the atmosphere (the length of time that carbon is sequestered) and to penalize for release of older carbon sources.

Changes in water level associated with various uses of reservoirs, including hydropower production, can influence carbon burial and sequestration. Seasonal drawdown for flood control resuspends sediment and results in high sedimentation rates in deeper parts of the reservoir [60], where methane produced may be oxidized before reaching the atmosphere. Research is needed to understand the superimposed effects of short-term (i.e., diurnal) water level fluctuations on carbon burial. The redistribution of sediments by seasonal drawdown may reduce carbon available for methanogenesis in reservoir perimeters.

Consideration of time scale has been identified as a need for carbon accounting in general. In an effort to rectify this, the social cost of emissions now versus later in terms of climate warming impact, and the net present value of delayed emissions (i.e., discounted utility) [61] were accounted for in the 2nd State of the Carbon Cycle Report [62]. From an economic perspective, a trade-off exists between utility (e.g., use of wood products or biofuel) and sequestration in forests. Carbon sequestration in forests requires landowners to defer profit from cutting trees (an opportunity cost). For the purposes of carbon trading, the 'carbon debt' of forestry is the time required to regrow carbon in trees to the quantity that would have existed without harvest [63]. For terrestrial energy sources, carbon accounting includes calculation of a carbon 'payback period' that measures the time until carbon combusted (i.e., for energy) is recovered through sequestration [64]. By analogy, in aquatic systems, the payback period of degassing (i.e., GHG emissions attributed to withdrawal of hypolimnetic water to generate energy when methane concentrations are high) is the time required to recover carbon in sediment that would have been stored if the hydropower project had not been operating. To represent time, current accounting methods for terrestrial systems sometimes use the 'global hectare', defined as the world's annual amount of biological production for human use and human waste assimilation, per hectare of biologically productive land and fisheries. This metric recognizes that terrestrial carbon storage is higher during periods of higher productivity [65,66], but it has been criticized for neglecting the role of agricultural inputs, such as fertilizer [65]. The intent is to measure whether society is 'living on the interest' generated by ecosystems, instead of depleting natural capital.

6. Attribution: what are the appropriate counterfactual scenarios?

6.1. State of the science

In the assessment of net GHG emissions from terrestrial ecosystem, the carbon footprint is developed by calculating the difference between carbon emissions for a specified economic future scenario and a counterfactual or 'business-as-usual' scenario [67,68]. The counterfactual describes what the carbon dynamics of the specified land area would be in the absence of the targeted activity (e.g., a forest sequestration project) over a specified time horizon. The question for hydropower then becomes what the carbon dynamics of the affected watershed and associated freshwaters would be, either in the absence of the associated reservoir or the absence of regulated discharge from the reservoir to generate electricity. We refer to these as the 'reservoir' counterfactual and the 'hydropower' counterfactual, respectively.

6.2. Attribution to reservoirs

The state of the science is to attribute all GHG emissions from reservoirs without reference to a counterfactual case and to neglect carbon burial. Some efforts have been made to determine which carbon fluxes constitute new net fluxes to the atmosphere relative to a pre-reservoir counterfactual [25] (Fig. 1). Methane plays a central role in this calculation because of its high global warming potential, the age of carbon being processed, and because most CO_2 emissions would have occurred anyway. The only new sources of CO_2 emissions are degradation of soil carbon that is flooded in the formation of a new reservoir and oxidation of methane produced within the reservoir and its sediments [25].

Younger, more-labile carbon originating in the water column (i.e., algae) is fixed from and quickly returned to the atmosphere as CO_2 [69]. However, when algae and other plants within the reservoir die and decompose, they produce anoxic conditions that favor methanogenesis in the hypolimnion. As a result, there is a positive relationship between methane generation and trophic status [17]. This is why reservoir carbon footprint analyses focus on allochthonous carbon from terrestrial sources, some portion of which produces new methane and, another portion that produces new CO_2 emissions [18]. The 'greening' (eutrophication) of lakes and reservoirs, caused by a combination of excess nutrients and climate warming, could therefore substantially increase methane emissions [70] (Fig. 7).

