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REVIEW ARTICLE

Trends and Knowledge Gaps in Amazonian Fish Ecology Research: A Topic Modelling Review

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ABSTRACT

The Amazon basin is home to one of the richest aquatic ecosystems, playing a key role in maintaining global biodiversity and ecosystem services. Despite extensive studies on fish diversity in the region, gaps remain in understanding broad processes to inform management strategies, such as the socioeconomic aspects of fisheries and the long-term effects of environmental change on fish populations. We used topic modelling, a machine learning technique, to analyse 400 peer-reviewed articles on Amazonian fish ecology published over the last 50 years. We identified 13 distinct topics, grouped into five main themes: Ecosystem dynamics, Evolutionary ecology, Hydrological processes, Impact assessments, and Management and Conservation. Results revealed an emphasis on Trophic ecology and Feeding dynamics, Fisheries management, and Evolutionary and Molecular ecology, which make up a large part of the literature. However, topics like Functional extinction and ecosystem consequences and Flood pulse dynamics are less represented, indicating important research gaps. Temporal analysis revealed a shift from early emphases on hydrological processes and participatory management toward contemporary priorities centered on functional ecology, trophic dynamics, and applied management. These findings offer insights for future research and underscore the need for integrated, interdisciplinary approaches to address the region's complex ecological challenges and promote evidence-based conservation and management strategies.

1 | Introduction

The Amazon basin is the largest freshwater drainage system in the world, covering approximately 6,000,000 km^2 and accounting for nearly 20% of global river discharge (Dagosta and de Pinna 2019; Jezequel et al. 2020). These hydrological characteristics underpin one of the most diverse freshwater ecosystems on the planet. The region's complex interplay of biotic and abiotic features supports an exceptional diversity of fishes, currently estimated at around 2716 species, of which 1696 are endemic (Dagosta and de Pinna 2019; Jezequel et al. 2020). Understanding this extraordinary diversity, however, requires placing it within the broader structural and functional framework of Amazonian freshwater ecosystems (Alho 2012).

The aquatic habitats in the Amazon basin play a key role in sustaining this fish diversity (Begossi 2014; Guayasamin et al. 2024). By supporting a wide array of ecological functions, these habitats provide the foundation for processes in which fish are central components. Fish play a crucial role in ecological processes and contribute to human well-being by providing essential ecosystem services, including nutrient cycling, sediment regulation, and water quality (Holmlund and Hammer 1999; Pelicice et al. 2023). Fish also contribute to food security for millions of people worldwide, serving as a primary source of protein, macronutrients, and livelihoods, especially in low- and lower-middle-income countries (Youn et al. 2014; McIntyre et al. 2016; Arshad et al. 2022). In food webs, fish populations support biodiversity processes and serve as indicators of ecosystem health (Pinna et al. 2023). Beyond these roles, their cultural, recreational, and aesthetic value enriches human communities and highlights the importance of conserving aquatic ecosystems (Waechter et al. 2024).

Research on Amazon basin fish fauna has intensified, encompassing topics such as diversity patterns across different basins (Cantanhede et al. 2023), the sustainability of fishing practices (Almeida et al. 2001; Andrade et al. 2022), the effects of habitat complexity on trophic interactions (Pinheiro et al. 2024), and the impacts of climate change on fish assemblages (Cajado et al. 2022; Scherer et al. 2023). This surge in research is not unique to Amazonia but reflects a broader global trend (Jarić et al. 2012). Over the past few decades, there has been a marked increase in scientific output in fisheries science (Aksnes and Browman 2016), alongside growth in specialised journals in the field (Mather et al. 2008). This global expansion in fish and fisheries research has been driven by the importance of fisheries resources for food security, increasing concern over declining fish stocks, and the recognised importance of science in guiding sustainable resource management (Jarić et al. 2012).

As research output in fish and fisheries science continues to grow, conducting systematic reviews based solely on manual reading has become increasingly challenging due to the time-intensive nature of this approach. Moreover, traditional systematic reviews face recognised limitations when applied to large, heterogeneous, and thematically broad bodies of ecological literature. While highly effective for addressing narrowly defined questions, manual review-based approaches may struggle to synthesise multidimensional research agendas, long-term thematic dynamics, and latent patterns across extensive corpora, potentially introducing selection and interpretative biases (Westgate and Lindenmayer 2017; Haddaway et al. 2020). These challenges have motivated the growing adoption of automated and semi-automated approaches, such as text mining and machine learning, as complementary tools for large-scale ecological synthesis (Linnenluecke et al. 2020; Sundaram and Berleant 2023). This limitation is particularly evident when addressing persistent gaps in our understanding of Amazonian fish diversity. Much of the research has concentrated on specific geographic and ecological aspects, often overlooking other areas of equal importance (Reis et al. 2016). A global review of fisheries studies from 1990 to 2016 found a strong emphasis on behavioural ecology, morphology, and diet (Syed et al. 2018). However, this focus has often come at the expense of other critical areas, such as the socioeconomic dimensions of fisheries, which are essential for achieving a holistic and sustainable approach to resource management. Addressing these imbalances requires the integration of emerging analytical tools, such as text-mining and machine learning, to identify research trends and uncover underexplored topics systematically.

In the present study, we combined text-mining tools with topic modelling, a machine learning technique that uncovers latent topics in a large set of documents (a corpus) (Blei 2012; Murakami et al. 2017). By statistically grouping patterns of co-occurring words, topic modelling allows us to identify dominant and less emphasised research themes across extensive corpora. This approach offers methodological advantages, including reduced subjectivity in thematic classification, the ability to synthesise heterogeneous bodies of literature, and the capacity to examine long-term changes in research emphasis in a consistent and reproducible manner (e.g., Westgate et al. 2015; Syed et al. 2018; Luiz et al. 2019; Anderson et al. 2021). These features make topic modelling particularly suitable for large-scale ecological syntheses, such as studies of Amazonian fish ecology, where ecological, geographical, and socio-environmental dimensions intersect across decades of research.

Although topic modelling has been most widely applied in fields such as political science, economics, and the humanities, its use has expanded rapidly within ecology, conservation biology, and aquatic sciences as a tool for identifying research trends and knowledge gaps (Westgate et al. 2015; Dias et al. 2016; Luiz et al. 2019; Anderson et al. 2021). Here, we investigated the themes addressed in fish ecology studies in the Amazon over the past 50 years. In this study, the term 'Amazon' refers to the Pan-Amazonian region, encompassing the Amazon and Orinoco basins, the Araguaia–Tocantins system, and adjacent estuarine zones. These systems are often considered together due to their shared biogeographic history, overlapping fish faunas, and common ecological and hydrological processes that shape freshwater biodiversity across northern South America (Willis et al. 2010; Lowe-McConnell 2012; Dagosta and de Pinna 2019). Specifically, this study addresses the following questions: (1) What are the main themes in research on fish ecology in the Amazon? (2) How has research on Amazonian fish ecology evolved over time? and (3) What research gaps exist in Amazonian fish ecology?

Based on the historical development of fish ecology and fisheries research, which has traditionally emphasised biotic interactions, community structure, trophic relationships, and life-history traits, we anticipated that classical ecological themes, such as trophic ecology, community structure, biogeography, and life-history strategies, would be more prevalent in the literature on Amazonian fishes (Jarić et al. 2012; Aksnes and Browman 2016; Syed et al. 2018). In contrast, socio-ecological and human-dimension topics have historically received comparatively less attention within ecological research, particularly in freshwater systems, and were therefore expected to be less represented (Jarić et al. 2012; Syed et al. 2018).

