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Mapping Research on Hydropower and Sustainability in the Brazilian Amazon: Advances, Gaps in Knowledge and Future Directions

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Abstract

In the last twenty years, multiple large and small hydroelectric dams have begun to transform the Amazonian region, spawning a growing volume of academic research across diverse disciplinary and interdisciplinary fields. In this article, we offer a critical review of recent research related to hydropower and sustainability with a focus on the Brazilian Amazon. We revisit the sustainability concept to include the contribution of various knowledge fields and perspectives for understanding, managing and making decisions about social-ecological systems transformed by dams. We conducted a literature review in Web of Science of academic publications, centering our review in the past 5 years (2014-2019) on diverse aspects of hydropower planning, construction, operation and monitoring in the Brazilian Amazon. We present results of a co-occurrence network analysis of publications, highlighting bridging fields, network disconnections, and opportunities for interdisciplinary research. Finally, we report recent advances in the understanding and management of social-ecological systems in Amazonian watersheds, including biophysical, socioeconomic, governance and development processes linked to hydropower planning and implementation. This review identifies knowledge gaps and future research directions, highlighting opportunities for improved communication among scientists, practitioners, decision-makers, indigenous peoples and local communities.

Highlights

- Analysis of co-occurrence network of hydropower-related academic publications in the Brazilian Amazon revealed growing interest and multidisciplinary engagement on the topic in the past 10 years.
- The fields of Environmental Sciences and Studies, Ecology, Water Resources and Green and Sustainable Science and Technology may serve as bridging disciplinary areas to stimulate interdisciplinary knowledge production, facilitate cross-disciplinary communication, and bridge the science-knowledge-policy gap.
- Brazilian universities and researchers have demonstrated strong leadership in scientific research on hydropower in the Amazon, and funding from Brazilian agencies CNPq and CAPES has been critical to support scientific advances in hydropower studies.
- In the past five years, there has been growing focus in basin-wide, large scale systemic analyses of hydropower effects on Amazonian social-ecological systems.
- Social science research on hydropower in the Brazilian Amazon has focused on social conflicts and social movements, human rights, socio-economic development, and public health impacts and benefits with a strong focus on the Belo Monte dam.
- Scientists need to do a better job in communicating hydropower-related research findings to policy-makers and local populations.

Key words: hydroelectric dams, hydropower, interdisciplinary research, social network analysis, co-occurrence analysis, sustainability, Brazilian Amazon.

1. Introduction

The Amazon River basin is the largest freshwater system in the world, providing critical benefits to local populations, national societies and humanity at large. Despite the relatively conserved state of Amazonian watersheds compared to US or European rivers, these ecosystems are facing rapid transformations caused by agricultural expansion, urbanization, overharvesting of animal and plant species, and infrastructure development [1–4].

As a region of global superlatives hosting enormous cultural and biological diversity, the Amazon is also a relatively untapped source of energy for Latin American countries reliant on hydroelectric energy [5]. Construction of hydroelectric dams (both large and small) on tributaries of the Amazon River in Brazil (see Figure 1) has advanced over the past two decades as a result of long-term governmental plans geared towards increased energy security, economic growth, industrialization and improved living standards [5–7]. These efforts are part of the Initiative for the Integration of the Regional Infra-structure of South America (IIRSA), which seeks to transform Amazonia into a continental source of hydropower and linked by an intermodal hub of roads, ports, waterways, and railroads [8]. The effects of social-ecological transformations triggered by dams, such as resource extraction and associated infrastructure development in the Brazilian Amazon, will be magnified by existing and proposed dams in the Amazon-Andes region [2,9,10]. The rapid pace of planned development, the spatial scale of effects, and the potential for detrimental and irreversible loss of biodiversity and globally important environmental services, make this hydrologic transformation unprecedented in its consequences. Large dams are predicted to have wide-spread impacts on watersheds, forests, people, economies and climate, from local to global scales [2,11,12]. Small dams are also modifying the Amazon landscape at an increasing rate, supported by international and national policies and regulations that often include less strict environmental licensing processes [13,14].

Despite a history of hydropower development in the Amazon since the 1970s the cumulative, synergistic and long-term effects of dams on rivers, forests, and social systems are still underestimated in planning, decision-making and management [2,15–18]. Gaps in understanding are largely due to lack of rigorous, independent research, lack of articulation and integration of existing data and knowledge, as well as due to a piece-meal approach to studies informing environmental and social impact assessments and mitigation. Further, the short time period allowed for pre- and post-dam monitoring limits opportunities for improving management and possible dam re-operation to better meet multiple objectives, efforts that have been implemented in other regulated rivers of the world (e.g., Colorado River in US) [19].

Sustainability science focuses on generating, articulating and applying knowledge to development problems, governance and decision-making, from local to global scales [20]. In order to meet the needs of present generations without compromising those of future generations, as sustainability is defined, decision-makers need to map-out and consider the best existing science and knowledge. This entails including multiple perspectives (i.e. embracing pluralism), options and trade-offs in planning and decision-making, and requires greater integration of diverse types of information and knowledge held by diverse social groups, scientists, practitioners and other relevant actors [21–23].

Social-ecological systems (SES) can be conceptualized as systems composed of hierarchical nested elements: resource units (natural) and users (human), resource systems (linked natural-human systems), governance systems and wider social, economic and political settings at different scales [24]. We broadly define institutions as systems of established and prevalent social rules that structure social interactions [25]. Governance includes the development and application of principles, rules and norms and the enabling of institutions that guide public and private interactions in managing social-ecological systems [26]. Managing SES sustainably in the context of dams involves: 1) understanding and modeling the interactions of a system's components at different spatial and temporal scales; and 2) making informed decisions based on assessment of these interactions [27,28].

In Amazonian countries, insufficient assessment and monitoring of social-ecological transformations associated with hydropower is worsened by the limited and/or inadequate participation of social actors in the planning, construction, monitoring, mitigation and operational stages of dam implementation [29–32]. Inconsistencies within and across governmental institutions and policies and poor communication between stakeholders (academics, civil society, government, private companies, communities) have exacerbated social conflicts, increased judicialization processes, and resulted in poor performance of mitigation and monitoring programs [30,33–35]. In particular, the recent planning and construction of hydroelectric dams across major river basins in the Brazilian Amazon (Tocantins, Madeira, Xingu and Tapajós) have triggered violent conflicts, have lacked adequate consultation with indigenous and traditional communities, and have been notorious for violation of human rights and corruption scandals [33,36,37].

In this article, we review recent advances in research and knowledge production on hydropower development in the Brazilian Amazon in the last five years, identifying progress on key themes and knowledge fields, as well as knowledge gaps and future research directions. The synthesis and review process, including the definition of key fields, themes and critical questions, were done through analyses using the Web of Science database (WOS), as well as from collaborative work done among members of the Amazon Dams Research Network (ADN/RBA/RIRA)[1]. We begin by presenting results of analyses conducted using WOS database focused on publications about Brazilian and Amazon dams, showing how research on this topic has developed through time. We then provide a co-occurrence network analysis for a subset of 290 articles about Brazilian Amazon hydroelectric dams published in the last 5 years (2014-2019), highlighting the main academic fields that are contributing knowledge on this topic, how they are connected, what fields are more central to this subject, and which ones are acting as disciplinary bridges. Next, we present a critical analysis of this set of publications, providing information on academic fields, institutions and funding sources. Finally, we offer a critical review of recent advances, gaps of knowledge and future research directions.

[1] The Amazon Dams Network is a transdisciplinary international network of researchers and various stakeholders studying hydropower development in the Amazon. It is named Amazon Dams Research network in the US (ADN); Rede de Pesquisa em Barragens Amazônicas (RBA) in Brazil; and "Red de Investigación en Represas Amazónicas" (RIRA) in Amazonian Spanish-speaking countries. More information: www.amazondamsnetwork.org

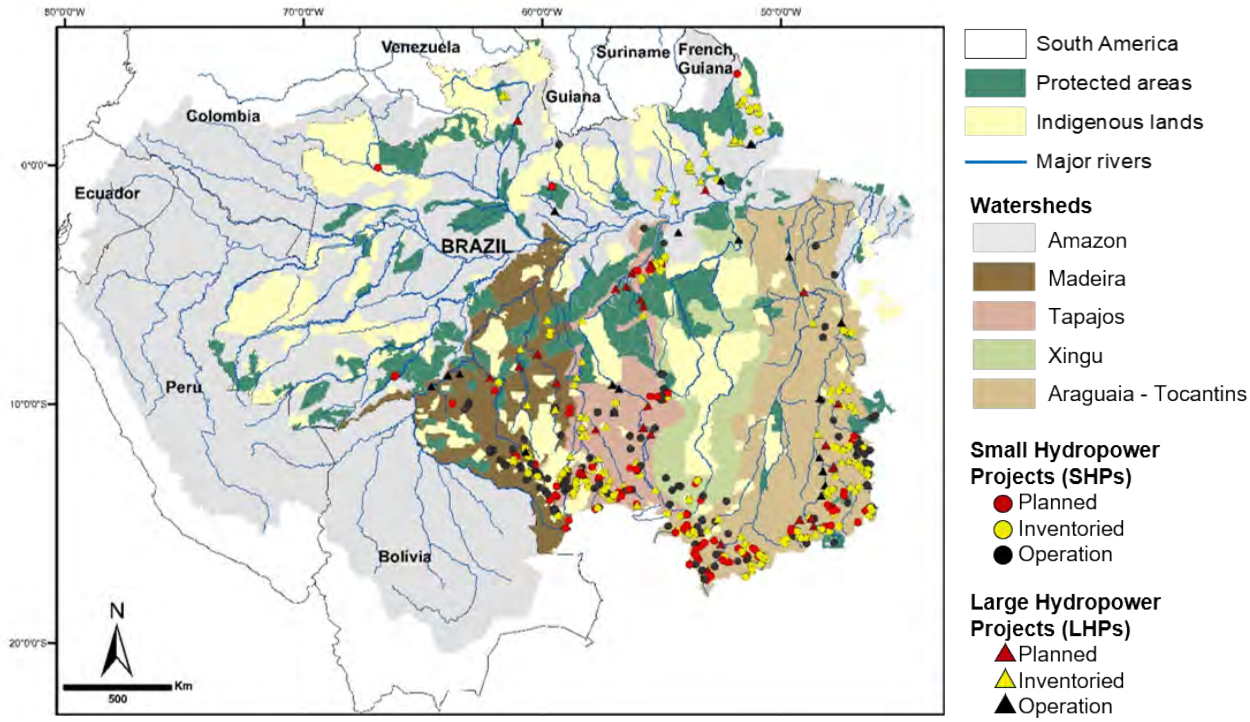

Figure 1. Map of the Amazon basin showing small (SHPs) and large (LHPs) hydropower projects planned, inventoried and in operation in major Brazilian watersheds. Sources: SHPs and LHPs: ANEEL (2019); Protected Areas, Brazilian rivers, watersheds: MMA; Indigenous lands: FUNAI; South America rivers: HydroSHEDS.

