Universidade Federal do Amapá

Pró-Reitoria de Pesquisa e Pós-Graduação

Programa de Pós-Graduação em Biodiversidade Tropical

Mestrado e Doutorado

UNIFAP / EMBRAPA-AP / IEPA / CI-Brasil

EDUARDO RODRIGUES DOS SANTOS

IMPACTOS DE HIDRELÉTRICAS À VERTEBRADOS NA AMAZÔNIA BRASILEIRA

MACAPÁ, AP

2021

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Dissertação apresentada ao Programa de Pós-Graduação em Biodiversidade Tropical (PPGBIO) da Universidade Federal do Amapá, como requisito parcial à obtenção do título de Mestre em Biodiversidade Tropical.

Orientador: Dr. Darren Norris

MACAPÁ, AP

2021

Dados Internacionais de Catalogação na Publicação (CIP)
Biblioteca Central da Universidade Federal do Amapá
Elaborada por Jamile da Conceição da Silva – CRB-2/1010

Santos, Eduardo Rodrigues dos.
Impactos de hidrelétricas à vertebrados na Amazônia brasileira. / Eduardo Rodrigues dos Santos; orientador, Norris Darren. – Macapá, 2021.
42 f.

Dissertação (Mestrado) – Universidade Federal do Amapá, Coordenação do Programa de Pós-Graduação em Biodiversidade Tropical.

1. Usina hidrelétrica - Amazônia. 2. Usina hidrelétrica – Barragem – Aspectos ambientais. 3. Impacto ambiental. 4. Vertebrados. I. Darren, Norris, orientador. II. Fundação Universidade Federal do Amapá. III. Título.

333.7 S237i
CDD. 22 ed.

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IMPACTOS DE HIDRELÉTRICAS À VERTEBRADOS NA AMAZÔNIA BRASILEIRA

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Dedico essa dissertação a toda minha família.

AGRADECIMENTOS

Agradeço essa Conquista, primeiramente aos meus pais, que sempre me apoiaram nas minhas decisões, principalmente na de partir em uma nova jornada no extremo norte do país.

Agradeço a minha esposa, Vera, por ter sorrido comigo em momentos felizes e também apoiado em momentos difíceis.

Agradeço a meus amigos de sala de aula, Andrea, Marcelo, Cassiano, Estefany e Maria por terem sido pilares sólidos de parceria desde 2019.

Agradeço aos professores e a coordenação do PPGBIO por todo suporte nas mais diversas situações e também a CAPES pelo fornecimento da bolsa de pesquisa.

Agradeço ao meu orientador Darren Norris e toda equipe do LECoV pelo suporte e apoio durante essa pós-graduação.

“O abutre ronda

Ansioso pela queda (Sem sorte)

Findo mágoa, mano

Sou mais que essa m**** (Bem mais)

Corpo, mente, alma, um, tipo Ayurveda

Estilo água, eu corro no meio das pedras”

(Emicida)

RESUMO

Rodrigues, Eduardo. Impactos de Hidrelétricas à Vertebrados na Amazônia Brasileira. Macapá, 2021. Dissertação (Mestre em Biodiversidade Tropical) – Programa de Pós-graduação em Biodiversidade Tropical – Pró-reitora de Pesquisa e Pós-Graduação - Universidade Federal do Amapá.

A Amazônia Brasileira tornou-se protagonista uma expansão de usinas hidrelétrica. Essa expansão pode trazer várias mudanças na região, alterando a velocidade das águas e modificando a paisagem. Foi realizada uma revisão sistemática da literatura científica de estudos que analisaram os impactos de usinas hidrelétricas sobre vertebrados na Amazônia Legal Brasileira. Nossa busca inicial identificou 511 publicações, após a seleção seguindo as etapas descritas nos Principais itens para relatar Revisões sistemáticas e Meta-análises (PRISMA), obtivemos um total de 24 estudos que eram relevantes para o escopo desta revisão. Houve um aumento no número de usinas hidrelétricas operacionais e também um aumento na quantidade de estudos publicados, porém os estudos não foram distribuídos geograficamente de maneira uniforme. Descobrimos que a maioria (20) dos estudos avaliou impactos em peixes e a grande maioria (22) não apresentou evidências robustas desses impactos. Esses resultados demonstram uma falta de compreensão dos reais impactos das barragens hidrelétricas sobre a vida selvagem na Amazônia brasileira. As informações apresentadas nesta revisão podem orientar o desenvolvimento de novas pesquisas que busquem evidências robustas em toda a Amazônia brasileira.

Palavras-chave: Amazônia, barragem, conservação baseada em evidências, energia hidrelétrica, avaliação de impacto, desenho de estudo, vertebrados

ABSTRACT

Rodrigues, Eduardo. Impacts of Hydroelectric Power Plants on Vertebrates in the Brazilian Amazon. Macapá, 2021. Dissertação (Master in Tropical Biodiversity) – Portgraduate Program in Tropical Biodiversity Pro-rectory of Research and Postgraduate Federal University of Amapá.

Brazilian Amazon has become a stage for recently hydroelectric expansion. This expansion can bring several changes in the region, changing the speed of the water and modifying the landscape. We reviewed the scientific literature for studies that analyzed the impacts of hydroelectric plants on vertebrates in the Legal Brazilian Amazon. Our initial search identified 511 publications, after selection following the Preferred Reporting Items for a Systematic Review and Meta-analysis, we obtained a total of 24 studies that were relevant to the scope of this review. We found that there was an increase in the number of operational hydroelectric plants and also an increase in the number of published studies, however the studies were not evenly distributed geographically. We also found that the majority (20) of the studies evaluated impacts on fish and the vast majority (22) did not present robust evidence of these impacts. These results demonstrate a lack of understanding of the real impacts of hydroelectric dams on wildlife in the Brazilian Amazon. The information presented in this review can guide the development of new research that seeks robust evidence across the Brazilian Amazon.

