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Understanding Hydropower Impacts on Amazonian Wildlife is Limited by a Lack of Robust Evidence: Results From a Systematic Review

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Abstract

Background and Research Aims: Although hydropower provides energy to fuel economic development across Amazonia, strategies to minimize or mitigate impacts in highly biodiverse Amazonian environments remain unclear. The growing number of operational and planned hydroelectrics requires robust scientific evidence to evaluate impacts of these projects on Amazonian vertebrates. Here, we investigated the existing scientific knowledge base documenting impacts of hydropower developments on vertebrates across Brazilian Amazonia. **Methods**: We reviewed the scientific literature from 1945 to 2020 published in English, Spanish, and Portuguese to assess the temporal and spatial patterns in publications and the types of study design adopted as well as scientific evidence presented. **Results**: A total of 25 published articles documented impacts on fish ($n = 20$), mammals ($n = 3$), and reptiles ($n = 2$). Most study designs (88%) lacked appropriate controls, and only three studies adopted more robust Before-After-Control-Impact designs. The published evidence did not generally support causal inference with only two studies (8%) including appropriate controls and/or confounding variables. **Conclusion:** Decades of published assessments (60% of which were funded by hydropower developers or their subsidiaries) do not appear to have established robust evidence of impacts of hydropower dams on Amazonian vertebrates. This lack of robust evidence could limit the development of effective minimization and mitigation actions for the conservation of diverse vertebrate groups impacted by hydropower dams across Brazilian Amazonia. **Implications for Conservation**: To avoid misleading inferences, there is a need to integrate more robust study designs into impact assessments of hydropower developments in the Brazilian Amazon.

Keywords

Amazon, dam, evidence-based conservation, hydropower, impact evaluation, study design, vertebrates

Introduction

The development and operation of hydropower generate multiple environmental and social impacts across tropical regions, including habitat destruction, changes in river flow, habitat fragmentation, and overhunting (Aurelio-Silva et al., 2016; Benchimol & Peres, 2015; Bueno & Peres, 2019; Cosson et al., 1999; Palmeirim et al., 2017). The increasing demand for hydropower in tropical regions means there is an urgent need to understand impacts and establish minimization and mitigation actions necessary to ensure sustainability of these developments (Albert et al., 2021).

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In tropical South America, hydropower dam projects are increasingly common (Almeida, Shi, et al., 2019; Finer & Jenkins, 2012; Latrubesse et al., 2017; Winemiller et al., 2016). For example, in 2021, the Legal Brazilian Amazon (an area comprising nine states and covering approximately 5 Mkm^2 [(IBGE, 2020)]) has 29 operational hydropower dams (including only those with installed power >30 MW) and an additional 93 in process of regularization and construction (SIGEL, 2021). Inundation hydropower dams with large reservoir storage (e.g., Balbina Dam in Brazil) make substantial changes to both the landscape and water flow (Egré & Milewski, 2002; Fearnside, 1989). In contrast, projects using run-of-river dams use the natural river flow to generate energy and can therefore reduce environmental impacts in certain cases (Egré & Milewski, 2002). Yet due to highly seasonal rainfall and river flow rates, the vast majority of Amazonian run-of-river dams include reservoirs, for example, Belo Monte (Fearnside, 2006; Hall & Branford, 2012) and as such can generate drastic impacts on flowrates (Almeida, Hamilton, et al., 2019; Mendes et al., 2021).

Vertebrates have great importance in the management of tropical forest ecosystems (Janzen, 1970). This includes seed dispersal, predation, regulation of water quality, and nutrient and carbon cycles in both terrestrial and aquatic ecosystems (Böhm et al., 2013; Fletcher et al., 2006; Raxworthy et al., 2008). The Amazon basin is renowned for its globally important biodiversity (Dirzo & Raven, 2003; Malhi et al., 2008). The Amazon basin has a large vertebrate biodiversity (Da Silva et al., 2005), and the total number of freshwater fish species present in the Amazon basin represents ∼15% of all freshwater fishes described worldwide (Jézéquel et al., 2020). Additionally, for three groups of terrestrial vertebrates (birds, mammals, and amphibians), the Brazilian Amazon has a higher overall species richness compared with other Brazilian biomes (Jenkins et al., 2015).

Amazon biodiversity is increasingly threatened by several factors, including habitat loss and fragmentation and climate change (Dudgeon et al., 2006; Laurance et al., 2011; Li et al., 2013; Malhi et al., 2008; Michalski & Peres, 2007; Schneider et al., 2021). One of the major threats to Amazonian biodiversity identified by the International Union for Conservation of Nature is the construction of hydropower dams (IUCN, 2021). These constructions make a direct impact on the local environment and an indirect impact on a large scale, extending across the entire river basin (Carvalho et al., 2018). Expansion of hydropower developments in the Brazilian Amazon started in the 1980s (Fearnside, 2001; Junk et al., 1981), but only since 1986 does Brazilian legislation require that developers produce a mandatory Environmental Impact Assessment (EIA), which evaluates the impact of the project and provides necessary minimization and mitigation actions. Although millions of dollars were invested, these EIAs are widely criticized as overly simplistic (Doria et al., 2018; Fearnside, 2014; Gerlak et al., 2020; Glasson & Salvador, 2000; Simões et al., 2014).