2. Methods

This review is based on compilation, synthesis and analysis of data from academic publications found in Web of Science[2] (WOS) database (including all databases available) for different time periods and with different geographic foci. We initially conducted a search using the terms “Brazil” AND “dam and/or dams; and/or hydroelectric; and/or hydropower” for the 1968-2019 period (50 years), which produced 3,866 records. We then conducted a search for the

[2] The Web of Science (WOS), previously known as Web of Knowledge, is an online subscription-based scientific citation indexing service that provides a comprehensive citation search. The Web of Science Core Collection consists of six online databases: Science Citation Index; Social Sciences Citation Index; Arts & Humanities Citation Index; Emerging Sources Citation Index; Book Citation Index; and Conference Proceedings Citation Index. Additional databases available in WOS searches include SciELO Citation Index; BIOSIS Citation Index; MEDLINE®; CABI; and Zoological records. Website: https://clarivate.com/products/web-of-science/ Source: Wikipedia: https://en.wikipedia.org/wiki/Web_of_Science, accessed May 25, 2019.

same period replacing “Brazil” by “Amazon or Amazonian” as a key word, which produced 847 records. The first year to present a publication record on this topic for Brazil was 1973.

We conducted an analysis of themes and co-occurrence patterns in existing published research on dams focused on hydropower development in the Brazilian Amazon. Analyses of co-authorship patterns in journal articles have been used to measure the growth of team science [38], study the evolution of scientific fields [39], identify research groups and communities [40,41], explain research performance [42], and identify influential scientists [43], among other things. While co-authorship studies improve our understanding of the interactions among scientists, a co-occurrence analysis can reveal the connections and gaps between the academic disciplines that shape academic knowledge production.

For the analysis of co-occurrence of subject categories in the same publications, we cleaned the initial dataset of 471 records to include only publications related to hydropower in the Brazilian Amazon, which produced a set of 339 peer-reviewed articles for the 2014-2019 period, from which we selected a subset of 290 records from the Web of Science Core Collection, for which full data on co-authorship, WOS categories, organizations and funding was available. We used this subset to characterize the most studied topics in recent research related to hydropower, identify which WOS subject categories are represented, and measure how and where these subject categories appear together. Whenever a publication in the data is relevant to multiple WOS categories, this is recorded as a co-occurrence for the publication. We grouped and analyzed the data using BibExcel to export the publication records from WOS to Excel and R, RStudio and Igraph to produce the co-occurrence network visualizations.

The main limitations of the method and analyses conducted are: a) although WOS includes the SciELO[3] database, it does not capture relevant publications produced by academics in Brazil and in other Amazonian countries that are not indexed in SciELO; b) Although SciELO includes publications in other languages than English, translation issues and the ways in which articles

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[3] The SciELO - Scientific Electronic Library Online - is a bibliographic database, digital library, and cooperative electronic publishing model of open access journals. It was created to meet the scientific communication needs of developing countries and provides an efficient way to increase visibility and access to scientific literature. Originally established in Brazil in 1997, there are currently 14 countries in the SciELO network and its journal collections: Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Mexico, Peru, Portugal, South Africa, Spain, Uruguay, and Venezuela. Website: https://www.scielo.org/en/. Source: Wikipedia: https://en.wikipedia.org/wiki/SciELO, accessed May 25, 2019.

and key words are indexed may lead to neglecting publications; c) WOS, which focuses solely in the academic literature, does not capture important knowledge production in the form of books, reports, policy briefs and other formats, developed by civil society groups including local authors and communities, non-governmental organizations (NGOs), and indigenous peoples and organizations; and d) Although the search on all WOS databases produced an original set of 339 articles for the 2014-2019 period, including records from SciElo (17), BIOSIS(2), MEDLINE(1), CABI (25) and Zoological Record (4), the co-occurrence analyses, as well as data on organizations, funding sources and WOS disciplinary categories was available only for a subset of 290 articles. However, for our qualitative analysis and description of recent advances, gaps of knowledge and research directions, we used the full set of 339 articles.

3. Academic Research on Hydroelectric Dams in the Brazilian Amazon

Figure 2 shows the distribution of publications per year in WOS datasets, illustrating the growing scientific interest and output regarding hydroelectric development in Brazil and in the Amazonian region over the past twenty years. After 2000, there is sharp and continued growth in publications on hydropower in Brazil and in the Amazon., showing an acceleration in the last 5 years.

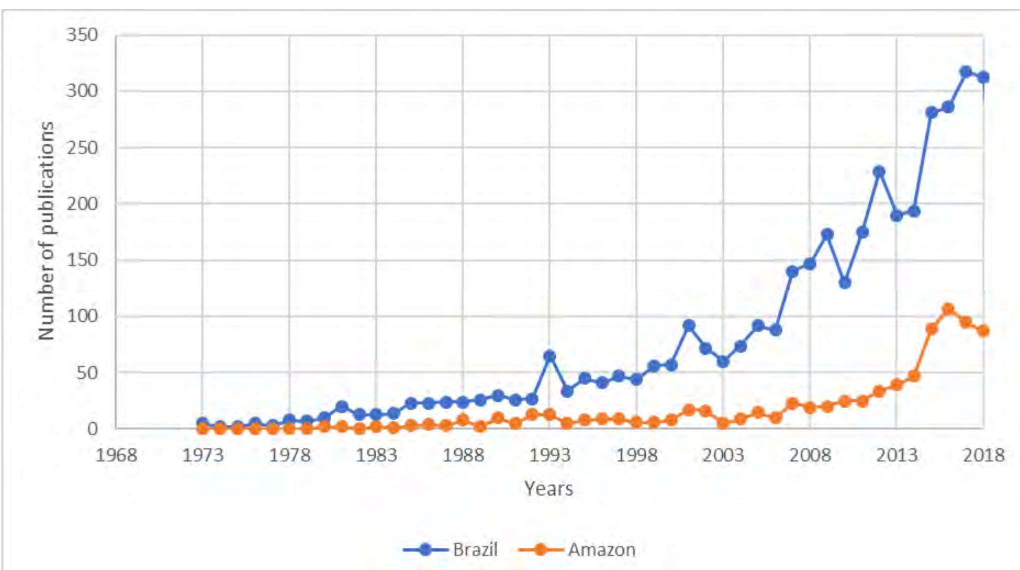

Figure 2. Number of publications related to Brazilian and Amazonian hydroelectric dams in Web of Science (WOS) for the 1973-2019 period.

Our analysis of the WOS subject categories reveals the multidisciplinary nature of hydroelectric development research in the Brazilian Amazon. Of the approximately 250 subject categories in the WOS database, 56 appear in this dataset. A full list of the WOS categories in the diagram is provided in the Supplementary Materials (SM1).

An analysis of connections within and between disciplinary or thematic clusters in the co-occurrence network helps us understand how researchers with different academic backgrounds tend to develop interdisciplinary teams (Figure 3).

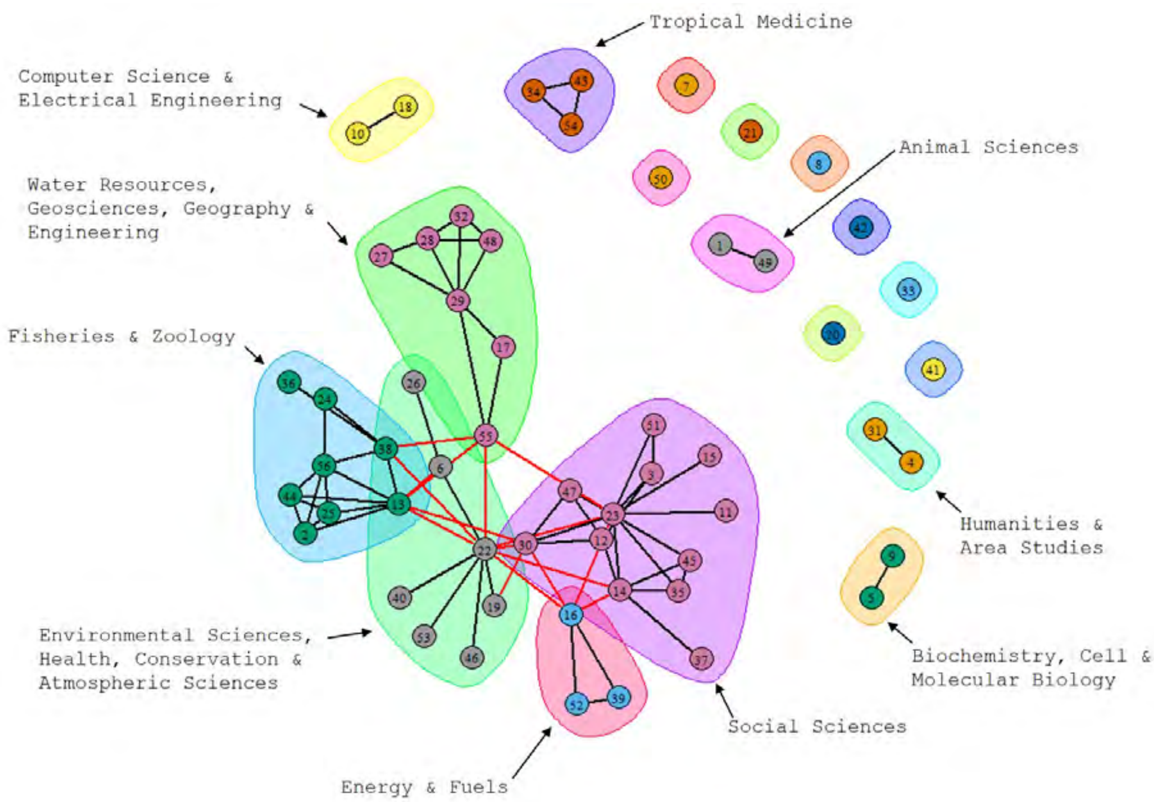

Figure 3. Network of co-occurrences between WOS subject categories in publications focusing on Brazilian Amazon hydroelectric dams for the 2014-2019 period. Nodes are WOS categories, links are co-occurrences (black lines between nodes show connections between categories within the same Louvain cluster, while between-cluster connections are shown as red lines). Node numeric IDs and corresponding categories are provided in the Supplementary Materials (SM1). Colored polygons are Louvain clusters [44].