A similar thought experiment can be conducted for carbon burial. Lakes, reservoirs, floodplains, and wetlands trap organic material, that is protected from decomposition if it is buried quickly in sediments. Deeper in the sediments, buried carbon is less accessible to methanogens and other heterotrophic bacteria [20]. More generally, riparian zones and floodplains provide significant carbon storage in the form of large woody debris and floodplain sediment [56]. Clearly burial occurs in reservoirs, but the question is how this compares with a pre-dam situation. Some researchers claim that allochthonous carbon buried in sediments of reservoirs can be neglected because it would have been buried somewhere along the route to the ocean, or, ultimately, in the ocean [25]. However, riverine depositional environments expose sediments to oxygen. It is likely that a higher fraction of terrestrial organic carbon will become mineralized (emit CO_2) and that less will be buried in downstream river floodplains than in reservoirs [21,22].

Does encountering a reservoir increase or decrease the likelihood of carbon reaching the atmosphere with high radiative forcing and the expected time to such an event? Only the change in burial efficiency of allochthonous organic carbon should be attributed to reservoir inundation [25]. Buried autochthonous carbon (e.g., algae) is already accounted for by the change in partial pressure and the resulting increased concentration of CO_2 [25]

6.3. Attribution to hydropower

Reservoirs serve multiple purposes. The current top-down approach to attributing emissions to hydropower is based on assigning it a portion of total reservoir emissions. Emissions have first been estimated for reservoirs and then a portion attributed to hydropower by assigning a weight to hydropower generation among multiple purposes [10]. If hydropower is ranked k out of n purposes, then the weight assigned is given by f_k below [10].

$$f_k = \frac{(k + n + 1)}{(1 + 2 + \ldots + n)} = \frac{k}{(2 + \ldots + n - 1)}$$

An alternative, but similar, example of a use-based attribution approach is found in the G-res modeling tool, developed by the International Hydropower Association [50]. The G-res model attributes GHG emissions to hydropower based on the percentage of influence over the operating rule curve.

6.4. Challenges with the state of the science

6.4.1. Attribution to reservoirs

In terrestrial carbon accounting, both direct and indirect emissions are accounted for in a life-cycle assessment by defining a counterfactual scenario. Indirect emissions are those caused by land-use change (e.g., replacing vegetation that sequesters more carbon with vegetation that sequesters less). In the case of hydropower, the International Energy Agency calls for defining net emissions by subtracting an appropriate counterfactual. However, most published estimates report gross emissions, i.e., they neglect pre-flooding emissions [10] that have been used to estimate a global carbon footprint for hydropower.

6.4.2. Attribution to hydropower

There is no relationship between how much society values hydropower from a reservoir and GHG emissions attributable to hydropower, as is implied by current attribution methods. The ordinal ranking scheme used to assign emissions to hydropower against other purposes of a reservoir (Equation 1) has no mathematical or conceptual relationship with the actual biophysical influence of generating electricity on carbon dynamics (compared to a reservoir without turbines). The use of rankings as a way to elicit and value human preferences is not without precedent, but requires rigor [71], and should apply to externalities that cannot be separated based on physical properties that apply to one, and not another, end-use. To attribute emissions based on why humans value reservoirs can lead to ridiculous conclusions. For example, it is well-known that humans prefer clear lakes over ones that are murky [72]. Should we therefore assign higher emissions to clearer areas of

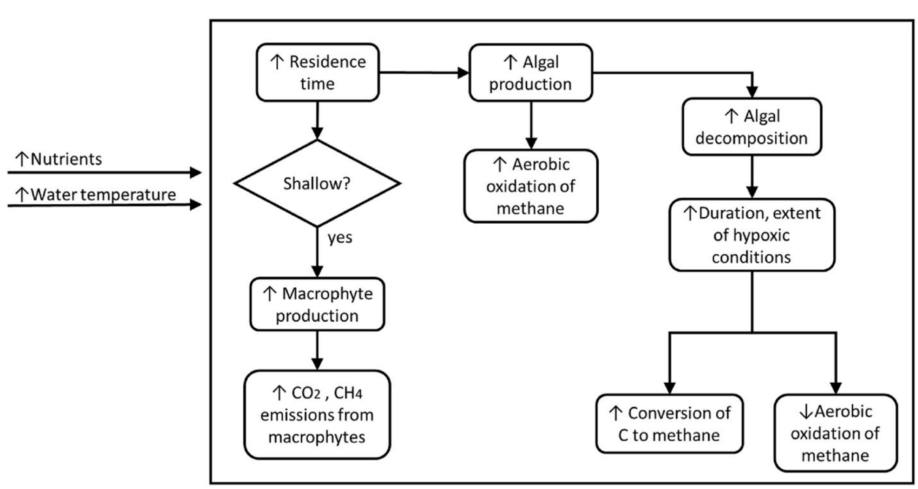


Fig. 7. Indirect pathways by which autochthonous production can cause anoxia and generate methane.

reservoirs, even though areas with higher influx and deposition of sediment can be shown to emit more methane?