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

SUMÁRIO

1. INTRODUÇÃO GERAL

Uma das regiões tropicais com maior biodiversidade do mundo é a Amazônia Brasileira ou Amazônia Legal (Jenkins et al. 2013, Jézéquel et al. 2020b) uma região localizada dentro das fronteiras do Brasil que possui aproximadamente 70% de toda Bacia Amazônica e reúne 40% das florestas tropicais restantes no planeta terra (Laurance et al. 2001, Kirby et al. 2006). A Amazônia Brasileira está dividida entre 8 estados da Federação, sendo eles: Acre, Amapá, Amazonas, Mato Grosso, Pará, Rondônia, Roraima, Tocantins (Brasil 1966). Essa região tem como principal característica seu vasto ecossistema hídrico, sua densa floresta tropical úmida e uma grande variedade de espécies de animais e vegetais (Dirzo and Raven 2003, Foley et al. 2007, Malhi et al. 2008). Essa vasta quantia de riquezas naturais providenciam serviços ecossistêmicos, cruciais para a sobrevivência, bem-estar e desenvolvimento humano (Costanza et al. 1997). E devido à alta demanda advinda do aumento populacional a geração de energia elétrica se tornou um dos serviços ecossistêmicos mais importantes para a vida humana (Fu et al. 2014, Enerdata 2020). E no Brasil a produção de energia é majoritariamente hidráulica ou seja originária das usinas hidrelétricas ocupando o 8° lugar entre os maiores geradores de energia hidráulica do mundo (EPE 2020), isso se deve ao relevo e o potencial hidrelétrico dos rios do país. A Amazônia Brasileira tem destaque na produção de energia hidráulica, sendo responsável por 23% de toda geração de energia do país (EPE 2020). Parte dessa geração de energia vem das 29 usinas hidrelétricas (>30MW) operacionais na Amazônia Brasileira (ANEEL 2021, SIGEL 2021b). A instalação desses empreendimentos na Amazônia remonta os anos 70, quando a primeira usina hidrelétrica foi construída e iniciou as operações, sendo ela a usina de Coaracy Nunes no estado do Amapá(SIGEL 2021b).

E a construção das hidrelétricas na Amazônia Brasileira é controversa e vem sendo contestada há alguns anos, devido a seus impactos sociais e ambientais, a exemplo das hidrelétricas de Santo Antônio e Jirau em Porto Velho, capital de Rondônia(Athayde et al. 2019c, Fearnside 2019, Baird et al. 2021). Estes impactos foram contestados durante anos e negligenciados pelos governantes que até removeram partes de unidades de conservação para criação de barragens mesmo antes de qualquer aprovação pelos órgãos competentes (Fearnside 2019).

Existem diversos tipos de projetos de Usinas Hidrelétricas, no Brasil os mais comuns são os: os projetos de represamento e à fios d'água (ANEEL 2021). Os projetos de Usinas Hidrelétricas de Inundação (e.g UHE Balbina), possibilitam regular o nível da água, principalmente para prover energia durante os períodos de escassez hídrica, sendo assim, devido a inundação de uma vasta região para criação de um reservatório(Egré and Milewski 2002). Já as hidrelétricas à fio d'agua (e.g UHE Belo Monte) utilizam o fluxo natural para geração de energia, eles podem ou não ter algum tipo de reservatório, sua produção de energia varia de acordo com o período do ano. (Egré and Milewski 2002, Fearnside 2010).

Recentes estudos apontam que as usinas hidrelétricas não são tão eficazes quanto a produção de energia e geram danos desnecessários e irreversíveis ao meio ambiente(Lebel et al. 2020, Chaudhari et al. 2021). As hidrelétricas estão caracterizadas pela União Internacional para a Conservação da Natureza (IUCN) como um risco para a biodiversidade e a sua expansão de é uma grande ameaça para a biodiversidade Amazônica (Fearnside 2001, Castello et al. 2013b, Athayde et al. 2019c, Fearnside 2019). Elas afetam direta e indiretamente diferentes espécies e sua distribuição, devido às construções de barragens, aumento do nível de água, construção de estradas, aumento populacional, passagens de linhas de energia, esses impactos podem abranger toda a bacia hidrográfica na qual a Usina Hidrelétrica está inserida. (IUCN 2020, ANEEL 2021).

As primeiras evidências apresentadas em forma de artigos científicos ou capítulos de livros, sobre os impactos das hidrelétricas sob o meio ambiente no mundo datam a década de 70 (Duthie and Ostrofsky 1975, Efford 1975, Elshamy 1977, Porter 1977) e ocorreram em diversos países pioneiros. Os autores apresentam evidências à potenciais impactos, como a mudança das condições naturais dos rios, alterações químicas e potenciais impactos a vida animal (Elshamy 1977).