The various disciplinary and thematic clusters classified according to WOS disciplinary categories are nodes and the linkages among them are ties. Isolates are nodes not peripherical to the network, which are not directly connected to any network node, such as Computer Science and Electrical Engineering, Tropical Medicine, Animal Sciences and others. The nodes in the center represent subsets of multi or interdisciplinary/thematic clusters that are connecting with other disciplinary fields. As an example of a connection between disciplines, Water Resources (55) is a hub of connections between all fields except for Energy and Fuels. The fields of Ecology (13), Environmental Sciences (22), Green and Sustainable Science and Technology (30) and Energy and Fuels (16) provide connections between the other "satellite" fields. By detecting subject categories that span researchers from different disciplinary clusters, we can design strategies to create research bridges and facilitate communication and collaboration across disciplinary divides.

In addition to identifying the linkages between subject categories, our analysis also identifies some of the gaps that may be fertile ground for knowledge creation. For example, in Fig. 3 there is no connection between the Electrical Engineering/Computer Science cluster and the Water Resources cluster, which may represent an opportunity for collaboration. Tropical Medicine is also an isolate cluster, that could be connected to Zoology and Health Sciences. Table 1 lists the top ten subject categories in Brazilian dam-related publications that have the most ties to categories in other disciplinary clusters in Fig. 3. While these examples of categories do not always align exactly to traditional academic disciplines, they help us understand the types of cross-cutting bridging subjects of interest to people who study dams in Brazil.

Table 1. Top ten Web of Science categories with ties to other Louvain groups.

ID	WOS Category	In Group Ties	Out Group Ties
22	Environmental Sciences	5	7
13	Ecology	5	4
30	Green & Sustainable Science & Technology	3	4
55	Water Resources	2	4
16	Energy & Fuels	2	4
23	Environmental Studies	10	3
14	Economics	5	2
38	Marine & Freshwater Biology	4	2
6	Biodiversity Conservation	2	1
19	Engineering, Environmental	1	1

Additional analyses of the network measured centrality[4] of different subjects in the networks and captured the level of involvement, bridging, and influence of nodes [45]. The fields of Environmental Sciences (22), Water Resources (55), Marine and Freshwater Biology (38), Environmental Studies (23), Energy and Fuels (16), Ecology (13), Geosciences (29), Economics (14), Green and Sustainable Science and Technology (30) and Zoology (56) present a high degree of centrality, and are the most connected to other sub-fields, providing support for interdisciplinary research and cross-disciplinary communication. The fields of Environmental Sciences (22), Water Resources (55), Marine and Freshwater Biology (38), Environmental Studies (23), Ecology (13) and Geosciences (29) present a high degree of betweenness, connecting fields that otherwise would not be connected and may facilitate relevant collaboration and communication across disconnected fields. The interdisciplinary field of Green and Sustainable Science and Technology (30) provides an important connection between biophysical/environmental and social sciences fields.

[4] Degree centrality is a simple measure of the number of connections a node has in a network, capturing involvement and potential influence. Betweenness centrality measures the extent to which a node sits on the shortest path between other nodes, capturing bridging and brokerage between otherwise disconnected areas of the network [45].

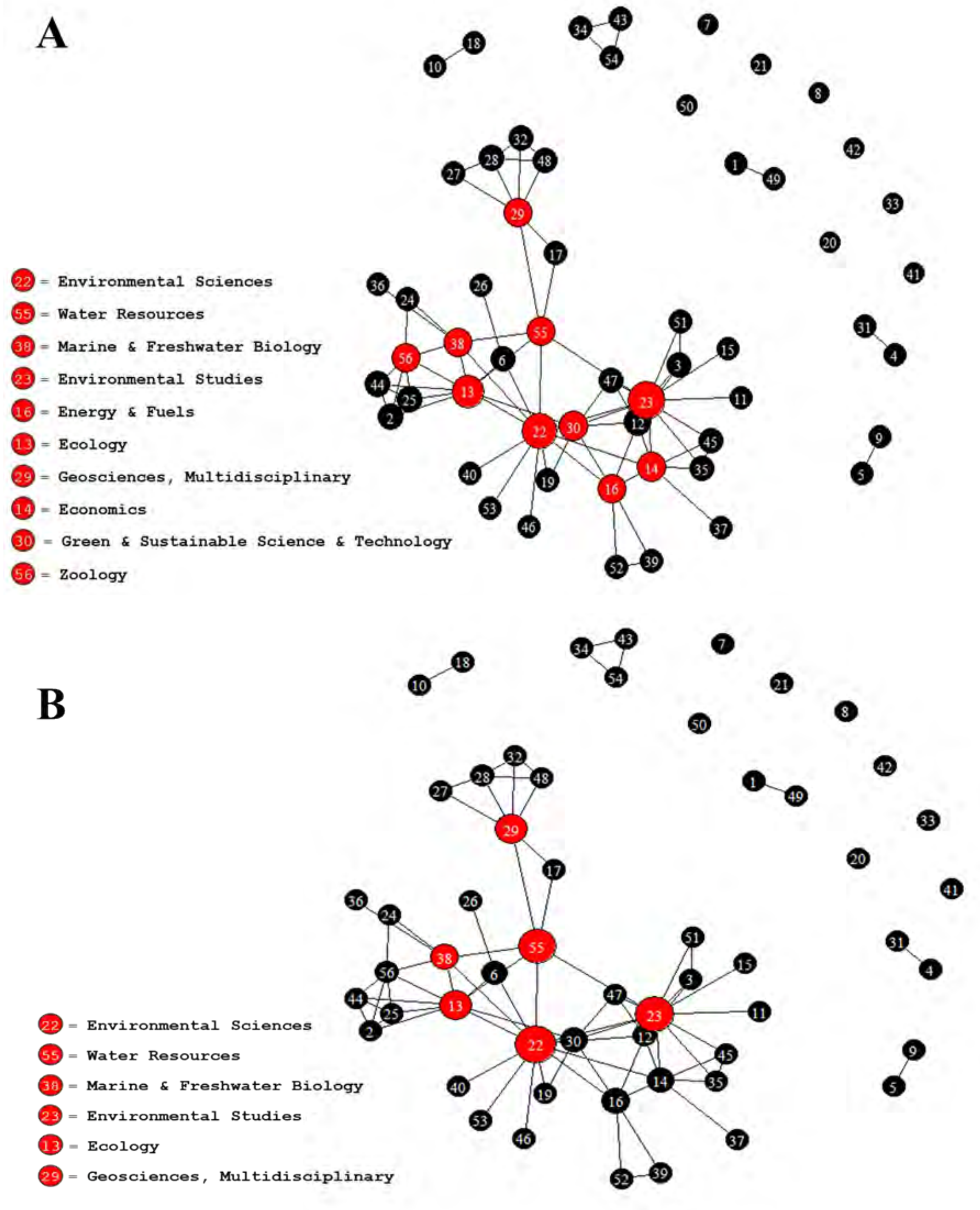

Figure 4. Network of co-occurrences between WOS subject categories in Brazilian hydroelectric dam publications. (A) Categories sized by degree centrality. Larger sizes represent subjects that have more connections between categories. (B) Categories sized by betweenness centrality. Larger sizes represent subject categories that connect categories that are otherwise unconnected in the network. Red nodes represent disciplinary fields with high centrality and betweenness values.

Box 1. Organizations and Funding of Research on Hydropower in the Brazilian Amazon

The principal organizations of authors publishing peer-reviewed research on Amazonian hydropower in the last five years are Brazilian Universities, among which the National Institute for Amazonian Research (INPA) plays a leading role (49 records) followed by Federal Universities of: Pará (UFPA, 34); Rondônia (UNIR, 27); Rio de Janeiro (UFRJ, 27); Amazonas (UFAM, 19); and Universidade de São Paulo (USP, 18), and ten other Brazilian Universities (see SM 2). Internationally, authors and co-authors of these publications are from the University of Florida (UF, 11), University of East Anglia (11), Institute de Recherche pour Le Development (IRD, 10), Centre National de la Recherche Scietifique (CNRS, 7), Michigan State University (MSU, 7) and Sorbonne Université (7), among others. Authors from Brazilian and international NGOs have also contributed for this topic, including the World Wildlife Fund (WWF), the Wildlife Conservation Society (WCS), the Conservation Strategy Fund (CSF), The Nature Conservancy (TNC) and the Instituto de Pesquisas da Amazônia (IPAM), among others.

Research funding has been provided mainly by Brazilian government research agencies, notably by the National Council for Scientific and Technological Development (CNPq), with 39.3% of the publication records, followed by the Coordination for the Improvement of Higher Education Personnel (CAPES, 22.1%), the São Paulo State Research Foundation (FAPESP, 7.2%), the Amazonas State Research Foundation (FAPEAM 6.6%) and INPA (5.5%) (Figure 5). Outside Brazil, the main funding agencies are the National Science Foundation (NSF) and the Natural Environment Research Council (NERC), with 4.5% and 3.8% of the records (additional details in SM 3). It is also important to note the contribution of the private sector, represented by the dam-building companies Santo Antônio Energia (3.8%, Santo Antônio dam in the Madeira river) and Norte Energia (2.1%, Belo Monte dam in the Xingu river). Two international NGOs with programs in Brazil also appeared among the top 20 funding organizations: the World Wildlife Fund (WWF, 2.4%) and the Wildlife Conservation Society (WCS, 2.1%).