2 | Methods

2.1 | Data Collection

We conducted a systematic literature search for studies on fish ecology in the Amazon using the Web of Science, Scopus, and SciELO databases. These databases were selected to ensure both thematic relevance and geographical representativeness. Web of Science and Scopus offer broad coverage of peer-reviewed literature across multiple disciplines, while SciELO complements this scope by indexing regionally produced research often underrepresented in global databases. Additionally, all three platforms provide standardised and exportable metadata essential for the bibliometric and topic modelling analyses conducted in this study. Although Google Scholar may appear useful, it was not considered due to the inclusion of non-curated sources and a lack of metadata export functionality required for systematic processing. Google Scholar also does not provide the same level of quality control regarding articles from predatory journals as the other databases (Ross-White et al. 2019). The search was performed in English using the following Boolean search string in the titles, abstracts, and author keywords: (fish* AND ecolog* AND amazon*) NOT (taxonom* OR parasit* OR aquacultur* OR marine OR sea OR "fish farming" OR hatcher* OR "fish breeding" OR "species descript*" OR systematic OR "phylogenet* analysis"). We collected peer-reviewed original articles published between 1974 and 2024, excluding reviews, book chapters, book reviews, conference proceedings, notes, letters, grey literature, and those conducted outside of Amazon. The initial search yielded 876 articles (Web of Science: 296, SciELO: 69 and Scopus: 511). After removing duplicates and screening, 400 articles were retained. Articles published in Spanish and Portuguese were also included in this review, as long as they provided a title and abstract in English, ensuring consistency in text processing and interpretation. Studies were included if they were conducted within the Amazon region and either addressed fish ecology directly (e.g., assemblage structure, behaviour, trophic interactions) or the impacts of environmental drivers (e.g., hydrological processes, climate change, and land use) on Amazonian fish communities. Conversely, studies were excluded if they were conducted outside the Amazon or mentioned fish only tangentially without providing substantial ecological data. A flow diagram summarising the identification, deduplication, and screening steps used to construct the final corpus is provided in Figure S1. All records were imported into Zotero v. 6.0.36. Duplicates were identified using the software's built-in function, which highlights records with overlapping metadata. These were then manually reviewed and excluded. Articles outside the scope of the study were removed after screening titles and, when necessary, abstracts. Following this screening process, 400 articles met the inclusion criteria for analysis. These articles were exported from Zotero in CSV format and imported into R software v. 9.0.463 (R Core Team 2023) for topic modelling.

2.2 | Data Preprocessing

We generated the article content (Table S1) by combining texts extracted from the title, abstract, and author keywords (if available). Because unstructured data often has irrelevant information, it was necessary to process the text for model training and further analysis. The tm package (Feinerer and Hornik 2023) was used for text preprocessing. The model employed in this study operates as a bag-of-words, where each document consists of sequences of individual words. Therefore, our preprocessing began with tokenization, which splits sentences into words, also known as unigrams (Syed et al. 2018). Next, all text was converted to lowercase, and punctuation, digits, and irrelevant characters were removed. Stopwords (e.g., 'the', 'that', 'this'), words that do not add meaningful content, and extra spaces were eliminated. The remaining words were stemmed (reduced to their root form) and tested for bigrams and trigrams. Bigrams and trigrams are pairs or groups of words that may lose their semantic meaning when analysed separately (Luiz et al. 2019). For example, the bigram 'fish population'; if you only look at 'fish', you might think of a single aquatic animal. Or, if you look at 'population', you might think of a group of living organisms (humans or other animals). Nevertheless, when combined as 'fish population', the phrase refers to a group of fish in a particular habitat. Using the *ngram* package (Schmidt and Heckendorf 2023), we automatically identified common word combinations. Visually, we inspected and grouped *n*-grams by connecting words with underscores (e.g., 'fish population' became 'fish_population' or 'small scale fisheries' became 'small_scale_fisheries'). To clean the data, we removed some custom words (e.g., 'able', 'achieve', 'across', 'additionally', 'aim') that are not stopwords but also do not contribute meaningful content, as well as number words. We removed rare and extremely frequent terms based on their total corpus frequency. Rare terms were defined as those with a total frequency ≤ 10 across the entire corpus, whereas very common terms were defined as those with a total frequency ≥ 1253. These thresholds were determined after inspecting the empirical frequency distribution of terms in the document–term matrix, where rows represent documents, columns represent terms, and cell values indicate the frequency of each term within a document. This filtering reduces noise from uninformative terms, enhancing topic interpretability and model stability (Silva and Ribeiro 2003; Westgate et al. 2015).

2.3 | Topic Modelling

We used the Latent Dirichlet Allocation (LDA) model to extract topics from our text collection (Figure 1). Topics are sets of words that tend to occur with a certain frequency and often appear together in a specific context. Therefore, a topic can be viewed as a probability distribution over the words in a particular vocabulary, indicating which words are most likely to appear in a text related to that topic (DiMaggio et al. 2013). LDA analyzes the words in a document and estimates the likelihood of both the visible elements (words) and the underlying structures (topics) that may be present in the text (Asmussen and Møller 2019). LDA models assume that each document contains different topics in varying proportions. For example, in our study, a document might be 60% about 'diversity patterns', 30% about 'reproduction', and 10% about 'fisheries management'.

A critical step in implementing LDA is the selection of an optimal number of topics (k) before generating outputs. We determined the optimal number of topics by calculating a coherence score for each model, selecting the k value that maximised this score as proposed by Deveaud et al. (2014). We created 30 different LDA models varying the k-parameter from 2 to 30 using the package *ldatuning* (Nikita 2020). Once the optimal number of topics was determined, we ran the LDA using the package *topicmodels* (Grün and Hornik 2011). The LDA outputs a list of terms and their associated probabilities for each topic but does not automatically assign semantic labels. To label the topics, we inspected the 30 highest-probability terms for each topic, which provided a clear and interpretable representation of their dominant semantic content. When necessary, we also examined the articles in which each topic was most prevalent to refine topic interpretation. Finally, we manually validated

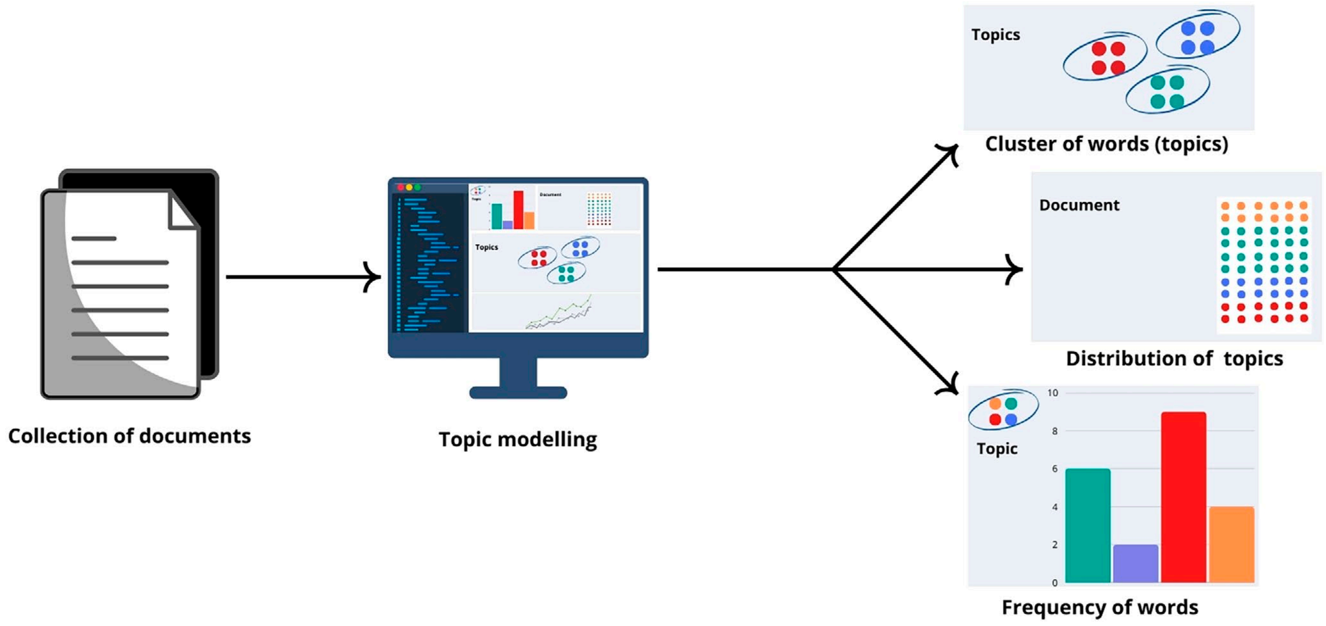

FIGURE 1 | Schematic representation of the topic modelling approach, screening the documents to find topics addressed in the literature.

the resulting topics by reviewing their word distributions and assigning descriptive labels that reflected their relevance within the study's context.