To date, evidence documenting hydropower impacts on tropical vertebrates is limited compared with that available from temperate regions (Arantes et al., 2019; He et al., 2018; Turgeon et al., 2021). There have been numerous isolated studies documenting hydropower dam impacts on vertebrates, as the social, cultural, nutritional, and economic importance of fish means this vertebrate group has been intensely studied across the globe (Liermann et al., 2012; Rytwinski et al., 2020; Turgeon et al., 2021). In tropical South America, modelling studies have integrated species range maps to evaluate hydropower impacts across the Amazon basin on several vertebrate groups (including birds [Vale et al., 2008] and frogs [Silva et al., 2018]) and individual species, for example, dolphins (Araújo & Wang, 2014). With more localized studies quantifying impacts on fisheries (Arantes et al., 2019) and fish communities (dos Santos et al., 2017; Lima et al., 2018). Yet, compared with temperate regions, few reviews synthesize current knowledge regarding impacts of dams on Amazonian vertebrates. For example, the Environmental Evidence database (https://environmentalevidence.org/completed-reviews/?search=dam, accessed July 14, 2021) includes reviews of hydropower dam impacts, on fish mortality (Algera et al., 2020) and fish productivity (Rytwinski et al., 2020), but only from temperate regions.

Systematic reviews summarize and evaluate studies, making evidence available for decision-makers (Gopalakrishnan & Ganeshkumar, 2013). A number of reviews document impacts of dams across the Amazon (Athayde, Mathews, et al., 2019; Ferreira et al., 2014; Lees et al., 2016). Recently several studies reviewed hydropower impacts on water flow, sediments, and on aquatic Amazonian species, mostly fishes (Athayde, Mathews, et al., 2019; Castello et al., 2013; Latrubesse et al., 2017; Turgeon et al., 2021). But, these reviews did not evaluate the quality of evidence presented in the primary studies. Indeed, to our knowledge, there have been no systematic reviews of hydropower impacts on Amazonian vertebrates.

In this systematic review, we evaluated the scientific literature reporting hydropower impacts on vertebrates in Brazilian Amazonia. Specifically, we addressed the following questions: (1) what are the temporal and spatial patterns of articles, (2) study designs adopted, and (3) evidence types generated.

Methods

Study Identification and Selection

We focused on vertebrates as this group includes fish which is perhaps the most intensively studied wildlife group in terms of hydropower impacts globally (Algera et al., 2020; Arantes et al., 2019; Turgeon et al., 2021). Additionally, this group also includes "mega-fauna" (vertebrates >30 kg) that have a disproportionately high risk of extinction (Turvey et al., 2010) and extirpation due to hydropower developments (He et al., 2018). As such vertebrates should present a best case scenario for the scientific evidence documenting hydropower impacts on Amazonian wildlife. Searches were conducted for articles published from 1945 to 2020 using four different databases: ISI Web of Science (Core Collection), SCOPUS, PubMed Central, and SciELO Analytics. The databases were searched using the following combination of terms: (Amazon*) and (hydroelectric or hydropower or dam) and (mammal or fish or bird or reptile or amphibian or vertebrate) and (impact* or effect*). The same terms were translated and searches repeated in Portuguese and Spanish (official languages of the five countries in the Amazon basin, Supplementary Material Appendix 1). Searches were conducted twice, once on March 28, 2020 and again on March 29, 2021 to update publications from 2020.

Studies were selected following guidelines established by the Preferred Reporting Items for a Systematic Review and Meta-analysis (PRISMA [Moher et al., 2015; Shamseer et al., 2015], Figure 1). First, we screened all titles, keywords, and abstracts and excluded duplicates and any studies that were not related to hydropower developments and vertebrates within the Legal Brazilian Amazon. This region (comprising nine Brazilian states covering 5 Mkm^2 [(IBGE, 2020)]) was selected as it includes a wide range of tropical ecosystems and hydropower developments regulated by the same legal and governmental institutions, which enabled us to reduce confounding external factors that can affect design and implementation of impact assessments. The full-text of all articles that passed initial screening was then read to establish eligibility.

As our focus was on evaluating impacts, the studies needed to include results from comparisons with at least one of the following: control areas (including space-for-time) and/or the impacted area after the hydropower was operational. Selected articles needed to present basic data/primary studies (Salafsky et al., 2019) from operational hydropower dams. Laboratory experiments, modelling studies, simulations, reviews, and meta-analysis were not included. Studies that used novel reservoir environments to test theories (e.g., species-area relationships on reservoir islands) were also not included. In addition, studies with lists of species compared with other areas in only a qualitative narrative form or where comparisons were only discussed (not included as part of the sampling methodology or analysis) were also excluded at this stage.

Based on the initial results, few studies were returned for some regions of the Legal Brazilian Amazon. To examine if the search terms were generating a strong effect, we updated the term used to establish geographic range of results (Amazon*), with the addition of a state name (Amazon* or Mato Grosso). This state was chosen as it included a relatively large number of dams and few studies. Full searches were repeated with this updated term on August 2, 2021. As no additional studies were added to the final selected list, we