Many CNPq and CAPES programs have supported the internationalization of science through initiatives such as the Science Without Borders Program, which was terminated during the presidential administration of Michel Temer. Brazilian science is to face a large budgetary cut under current president Jair Bolsonaro, who in April of 2019 announced that the budget of the Ministry of Science, Technology, Innovation and Communication would be cut in half, and CNPq scholarship programs would be cut as well[5]. Our analyses show that Brazilian science and funding has been critical to advance research on Amazonian hydropower. Continued funding support is needed to address the risks and uncertainties that a changing climate and a changing Amazon are already experiencing given the fast-paced development of socio-economic activities and the advance of extractive and infrastructure frontiers [46,47].

[5] Brazil slashes funding to scientists. The planet may suffer: https://www.nationalgeographic.com/environment/2019/04/brazil-cuts-funding-scientists-grad-students-environment-suffers/

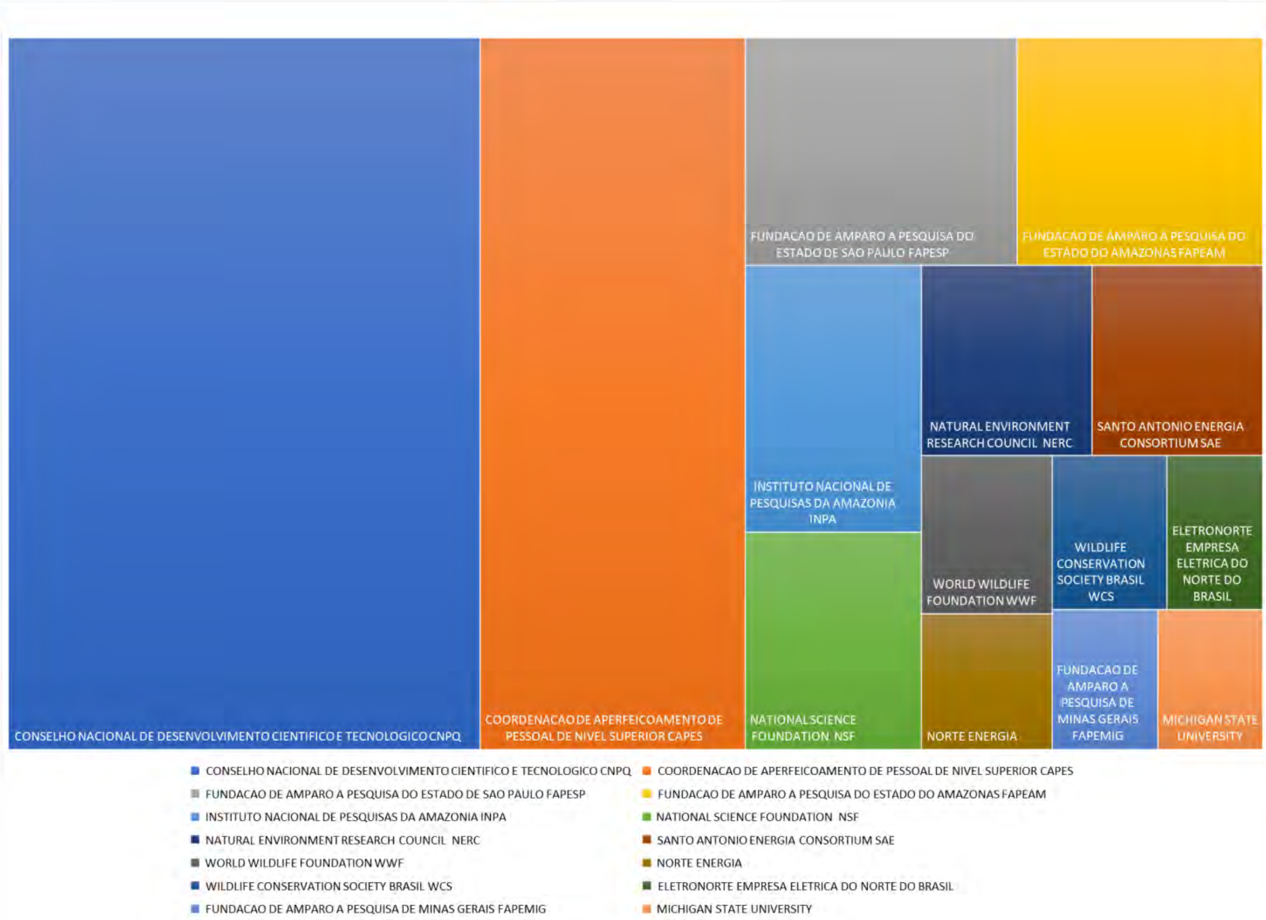

Figure 5 (Box 1). Treemap graph showing the main funding agencies (with 5 or more records) for peer-reviewed publications on hydroelectric dams in the Brazilian Amazon, from a subset of 290 Web of Science publications, for the 2014-2019 period. Additional information available in Supplementary Materials # 3 (SM 3).

4. Recent advances and gaps of research on hydropower in the Brazilian Amazon

For the subset of 290 articles published between 2014-2019 focusing on hydropower in the Brazilian Amazon, Environmental Sciences occupies the leading position with 60 records, followed by Ecology (32), Energy and Fuels (30), Biodiversity Conservation (28), Multidisciplinary Sciences (28), Environmental Studies (26), Green Sustainable Science Technology (26), and Water Resources (22). In addition to the field of Environmental Studies, Social Sciences are also represented in Environmental Sciences and Multidisciplinary Sciences, as well as in Geography (19), Economics (11), Interdisciplinary Social Sciences (9), Law (7) and Development Studies (6) (see SM 4 for more details). Determining an exact fit for articles within the WOS categories can be difficult, since they often fall in more than one category, and there is a lack of clear criteria distinguishing some categories, especially for the more multi- and/or interdisciplinary fields such as Environmental Sciences and Multidisciplinary Sciences. For example, Biodiversity Conservation is a highly ranked category, but can be assumed to be represented in other fields such as Ecology, Fisheries, Marine and Freshwater Biology and Environmental Sciences. Climate change also did not appear as a separate category, but an additional search reveals that 32 of the 290 records from WOS Core Collection mention or focus on climate change issues related to hydropower.

By compiling and synthesizing the recent literature from this 2014-2019 subset, we identified three main areas of interdisciplinary research that represent the current state of knowledge on hydropower and sustainability in the Brazilian Amazon: **a) Biophysical and social-ecological processes; b) Energy and infrastructure;** and **c) Governance, development and social benefits and impacts of dams**. Belo Monte dam in the Xingu has the highest number of publications (62), followed by Santo Antônio and/or Jirau dams in the Madeira river (38), Tapajós (14) and Tocantins dams (14). Below, we synthesize main advances and knowledge gaps drawing from the complete set of 339 publications for the 2014-2019 timeframe, detailed on Table 2.

4.1 Biophysical and social-ecological processes

Water is arguably *the* defining physical characteristic of the Amazon basin. Water quantity and quality are integrators of the coupled natural and human processes that occur within the watershed [48], and both are directly and indirectly affected by hydropower [11]. Dam construction [2,49], land use change [50,51], climate change [52,53], and their interactions [12] have all been shown to play major roles in altering riverine hydrology in the Amazon [54], with cascading effects across social and ecological systems [55]. For example, changes in riverine hydrology and connectivity alter patterns of floodplain forest inundation [56] and productivity [12], interrupt fish migrations [3,11], reduce fisheries production [51], and modify catchment sediment transport [2] and biogeochemistry [57–61] across vast spatiotemporal scales. While flow and sediment transport are well described via process-based watershed models [62], and several watershed models have been developed and applied to the Amazon basin [48,63] and sub-basin scales [64–67], model application within the broader context of social, ecological, and climate change is less developed. This more comprehensive approach is crucial for: 1) developing relevant future scenarios; 2) testing conceptual models of system behavior; and 3) guiding adaptive management strategies [68–71]. For example, Stickler et al. [12] and Mohor et al. [72] show how projected increases in deforestation and decreases in rainfall are likely to reduce electricity generation potential, exemplifying how interactions among hydropower, land use, and climate drive future system states. Additional work is needed to couple watershed-scale hydrological and sedimentological models with models of ecosystem functions and services to better predict hydropower impacts on ecological and social systems. These efforts are limited, however, by gaps in understanding about specific interactions among several biophysical processes (e.g., hydrology and geomorphology, fish and fisheries, terrestrial ecosystem feedbacks, and climate change), which we aim to synthesize below and in Table 2.

Perhaps most obviously, dam-induced changes in the physical and chemical regimes of rivers alter the diversity, composition, distribution and abundance of fish [10,73,74], threatening one-third of the world's freshwater fish biodiversity [3]. Changes in the seasonal flood pulse and river connectivity interrupt the migration, recruitment, and development of Amazonian fish species [10,75], negatively impacting reproduction and reducing catches both upstream and downstream of dams [10,75,76]. Transformations in Amazonian fisheries have significant local, regional, and transnational socio-economic impacts [33,76,77], which are also of critical cultural and economic importance for indigenous peoples and riverine communities [78]. While biological, functional [79] and trophic indicators [80] of fish diversity and abundance have been developed, a lack of long-term monitoring in the Amazon Basin makes identification of impacts and trade-offs during the dam planning and licensing processes extremely difficult [33,77]. Other major knowledge gaps include a limited understanding of flow-ecology relationships for the incredible diversity of Amazonian fish species [85] and inadequate guidance for hydropower and fish passage design that prevent fish mortality and injury [81] and which are relevant to the local setting and species [87].