E dentre os grupos de animais impactados pelos efeitos das hidrelétricas, estão os vertebrados(IUCN 2020). Eles possuem um papel fundamental para a manutenção das florestas tropicais e rios, sendo de grande importância para manter sua frágil estrutura, os vertebrados possuem diversas funções como distribuição de sementes, controle populacional por meio da predação, bioindicadores, manutenção dos serviços do ecossistema, entre outros (Dudgeon et al. 2006, Fletcher et al. 2006, Raxworthy et al. 2008, Böhm et al. 2013). Vertebrados como os peixes possuem uma grande importância comercial, social e cultural na Amazônia Brasileira, visto que a pesca artesanal na região providência alimentos e oportunidades de emprego para muitas famílias (Junk et al. 2007, Hallwass et al. 2013, de Jesus Silva et al. 2017). E há uma uma vasta quantidade de vertebrados endêmicos(Mares 1992, Dagosta and Pinna 2019) e também muitas espécies vulneráveis ou em risco de extinção(Lees et al. 2016a) localizados nessa região, mudanças nas dinâmicas do ecossistema aquático causadas pelas modificações que uma hidrelétrica causa no ambiente que podem acelerar o processo de extinção de espécies ao longo da Amazônia Brasileira(Castello et al. 2013c, Benchimol and Peres 2015a, Röpke et al. 2017, He et al. 2019). Sendo assim diagnosticar os impactos, obtendo assim evidências e buscar definir critérios objetivos para a conservação dos vertebrados da Amazônia tornou-se cada dia mais necessário(Hoffmann et al. 2010).

E buscando avaliar e sintetizar as evidências apresentadas pelos estudos que buscam compreender os impactos das hidrelétricas sob os vertebrados da Amazônia Brasileira, optou-se pela realização de uma revisão sistemática dos estudos publicados sobre a temática. Uma revisão sistemática é um resumo da literatura que busca através de métodos claros e que podem ser reproduzidos por qualquer pessoa, avaliar e sintetizar sobre um determinado assunto, a revisão sistemática sintetiza resultados de diversos estudos primários e analisa a relação entre eles, sua metodologia, suas evidencias e possíveis vieses(Gopalakrishnan and Ganeshkumar 2013a).

Nesta revisão sistemática, buscou-se avaliar a literatura cientifica existente sobre os impactos das hidrelétricas à vida selvagem na Amazônia Brasileira, para identificar os estudos realizados durante os anos, bem como a literatura esta dispersa geograficamente e pelo tempo, quais grupos de animais foram pesquisados e avaliar quais tipos e qualidade de evidencias foram utilizadas.

1.1. HIPÓTESES

- A literatura cientifica atualmente se concentra em estudos que analisam os impactos das hidrelétricas em vertebrados aquáticos.
- Os estudos são em sua grande maioria concentrados em determinadas regiões, com diversas lacunas geográficas.
- A maioria dos estudos não apresenta evidencias robustas sobre os impactos à vida selvagem.

1.2. OBJETIVOS

1.2.1. GERAL

Caracterizar e avaliar os estudos realizados sobre hidrelétricas na Amazonia, focando em também identificar padrões de pesquisa.

1.2.2. ESPECÍFICOS

- Identificar os principais grupos de vertebrados estudados.
- Identificar a concentração geográfica dos estudos.
- Identificar os desenhos amostrais e tipos de evidencias produzidos.

1.3. REFERÊNCIAS

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2. ARTIGO CIENTÍFICO –Understanding hydropower impacts on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review

Understanding hydropower impacts on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review

Artigo submetido ao periódico "Tropical Science Conservation"

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Artigo em revisão pela Tropical Science Conservation em 26 de julho de 2021(TRC-21-0067)

2.1 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 24 published articles documented impacts on fish (n = 20), mammals (n = 3) and freshwater turtles (n = 1). Most study designs (87.5%) 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 (8.3%) including appropriate controls and/or confounding variables.

Conclusion: Decades of published assessments (54.2% of which were funded by hydropower developers or their subsidiaries) do not appear to have established robust evidence of impacts of hydropower developments on Amazonian vertebrates. This lack of robust evidence could limit the development of effective minimization and mitigation actions for the diverse vertebrate groups impacted by hydroelectrics 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, vertebrate

2.2 INTRODUCTION

The development and operation of hydroelectric power plants generates multiple environmental and social impacts across tropical regions, ranging from habitat destruction to changes in river flow, habitat fragmentation, and overhunting (Cosson et al. 1999, Benchimol and Peres 2015b, Aurelio-Silva et al. 2016, Palmeirim et al. 2017, Bueno and Peres 2019). The increasing number of hydroelectrics in tropical rivers means there is an urgent need to understand impacts to establish minimization and mitigation actions necessary to ensure sustainability of these developments.

In South America, hydropower projects with reservoirs and run-of-river dams are common (Finer and Jenkins 2012). For example, in 2021 Brazilian Amazonia has 29 operational hydroelectric power plants (including only those with installed power > 30 MW) and an additional 93 in process of regularization and construction (SIGEL 2021a). Projects with reservoir storage (e.g. Balbina dam in Brazil), make it possible to adjust the level of water to produce energy during periods of water scarcity, which can make substantial changes to both the landscape and water flow (Fearnside 1989, Egré and Milewski 2002). Projects using run-of-river dams use the natural river flow to generate energy and reduce environmental impacts (Egré and Milewski 2002). Yet due to highly seasonal rainfall and river flow rates the vast majority of Amazonian run-of-river dams include reservoirs e.g. Belo Monte (Fearnside 2006, Hall and Branford 2012) and as such generate drastic impacts on flowrates (Mendes et al. 2021).

The Amazon rainforest is reknowned for its globally important biodiversity and availability of hydric resources (Dirzo and Raven 2003, Malhi et al. 2008). The Amazon basin has a large vertebrate biodiversity (Silva et al. 2005). For example, the total number of freshwater fish species present in the Amazon basin represents ~15% of all freshwater fishes described worldwide (Jézéquel et al. 2020a). Similarly, 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). 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 (Fletcher et al. 2006, Raxworthy et al. 2008, Böhm et al. 2013).