6.5. Suggested improvements

6.5.1. Attribution to reservoirs

To improve attribution of emissions to reservoirs, a better understanding of methane emissions in pre-inundation landscapes is needed. Watershed-scale ecosystem models could be used to quantify where high-emitting ecosystems with moderate carbon storage, such as wetlands and floodplains, were displaced and where ecosystems with high carbon storage and low methane emissions, such as forests, were displaced. In addition, differences in the expected efficiency and duration of carbon burial should be estimated between pre- and post-inundation. For hydropower, the International Hydropower Association provides reservoir sustainability guidelines for climate regulation and resilience that recommend measurement of emissions before and after formation of a reservoir (i.e., 'net emissions') [73].

6.5.2. Attribution to hydropower

Research is needed to understand specific ways in which hydropower alters carbon dynamics in reservoirs (e.g., changes in fluctuation/inundation patterns, degassing through turbines, and downstream [74]). We note that regulation of flows can be for different purposes. For example, reservoir drawdown in fall is primarily done to prepare for winter or spring flooding. Changes in redox conditions can elevate methane emissions during drawdown [42,75], but these changes may not occur quickly enough to deplete the redox cascade during short-term diurnal fluctuations to meet peak demand. Research is needed to examine whether a relationship exists between field-quantified hydropower and reservoir net emissions or not (at an annual scale).

In actuality, the carbon impact of powering a dam depends on how changes in water level and turbine degassing or spill changes the proportion of carbon that is converted to methane, and whether hydropower generation slows the return of carbon to the atmosphere [69]. The counterfactual for a hydropower project is the change in the global warming potential of the fluvial network before and after a dam is powered and begins to regulate flows to produce electricity when it is required by the electricity grid.

More research is needed to monitor emissions directly attributable to hydropower, such as degassing of methane from turbines [76], seasonal changes in degassing through the turbines as a function of intake height, and changes in methane generation caused by seasonal and diurnal timing of flow releases to meet electricity demand [77]. With a better understanding of reservoir biogeochemistry, it will be possible to model how operating reservoirs to support the electricity grid might change net emissions.

One gap in our knowledge is understanding how short-term diurnal fluctuations in reservoir water level influence carbon emissions. GHG emissions associated with reservoir drawdown, which takes place in fall for purposes of flood control (not hydropower), has been studied [60]. GHG emissions are episodic, with peaks during fall turnover [78] (for example), and can be predicted at an annual basis from methane that accumulates in the hypolimnion during periods of anoxia [18]. However, less is known about the effects of short-term diurnal load-following operations on methane dynamics or emissions, i.e., 'carbo-peaking' [18,78].

Model-based research is especially important in the broader and evolving context of renewable portfolios as hydropower facilitates the integration of variable renewables like wind and solar [79]. Modelling of physical processes is needed to provide project owners with tools for valuing carbon credits and research is needed to extrapolate from individual hydropower reservoirs to produce carbon inventories at project, national, and global scales. These challenges are by no means insurmountable.

7. Understanding hydropower carbon footprints in the context of the electricity portfolio

7.1. State of the science

In the US, electricity production was responsible for 26.9% of GHG emissions (5142 [80] to 5551.3 [81] MMT CO_2eq), all but 7% were from fossil fuels [81]. Natural gas represents 32% of US power generation and 29% of GHG emissions [80]. Because natural gas is the marginal (last-added) generating asset for most electricity systems, it is the most-likely fossil fuel to be displaced by hydropower. Therefore, the potential for hydropower to displace fossil-fuel emissions is high and displaced carbon is relevant to quantifying a carbon footprint. Currently, both natural gas and hydropower have the flexibility to provide ancillary (grid-stabilizing) services when variable renewables (wind and solar) are not available. Comparisons are typically made by normalizing emissions by kWh. Methods differ in whether they focus on just the energy production phase or include other parts of the energy life cycle.