Beyond the river, terrestrial ecosystem transformations associated with dams are poorly understood in the Amazon [9] and worldwide. Dams cause direct deforestation via reservoir impoundment [82]. Dams, however, cause significant indirect forest loss and degradation through at least three pathways [55]. First, land use change associated with dams causes deforestation and degradation of upland forests [83–87]. Second, dams alter river and floodplain hydrology, which changes the structure and function of riparian and floodplain forests [88–93]. Third, dam-associated infrastructure (e.g., transmission lines; [94]) causes additional direct and indirect deforestation. Together, these dam-induced terrestrial ecosystem impacts have cascading effects on biodiversity and ecosystem services [95], with evidence of wide-ranging impacts on birds [96–98], mammals [99], insects [100], and reptiles [101]. Current research tends to focus on a single dam, and there is a need to broaden this perspective to consider cumulative impacts, both from multiple dams and from interacting drivers. For example, indirect links between dams and deforestation may intensify synergies between forest loss and climate change, that alter fire dynamics and river flows across basins [12,53,102]. Overall, the mechanisms by which dams impact forests, land-cover, and livelihoods (e.g., Bro et al. [103]) need to be better understood to predict, manage and mitigate these impacts.

Interactions among dams, water, fish, and terrestrial ecosystems are all affected by (and affect) the climate through biophysical drivers and feedbacks. Notably, tropical dams and reservoirs have been shown to emit significant amounts of greenhouse gases (GHGs) [104]. While a considerable amount is known about GHG emissions from Amazonian dams [105], additional measurements are needed to reduce uncertainties and support better process-based emission models [60,61]. However, we argue that the most pressing need is the interpretation of existing information to inform policy, since changes in the methods for estimating GHG emission are more likely to affect the magnitude of emissions attributed to dams than additional measurements. For example, adopting a 20-year vs. 100-year time period when equating the warming potential of carbon dioxide and methane emissions would drastically alter assessments of the overall efficiency of dams as a renewable electricity source. We contend that the shorter timeframe is more relevant to the period when new and planned Amazon dams will emit large amounts of methane. Such emissions will have outsized effects on global warming, which are projected to drive changes in precipitation and temperature regimes and negatively affect many biophysical processes [102,106].

4.2 Energy and infrastructure

Energy and infrastructure are important themes related to hydropower governance and sustainability of the Amazon. Public policies and institutions related to hydroelectric development include, for instance, watershed management policies, electric sector reforms, environmental impact assessments, mitigation and monitoring policies and processes, economic and non-economic valuations, and decision-making instruments at different scales. There are gaps of knowledge and opportunities for improvement of licensing policies and social-environmental impact assessment instruments [14,107–109]. One such knowledge gap is a surprising paucity of research and publications about small dams across Brazilian and Amazonian watersheds [14]. Incentives and policy regulations have contributed to a five-fold increase in the number of small dams in the last 20 years, with 87 currently operating and 256 inventoried in Brazilian Amazonian rivers [13,110]. There is a need for research on the socio-economic costs and benefits of both large and small dams, including the cumulative impacts of cascades of dams on Amazonian river systems [14]. The same is true for transmission lines, which licensing processes and impact evaluation have been conducted independently and not articulated with hydropower planning [94]. It is necessary to move from the project-to-project logic to adopt planning instruments such as the Strategic Environmental Assessment at regional and basin-wide scales, as the Brazilian Federal Court of Auditors (TCU) recently recommended after assessing lessons learned from dam development in the Amazon [111].

Studies focusing on trade-offs between diverse energy generation options, as well as on future scenarios of energy production risks and costs under climate change are extremely important to inform infrastructure planning and climate change adaptation and mitigation investments in an integrated way [5,112–114]. Lucena et al. [112] found that climate change impacts can lead to higher emissions in the absence of climate mitigation policies, and that mitigation can lead to a lower total investment level.

Research conducted under the Energy and Fuels WOS theme has also focused on technological tools to aid in planning and reducing the economic risk on dependency on the hydro-thermal operating system in place in Brazil; comparison of pumped-storage versus conventional reservoir dams; as well as on energy efficiency; innovations and alternative energy generation sources contributing to diversify the energy generation mix [5,115–117].

Fewer research efforts and publications have focused on cost overruns and delays in the construction of mega infrastructure projects. Callegari et al. [118] estimated the probability distribution function of cost overruns and delays in the construction of Jirau, Santo Antônio and

Belo Monte dams in the Brazilian Amazon, finding a cost overrun of respectively 91%, 64% and 70% more than the initial budget for all three cases. Based on this technique, the authors suggest that policy makers should increase their budgets around 75% above the initial estimates to ensure within 50% certainty that their final costs will be within budget. According to these estimates, and experiences from other parts of the world, the bigger the project, the higher the risk of cost overruns with greater exposure to macroeconomic risks [119], raising the question that if the numbers were higher as they should be whether the dams would be economically justifiable.

4.3 Governance, development and social impacts and benefits of dams

Despite global efforts (e.g., World Commission of Dams report of 2000 [120]) directed to improve public participation, transparency and protection of human rights in hydropower planning and implementation, several problems still persist across the global north and south [30] in regard to governance, development and social impacts of dams.

Kirchherr and Charles [121] proposed a “matrix framework” to guide scholarly research on the social impacts of dams, defining three main components: Infrastructure, Livelihood and Community, each one with sub-components, and connected to the dimensions of space, time and value (positive or negative). The Infrastructure component can be compared to the “Energy and Infrastructure” theme above (4.2). Aspects of the other components and sub-components will be briefly approached here under the socio-economic and socio-cultural change and public health and sanitation topics. In this framework, we miss a rights / justice sub-component under the Community component, as well as a Governance component, to include public participation and power in decision-making.

The definition of “who is impacted” (“*atingidos*” in Portuguese) is crucial in the characterization of social impacts and compensation of hydropower development in the Amazon [122]. Despite similarities of socio-economic benefits and negative impacts of dams around the globe [121], the Amazonian region has some specificities that need to be considered in both planning and decision-making (Figure 6). These are related to, for example, the huge social and cultural diversity present in the region, where indigenous ethnicities, Afro-descendant groups, riverine communities, urban populations, family farmers and others, share the region and its water and forest resources [123,124].

In the recent cases of Belo Monte and Santo Antônio and Jirau dams, the construction of dams has led to social conflicts [125–127], judicialization [35], violation of human rights [37,128,129], gender differentiated impacts and violence [129,130], and destruction of indigenous and traditional communities' livelihoods and sacred sites [35,103,131–136]. Indigenous communities and social movements have formed alliances that strengthened resistance against these projects [136,137]. Several indigenous peoples and local communities have developed community consultation protocols in a process of self-regimenting the International Labour Organization (ILO 169) Convention (of which Brazil is signatory), which determine the right to Free, Prior and Informed Consent of indigenous peoples and traditional populations in relation to projects, policies or activities that may affect their livelihoods and/or territories [138–140].

Figure 6. Public hearing for the Belo Monte hydroelectric dam held in Altamira, Brazil, in 2009. Photo: Lalo de Almeida, courtesy.

Often, local communities do not have access to scientific publications describing the system that they live in and that they understand from their own perspective [141,142]. For instance, fishers affected by the Madeira dams have asked ADN researchers to translate findings of their research in a way that they could understand [141]. On the other hand, indigenous and local knowledge[6] (ILK) held by indigenous peoples and local communities who have a long-term experiential knowledge of Amazonian social-ecological systems are frequently disregarded in the process of planning and decision-making [124,131,143].

Hydroelectric dams may affect human health in different ways, upstream and downstream, in both rural and urban settings. Dams can impact human health through changes in water quality, groundwater contamination [144], changes in access to sanitation and medical services due to the increased flow of people and workers to the dam sites [145,146], psychological impacts by loss of traditional livelihoods and displacement [134,147], changes in livelihood styles [30,37,130], food security and diets [33,148] , increased spread of infectious and sexually transmitted diseases [149,150], increased exposure to mercury and others [151]. We found a big gap in publications focusing on sexually transmitted diseases in the dataset compiled from WOS, despite the expected increased risk of STDs associated with hydropower development.

Regarding socio-economic development, although the primary benefits of a hydroelectric plant are found at the national scale [152], it is at the local and regional scales that the main negative impacts of forced displacement and resettlement, deforestation of productive land, abrupt population increase, increased demand for infrastructure and services, loss of social cohesion, and impacts on livelihoods and loss of income are felt [30,103,119,153–157]. Contrasting to this suite of potential negative impacts, dam builders and supporters defend the argument that hydroelectric plants promote improvements in the socioeconomic conditions of the

[6] In this paper we adopt the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (UN IPBES 2016) definition of Indigenous and traditional populations: "Indigenous and local knowledge systems are understood to be dynamic bodies of integrated, holistic, social and ecological knowledge, practices and beliefs pertaining to the relationship of living beings, including people, with one another and with their environment. Indigenous and local knowledge is grounded in territory, is highly diverse and is continuously evolving through the interaction of experiences, innovations and different types of knowledge (written, oral, visual, tacit, practical and scientific). Such knowledge can provide information, methods, theory and practice for sustainable ecosystem management. Indigenous and local knowledge systems have been, and continue to be, empirically tested, applied, contested and validated through different means in different contexts"[171].

host localities [158,159]. This controversy has motivated the emergence of research aiming to elucidate if and how hydroelectric dams may be inducers or constrainers of local development.

For the Jirau, Santo Antônio and Belo Monte hydroelectric plants, Moran et al. [30] found that promised jobs practically disappeared in less than 5 years after construction. Studies carried out in other Brazilian regions show that temporary economic growth during the construction phase is frequently the main benefit associated with hydropower implementation in municipalities flooded by dams [159–162]. However, economic growth is generally not accompanied by or not correlated with improvements in other social development indicators such as social inequality, child labor, sanitary problems, fertility rate, and education [159,163].

Randell [164] conducted a longitudinal study of wealth and subjective well-being perception among communities displaced by the Belo Monte dam, finding that the majority of interviewed people reported increased wealth, particularly those that did not own land prior to dam construction, those who gained assets, and those who remained closer to the original study area. Nevertheless, the author recognizes the importance of collecting additional data after the completion of dam construction, as well as to include other affected social groups and populations in such studies.