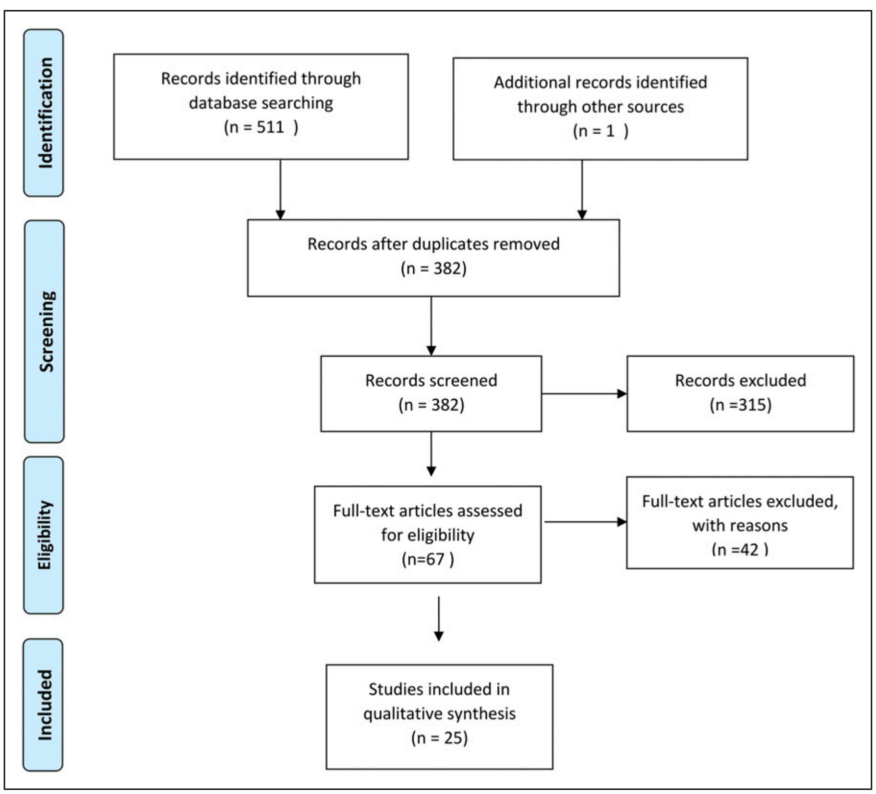

Figure 1. PRISMA flow chart. Showing process used to assess and select studies.

decided to retain results from the original search terms and not proceed with any additional search term refinements.

Study Data Extraction

Each study was evaluated by one author (ERS), who compiled: publication year, vertebrate groups, period of data collection, study design, geographic coordinates for the studied dams (obtained by joining dam name with coordinates provided by SIGEL (2021)), evidence type, and whether the study received funding/data from the developer/operator (Supplementary Material Appendix 2). Study design typology followed definitions in Christie et al. (2019), and evidence types were classified following Burivalova et al. (2019) (Table 1). Although there is no agreed classification across different scientific disciplines, we followed Burivalova et al. (2019) in including Case-Control II and Quasi-Experimental as evidence types that should enable causal inference to be established. Finally, the PRISMA process and data extraction stages were independently reviewed by two authors (DN and FM) and corrections made to ensure reproducibility and consistency.

Hydropower Dam Data

To contextualize the systematic literature review, we compiled data on the operational hydropower dams in the Legal Brazilian Amazon. For each hydropower dam, we obtained geographic coordinates, operational start date, and installed capacity from the Brazilian Electric Sector Geographic Information (SIGEL—Sistema de Informações Georreferenciadas do Setor Elétrico"), provided and maintained by the Brazilian National Agency of Electricity (ANEEL—"Agência Nacional de Energia Elétrica", downloaded from: https://sigel.aneel.gov.br/Down/, accessed on March 30, 2021). We retained only hydropower dams with an installed capacity greater than 30 MW. We used ArcGIS 10.3 (ESRI, 2015) in order to produce the final distribution map of the hydropower dams and study locations. We chose 30 MW as a representative sample of current operational hydropower dams in the study region as hydropower dams >30 MW (classified as large [30–1000 MW] and mega-dams [>1000 MW]) represented 52% of operational and planned dams across the Amazon basin (Latrubesse et al., 2017). Installed capacity was not included as part of our literature search or selection/inclusion/exclusion criteria, only to obtain an informative sample of the current distribution of hydropower dams.

Data Analysis

All analyses were performed in R (R Development Core Team, 2020) with functions available in base R and "tidyverse" collection of packages (Wickham et al., 2019). Patterns in the geographic and temporal distribution of publications were evaluated using maps and descriptive analysis. As Brazilian states are an important administrative and legislative unit for the management of environmental resources, we compared the distribution of hydropower dams and publications between the nine states of the 5 Mkm^2 Legal Brazilian Amazon (Acre, Amapá, Amazonas, Mato Grosso, Maranhão, Pará, Rondônia, Roraima, and Tocantins, [(IBGE, 2020)]). The distribution of study designs and evidence types were compared between studies that (i) received funding and/or data from the hydropower developer/operator and (ii) independent research studies without any declared association with the hydropower developer/operator.

Results

Temporal and Spatial Distribution of Studies

A total of 25 peer-reviewed studies were included in our systematic review, most of which (n = 17) were published between 2015 and 2020 (Figure 2). The first article found was published in 1981 (Junk et al., 1981). This was 4 years after the hydropower dam under study ("Curuá-Una") became operational in 1977 and 6 years after the first hydropower dam became operational in the Legal Brazilian Amazon in 1975 (Figure 2). Although the number of operational hydropower dams increased steadily in the subsequent decades,

Table 1. Study Designs and Evidence Types. Typology used to Classify Selected Studies. Descriptions Summarized From Christie et al. (2019) and Burivalova et al. (2019).

Study Design	Description
After	Sampling data post-impact without a control or data before
Before–after	Sampling data before and post-impact without a control
Control-impact	Sampling data from a control area and compare with post-impact data
Before-after control-impact	Sampling data before and post-impact with a control
Evidence type	**Description**
Case report	Descriptive data from the intervention and its effects, made by interviews, perception, or sense of fairness
Case–control I	Studies that compare a metric before and after an intervention
Case–control II	Studies that compare a metric before and after an intervention taking confounding variables into account
Quasi-experimental	Studies that compare a metric before and after with a control unit similar as possible to treatment units

the number of published articles started to increase only recently (Figure 2). After the first published study, there was a 12-year gap until the next publication, and few studies ($n = 4$) were published by 2012, despite there being 15 operational hydropower dams in 2010.