Although this review focuses mainly on the production phase, we recognize the importance of considering other parts of the life cycle when making comparisons among energy sources. Cradle-to-grave hydropower life cycle assessments (LCAs) consider dam construction (raw material extraction and processing, transportation, assembly), dam operation, and maintenance of the hydroelectric system [82]. In addition, the use of energy and carbon in the manufacture of turbines, transmission, and distribution over the lifespan of a generating asset. Rarely, end-of-life carbon costs (e.g., decommissioning, disposal) may be considered [49,83]. Rarely are end-of-life (decommissioning of a dam and disposal of carbon-laden sediments stored behind it) considered [84]. The highest reported contributions are from dam construction and use of fossil-fuels for transportation [85]. Reviews of LCA-based estimates, including those for different types of hydropower projects, are reported in the Supplemental Information.

Carbon intensity (power-normalized emissions) is the main sustainability indicator used in decision making at the international level, for example, it is used as a driver for the funding of new hydropower development. Because projects with a higher power density have lower carbon intensity, the UN Framework Convention on Climate Change finances and grants carbon credits only to projects with power densities above four MW km^{-2} and those with power densities above ten MW km^{-2} are assumed to have negligible emissions [86]. The International Hydropower Association's Hydropower Sustainability Assessment Protocols do not estimate GHG emissions from reservoirs associated with plants that generate less than five W m^{-2} unless emissions exceed 100 gCO_2 kWh^{-1} [73,87].

7.2. Challenges with the state of the science

Comparisons among energy sources are challenging for several reasons. Completely different system boundaries are used for fossil fuels and renewables. For fossil fuels, historical emissions from the land footprint of the biomass that became buried and pressurized over eons are excluded [88–90]. Use of fossil fuels increases the total carbon pool available for processing by releasing very old carbon. By comparison, it hardly bears mentioning that the carbon footprint of exploration is usually excluded, leaving only those that occur during and after oil and gas extraction from subterranean reserves. As a result of these discrepancies, foot-printing methods erroneously suggest that fossil fuels have a smaller land and carbon footprint per unit energy than renewable sources [91]. The majority of the supply chain for fossil energy is outside the system boundaries adopted for LCA, leading to artificially high energy densities (low carbon intensities) that should not be compared with those of renewables.

Renewable energy can influence global warming in two ways: (1) by offsetting the footprint of fossil fuels such as natural gas (after accounting for use of fossil fuels in production), and (2) by altering when and where carbon is stored or returned to the atmosphere, and in what form. Of these, the first is by far the greatest concern because of the age of the carbon emitted by fossil fuel combustion. The question should not be how much carbon is emitted, but rather the rate at which carbon inputs to the system are returned to the atmosphere and the age of that carbon.

Normalizing by power generation implicitly treats different energy sources (and energy storage) as independent, substitutable or competing resources, when in fact they are, to some extent, complementary and integrated by power markets. For example, pumped storage projects, which supply over 90% of energy storage in the US, have the highest LCA-based carbon footprint among hydropower project types because fossil fuels are often used to do the pumping (see Supplemental Information), but in future, these projects provide opportunities to replace fossil fuels with wind power both for local pumping and for the grid as a whole [92]. Hydropower infrastructure (including the dam, reservoir, electrical/mechanical systems) provides ancillary services, i.e., operations that support or maintain grid stability. These services include using flexible storage or water-releases that allow for frequency control, balancing variable renewables such as wind and solar, and enabling recovery or restoration for other power plants during grid outages (i.e., black start). In short, the value of storage to enhance grid resilience may at times exceed the value of hydropower generation. Without this storage, wind and solar generation would need to be curtailed and would not be able to grow to represent a large fraction of electricity portfolios [79]. Furthermore, when the carbon emissions are assessed over the full life cycle of a hydropower project (i.e., using LCA), many parts of the carbon footprint (e.g., transportation, transmission and distribution) are shared among generating assets [83]. It should also be noted that LCA results [93] have been found to be very sensitive to error in the normalizing quantity, sometimes reversing the result from a source to a sink or *vice-versa* [93]. For reservoirs, the danger of normalizing by the ratio of emissions per MWh is amplified by the practice of allocating based on ranked reservoir purposes, i.e., very high footprints are assigned to reservoirs that serve other purposes but generate a small amount of hydropower.