Amazon biodiversity is increasingly threatened by several factors, including habitat loss and fragmentation and climate change (Dudgeon et al. 2006, Michalski and Peres 2007, Malhi et al. 2008, Laurance et al. 2011, Li et al. 2013, 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 hydroelectric power plants (IUCN 2020). These constructions make a direct impact on the local environment and an indirect impact on a large scale, extending through the entire hydrology basin that is inserted (Carvalho et al. 2018). Expansion of hydropower developments in the Brazilian Amazon started in the 1980s (Junk et al. 1981, Fearnside 2001), but only since 1986 does Brazilian legislation requires that developers need to produce a mandatory Environmental Impact Assessment (EIA), that 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 and generalist (Fearnside 2014, Simões et al. 2014, Gerlak et al. 2020).

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

In this review, we evaluated the scientific literature reporting hydroelectric 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.

2.3 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 (Arantes et al. 2019, Algera et al. 2020, Turgeon et al. 2021). 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, SCOPUS, PubMed and Scielo. 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. Searches were conducted twice, once on 28 March 2020 and again on 29 March 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 hydroelectric developments and vertebrates within the legal Brazilian

Amazon. 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 hydroelectric was operational. Selected articles needed to present basic data/primary studies (Salafsky et al. 2019) from operational hydroelectrics, as such laboratory experiments, 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 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.

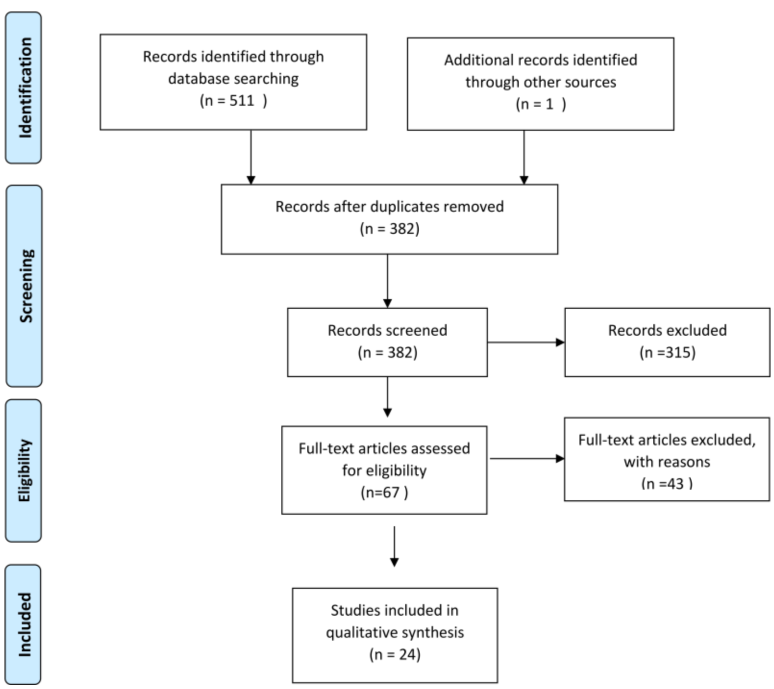

Figure 1. PRISMA flow chart. Showing process used to assess and select studies.

Study data extraction

Each study was evaluated by one reviewer, 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 (2021a)], evidence type and whether the study received funding/data from the developer/operator (Supplemental Material 1). Study design typology followed definitions in Christie et al. (2019) and evidence types were classified following Burivalova et al. (2019) (Table 1). Finally, the PRISMA process and data extraction stages were independently reviewed by two researchers (DN and FM) and corrections made to ensure reproducibility and consistency.

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 cofounding variables into account.
Quasi-Experimental	Studies that compare a metric before and after with a control unit similar as possible to treatment units.

Hydroelectric data

To contextualize the literature review we compiled data on the operational hydroelectric plants in the legal Brazilian Amazon. For each hydroelectric plant we obtained geographic coordinates, operational start date and power output 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 30 March 2021). We retained only hydroelectric power plants (HPPs) with an installed power greater than 30 MW. We used ArcGIS 10.3 (ESRI 2015) in order to produce the final distribution map of the hydroelectric plants and study locations.

Data Analysis

All analyses were performed in R (R Development Core Team 2020). 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 hydroelectrics 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 was compared between studies that i) received funding and/or data from the hydroelectric developer/operator and ii) independent research studies without any declared association with the hydroelectric developer/operator.

2.4 RESULTS

Temporal and spatial distribution of studies

A total of 24 peer-reviewed studies were included in our review most of which (n = 16) were published between 2015 and 2020 (Figure 2). The first article found in our review was published in 1981 (Junk et al. 1981). This was four years after the hydroelectric plant under study ("Curuá-Una") became operational in 1977 and six years after the first hydroelectric plant became operational in the legal Brazilian Amazon in 1975 (Figure 2). Although the number of operational hydroelectrics increased stedily in the subsequent decades, 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 hydroelectrics in 2010.