Based on our inclusion criteria, we were able to identify studies assessing impacts on three groups of vertebrates (Figure 2): fish ($n = 20$), mammals ($n = 3$), and reptiles ($n = 2$). There were no integrated studies including species from different groups. The major research interest was related to fish (80.0% of studies) with the four articles published during the first three decades (1981–2013) focusing exclusively on this group (Figure 2). The three mammal studies (Calaça & de Melo, 2017; Calaça et al., 2015; Palmeirim et al., 2014) were published between 2014 and 2017 and all focused on the semi-aquatic giant otter (*Pteronura brasiliensis*). The two reptile studies assessed impacts on dwarf caimans (*Paleosuchus palpebrosus* and *Paleosuchus trigonatus* [Campos et al., 2017]) and yellow-spotted river turtles (*Podocnemis unifilis*, [Norris et al., 2018]).

The studies assessed impacts caused by 12 of the 29 operational hydropower dams >30 MW in the Legal Brazilian Amazon (Table 2). Impacts of large (30–1000 MW) and mega-dams (>1000 MW) were investigated, but there were no studies of small hydropower dam impacts, with the lowest capacity of a studied dam being 42.8 MW (Curuá-Una dam, Table 2). The size-class distribution of the studied dams (0, 58.3, and 41.7% for small, large, and mega-dams, respectively) was significantly different (Fisher's Exact Test $p < .0001$) to the size-class distribution of 288 planned dams (48, 45, and 7% for small, large, and mega-dams, respectively) reported by Latrubesse et al. (2017). The distribution of studies tended to follow the installed capacity of the dams in each state (Figure 3), and we found a positive but not significant correlation between installed capacity and number of studies per hydropower dam (Spearman Correlation rho = 0.41, $p = .181$).

Nearly half of studies ($n = 12$) investigated impacts of only three hydropower dams, namely Jirau and Santo Antônio ($n = 8$, with six studies including both) in the state of Rondônia and Peixe Angical ($n = 4$) in Tocantins state. The two most intensely studied dams (Jirau and Santo Antonio, installed capacity 3750 and 3568 MW, respectively) accounted for 32% of all studies, and nearly half (8 of 17) of recent studies published since 2015. The remaining nine hydropower dams had one or two studies each (Table 2). We also found a weak positive correlation between the number of hydropower dams and number of published studies per state (Spearman Correlation rho = 0.21, $p = .686$). Mato Grosso was the state with most hydropower dams ($n = 13$), but was severely under-represented with only two published studies (Figure 3), both of which focused around the recently operational Teles Pires dam (1,819 MW, operational in November 2015, [Calaça & de Melo, 2017; Calaça et al., 2015]).

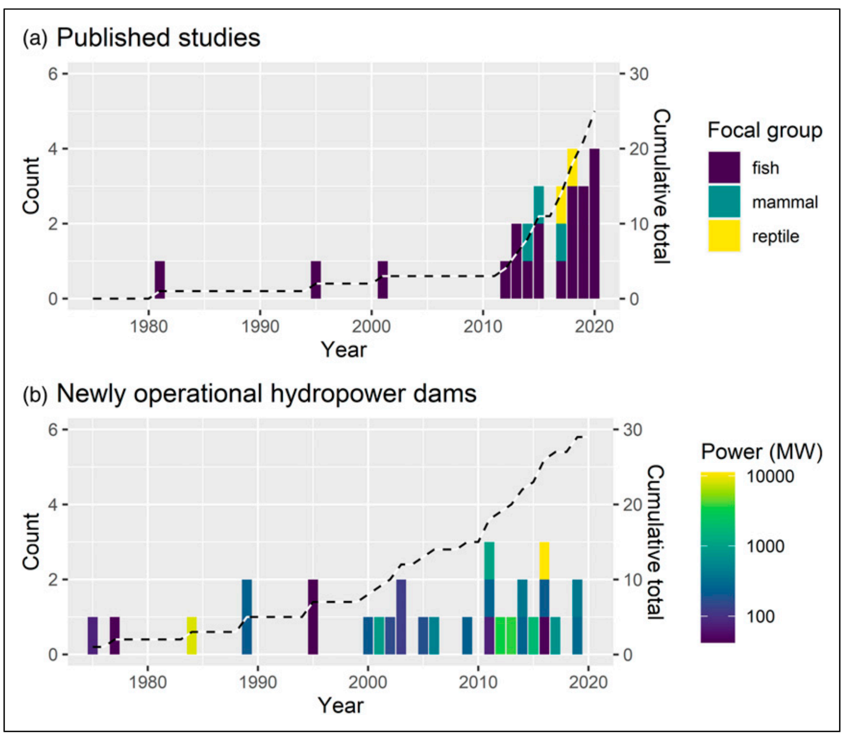

Figure 2. Temporal distribution of published studies and operational hydropower dams. Annual frequency of (a) published articles documenting impacts on vertebrates ($n = 25$) and (b) newly operational hydropower dams >30 MW ($n = 29$) across the Legal Brazilian Amazon (area comprising nine states and covering approximately 5 Mkm^2). Dashed lines show cumulative totals.

Study Design and Evidence Type

Most studies (88.0%) adopted either "After" (n = 6) or "Before-After" (n =16) study designs (Figure 4). Only three studies used a Before-After Control-Impact design, two with fish (Araújo et al., 2013; Lima et al., 2018) and one with turtles (Norris et al., 2018).

Most publications (92.0%, n = 23) did not support causal inference, presenting evidence from either Case-report (n = 6) or Case–Control I (n = 17) studies (Figure 4). Only one Quasi-Experimental study was found, which included data collected pre- and post-reservoir formation with both impacted and control areas and analysis to explicitly test the Before-After Control-Impact interaction (Norris et al., 2018). The proportion of independent (n = 10) and operator funded (n = 15) studies was similar (Chi-squared = 0.13, df = 1, p = .258), and there was no significant difference in the frequencies of study designs or evidence types between independently or operator-funded studies (Figure 4, Fisher's Exact Test p = 1.000 and .591 for study designs and evidence types, respectively).