2.4 | Model Stability

To evaluate the robustness of the final topic structure, we assessed model stability using a multi-seed resampling procedure. The LDA model was re-estimated 20 times with different random seeds while keeping all hyperparameters constant. For each run, we extracted the 50 top-ranked terms for each topic, which capture the most informative and representative elements of the underlying semantic structure. Pairwise topic similarity across runs was quantified using Rank-Biased Overlap (RBO), a metric designed for comparing ranked lists and for weighting higher-ranked terms more strongly (Webber et al. 2010). Topics were optimally matched across runs using the Hungarian algorithm, and the mean RBO similarity of aligned topics was used as the stability metric, following recent recommendations for assessing the internal reproducibility of probabilistic topic models (Webber et al. 2010; Mantyla et al. 2018; Hosseiny Marani and Baumer 2023).

2.5 | Topic Distribution, Similarity, and Prevalence

To assess the similarity between topics generated by the LDA model, we calculated the Bray-Curtis distance based on their word distributions shown in the word-topic probability matrix, representing the likelihood of each word being associated with each topic. Using the resulting distance matrix, we conducted a Non-metric Multidimensional Scaling (NMDS) to obtain a two-dimensional representation of topic coordinates.

To verify topic prevalence, we identified the dominant topic in each document and counted the number of documents where each topic was dominant. Finally, we categorised these topics according to predefined thematic groups and visualised them in an NMDS plot. The bubble size reflected the number of articles in which each topic dominated (topic prevalence), and colour coding represented thematic categories in which these topics were categorised.

2.6 | Research Gap Analysis

To quantify the similarity structure among topics, we computed a dissimilarity matrix based on the topic weight matrix (W-matrix; Table S2), where rows represent documents and columns represent topic probabilities (derived from the posterior distribution of the LDA model). First, non-informative columns were removed, and the matrix was transposed so that each topic represented a variable and each article an observation. Euclidean distances were then computed between topics to quantify how differently they were distributed across the corpus. The resulting distance matrix was normalised to a 0–100 scale to facilitate comparison. Finally, these distances were visualised as a heatmap, allowing the detection of clusters of closely related topics and the identification of sparsely connected areas that represent underexplored research domains.

2.7 | Topic Popularity

To assess the popularity of topics in the literature, we analysed our dataset of 400 articles, each linked to proportions allocated to 13 topics (W-matrix). The articles were grouped into five-year intervals to assess temporal trends. However, the period from 1974 to 1989 was combined into a single group due to the limited number of publications, which prevented a few early studies from disproportionately influencing the overall analysis. We calculated the average proportion of each topic within these intervals. Topics were ranked based on their average proportions, allowing us to observe how their rankings changed across intervals. A bump plot was created to visualise these rankings, with lines illustrating each topic's progression.

2.8 | Specificity Versus Generality

To evaluate the specificity and generality of topics, we used the W-matrix generated by the LDA, where each row represents a document and each column corresponds to a topic. This matrix reflects the probability or weight of each topic across documents. We identified the dominant topic for each document by selecting the one with the highest probability.

We calculated two mean values for each topic to measure specificity and generality. Specificity (referred to as 'selected') reflects the average weight of the topic in documents where it was the primary focus, indicating how prominently the topic appears when it dominates. Generality ('unselected') shows the average weight of the topic across documents where it was present but not the main focus, indicating how often and significantly the topic appears in different contexts. Topics with high 'selected' and 'unselected' are considered versatile because they demonstrate strong relevance both as primary and secondary topics, highlighting their broad applicability across various document themes.

3 | Results and Discussion

The automated method used for topic selection revealed an optimal coherence score of 13 topics ($k=13$). The stability assessment showed that the model produced consistent thematic structures across independent runs. The mean RBO similarity between replicated topics was 0.56 (±0.05 SD), which reflects a moderate and expected level of stability for probabilistic topic models applied to heterogeneous ecological corpora. This value is comparable to those reported in previous evaluations of LDA stability; for example, Mantyla et al. (2018) have found RBO scores in a similar range (0.60) when assessing topic reproducibility under multiple random initializations. The full stability matrix and summary statistics are provided as Supporting Information (Table S3).

The LDA model identified a set of ecology-related topics, which we manually labelled as follows: *(1) Fish ecology and mercury contamination, (2) Functional extinction and ecosystem consequences, (3) Flood pulse dynamics, (4) Evolutionary and molecular ecology, (5) Biogeography, (6) Climate change impacts, (7) Community-based management, (8) Ecological impact of dams and hydropower, (9) Spatial-Ecological modelling, (10) Trophic ecology and Feeding dynamics, (11) Life history strategies, (12) Fisheries management, and (13) Fish community structure*. We grouped these topics into five broad themes, according to their primary focus: Ecosystem dynamics ($n=3$), Evolutionary ecology ($n=3$), Hydrological processes ($n=1$), Impact assessments ($n=4$), and Management and conservation ($n=2$). The full list of articles is available in the Supporting Information (Table 1, Table S4). To allow readers to directly assess semantic coherence and topic interpretability, representative high-weight articles for each topic are provided in Table S5.

We observed a prominence of particular taxa and geographic references within specific topics, likely reflecting both biological properties of Amazonian fishes and historical trajectories of research effort, rather than artefacts of the topic modelling procedure. For instance, the recurrent association of gymnotiform fishes with the topic *Evolutionary and Molecular ecology* is consistent with their long-standing role as model organisms in studies of speciation, electric communication, and genomic diversification in Neotropical freshwater systems (Albert and Crampton 2005; Smith et al. 2016; Peixoto and de Pinna 2022). Similarly, the frequent appearance of catfishes in the topic *Climate change impacts* mirrors their ecological and physiological characteristics, such as sensitivity to hydrological variability and thermal regimes. For example, studies in the lower Amazon have shown that climatic drivers like sea surface temperature can explain significant variation in giant catfish (*Brachyplatystoma* spp.) catch dynamics (Cruz et al. 2020), and that interannual flood and drought intensity influence growth rates of Amazonian catfish (*Pseudoplatystoma fasciatum*) (Pereira et al. 2024). Broader assessments indicate that tropical freshwater fishes are disproportionately threatened by future changes in temperature and flow extremes (Barbarossa et al. 2021), and Amazonian species exhibit physiological vulnerabilities to elevated water temperatures and altered oxygen regimes (Val and Wood 2022). Life history studies also underscore the reliance of migratory catfish on natural hydrological connectivity, which is susceptible to climatic and hydrological change (Hauser et al. 2018). Reflecting these ecological sensitivities, the strong association of Brazil with the topic *Ecological impact of dams and hydropower* reflects not only the concentration of large hydroelectric projects within the Brazilian Amazon, but also the predominance of environmental impact assessments and long-term monitoring programs conducted in this region (Doria et al. 2018; da Silva et al. 2020; Keppeler et al. 2022; Arantes et al. 2023).

Trophic ecology and Feeding dynamics ($n=56$), *Fisheries management* ($n=39$), and *Evolutionary and Molecular ecology* ($n=37$) stand out as the most frequent topics in our collection, and were given more weight than any other topic in more papers. These three topics, together, dominated topic weight in approximately 33% of the articles. On the other hand, *Functional extinction and ecosystem consequences* ($n=21$) and *Flood pulse dynamics* ($n=22$) were the least frequent topics, dominating weight in ~5.2% and ~5.5% of the articles, respectively (Figure 2).

The centrality of *Trophic ecology and Feeding dynamics* is expected, given that the Amazon is a highly complex and dynamic ecosystem, with unique characteristics such as seasonal flood regimes (Marengo and Espinoza 2016), high biological diversity (Guayasamin et al. 2024), and intricate food webs (Zingel et al. 2024). Understanding this trophic dynamism is particularly valuable because it provides insights into the relationships between organisms and their food sources, which in turn serve as a key indicator of ecosystem health (Ceia and Bessa 2024). Such an approach is particularly relevant in the Amazon, where the high biological diversity encompasses a vast array of life forms, ecological functions, chemical compounds, and genetic resources (Guayasamin et al. 2024). In this region, trophic interactions are strongly structured by hydrological cycles, with flood-season habitat expansion increasing food availability,

TABLE 1 | Uncovered topics from 400 research articles on Amazonian fish ecology published between 1974 and 2024, identified using Latent Dirichlet Allocation. The column 'Topic' refers to the number of the topic (1 to 13), 'Topic name' is the name assigned to each topic, 'Topic top words' is the top thirty most probable words, 'Theme' represents the main field related to each topic, and 'Topic description' is a brief conceptual definition for each topic.