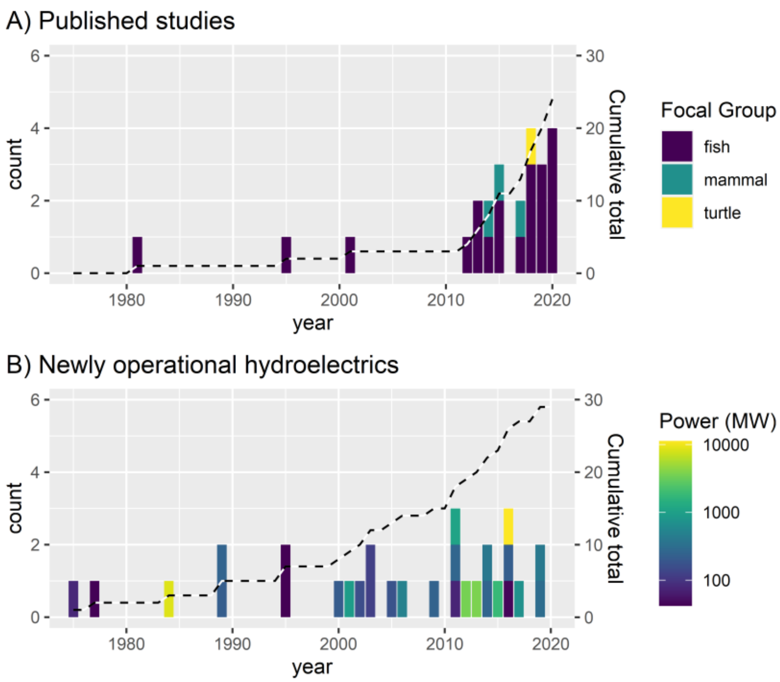

Figure 2. Temporal distribution of published studies and operational hydroelectrics. Annual frequency of A) published articles documenting impacts on vertebrates (n = 24) and B) newly operational hydroelectrics (n = 29) across the legal Brazilian Amazon. Dashed lines show cumulative totals.

Based on our inclusion criteria we were able to identify studies assessing impacts on only three groups of vertebrates (Figure 2): fish (n = 20), mammals (n = 3) and turtles (n = 1). The major research interest was related to fish (83.3% 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 (Palmeirim et al. 2014, Calaça et al. 2015, Calaça and de Melo 2017) were published between 2014 and 2017 and all focused on the semi-aquatic Giant Otter (*Pteronura brasiliensis*). The study assessing impacts on turtles (Norris et al. 2018) focused on the Yellow-spotted River Turtle (*Podocnemis unifilis*).

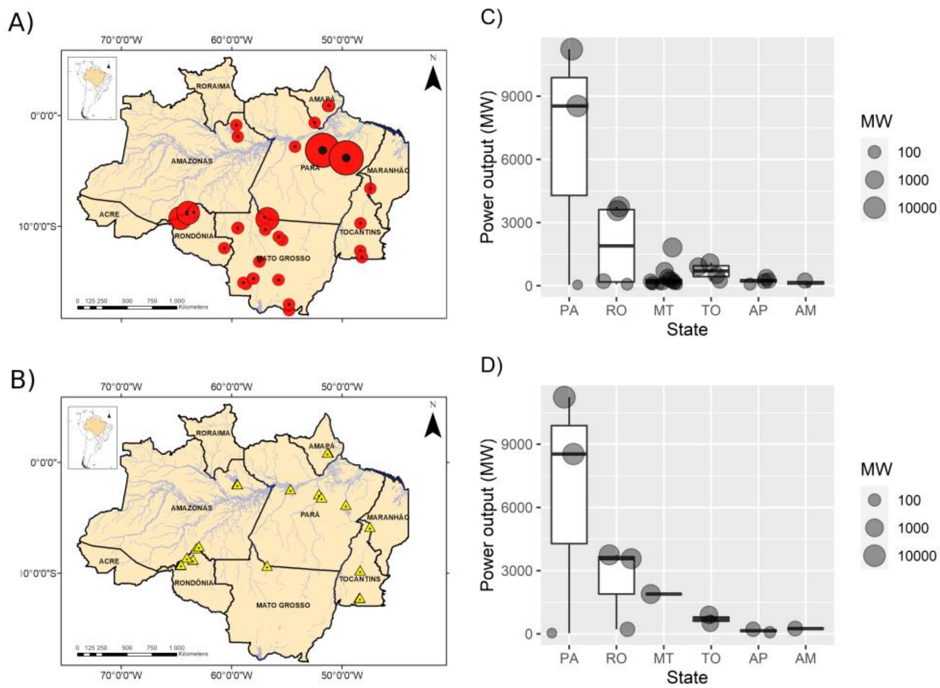

Figure 3. Spatial distribution of published studies and operational hydroelectrics. Geographic location of A) operational hydroelectrics (circles, n = 29) and B) studies documenting impacts on vertebrates (triangles, n = 24) across the legal Brazilian Amazon. The size of the circles showing hydroelectric locations is proportional to the power output of each hydroelectric, and light grey lines represent major rivers. Plots show distribution of power output (MW) by C) State of all 29 operational hydroelectric and D) The 12 hydroelectrics included in 24 studies. The sequence of States is ordered by total power output of operational hydroelectrics in each state (high to low from left to right).

The studies assessed impacts caused by 12 of the 29 operational hydroelectric plants. The distribution of studies tended to follow the power output of the dams in each state (Figure 3) and we found a positive but insignificant correlation between power output and number of studies per hydroelectric power plant (Spearman Correlation rho = 0.41, p = 0.181). Nearly half of studies (n = 11) investigated impacts of three power plants, namely Jirau and Santo Antônio (n = 7, with 6 studies including both) in the state of Rondônia and Peixe Angical (n = 4) in Tocantins. With the two most intensely studied hydroelectrics (Jirau and Santo Antonio, power output 3750 and 3568 MW respectively) accounting for 7 of the 13 studies published since 2017. The remaining 9 hydroelectric plants had one or two studies each. We also found a weak positive correlation between the number of hydroelectrics and number of published studies per state (Spearman Correlation rho = 0.21, p = 0.686). Mato Grosso was the state with most hydroelectric power plants (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 et al. 2015, Calaça and de Melo 2017)].