Discussion

Our systematic review showed that (1) there was a tendency for studies to be concentrated on large hydropower dams, (2) the majority of studies focused on fish, and (3) although there is an increasing number of studies documenting impacts of hydropower dams on Amazonian vertebrates, weak sampling designs resulted in a lack of robust evidence. We first turn to discuss the biases and gaps in the scientific literature and then explore lack of evidence due to weak sampling designs.

Table 2. Studies of Operational Hydropower Dams in the Legal Brazilian Amazon. Data for Hydropower Dams with Installed Capacity >30 MW Obtained From the Online Database Maintained by the Brazilian National Agency of Electricity (ANEEL—"Agência Nacional de Energia Elétrica", Downloaded From: https://sigel.aneel.gov.br/Down/, Accessed on March 30, 2021, [SIGEL, 2021]).

	Name	State	Operational	Number of Studies	Installed Capacity (MW)
1	Balbina	Amazonas (AM)	1989	1	249.75
2	Coaracy Nunes	Amapá (AP)	1975	2	78.00
3	Santo Antônio do Jari	Amapá (AP)	2014	0	392.95
4	Ferreira Gomes	Amapá (AP)	2014	0	252.00
5	Cachoeira Caldeirão	Amapá (AP)	2016	1	219.00
6	Juba II	Mato Grosso (MT)	1995	0	42.00
7	Juba I	Mato Grosso (MT)	1995	0	42.00
8	Manso	Mato Grosso (MT)	2000	0	210.00
9	Itiquira (Casas de Forças I e II)	Mato Grosso (MT)	2002	0	157.37
10	Guaporé	Mato Grosso (MT)	2003	0	120.00
11	Jauru	Mato Grosso (MT)	2003	0	121.50
12	Ponte de Pedra	Mato Grosso (MT)	2005	0	176.10
13	Dardanelos	Mato Grosso (MT)	2011	0	261.00
14	Teles Pires	Mato Grosso (MT)	2015	2	1819.80
15	Salto Apiacás	Mato Grosso (MT)	2016	0	45.00
16	São Manoel	Mato Grosso (MT)	2017	0	700.00
17	Colíder	Mato Grosso (MT)	2019	0	300.00
18	Sinop	Mato Grosso (MT)	2019	0	401.88
19	Curuá-Una	Pará (PA)	1977	1	42.80
20	Tucuruí	Pará (PA)	1984	2	8535.00
21	Belo Monte	Pará (PA)	2016	1	11233.10
22	Samuel	Rondônia (RO)	1989	1	216.75
23	Rondon II	Rondônia (RO)	2011	0	73.50
24	Santo Antônio[a]	Rondônia (RO)	2012	8[a]	3568.00
25	Jirau[a]	Rondônia (RO)	2013	6[a]	3750.00
26	Luís Eduardo Magalhães (Lajeado)	Tocantins (TO)	2001	2	902.50
27	Peixe Angical	Tocantins (TO)	2006	4	498.75
28	São Salvador	Tocantins (TO)	2009	0	243.20
29	Estreito	Tocantins (TO)	2011	0	1087.00
	Totals			25[a]	**35738.95**

[a]6 studies included both Jirau and Santo Antônio dams.