In general, these studies show two convergences: that there is short-term economic growth followed by medium-term shrinkage (probably due to the large investments that occur during the construction phase); and that the results achieved are quite dependent on each study's context, making it hard to estimate standards that allow for an integrated view. Socio-economic impacts are complex, occur through multiple spatiotemporal scales [165,166] and involve multiple dimensions [121,167].

5. Future directions and conclusions

The analysis of hydropower-related publications in the Brazilian Amazon illustrates a high degree of interdisciplinary research related to the sub-fields of environmental sciences, ecology and water resources, but indicates that research bridging these fields, especially the green and sustainable science and technology and the energy and fuels categories provide opportunities for new integrative knowledge production. Further, we suggest that analyses of existing legal and policy frameworks and instruments might be used as points of departure to identify knowledge gaps, synthesize existing information, and provide policy-oriented solutions that can be e implemented through social learning and management approaches [168].

The map of institutions and funding organizations involved in research on hydropower in the Brazilian Amazon demonstrates the important leadership that Brazilian researchers and universities play in advancing research on this topic, as well as the fundamental support provided by the Brazilian funding agencies. It is critical to provide the necessary support for strengthening science education and research in Brazil, especially in Amazonian universities, which are well positioned to address the local challenges and risks associated with existing and planned hydropower pprojects. This can be further supported by enhancement of undergraduate and graduate programs providing students and faculty with opportunities for national and international mobility[7], securing funding for scholarships, field research and equipment, and by partnering with national and international agencies and institutions.

To move towards more resilient and sustainable pathways for the Brazilian Amazon, future research on Amazonian hydropower might focus on deepening the understanding of:

a) The inclusion of direct and indirect impacts, who is impacted and what are the impacted areas in research frameworks and licensing instruments, which may alleviate the mismatch between scientific findings, policy instruments, and the reality on the ground. This has also important implications for managing conflicts and legal processes around the definition of who will be compensated by dam-companies and the planning of displacement and resettlement programs.

b) Temporal variation and magnitude of impacts on linked aquatic, terrestrial and social subsystem as well as understanding, mitigating, monitoring and compensating upstream and downstream impacts. This has important implications for designing and operating dams, duration of monitoring and mitigation programs, development of compensation programs, and understanding cumulative and synergistic impacts in watershed and regional planning.

c) The distribution of costs and benefits of large and small dams across temporal and geopolitical scales, considering multiple valuation approaches, the diversity of stakeholders receiving the benefits and bearing the costs of these projects, as well as gender and intergenerational differences and implications.

[7] Such as the "Bionorte" program, the Pró-Amazônia Program, the PROCAD, the Science Without Borders, and others supported by CAPES: https://www.capes.gov.br/

d) Geopolitical issues around transnational rivers and dams, which are relevant for the Amazon, the Mekong, the Congo and other transnational watersheds around the world. Flows of water, sediment, fish and other aquatic and terrestrial animal species, climate and often people are not restricted by political boundaries. Understanding these processes requires basin-wide efforts and long-term monitoring. In the policy arena, managing these systems involves promoting international and cross-sectorial dialogue and negotiation, enhanced public participation and transnational watershed independent committees to inform and influence decision-making on transnational rivers [2].

e) Assessment of cumulative impacts that take the perspective that the biological, social and economic impacts in a locality are product of the interaction of hydroelectric-triggered transformations with other existing projects and actions [121,169,170]. In this cumulative perspective, the focus is no longer the hydroelectric project, but becomes the local and regional social-ecological systems affected by multiple actions or projects (e.g. dams, climate change, demographic change, etc.). To address cumulative impacts, understanding must involve the local and regional natural resource bases, the knowledge and input of indigenous and local communities, and local and regional social and governance contexts that shape social-ecological systems.

The synthesis of recent academic production on hydropower development in the Brazilian Amazon provided in this article provides evidence of the unsustainable path created by large and small dams built in Amazonian rivers from a social, economic or environmental standpoint. As it is impossible to quantify monetarily many impacts, for example the loss of fish species due to interruption of migratory routes or the symbolic loss of place-based livelihoods, it is not possible to fully calculate, mitigate and compensate important costs associated with the construction of large and small dams in the world's largest tropical system.

Finally, this synthesis identifies gaps in communication that exist within and between scientists, civil society and local communities, private sector and policy and decision-makers. Efforts need to be directed to bridge these gaps through several strategies and tools. Social learning forums and opportunities could support dialogue and learning from previous experiences of dam implementation, moving away from the project scale to embrace regional and basin-wide strategic research and planning approaches.

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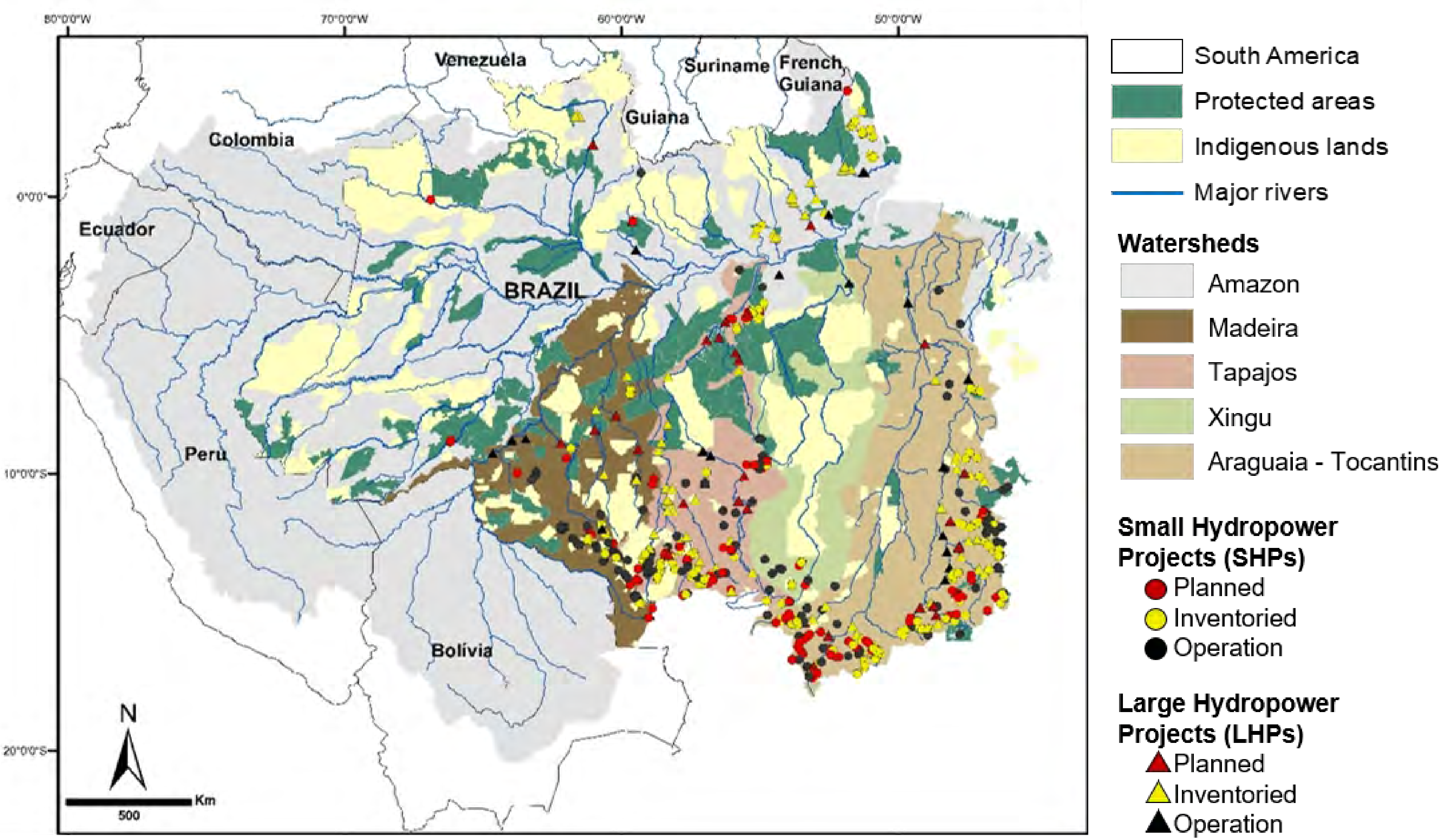
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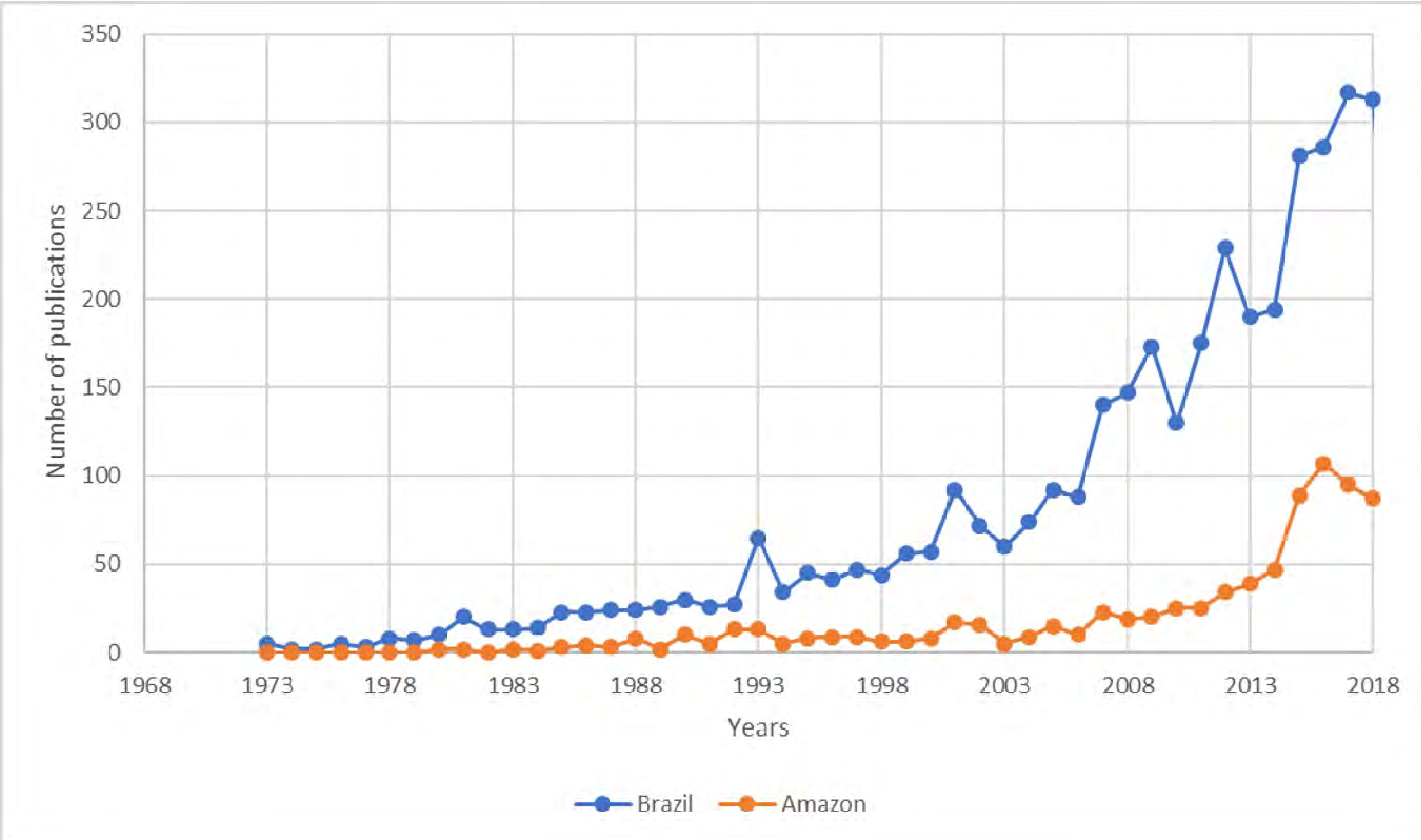