Study Design and Evidence Type

Most studies (87.5%) adopted either "After" (n = 6) or "Before-After" (n = 15) 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).

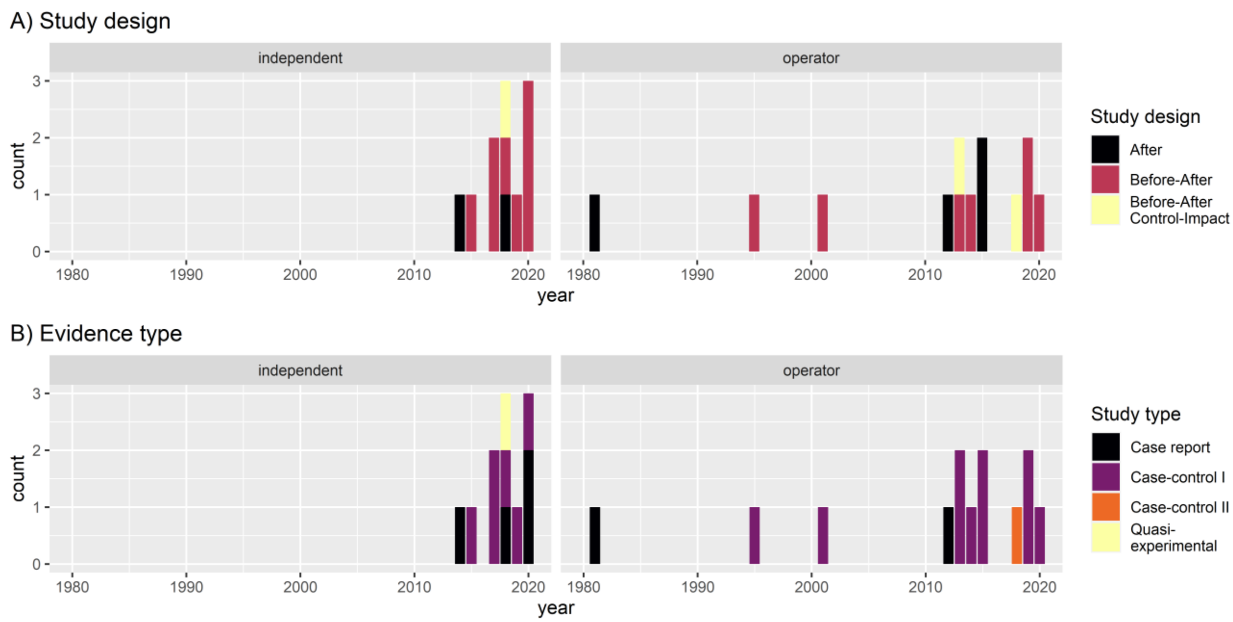

Figure 4. Temporal distribution of study designs and evidence types. The A) study design used and B) type of evidence produced by 24 published articles documenting impacts hydroelectric developments on vertebrates across the legal Brazilian Amazon. Classification follows previously published definitions 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”).

Most publications (91.7%, n = 22) did not support causal inference, with evidence coming from either Case-report (n = 6) or Case-Control I (n = 16) 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 = 11) and operator funded (n = 13) studies was similar (Chi-squared = 0.17, df = 1, p = 0.683) 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 = 0.725 and 0.288 for study designs and evidence types respectively).

2.5 DISCUSSION

Our systematic review showed that (1) studies focused on understanding the impacts of hydroelectrics on Amazonian vertebrates are increasing, but weak sampling designs resulted in a lack of robust evidence, (2) the majority of studies focused on fish, and (3) there was a tendency for studies to be concentrated on high potency “mega” hydropower plants. We first turn to discuss the lack of evidence due to weak sampling designs and then explore the focus on selected vertebrate groups, discrepancy on studies focused on large dams and lack of integrated studies.

The lack of robust evidence was surprising considering hydropower development impacts are so strong and well known at a global scale (Liermann et al. 2012, Grill et al. 2019, Maavara et al. 2020). 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 23 June 2021). Our results show that scientific evidence documenting the impacts of both was generally weak (i.e. below expected best practice). A finding that supports recent analysis showing a link between superficial impact assessments and a lack of social and environmental sustainability of Amazonian hydropower developments (Fearnside 2018, Gerlak et al. 2020).

We found that studies generally adopted weak sampling designs (e.g. lacking controls) and lacked evidence necessary to generate reliable inference (Christie et al. 2019, Salafsky et al. 2019, Christie et al. 2021). Most of the studies found in our review focused on fishes and are therefore likely to represent best-case scenario in terms of scientific knowledge and evidence base. In fact, this finding follows global patterns where fishes were one of the most frequently studied groups used to evaluate effects of hydroelectric 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 the most intensively studied group (Turgeon et al. 2021). Moreover, there is a lack of studies on multiple vertebrate groups, which is essential to understand hydroelectric effects on complex hydrological systems such as the Amazon (Park and Latrubesse 2017).

Our review showed a lack of studies assessing multiple hydroeletrics and/or multiple vertebrate groups along the same river. In Brazil, several hydroelectric plants belonging to different operators are commonly arranged in the same river, creating “cascades” (Mendes et al. 2017, Athayde et al. 2019a). Although many studies focus on mega-dams,the combined effect of multiple hydroelectrics, which can cause cumulative impacts (Athayde et al. 2019a) remains poorly documented. 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 output 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 drasticly altered both upstream and downstream flow rates and following the installation of the second dam (Ferreira Gomes) in 2014 the rivers downstream course became divided, draining predominantly to the Amazon river not the Atlantic Ocean (Silva dos Santos 2017). Whilst individual studies focus on fish (Sá-Oliveira et al. 2015, Sá-Oliveira et al. 2016) and turtles (Norris et al. 2018, Norris et al. 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.