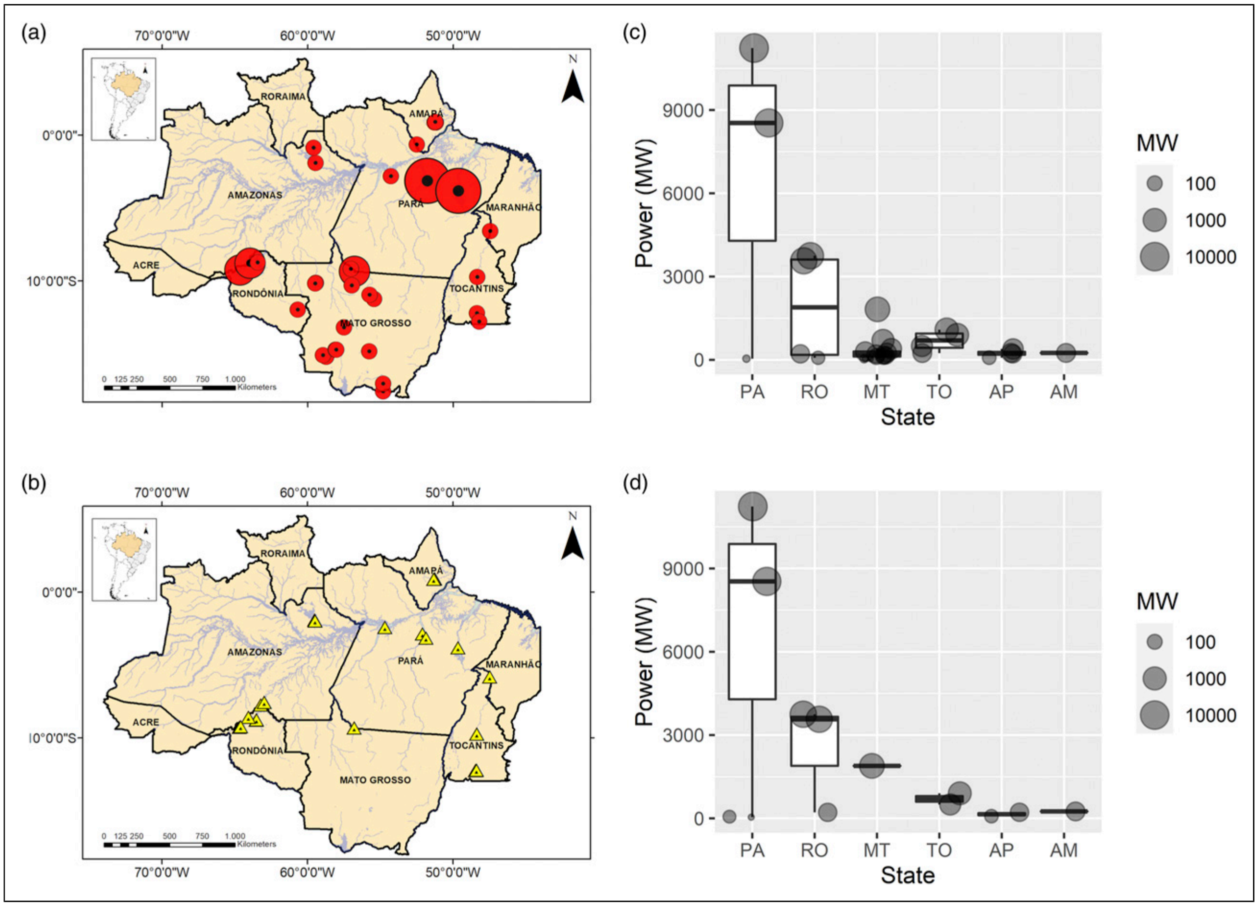

Figure 3. Spatial distribution of published studies and operational hydropower dams. Geographic location of (a) operational hydropower dams >30 MW (circles, n = 29) and (b) studies documenting impacts on vertebrates (triangles, n = 25) across the Legal Brazilian Amazon. The size of the circles showing dams locations is proportional to the power (installed capacity) of each hydropower, and light grey lines represent major rivers. Plots show distribution of power (MW) by (c) state of all 29 operational hydropower and (d) for the 12 hydropower dams included in 25 studies. The sequence of states is ordered by total power output of operational dams in each state (high to low from left to right).

Geographic, Dam-Type, and Taxonomic Bias in the Literature

We found that studies were not evenly distributed in relation to the geographic location of operational hydropower dams within the states in the Legal Brazilian Amazon. There was a concentration of studies in only three hydropower dams (Jirau, Santo Antônio, and Peixe Angical) located in Rondônia and Tocantins states. However, Mato Grosso state, which had the most large hydropower dams of any of the nine states, was severely under-represented with only two published studies. Thus, a better geographical representation of studies across Brazilian Amazonia is needed as hydropower impacts will vary across different regions that have distinct social, economic, and environmental characteristics (Albert et al., 2021; Almeida, Shi, et al., 2019; Castello et al., 2013; Doria et al., 2018).

Studies did not represent the planned expansion of smaller hydropower dams across the Amazon basin (Latrubesse et al., 2017). Indeed, we found that studies across Brazilian Amazonia were biased by a focus on mega-dams. A major part of the increasing number of studies since 2012 can be attributed to studies of only two dams (Jirau and Santo Antonio). Although the sustainability of both projects was questioned (Fearnside, 2014, 2015), both received certification by Hydropower Sustainability Assessment Protocol (https://www.hydrosustainability.org/published-assessments/santo-antonio and https://www.hydrosustainability.org/published-assessments/jirau, accessed June 23, 2021). Our results show that scientific evidence documenting the impacts of both dams was generally weak (i.e., below expected best practice). A finding that supports recent analysis showing a link between superficial EIAs and a lack of social and environmental sustainability of Amazonian hydropower developments (Baird et al., 2021; Doria et al., 2018; Fearnside, 2018; Gerlak et al., 2020; Kahn et al., 2014).

Our findings support those from previous studies that show that there is an urgent need to quantify impacts of small hydropower dams across Amazonia (Athayde, Duarte, et al., 2019). A recent study identified 351 proposed dams across