Topic	Topic name	Topic words	Theme	Topic description
1	Fish ecology and Mercury contamination	Water, speci, seed, mercuri, fish_speci, concentr, risk, pollut, studi, effect, potenti, analysi, articl, ecolog, anim, fruit, dispers, germin, sensit, frugivor, human, contamin, health, report, chemic, hg_concentr, level, assess, signific, experi.	Impact assessments	Addresses the dual role of fishes as seed dispersers and as bioindicators of environmental contamination.
2	Functional extinction and ecosystem consequences	Speci, function, ecosystem, divers, tropic, habitat, biodivers, scale, region, associ, trait, ecolog, contribut, extinct, freshwat, biomass, amazon_riv, aquat, product, assemblag, landscap, loss, multipl, human, understand, rare_speci, reduc, conserv, follow, wetland.	Ecosystem dynamics	Focuses on the role of rare species in maintaining functional traits, highlighting how species loss can trigger functional extinction and affect ecosystem functioning.
3	Flood pulse dynamics	Season, river, lake, flood, abund, floodplain, period, water, hydrolog, high, chang, floodplain_lak, import, higher, lower, drought, pattern, show, tempor, year, analyz, intens, tributari, dri, environ, cycl, densiti, flood_puls, low_wat, dry_season.	Hydrological processes	Focuses on the influence of seasonal and hydrological cycles, including flood pulses and droughts, on the structure, abundance, and dynamics of floodplain and lake ecosystems.
4	Evolutionary and Molecular ecology	Ecolog, genet, select, organ, adapt, describ, evolut, morpholog, popul, electr, diverg, limit, environ, known, major, evolutionary, anim, natur, phylogenet, gymnotus, molecular, neotrop, form, support, studi, dna, origin, gene, gymnotiform, bodi.	Evolutionary ecology	Covers ecological speciation, adaptive divergence, and the genetic and molecular mechanisms driving evolution in Neotropical fishes, emphasising environmental heterogeneity and selection.
5	Biogeography	Speci, river, basin, region, distribut, brazil, ecolog, upper, rio, divers, pattern, analysi, river_basin, famili, new, data, geograph, record, occurr, locat, provid, south_america, cichla, occur, barrier, repres, state, orinoco, present, freshwat.	Evolutionary ecology	Examines the spatial distribution of freshwater fishes in South American river basins, emphasising species assemblage patterns, environmental gradients, and potential dispersal barriers.
6	Climate change impacts	Amazonian, migrat, amazon_basin, catfish, behaviour, speci, ecolog, spawn, increas, larva, migratori, level, provid, temperatur, degre, event, juvenil, predat, hypoxia, siluriform, observ, otolith, physiolog, associ, climate_chang, rate, toler, import, activ, captur.	Impact assessments	Examines the physiological and behavioural responses of fishes to thermal and hypoxic stress, highlighting their tolerance limits and potential vulnerability to environmental changes.

(Continues)

TABLE 1 | (Continued)

Topic	Topic name	Topic words	Theme	Topic description
7	Community-based management	Manag, communiti, conserv, amazon, resourc, sustain, urban, develop, approach, monitor, arapaima, assess, import, system, common, ecosystem, network, includ, depend, social, natural_resourc, protected_area, studi, peopl, protect, rural, survey, amazonia, identifi, livelihood.	Management and conservation	Addresses community involvement in the sustainable management and conservation of natural resources, emphasising social-ecological systems, local livelihoods, and protection of species and ecosystems.
8	Ecological impact of dams and hydropower	Indic, area, impact, dam, effect, assess, studi, environment, ecolog, reservoir, brazil, river, downstream, chang, zone, integr, increas, estuari, consid, fish_fauna, decreas, develop, index, fish_commun, construct, compar, environmental_impact, caus, environ, upstream.	Impact assessments	Examines the ecological consequences of dams and hydropower on freshwater ecosystems, highlighting effects on fish communities, riverine habitats, downstream and upstream environmental changes.
9	Spatial-Ecological modelling	Model, differ, influenc, factor, environment, structur, variabl, spatial, variat, communiti, effect, dynam, process, analysi, connect, dispers, import, role, explain, respons, relationship, amazon, distanc, relat, present, climat, test, time, distribut, interact.	Impact assessments	Investigates the influence of spatial and environmental factors on floodplain fish communities, emphasising hydrological connectivity, dispersal processes, and community structure dynamics.
10	Trophic ecology and Feeding dynamics	Diet, food, feed, differ, trophic, prey, import, sourc, avail, consum, isotop, food_web, nich, item, aquat, studi, insect, stomach_cont, stable_isotop, index, energi, invertebr, food_item, trophic_ecolog, adult, feeding_ecolog, relat, stomach, vari, brazil.	Ecosystem dynamics	Examines the trophic ecology of freshwater fishes, focusing on diet composition, prey consumption, food web interactions, and feeding dynamics using stomach content and stable isotope analyses.
11	Life history strategies	Popul, individu, reproduct, size, biolog, studi, femal, relat, condit, growth, male, amazon, rang, sexual, life_histori, relationship, matur, number, system, natur, variat, group, year, compar, mean, speci, estim, age, behaviour, asexu.	Evolutionary ecology	Focuses on the life history of fishes, emphasising growth, reproduction, gonadal maturity, and individual and population-level variability to understand reproductive strategies and population dynamics.
12	Fisheries management	Fisheri, fisher, local, river, data, inform, catch, knowledg, fishermen, brazilian_amazon, manag, commerci, lek, studi, ecological_knowledg, small_scal, interview, research, stock, reserv, activ, indic, use, fishery_manag, main, econom, exploit, land, year, yield.	Management and conservation	Addresses the management and sustainability of fisheries, integrating local knowledge, scientific data, and community participation to assess stock, catch, and resource use.
13	Fish community structure	Stream, sampl, forest, habitat, fish_assemblag, site, fish_speci, local, collect, type, species_rich, rich, small, high, show, analys, composit, riparian, studi, deforest, amazonia, chang, domin, amazonian, aquat, cover, estim, ichthyofauna, assemblag, taxa	Ecosystem dynamics	Examines the structure and diversity of fish communities in streams, highlighting species composition, richness, and the influence of forested and riparian habitats on aquatic assemblages.

Note: Each topic lists the 30 most common words with the highest probability of appearing together.