7.3. Suggested improvements

We recommend several improvements. First, LCA and footprinting methods should not be used to compare renewable and non-renewable sources of electricity because the system boundaries are not comparable. Second, there is a need to measure and model GHG emissions that are directly tied to hydropower operations [42,94]. Third, total emissions of the electricity portfolio are not easily understood as independent contributions without accounting for how they are integrated by providing different advantages (e.g., storage, dispatchability, low cost, reduced emissions) at different times. Four, siting decisions are best made at the basin scale and not based on power densities of individual projects.

Recently more sophisticated ways of accounting for the generation carbon footprint of an electricity portfolio have been proposed [83]. The marginal emissions approach explores the relationship between changes in system electricity demand and the amounts of GHGs that would be emitted due to an extra unit of generation (marginal emissions). Accounting for marginal emissions can be considered on hourly, seasonal time scales and account for real-time emissions resulting from units coming on or offline to prevent curtailment of variable renewable production due to temporal mismatches between electricity supply and demand [83].

Alternatively, the time-varying carbon intensity approach quantifies temporal variations in carbon intensity for electricity generation systems from changes in the fuel mix based on fairly simple assumptions [83]. This approach considers the variation in emissions due to shifts in the portfolio at different scales (hourly, daily, seasonal) [95]. Given the shifts in electricity portfolios, including feedbacks is another future need for those conducting consequential analysis [96]. One might also consider real-time temporal variation in net emissions associated with operating a dam to produce hydropower when implementing this by linking a biophysical model to simulate the effects of reservoir fluctuations and degassing [97].

Finally, decisions made on a dam-by-dam basis based on carbon intensity are likely to ignore important win-win solutions that can be revealed by basin-scale planning [98,99]. Siting decisions made based on power density at individual proposed dams produce sub-optimal solutions compared to those that examine power and emissions as separate objectives at a basin scale. The benefits of using such an approach were demonstrated by a dam siting study spanning multiple countries in the Amazon [98]. The authors reached the conclusion that GHG emissions can be avoided by siting dams along steeper, upland tributaries with high head rather than in larger, lowland rivers [98].

8. Conclusions

In this paper, we reviewed the current state-of-the science in estimating net GHG emissions from reservoirs globally. We reviewed practices in carbon accounting and extracted a list of research needs and recommendations. First, an analysis of US reservoirs with GHG measurements showed high heterogeneity in time and space, suggesting a need to conduct systematic surveys. Second, when producing inventories, reservoirs are typically treated independently outside of the context of the inflowing network. However, carbon influxes to reservoirs set the upper bound for watershed sources of carbon available for processing. Third, we recommend focusing on measuring changes in slow carbon pools (sequestration in reservoirs) rather than those with quick turnover (e.g., algae). Fourth, to attribute emissions and sequestration to hydropower, a better understanding of relevant physical processes is needed to measure those directly attributable to hydropower.

On the modeling and analysis side, improved decision tools should emphasize the benefits of delaying the return of carbon to the atmosphere through carbon sequestration, and, more importantly, by avoiding emissions from older carbon sources. Hydropower producers should be eligible for carbon credits if they delay the return of carbon to the atmosphere through displacing use of ancient stored-carbon reserves and by sequestering inflowing carbon for long periods of time [63,87,100]. We recommend focusing on basin-scale siting decisions based on trade-offs between carbon emissions, energy generation, and other sustainability objectives, rather than on the potential carbon intensity of individual dams. Trapping of carbon-laden sediment by upstream dams will influence emissions from downstream dams.

We question the common practice of comparing sources of electricity in isolation based on carbon intensity. Energy sources are not directly comparable because they play different roles in supporting the electricity grid and differ in the age of carbon emitted. Furthermore, the carbon intensity of a hydropower project does not measure the ancillary services that it provides as part of an electricity portfolio. Projects that support integration of variable renewables to the grid will likely lower the carbon footprint for the electricity portfolio as a whole by enabling the intermittent use of wind and solar and by displacing natural gas.

Data availability

The data used to create figures and generate statistics presented by this review paper is available from primary sources identified in the text.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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