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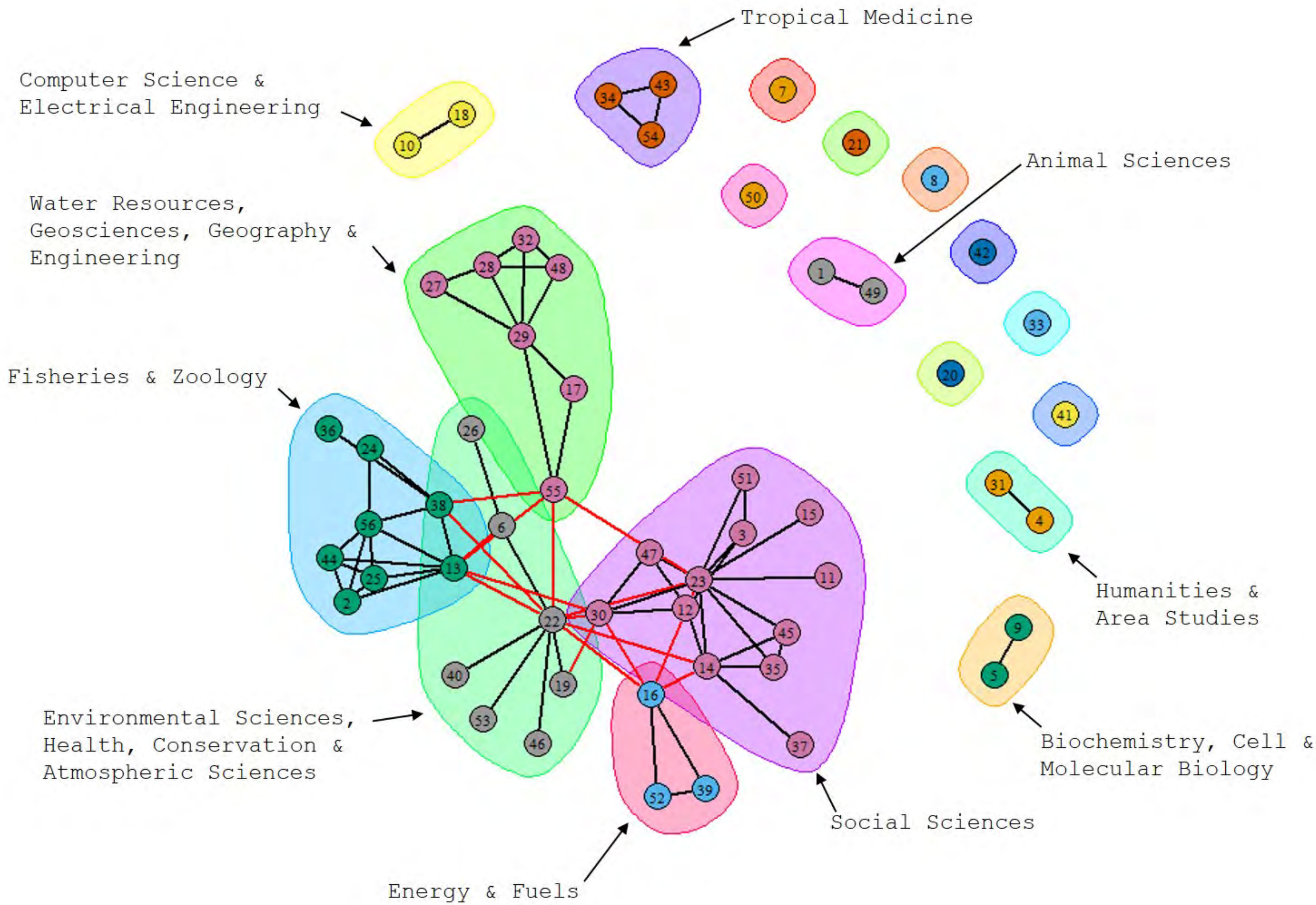
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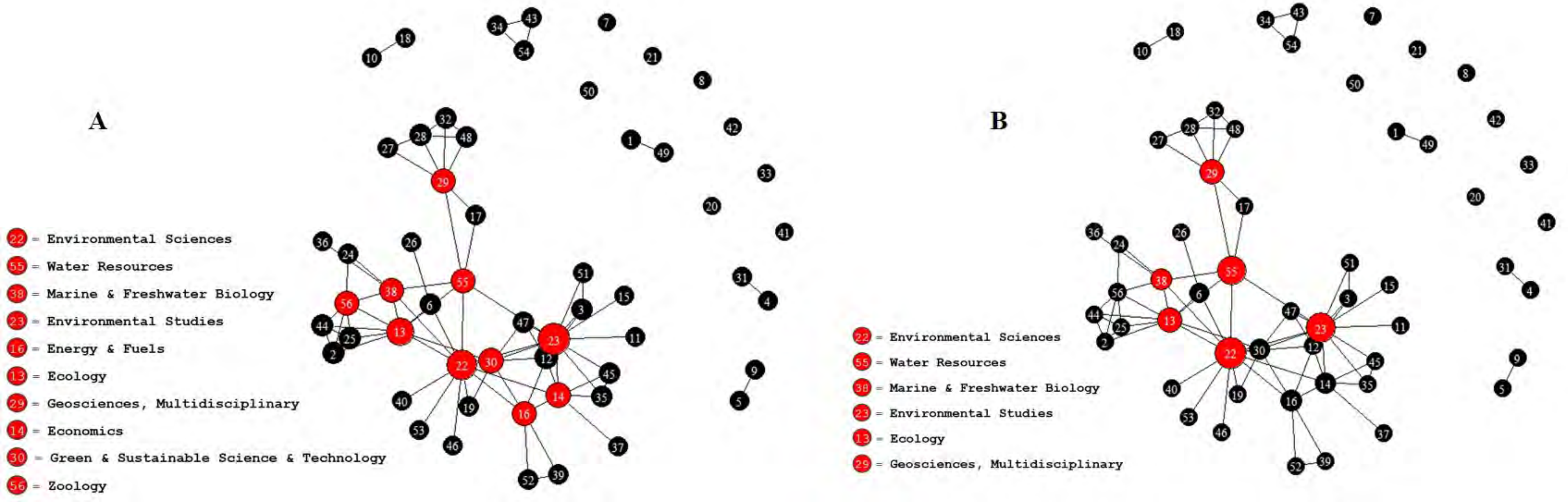
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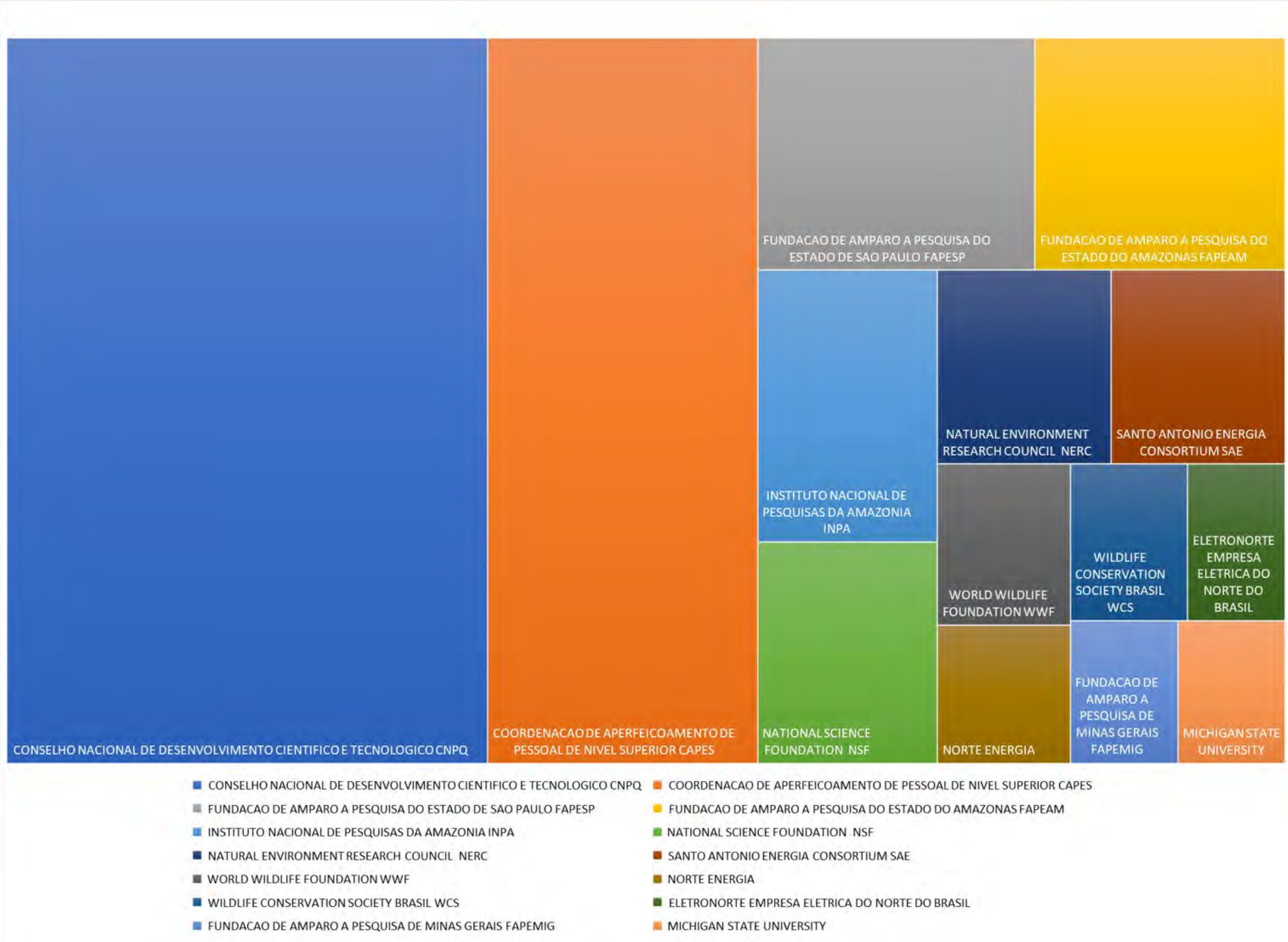
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Table 1. Top ten Web of Science categories with ties to other Louvain groups.