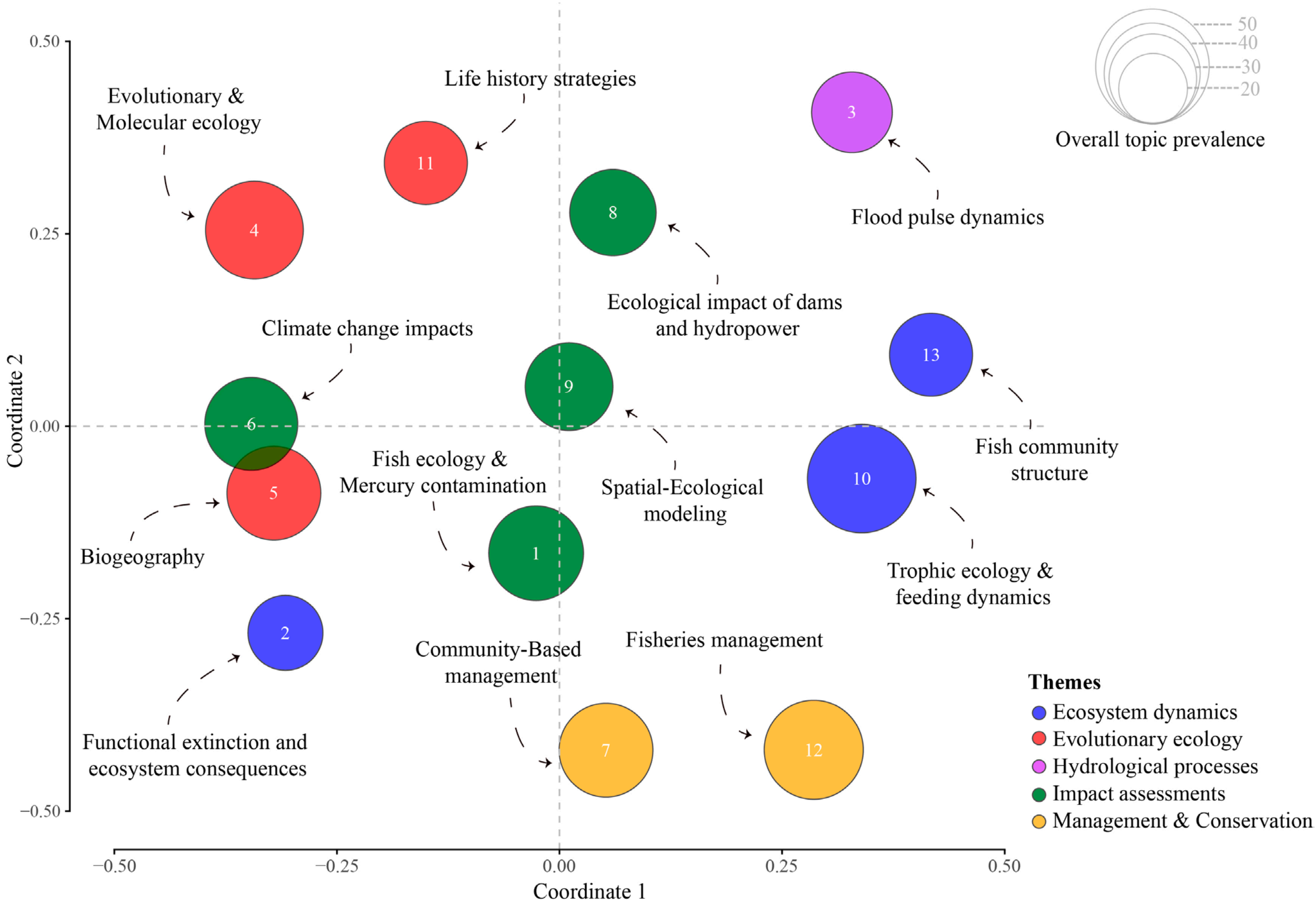

FIGURE 2 | Two-dimensional representation of the relationships between topics identified in the LDA analysis (via non-metric multidimensional scaling), highlighting the similarity in word distributions. Distances between bubbles represent semantic dissimilarity in word distributions among topics. Bubble size indicates the number of articles associated with each topic, reflecting their relative relevance in the collection, and colours represent the thematic categories assigned to each topic.

enhancing feeding and early life-stage survival, and enabling energy storage that sustains fish populations during the dry season (Röpke et al. 2017). Therefore, studies on feeding behaviour, diet composition, and resource partitioning are central to understanding species coexistence, community assembly, and functional differentiation across spatial and temporal scales. However, this is particularly concerning, since the topic *Floodplain pulse dynamics* emerged as the second least represented within our dataset, indicating that research has yet to devote sufficient attention to this key ecological driver, despite its central role in shaping fish communities.

Fisheries management, the second most prominent topic in our dataset, reflects the importance of fisheries not only as a research area but also as a daily reality in the Amazon, where fish are a vital source of protein and income for local communities (Junk 1984; Begossi et al. 2018). Its high frequency reflects sustained scientific engagement with stock assessment, exploitation impacts, and governance challenges in highly diverse freshwater systems, highlighting the tight coupling between ecological dynamics and human well-being. The prominence of this topic is further reinforced by recent evidence indicating that fishing in parts of the Amazon is currently unsustainable and would benefit from improved management strategies (de Matos et al. 2024).

Evolutionary and Molecular ecology as the third most frequent topic in our collection, possibly indicates the increasing effort to unravel the mechanisms that generate and maintain Amazonian biodiversity. In ecosystems as complex and dynamic as floodplain and upland streams, evolutionary processes operate in close interaction with ecological dynamics (Arias et al. 2018; Brunner et al. 2019). Molecular approaches have revealed fine-scale patterns of gene flow, local adaptation, and cryptic diversity that are often invisible through classical ecological surveys (Jansson et al. 2023). Yet, it is still unknown how ubiquitous eco-evolutionary dynamics are across different biological, spatial, and temporal scales, what their relative importance is at those scales, and how interactions across scales ultimately influence ecosystem stability and biodiversity (Brunner et al. 2019). These insights are crucial to understand how species respond to spatial heterogeneity, hydrological fluctuations, and biotic interactions, all of which impose strong selective pressures in Amazonian aquatic systems.

On the other end of the spectrum, *Functional extinction and ecosystem consequences* and *Flood pulse dynamics* were the least frequent topics in our dataset. Although these topics are still represented by a substantial number of studies, they have received relatively less attention than other topics. These themes remain ecologically important; functional extinction, in which species persist in low abundances but no longer perform their ecological roles (Sellman et al. 2016), can trigger cascading effects that influence community stability, ecosystem functioning, and the services upon which human populations rely (Colares, de Assis Montag, and Dunck 2022; Colares, Lobato, et al. 2022; Reader et al. 2023). Similarly, flood pulse dynamics are widely recognised as the principal driver of productivity, trophic interactions, and community structure in river–floodplain systems (Junk et al. 1989; Freitas et al. 2022). The low frequency of publications on these topics highlights a difference in research emphasis, rather than a complete lack of attention or a critical knowledge gap.

3.1 | Topic Distribution, Similarity, and Prevalence

The two-dimensional representation of topic relationships (via NMDS; Figure 2) revealed a high proximity between *Biogeography* and *Climate change impacts*. This proximity indicates that scientific discourse linking species distributions and large-scale spatial patterns is frequently associated with studies addressing environmental change and its consequences (e.g., Pecl et al. 2017; Hof et al. 2024). This suggests that research on Amazonian fish biogeography is often framed through the lens of climate-driven alterations, such as shifts in hydrological regimes (e.g., Röpke et al. 2022), temperature gradients (e.g., Campos et al. 2019; Jung et al. 2020), and habitat connectivity (e.g., Dubos et al. 2022; Caldas et al. 2023). The overlap does not imply that the two topics are identical, but rather that they share a common vocabulary and thematic space, pointing to an integrative research front where historical distribution patterns are increasingly studied in relation to ongoing and projected climate impacts (e.g., Röpke et al. 2017). This convergence emphasises both the relevance of climate change as a structuring force for biogeographic patterns (e.g., Dubos et al. 2022) and the need for approaches that disentangle historical drivers of diversity from emerging anthropogenic pressures.

The NMDS also revealed a notable proximity between the topics *Fish community structure* and *Trophic ecology and Feeding dynamics*. This association is not surprising, since community composition and trophic interactions are inherently linked because the way species assemble within habitats directly shapes and is shaped by resource use, feeding strategies, and energy flow (Winemiller et al. 2008; Röpke et al. 2017; Wootton et al. 2023). In Amazonian ecosystems, where seasonal flood pulses reorganise habitats and redistribute food resources, understanding feeding ecology becomes essential to explain patterns of species coexistence, niche partitioning, and functional differentiation (Junk et al. 1989; Sousa et al. 2022). We interpret this proximity as evidence that studies of Amazonian fish assemblages rarely examine species composition in isolation, instead placing it within the broader ecological dynamics that sustain ecosystem functioning.

3.2 | Research Gaps

The dissimilarity analysis revealed persistent gaps in how key domains of Amazonian fish ecology are integrated, with direct implications for policy design, management effectiveness, and conservation outcomes (Figure 3). The complete dissimilarity between *Fisheries management* and *Trophic ecology and Feeding dynamics* (1.00) highlights a critical disconnect between applied governance frameworks and the ecological processes that sustain fish productivity. In practical terms, this gap limits the ability of fisheries policies to incorporate information on energy flow, trophic dependencies, and food-web stability, which are essential for defining biologically realistic harvest limits and adaptive management strategies. To overcome this limitation, empirical data linking diet composition, trophic position, and productivity to exploited stocks must be integrated into fisheries assessment models.

Similarly, the strong separation between *Trophic ecology and Feeding dynamics* and *Fish ecology and Mercury contamination* (0.96) indicates that contaminant risk assessments are rarely informed by ecological context. This disconnect constrains policy development by focusing predominantly on human health thresholds while overlooking how trophic pathways, prey selection, and energy transfer modulate mercury bioaccumulation. Urgently needed data include species- and guild-specific diets, trophic positions, and habitat use, integrated with contaminant measurements. Such information would allow environmental regulations and public health guidelines to better anticipate ecological feedbacks and cumulative impacts across food webs.