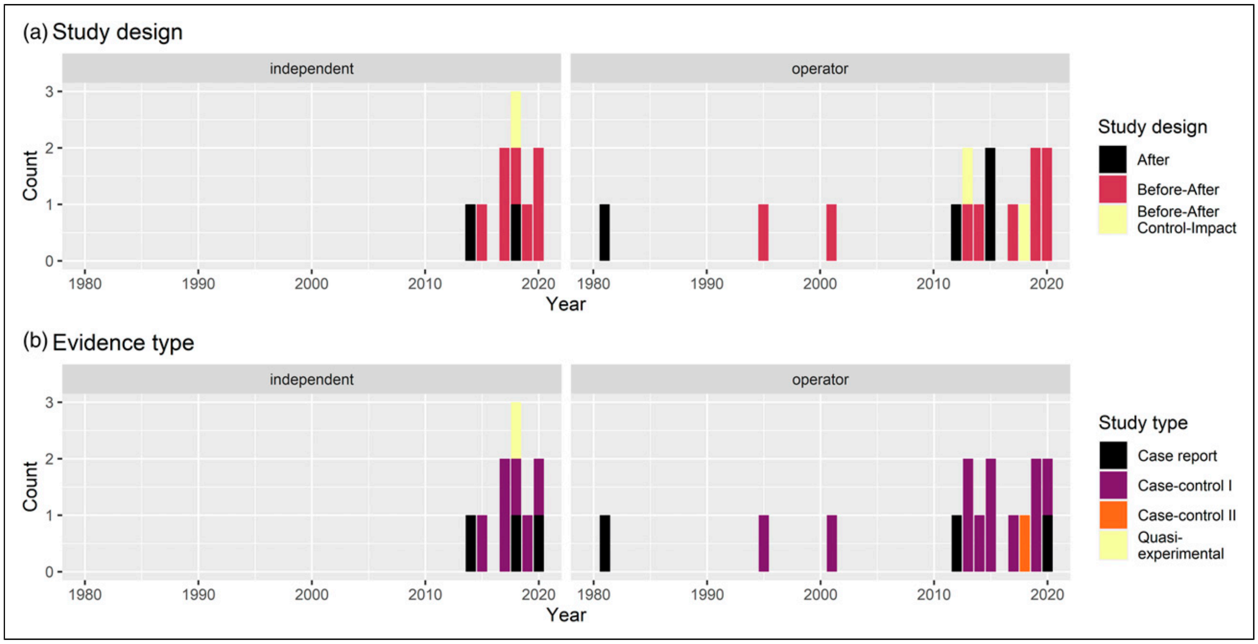

Figure 4. Temporal distribution of study designs and evidence types. The (a) study design used and (b) type of evidence produced by 25 published articles documenting impacts of hydropower dams on vertebrates across the Legal Brazilian Amazon. Typologies follow previously published definitions of study designs (Christie et al., 2019) and evidence types (Burivalova et al., 2019). Studies are grouped into those conducted without financial support from the developer/operator ("independent") and those that received financial support or data from the developer/operator ("operator").

the Amazon basin with installed capacity >1 MW (average 262 MW, [Almeida, Shi, et al., 2019]), with an earlier study suggesting that nearly half (48%) of 288 planned dams were <30 MW (Latrubesse et al., 2017). Although international assessments include measures such as power density (ratio of electricity generation capacity to reservoir flooded area [Almeida, Shi, et al., 2019]) to establish carbon credits for hydropower developments (Clean Development, 2018), such metrics are not applied within Brazilian legislation for hydropower developments (Doria et al., 2018; Fearnside, 2015; Gerlak et al., 2020). For example, the need for and quality of EIAs are simplistically determined by installed capacity, with vastly streamlined requirements for small hydropower developments (less than or equal to 50 MW for future hydropower dams [MME, 2021]). As such there is a clear need for independent and scientifically robust assessment of small hydropower dam impacts across the Legal Brazilian Amazon.

Most of the studies found in our systematic review focused on fishes. This finding follows global patterns where fishes were one of the most frequently studied groups used to evaluate effects of hydropower dams in both temperate (Algera et al., 2020) and tropical regions (Arantes et al., 2019). But, impacts of run-of-river dams are poorly studied even for fish (Almeida, Hamilton, et al., 2019; Turgeon et al., 2021). The lack of studies documenting impacts to aquatic mammals (freshwater dolphins and manatees) was particularly alarming. There is an urgent need for more robust studies to be developed that could enable effective mitigation actions including bypass canals to be implemented (at both existing and planned dams) to avoid predicted range-wide population declines (Araújo & Wang, 2014; Arraut et al., 2017) or even extinctions as experienced in other basins (Turvey et al., 2010). Such measures would also likely benefit other species including large bodied economically and culturally important fish species (Baird et al., 2021; Doria et al., 2018; Duponchelle et al., 2021; Sant'Anna et al., 2020) that are also heavily impacted by dams that are physical barriers to movements and migrations (He et al., 2018). Yet, there was a lack of studies on multiple vertebrate groups, which is essential to understand hydropower dam effects on complex and biodiverse tropical ecosystems such as the Amazon (Park & Latrubesse, 2017).

Our systematic review showed a lack of studies assessing multiple hydropower dams and/or multiple vertebrate groups along the same river. In Brazil, several hydropower dams are commonly arranged in the same river, creating "cascades" (Athayde, Duarte, et al., 2019; Mendes et al., 2017). Although many studies focus on mega-dams, the combined effect of multiple dams, which can cause cumulative impacts (Athayde, Duarte, et al., 2019), remains poorly documented (but see dos Santos et al., 2017). For example, Coaracy Nunes was the first dam installed in the Legal Brazilian Amazon in 1975; since then two additional dams have become operational along the same river, providing a total of three dams with a combined installed capacity of 549 MW (78, 252, and 219 MW) within a 18 km stretch of river. The impact of these multiple dams is thought to have drastically altered both upstream and downstream flow rates, and following the installation of the second dam (Ferreira Gomes) in 2014, the downstream river course changed, draining predominantly to the Amazon river, not the Atlantic Ocean (Silva dos Santos, 2017). While individual studies focused on fish (Sá-Oliveira et al., 2015, 2016) and turtles (Norris et al., 2018, 2020) along the impacted river, these studies focused on different dams and adopted different sampling designs, which limits the ability to integrate results for important basin-wide analysis necessary to inform mitigation actions.

Sampling Design and Evidence Types

The lack of robust evidence was surprising considering hydropower dam development impacts are so strong and well known at a global scale (Grill et al., 2019; Liermann et al., 2012; Maavara et al., 2020). We found that studies in the Legal Brazilian Amazon generally adopted weak sampling designs (e.g., lacking controls) and lacked evidence necessary to generate reliable causal inference (Burivalova et al., 2019; Christie et al., 2019, 2021; Salafsky et al., 2019). Although randomized-control is widely recognized as the most robust study design, logistically simpler designs such as before-after control-impact can be equally effective in generating robust evidence for impact assessments of abrupt changes induced by large-scale development projects including dam construction. Additionally, dams are so widespread across Amazonia (Anderson et al., 2018; Athayde, Duarte, et al., 2019; Grill et al., 2019) that there are few remaining free flowing river sections that could be included within a randomized-control design.