ID	WOS Category	In Group Ties	Out Group Ties
22	Environmental Sciences	5	7
13	Ecology	5	4
30	Green & Sustainable Science & Technology	3	4
55	Water Resources	2	4
16	Energy & Fuels	2	4
23	Environmental Studies	10	3
14	Economics	5	2
38	Marine & Freshwater Biology	4	2
6	Biodiversity Conservation	2	1
19	Engineering, Environmental	1	1

Table 2. Main advances and gaps for research on hydropower development in the Brazilian Amazon, organized by interdisciplinary topics from the literature review conducted for 339 publications obtained in the Web of Science for the 2014-2019 period.

Interdisciplinary Topic	Main Themes	Advances	Gaps	Main WOS Disciplinary Categories	Reference numbers
Biophysical and social-ecological processes	Hydrology and geomorphology	- Existing dams significantly impact hydrologic regime across Brazilian Amazon - Lowland dams with large reservoirs cause highest hydrologic alteration, but small dams are increasing rapidly and cause large impacts per electricity production - Existing and planned Andean dams threaten connectivity with major impacts to fish, sediments, and nutrients - Dam vulnerability index developed to guide future hydropower	- Cumulative ecohydrological impacts of small and large dams on flow regime and sediment/nutrient transport - Coupling watershed models with climate change models and models of specific ecosystem structure, function, and services - Uncertainty about range of potential future climate impacts on spatiotemporal trends in river flow - Potential for dam design or sediment management techniques to mitigate trapping	Environmental Sciences/Studies, Water Resources, Geosciences, Meteorology and Atmospheric Sciences	[2] [10] [11] [13] [49]
Biophysical and social-ecological processes	Fish and fisheries	- Freshwater fish diversity threatened by existing and planned dams globally - Andes-Amazon connectivity threatened by dams - Fisheries declines observed up- and downstream of major dam projects - Major impacts of fisheries losses across economic, social, and cultural systems - Limited explanatory power of hydrological control on fisheries production	- Species and/or functional-group-specific flow-ecology relationships - Data scarcity, both on spatiotemporal availability of ichthyofauna data as well as socio-economic impacts on livelihoods of fishers and resettled communities, including through the lens of gender and intergenerational differences. - Fish passage technologies relevant to tropical species and reservoirs	Ecology, Fisheries, Biodiversity Conservation	[3] [10] [33] [76-79] [81]

Table 2. Continuation.

Interdisciplinary Topic	Main Themes	Advances	Gaps	Main WOS Disciplinary Categories	Reference numbers
Biophysical and social-ecological processes	Terrestrial ecosystem feedbacks	- Direct and indirect land use change occurs from reservoir inundation, deforestation, changes in riparian and floodplain forest hydrology, and energy-associated infrastructure - Transmission line impacts likely exceed reservoir impacts (by area) and are under-acknowledged in dam planning and management - Coupled feedbacks between dams and deforestation may exacerbate connections between forest loss and climate, fire, and river flow	- Research tends to focus on a single dam, need to consider cumulative impacts from other dams and drivers of change. - Mechanisms by which dams indirectly impact forests, land-cover, and livelihoods need to be better understood to predict, manage and mitigate these impacts. - Need to study coupled impacts of land use change, climate change, and hydropower development on sediment production and transport	Environmental Sciences/Studies, Geosciences, Meteorology and Atmospheric Sciences, Ecology	[12] [48] [77 – 78] [82-87] [94] [102]
Biophysical and social-ecological processes	Climate change	- Tropical reservoirs may be a major source of methane, exacerbating global warming - Selection of reference time frame is critical for calculating net warming potential of hydropower-based electricity production - Global climate projections project spatially variable changes in precipitation, evapotranspiration, and flow regimes, with most drying in the south and southeast - Climate change projected to increase flows and inundation in NW Amazon and decrease flows in the eastern Amazon	- Need for regional climate models that include feedbacks among hydropower development, deforestation, reservoir emissions, warming and precipitation regimes - Impacts of greenhouse gas emission calculations and uncertainty are not represented in policy - Methane flux from dam degassing and downstream fluxes are poorly constrained - Net lifecycle carbon accounting for tropical hydropower remains hotly debated in the literature and policy arenas	Environmental Sciences/Studies Meteorology and Atmospheric Sciences Multidisciplinary Sciences Energy and Fuels Ecology Biodiversity Conservation	[15] [102] [104-106]

Table 2. Continuation.

Interdisciplinary Topic	Main Themes	Advances	Gaps	Main WOS Disciplinary Categories	Reference numbers
Energy and Infrastructure	Energy scenarios; alternatives and intersections with other infrastructure and power generation options; intersections between electricity generation and climate change; energy efficiency; technological tools; feasibility and siting of dams, critique of dams as clean energy; and public policies	- Opportunities to improve licensing processes and social-environmental impact assessment instruments - Paucity of research on small dams across the Amazon - Transmission lines are not integrated to hydropower planning - Climate change impacts can lead to higher emissions and higher cost in the absence of climate mitigation policies in hydropower planning - Investing in energy efficiency, innovations and alternative energy generation sources can contribute to lower dependency and risks of the thermo-hydro system - Estimates of cost overruns and delays in the construction of Jirau, Santo Antônio and Belo Monte dams totaled 91%, 64% and 70% above the initial budget	- Good practices in cumulative impact assessment at regional and basin-wide scales considering other infrastructure projects and relevant policies and programs - Developing tools to enhance access to data and information /public participation in decision-making - Integrated assessment evaluation and planning for small and large hydropower including transmission lines - Trade-offs between diverse energy choices and arrangements according to the perspective of different actors - Pluralistic valuation in environmental impact assessment - Integrated modelling of climate change, energy production from various sources, risks and costs - Investigating the cost of corruption for megaprojects - Investigating cost overruns and delays of projects	Environmental Sciences, Green Sustainable Science Technology, Environmental Engineering and Energy and Fuels	[5] [13 - 14] [18] [94] [111-112] [117-119] [168]

Table 2. Continuation.

Interdisciplinary Topic	Main Themes	Advances	Gaps	Main WOS Disciplinary Categories	Reference numbers
Governance, development and social impacts of dams	Public health and sanitation, infectious diseases, psychology and water contamination, socio-economic and cultural impacts, distribution of costs and benefits, social movements, social conflicts, psychological impacts and symbolic losses, human rights, development-forced displacement and resettlement and public policies	- Dams contribute to trigger infectious diseases outbreaks, which risks and costs are not accounted for during planning and licensing of projects. - Lack of data constrains the capacity to distinguish between positive and negative impacts, patterns, specificities and cumulative social impact processes at local, regional and basin-wide scales. - Belo Monte and Madeira dams have led to social conflicts, judicialization, violation of human rights, gender-differentiated impacts, and destruction of indigenous peoples and local communities' livelihoods. -Local communities do not have access to information produced by researchers and scientists. - Indigenous and Local Knowledge are not considered in planning and decision-making of hydropower. - Benefits of dams are realized at the national scale, while costs are felt in local and regional scales. - Socio-economic benefits and negative impacts are complex and occur through multiple spatiotemporal scales and involve multiple dimensions	- Identifying public policy gaps affecting basic sanitation, water resources and infectious diseases outbreaks in existing cases to inform planning. - Developing studies focusing on how different people (women, children, elderly, as well as diverse cultural groups) may be differently impacted by dams - Social impacts in general: difficulty defining who are "affected" by dams, which has socio-economic, rights and justice implications - Studies are done at the project scale, but effects are systemic and cumulative - Understanding the interconnections between forced displacement and social-ecological processes upstream and downstream of dams - More integrated studies are needed, moving from a project by project to a regional, systemic scale	Tropical Medicine, Social Sciences Interdisciplinary, Parasitology, Environmental Sciences and Environmental Studies, Geography, Economics, Law and Development Studies	[30] [34-35] [125] [130; 134] [144-146] [159-164]