Gaps between ecological and applied domains are also evident in the weak integration of *Trophic ecology and Feeding dynamics* and *Evolutionary and Molecular ecology* with *Community-based management* (dissimilarities of 0.91 and 0.81, respectively). While some degree of separation is expected due to disciplinary specialisation, ecological and evolutionary studies, such as those focusing on trophic ecology and feeding dynamics, typically prioritise quantitative analyses of species interactions, energy flow, and community assembly (e.g., Carvalho et al. 2018; Santos et al. 2019), whereas applied studies, including community-based management, often emphasise qualitative assessments, institutional frameworks, or participatory approaches (e.g., Hallwass et al. 2011; Gonçalves and dos Santos 2024). Community-based management has, in fact, received notable attention in the Amazon basin over the past decade, especially given growing evidence of its ecological benefits in maintaining fish stocks and enforcing harvest limits (Campos-Silva and Peres 2016; Campos-Silva et al. 2020). Yet, the magnitude of this gap points to a missed opportunity. Ecologically, it suggests that key insights into species coexistence, functional redundancy, and energy flow are seldom incorporated into discussions of management strategies, potentially limiting the ecological robustness of community-based initiatives. Filling this gap would require collective research agendas that explicitly link ecological processes with applied management, ensuring that conservation and fisheries governance are informed by both social and ecological dimensions.

A similar gap emerges between *Fish ecology and Mercury contamination* and *Fish community structure*, with a dissimilarity value of 0.7 indicating moderate isolation. Although the toxicological literature on mercury in Amazonian fishes has grown in recent years, much of it focuses on human health risks and bioaccumulation in specific species, especially piscivores. For example, a 2023 survey of fish markets across the Brazilian Amazon found that over 21% of analysed samples exceeded World Health Organization thresholds for safe consumption, with carnivorous species showing mercury levels nearly 14 times higher than

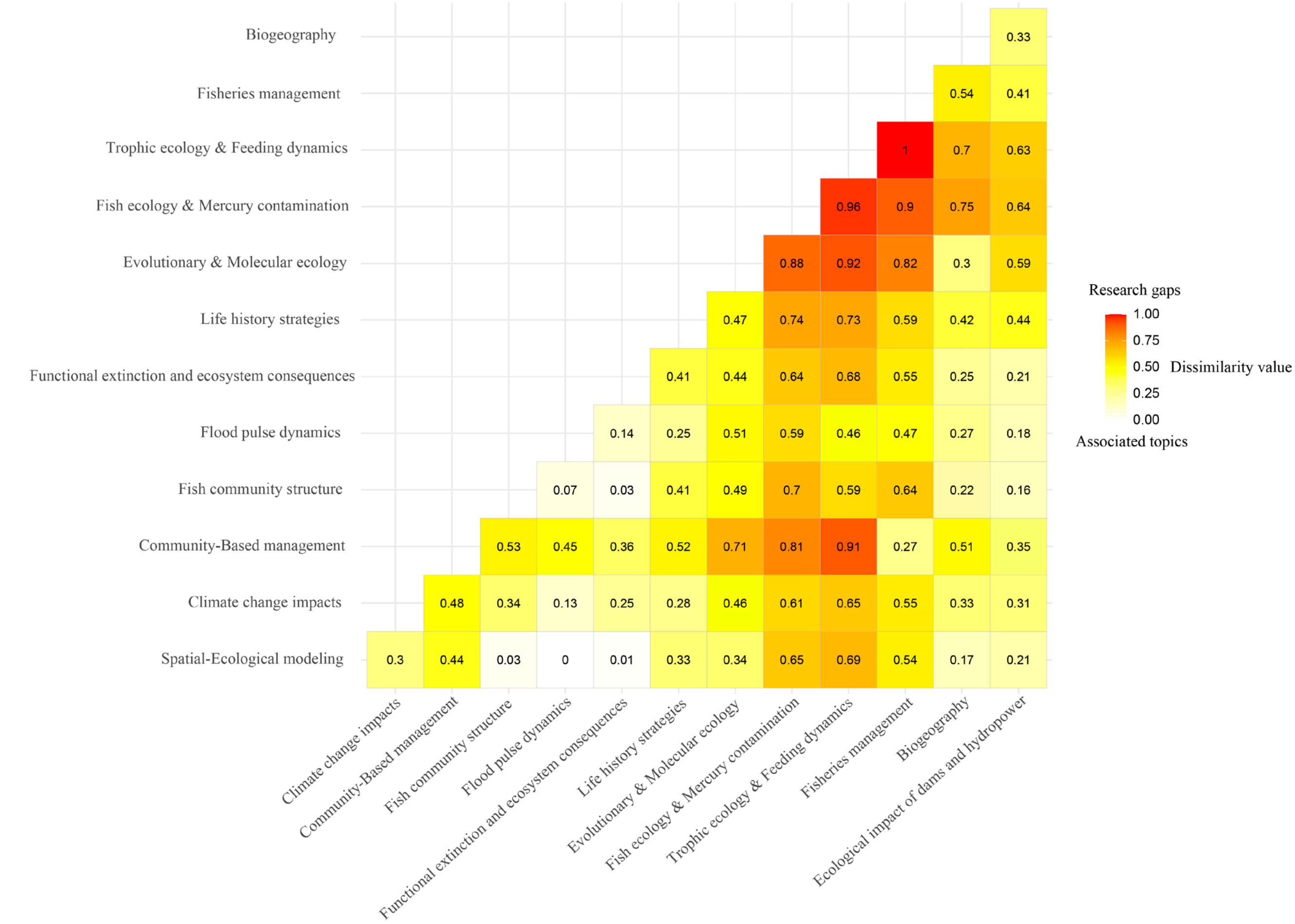

FIGURE 3 | Heatmap illustrating research gaps in the literature on Amazonian fish ecology research. The dissimilarity values, derived from the topic-per-article proportion distance matrix, are displayed within each square of the heatmap. These values indicate how rarely topics are studied together, with higher numbers representing greater research gaps. The colour gradient enhances this visualisation: darker or more intense colours correspond to higher dissimilarity values (larger gaps), while lighter or less intense colours indicate lower dissimilarity values (topics more frequently studied together).

those of non-carnivorous species (Basta et al. 2023). However, few of these studies engage directly with community-level ecological patterns. It remains unclear how mercury contamination influences species richness, trophic evenness, or functional diversity in floodplain fish communities. This gap is significant given the sublethal and behavioural effects of methylmercury exposure, which can impair reproductive success, change feeding behaviour, and ultimately reshape community dynamics (Depew et al. 2012; Driscoll et al. 2013). Without integrated ecological assessments, the broader ecological footprint of mercury likely remains underestimated.

Finally, we noted a limited integration of *Life history strategies* into applied studies. Traits such as growth rates, longevity, fecundity, and reproductive timing are key determinants of population resilience and are frequently used in sustainable fisheries models (Le Bris et al. 2015; Costa et al. 2024). Yet, our results suggest that many management strategies in the Amazon overlook these traits, potentially leading to policies that fail to account for species-specific vulnerabilities. Incorporating trait-based data into management frameworks would allow policies to better account for differential vulnerability among species, particularly under increasing fishing pressure and environmental change.

This lack of integration across domains can be partially explained through the lens of the knowledge shortfalls framework proposed by Hortal et al. (2015), which identifies seven key types of biodiversity knowledge gaps. Many of the disconnects observed in our analysis reflect overlapping Hutchinsonian shortfalls (limited understanding of species' ecological responses to environmental gradients), Raunkiæran shortfalls (limited knowledge of species' functional traits), and Eltonian shortfalls (incomplete understanding of species interactions). For example, the low number of studies linking mercury exposure or contamination to community-level attributes reveals a Hutchinsonian gap, while the underuse of trait-based approaches in community monitoring or participatory management aligns with the Raunkiæran dimension. The general disconnection between ecological structure and governance also signals Eltonian shortfalls, where we lack understanding of how human-mediated interactions (e.g., fishing pressure, regulation, cooperation) influence ecological dynamics across scales.