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 (Stickler et al. 2013, Athayde et al. 2019b, Resende et al. 2019) 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 and Peres 2007, Norris and Michalski 2009).

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 Environemnt over the past twenty 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, Christie et al. 2021).

However, we need to highlight that our review has some limitations, as we did not include "grey literature" in our searchers. Thus, it is important to recognize the potential for gaps or missing studies that were not published in peer-reviewed journals. On the other hand, as we would expect published studies to have more robust designs and anlaysis compared with the grey literature, our 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 hydroelectric impacts on vertebrates in the Brazilian Amazonia.

2.6 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 hydroelectric 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 focused within specific regions

   Future directions: Increase the number of studies all around Brazilian Amazon with a focus in Mato Grosso state, which has more than 50% of operational and planned hydroelectrics.

2. **Study groups.**

   Research gaps: The majority of studies focus on understanding the impacts on fish.

   Future directions: Increase studies focusing on other threatened vertebrate groups including amphibians, birds, mammals, and reptiles.

3. **Hydroelectric power plants.**

   Research gaps: Most of our reviewed studies were concentrated in three large hydroelectric power plants.

   Future directions: Increase number of studies to represent the distribution of operational and planned power output. This should include closer integration with university research teams to develop robust evidence as part of the necessary Environmental Impact Assessments.

4. **Study design and evidence.**

   Research gaps: There is currently a lack of robust evidence to evaluate impacts of hydroelectric power plants on Amazonian wildlife.

   Future directions: Studies need to include more robust designs (e.g. Before-After Control-Impact) to establish causal inference.

Acknowledgements

The Federal University of Amapá (UNIFAP) provided logistical support.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

2.7 FUNDING

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The data presented here were collected during ERS's master study, which was funded by a studentship from the Brazilian Federal Agency for Support and Evaluation of Graduate Education, Ministry of Education ("Coordenação de Aperfeiçoamento de Pessoal de Nível Superior" – CAPES —Grant: 675849). FM receives a productivity scholarship from CNPq (Grant: Process 302806/2018-0) and was funded by CNPq (Grant: 403679/2016-8).

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2.9 SUPPLEMENTARY MATERIAL

Understanding hydropower impacts on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review

Eduardo Rodrigues dos Santos, Fernanda Michalski, Darren Norris

Appendix 1. List of studies that evaluated hydropower impacts on vertebrates in the Legal Brazilian Amazon.

	Reference	Title	Focal Group	Dam Count	Study Design	Evidence Type
1	Junk et al. (1981)	Investigações limnológicas e ictiológicas em Curuá-Una, a	fish	1	After	Case report

	Reference	Title	Focal Group	Dam Count	Study Design	Evidence Type
		primeira represa hidrelétrica na Amazônia Central				
2	Santos (1995)	IMPACTOS DA HIDRELÉTRICA SAMUEL SOBRE AS COMUNIDADES DE PEIXES DO RIO JAMARI (RONDÔNIA, BRASIL)	fish	1	Before-After	Case–control I
3	de Merona et al. (2001)	Short term effects of Tucuruí Dam (Amazonia, Brazil) on the trophic organization of fish communities	fish	1	Before-After	Case–control I
4	Pelicice and Agostinho (2012)	Deficient downstream passage through fish ladders: the case of Peixe Angical Dam, Tocantins River, Brazil	fish	1	After	Case report
5	Araújo et al. (2013)	Changes in distance decay relationships after river regulation: Similarity among fish assemblages in a large Amazonian river	fish	1	Before-After Control-Impact	Case–control I
6	Hallwass et al. (2013)	Fishers' knowledge identifies environmental changes and fish abundance trends in impounded tropical rivers	fish	1	Before-After	Case–control I
7	Palmeirim et al. (2014)	Giant otter population responses to habitat expansion and degradation induced by a mega hydroelectric dam	mammal	1	After	Case report
8	Medeiros et al. (2014).	Short-term changes in energy allocation by Hemiodontidae fish after the construction of a large reservoir (Lajeado Dam, Tocantins River)	fish	1	Before-After	Case–control I
9	Sa-Oliveira et al. (2015)	Upstream and downstream responses of fish assemblages to an eastern Amazonian hydroelectric dam	fish	1	After	Case–control I
10	Sá-Oliveira et al. (2015)	Fish community structure as an indicator of the long-term effects of the damming of an Amazonian river	fish	1	After	Case–control I
11	Calaça et al. (2015)	Hydroelectric Dams: The First Responses from Giant Otters to a Changing Environment.	mammal	1	Before-After	Case–control I
12	Cella-Ribeiro et al. (2017)	Temporal fish community responses to two cascade run-of-river dams in the Madeira River, Amazon basin.	fish	2	Before-After	Case–control I
13	Calaça and de Melo (2017)	Reestablishment of giant otters in habitats altered by the filling of the Teles Pires hydroelectric dam in the Amazonia.	mammal	1	Before-After	Case–control I
14	Lima et al. (2018)	Using a trait-based approach to measure the impact of dam closure	fish	1	Before-After Control-Impact	Case–control II