As impacts were so poorly documented, it is unsurprising that there is limited evidence documenting the effectiveness of mitigation actions for vertebrates impacted by hydropower developments across Amazonia. For example, from a total of 48 actions identified in the Conservation Evidence database (https://www.conservationevidence.com/data/index?pp=50&terms=dam&country%5B%5D=&result_type=interventions&sort=relevance.desc#searchcontainer, accessed July 14, 2021), there were no studies from the Amazon basin. Although it is possible to suggest some general actions based on documented global experiences, to our knowledge no studies have evaluated effects of installing bypass channels for aquatic mammals (Berthinussen et al., 2021), and only three short-term studies (10–18 months) evaluated translocations, two in French Guiana, both for primates (Richard-Hansen et al., 2000; Vié et al., 2001) and one in central Brazil for lesser anteater (Rodrigues et al., 2009). Indeed, we could not find any studies that have implemented or evaluated mitigation actions that are likely to generate multiple conservation benefits such as post-reservoir filling habitat creation for vertebrate conservation in the Legal Brazilian Amazon.

The recent increase in deforestation and expansion of agricultural frontiers across northern and central Brazil (including states of the Legal Brazilian Amazon [Schneider et al., 2021]) combined with planned expansion of small and large hydropower dams is likely to generate synergistic impacts on vertebrates. We failed to find studies including important cofounding impacts such as deforestation (Stickler et al., 2013). Although deforestation and tree mortality have been widely documented as important impacts of Amazonian dams (Athayde, Mathews, et al., 2019; Resende et al., 2019; Stickler et al., 2013), no studies included these important cofounding variables in the assessments of vertebrates. For example, the lack of studies in Mato Grosso was particularly surprising considering previous studies on effects of forest fragmentation on vertebrates in this state (Michalski & Peres, 2007; Norris & Michalski, 2009). Studies were developed in isolation from basin-wide changes. Hydropower dams do not occur in isolation, but together with development impacts that can have irreversible changes to river basins and freshwater biodiversity. For example, in Colombia, a reduction in 99% of wetlands was associated mainly with agriculture (sugarcane), dam construction (for both hydropower and irrigation), and urban expansion (Ocampo-Marulanda et al., 2021).

We found few studies considering the overall number and investment in hydropower projects across the Legal Brazilian Amazonia. Even fewer studies were found when considering only those with a robust design and able to establish causal inference. It could be suggested that weak evidence is a reflection of a lack of investment in science and technology, together with a reduction in investment in the Brazilian Ministry of the Environment over the past 20 years (de Area Leão Pereira et al., 2019). Although there is undoubtedly support for such considerations, the lack of robust survey designs can also perhaps be attributed more simply to a failure of researchers to adopt robust designs (Christie et al., 2019, 2021).

One of the biggest challenges to implementing Before-After Control-Impact study designs comes from the need to know when a dam project is going to occur and then acting to acquire baseline data at relevant temporal and spatial scales before the new development starts. Currently, data on planned hydropower dams across Brazil are freely available online (SIGEL, 2021), and previous studies have compiled this information to establish research priorities (Almeida, Shi, et al., 2019; Latrubesse et al., 2017). What appears to be lacking is a coordinated multi-disciplinary effort to establish a network dedicated to monitoring and mitigating hydropower dam impacts across the Amazon basin. The adoption of more robust study designs that can be used by multiple disciplines to develop integrated studies and robust conservation evidence could then be used to establish and strengthen collaborations among researchers, policymakers, and stakeholders (Albert et al., 2021; Christie et al., 2021). This coupled with longer-term support and training of local research groups as well as local communities could help increase the robustness and relevance of studies evaluating hydropower dam impacts on the environment, fauna, and flora (Baird et al., 2021). Such actions would also likely support community-based conservation management that has been proven to be efficient across Amazonia (Campos-Silva et al., 2018; Norris et al., 2018), providing improved long-term conservation outcomes and engaging a far wider diversity of local people (Baird et al., 2021; Doria et al., 2018; Fearnside, 2018).

We need to highlight that our systematic review has some limitations, as we did not include "grey literature" in our searches. Thus, it is important to recognize the potential for gaps or missing studies that were not published in peer-reviewed journals. However, due to the superficial content of EIAs (Baird et al., 2021; Doria et al., 2018; Gerlak et al., 2020), we would expect peer-reviewed published studies to have more robust designs and analysis compared with grey literature or reports. Therefore, our systematic review, performed in searches across four different databases and in three languages, is likely to be a best-case representation of the scientific evidence base documenting hydropower impacts on vertebrates in the Brazilian Amazonia.

Implications for Conservation

There is an urgent need to take advantage of freely available data to organize and plan effective surveys and sampling strategies to evaluate sustainability of current and future hydropower dams across the Brazilian Amazon. Below we provide recommendations to help develop a more robust evidence base.

1. **Geographical distribution of studies. Research gaps:** Studies were concentrated in Rondônia and Tocantins states, and there were very few on Mato Grosso state. **Future directions:** Increase the number of studies all around Brazilian Amazon with a focus on Mato Grosso state, which not only has more than 50% of operational and planned hydropower dams but also continues to experience elevated deforestation rates.
2. **Study groups. Research gaps:** The majority of studies focused on understanding the impacts on fish, with no studies quantifying impacts on other aquatic vertebrate groups (e.g., freshwater dolphins and manatees). **Future directions:** Increase studies focusing on other threatened vertebrate groups including amphibians, birds, mammals, and reptiles. Focusing on areas used by multiple vertebrate groups (e.g., riverside nesting areas) can enable cost-effective integrated studies.
3. **Hydropower dam capacity. Research gaps:** Most of our reviewed studies were concentrated in three large hydropower dams. **Future directions:** Increase number of studies to represent the distribution of operational and planned power output, especially small (<50 MW) hydropower dams. This should include closer integration with university research teams to develop independent and robust evidence as part of the necessary EIAs.
4. **Study design and evidence. Research gaps:** There is currently a lack of robust evidence to evaluate impacts of hydropower dams on Amazonian wildlife. **Future directions:** Studies need to include more robust designs (e.g., Before-After Control-Impact) to establish causal inference.

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Supplementray Material

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