Altogether, these dissimilarities reveal a field where strong thematic cores like community ecology, trophic dynamics, and environmental stressors exist but often operate mostly independently. The limited co-occurrence between ecological structure and management-oriented topics suggests an opportunity for more integration and collaboration. Including metrics of diversity and trophic structure into community-based management approaches, or combining contaminant analysis with ecological responses at the community level, could greatly improve the explanatory and practical usefulness of Amazonian fish ecology. Future research would benefit from designing studies that intentionally connect these areas through interdisciplinary fieldwork, co-developed monitoring programs, and analytical frameworks that link ecological and social aspects of freshwater systems.

Importantly, the fragmentation patterns identified here are not necessarily unique to the Amazon basin. Syntheses of tropical freshwater research indicate that, in several well-documented megadiverse river systems, research has tended to concentrate on specific applied pressures, such as fisheries exploitation, hydropower development, and biodiversity loss, often advancing independently of integrative food-web, functional, and ecosystem-level approaches. As an illustrative case rather than a systematic comparison, studies from the Mekong River basin show a strong research orientation toward fisheries exploitation and flow regulation in the context of hydropower expansion (Dudgeon et al. 2006; Ziv et al. 2012; Winemiller et al. 2016). While we do not assess these systems quantitatively, this convergence in research emphasis suggests that the disconnections identified in Amazonian fish ecology may reflect broader tendencies in tropical freshwater research. In this sense, the topic-modelling framework applied here offers a transferable tool for identifying integration gaps in other megadiverse river basins.

3.3 | Topics Popularity

The temporal analysis of topic prevalence from 1974 to 2024 reveals distinct phases in Amazonian fish ecology research (Figure 4). Between 1974 and 1989, *Community-Based management* and *Flood pulse dynamics* dominated the research landscape, reflecting a strong emphasis on participatory conservation approaches and the foundational ecological importance of seasonal inundation. The formulation of the flood pulse concept by (Junk et al. 1989) was seminal in this period, providing a framework to understand the temporal and spatial variability of resource availability, habitat connectivity, and fish reproductive dynamics. Topics such as *Trophic ecology*, *Life history strategies*, *Fish community structure*, and *Fish ecology and Mercury contamination* occupied intermediate positions, indicating emerging attention to basic ecological mechanisms and anthropogenic impacts, whereas *Climate change impacts*, *Evolutionary and Molecular ecology*, *Spatial-Ecological modelling*, and *Functional extinction and ecosystems consequences* were peripheral, consistent with the early stage of these approaches.

From 1990 onward, the prominence of *Biogeography* grew substantially, peaking in the mid-1990s and mid-2000s, signalling increasing interest in macroecological patterns, species distributions, and connectivity. *Flood pulse dynamics*, while initially highly prevalent, exhibited fluctuating prominence over the decades, ranking 11th in 2020–2024, suggesting that its ecological principles have been increasingly integrated into broader frameworks rather than studied as an isolated topic. Meanwhile, *Spatial-Ecological modelling* emerged as a consistently prominent theme from 2000 to 2019, reflecting the adoption of quantitative, spatially explicit approaches for understanding habitat use, connectivity, and community structure. More recently, from approximately 2010 onward, topics emphasising *Functional extinction and ecosystem consequences*, *Fisheries management*, and *Trophic ecology and Feeding dynamics* have dominated the field, highlighting a shift toward applied, integrative, and conservation-oriented research.

Overall, the evolution of topic prevalence demonstrates a trajectory from early emphasis on participatory management and hydrological drivers, through decades of macroecological and spatially explicit approaches, toward contemporary priorities centered on functional ecology and applied management. This historical shift in research focus reflects a growing recognition of the earlier gaps we identified, where ecological insights were insufficiently

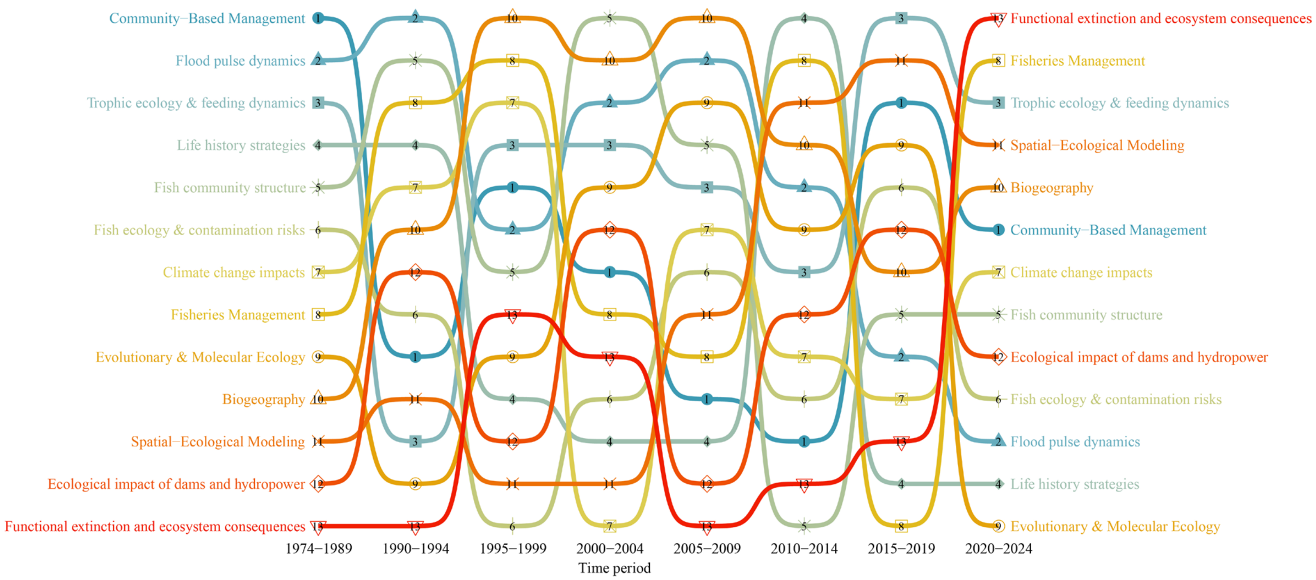

FIGURE 4 | Topic prevalence over time. Articles within each topic are grouped into five-year intervals (except for the first group), with rankings assigned from 1 (highest prevalence, shown at the top) to 13 (lowest prevalence, at the bottom) for each interval.

integrated into applied frameworks. Our findings show that recent studies have increasingly emphasised areas such as functional extinction, fisheries management, trophic ecology, and ecological modelling. We interpret this as a response to the need for a deeper understanding of species ecology, not only to design more effective conservation strategies but also to evaluate how fish communities are being reshaped by current and future environmental disturbances. For instance, do Nascimento et al. (2025) examined the combined effects of land-use change and environmental variables on the ecological health of Amazonian floodplain lakes, demonstrating the profound impacts of anthropogenic pressures on aquatic systems. Such studies exemplify how contemporary research is beginning to bridge ecological knowledge with applied challenges, yet they also reinforce the importance of further integrating long-standing ecological frameworks, such as life history strategies, flood pulse dynamics, and community-level processes, into management and policy.

3.4 | Topic Specificity Versus Generality

The specificity–generality distribution observed in our analysis uncovers key nuances in how different thematic areas shape the overall research landscape on Amazonian fish ecology (Figure 5). Topics in the upper-left corner of the plot, such as *Fish ecology and Mercury contamination*, display high specificity, reflecting their concentration in a relatively small number of studies with strong internal coherence and limited overlap with broader ecological themes. This pattern is expected, since ecotoxicological research often requires rigorous methodological protocols (e.g., chemical analyses, tissue sampling, toxicological assays) and is driven by highly localised environmental crises (Chapman 2002; Fent 2003; Crump et al. 2023). For example, mercury contamination in the Tapajós basin, largely associated with artisanal and illegal gold mining, has been one of the central focuses of ecotoxicological investigations in the Amazon (Lodenius and Malm 1998; Barbieri and Gardon 2009; Faial et al. 2015). These studies highlight serious risks to both aquatic biota and human health, but their specificity within our corpus suggests that findings remain largely restricted to case studies and have not yet been broadly incorporated into ecological or conservation frameworks. This points to an important gap, while such research generates detailed mechanistic understanding of contaminant pathways, its integration into management strategies, food security debates, and ecological modelling is still limited.