	Reference	Title	Focal Group	Dam Count	Study Design	Evidence Type
		in fish communities of a Neotropical River.				
15	Santos et al. (2018)	The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin	fish	2	Before-After	Case report
16	Norris et al. (2018)	Beyond harm's reach? Submersion of river turtle nesting areas and implications for restoration actions after Amazon hydropower development	turtle	1	Before-After Control-Impact	Quasi-experimental
17	Fitzgerald et al. (2018)	Diversity and community structure of rapids-dwelling fishes of the Xingu River: Implications for conservation amid large-scale hydroelectric development	fish	1	After	Case–control I
18	Melo et al. (2019)	Flipped reducetarianism: A vegan fish subordinated to carnivory by suppression of the flooded forest in the Amazon	fish	1	Before-After	Case–control I
19	Van Damme et al. (2019)	Upstream dam impacts on gilded catfish brachyplatystoma rousseauxii (Siluriformes: Pimelodidae) in the Bolivian amazon	fish	2	Before-After	Case–control I
20	Monaghan et al. (2020)	The impact of a hydroelectric dam on Neotropical fish communities: A spatio-temporal analysis of the Trophic Upsurge Hypothesis.	fish	1	Before-After	Case–control I
21	Peronico et al. (2020)	Community reassembly after river regulation: rapid loss of fish diversity and the emergence of a new state	fish	1	Before-After	Case–control I
22	Santos et al. (2020)	Damming Amazon Rivers: Environmental impacts of hydroelectric dams on Brazil’s Madeira River according to local fishers’ perception	fish	2	Before-After	Case report
23	Lima et al. (2020)	Fisheries and trophic structure of a large tropical river under impoundment	fish	2	Before-After	Case-control I
24	Sant'Anna et al. (2020)	Fishing Production of Pinirampus pirinampu and Brachyplatystoma platynemum Catfish has been Affected by Large Dams of the Madeira River (Brazilian Amazon).	fish	2	Before-After	Case report

Appendix 2. Operational hydroelectrics in the Legal Brazilian Amazon. Data for hydroelectrics with installed capcity > 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 30 March 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*	Rondônia (RO)	2012	7*	3568.00
25	Jirau*	Rondônia (RO)	2013	6*	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			**24***	**35738.95**

* 6 studies included both Jirau and Santo Antônio dams.

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3. CONCLUSÕES

A revisão sistemática realizada, revelou que os estudos que buscam evidências sobre os impactos das hidrelétricas na Amazônia Brasileira se concentram em determinadas regiões, especificamente em Porto Velho-RO, onde encontram-se as Usinas de Santo Antonio e Jirau, e também em Peixe-TO na Usina de Peixe Angical. Enquanto o estado do Mato Grosso, que possui mais de 50% das usinas hidrelétricas ativas, esta sub-representado, com apenas uma usina hidrelétrica estudada. A grande parte dos estudos (20) realizados buscou evidências dos impactos das hidrelétricas em peixes, apenas 3 estudaram mamíferos e 1 tartarugas. Vertebrados como aves e anfíbios estão subrepresentados. E por fim, foi revelado que faltam de evidências robustas para avaliar os impactos das hidrelétricas nos Vertebrados da Amazonia Brasileira. A maioria dos estudos precisam de desenhos amostrais mais robustos para poder estabeler uma inferência causal.

Chega-se a conclusão de que é necessário aumentar o número de estudos na Amazônia Brasileira, em estados sub representados e também considerando as usinas hidrelétricas com potência menor, buscando compreender melhor o efeito cascata. Recomenda-se a realização de estudos com foco em anfíbios, mamíferos, pássarose reptéis. E os estudos devem ter desenhos amostrais robusto para de fato apresentar evidências robustas.

4. ANEXOS

Comprovante de submissão do artigo “Understanding hydropower impactos on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review” para o periodico Tropical Conservation Science.

Understanding hydropower impacts on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review

Journal:	*Tropical Conservation Science*
Manuscript ID	TRC-21-0067
Manuscript Type:	Research Article
Date Submitted by the Author:	30-Jun-2021
Complete List of Authors:	Rodrigues dos Santos, Eduardo; Universidade Federal do Amapa, Postgraduate Programme in Tropical Biodiversity Michalski, Fernanda; Federal University of Amapá, Postgraduate Programme in tropical Biodiversity; Pró-Carnívoros Institute, Norris, Darren; Universidade Federal do Amapa,
Keywords:	Amazon, dam, evidence based conservation, hydropower, impact evaluation, study design, vertebrates
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 24 published articles documented impacts on fish (n = 20), mammals (n = 3) and freshwater turtles (n = 1). Most study designs (87.5%) 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 (8.3%) including appropriate controls and/or confounding variables. Conclusion: Decades of published assessments (54.2% of which were funded by hydropower developers or their subsidiaries) do not appear to have established robust evidence of impacts of hydropower developments on Amazonian vertebrates. This lack of robust evidence could limit the development of effective minimization and mitigation actions for the diverse vertebrate groups impacted by hydroelectrics 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.

Comprovante de mudança de status para “revisado” do artigo “Understanding hydropower impactos on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review” para o periódico Tropical Conservation Science.

From: **Tropical Conservation Science** <onbehalfof@manuscriptcentral.com>
Date: Mon, Jul 26, 2021 at 11:32 AM
Subject: Tropical Conservation Science - Decision on Manuscript ID TRC-21-0067

26-Jul-2021

Dear Dr. Norris:

Manuscript ID TRC-21-0067 entitled "Understanding hydropower impacts on Amazonian wildlife is limited by a lack of robust evidence: results from a systematic review" which you submitted to Tropical Conservation Science, has been reviewed. The comments of the reviewers are included at the bottom of this letter.

The reviewers have recommended some minor revisions to your manuscript. Therefore, I invite you to respond to their comments and revise your manuscript. Please could you do this by 09-Aug-2021 or before.

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