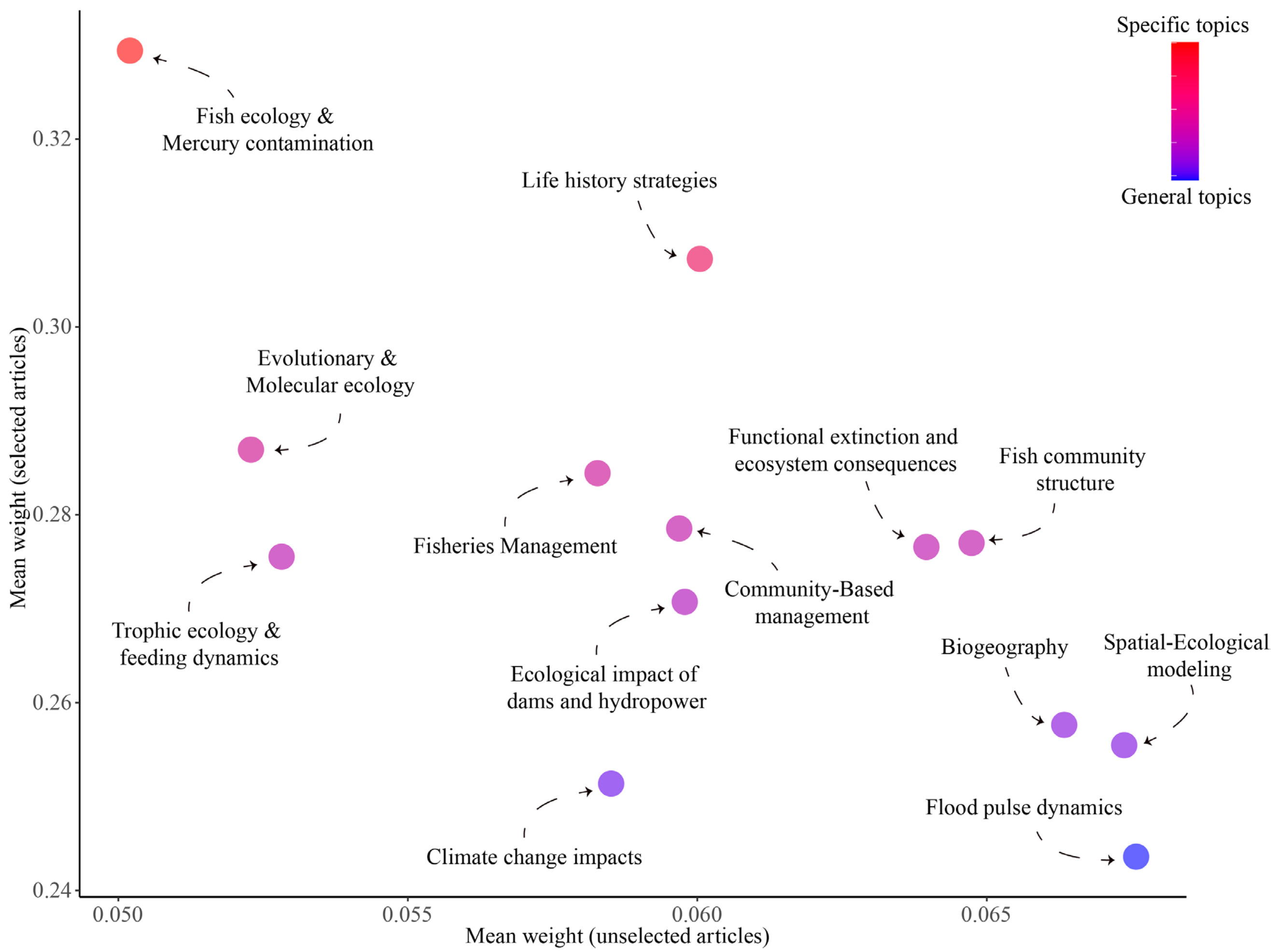

FIGURE 5 | Topic specificity/generality. Topics in the top-left corner are classified as more specific, with warmer colours indicating higher specificity (i.e., topics present mainly within a limited set of articles). Topics in the bottom-right corner are more general, represented by cooler colours, and appear across a broader range of articles in the corpus.

In contrast, topics located in the bottom-right quadrant, such as *Flood pulse dynamics*, *Biogeography*, and *Spatial-ecological modelling*, are more general and widely distributed across the dataset. Their generality reflects their status as conceptual pillars of Amazonian fish ecology. The flood pulse paradigm, for instance, is a unifying framework to explain hydrological seasonality, habitat connectivity, and life-history strategies, influencing both theoretical and applied research. Similarly, biogeographic studies provide broad-scale insights that connect Amazonian diversity patterns to macroecological and evolutionary contexts, while spatial-ecological modelling offers methodological tools adaptable to diverse research questions.

Taken together, the specificity/generality gradient not only clarifies the structure of research priorities but also underscores the dynamics by which highly focused studies can either remain isolated or evolve into central frameworks. Recognising which themes remain confined to case-specific agendas and which have achieved generality is critical for identifying research gaps and guiding future directions in Amazonian fish ecology.

3.5 | Limitations

Although Latent Dirichlet Allocation (LDA) is a classical and widely adopted method for topic modelling, we acknowledge that recent advances in contextual language models, such as embedding-based or neural topic models, offer richer semantic representations by leveraging word embeddings and contextual information (Devlin et al. 2019; Egger and Yu 2022; Kang et al. 2025). For example, comparative analyses have shown that BERTopic produces topic structures that differ meaningfully from classical methods when applied to real corpora, suggesting potential advantages in capturing nuanced themes (Egger and Yu 2022). These approaches can capture more nuanced relationships among ecological concepts. Even so, we opted to use LDA because it remains the most established, reproducible, and interpretable framework for large scientific corpora, allowing direct comparability with previous ecological reviews (e.g., Syed et al. 2018; Luiz et al. 2019). This choice represents a methodological limitation, and future studies may benefit from applying modern embedding-based models to further enhance semantic depth and topic coherence.

Consistent with this methodological choice, several limitations inherent to probabilistic, bag-of-words–based topic models should be acknowledged. While our study provides a comprehensive and data-driven synthesis of thematic trends in Amazonian fish ecology, the reliance of LDA on word co-occurrence patterns may not fully capture conceptual depth or disciplinary boundaries. Semantic similarities between topics may partly reflect shared terminology rather than true conceptual convergence. This can lead to an overestimation of thematic integration, especially in fields where descriptors are frequently reused across different ecological contexts. Additionally, our evaluation of the relative influence of each topic over time was based solely on the number of publications within that topic. This approach does not account for alternative bibliometric indicators, such as the citation impact of individual papers, which could reveal that a single highly cited article may exert greater influence than many less-cited works. While incorporating citation-based metrics would require a different analytical framework, we acknowledge this as a limitation of our current study and suggest it as a productive avenue for future research. In this context, embedding-based approaches like BERT or BERTopic could also be explored to capture both thematic richness and potential influence more accurately.

Another limitation of this study is that the text corpus was constructed exclusively from article titles, abstracts, and author keywords, rather than full-text content. Although this approach is standard in large-scale bibliometric and topic-modelling analyses and enables the synthesis of extensive and heterogeneous literature, it may overlook finer conceptual details, methodological nuances, or secondary themes that are discussed primarily in the main body of articles. Consequently, some topics may be represented in a more generalised form. Future studies could address this limitation by incorporating full-text analyses where data availability and computational constraints allow.

We also note that filtering out articles primarily focused on taxonomy and systematics, while necessary to define the scope of fish ecology, may have affected the prevalence of topics such as 'Evolutionary and Molecular ecology'. Some studies, particularly in population or conservation genetics, can bridge ecology and systematics, and their exclusion could affect the representation of topics. Future work could explore strategies to integrate these borderline studies to better capture the full spectrum of research.

4 | Conclusions

By systematically analysing literature on Amazonian fish ecology research over the last five decades, we identify clear patterns in how scientific attention has been distributed across themes, taxa, regions, and time.

Our results revealed three main gaps in the field. First, despite their recognised ecological and societal importance, socio-ecological and governance-related topics remain comparatively less represented than classical ecological themes, such as trophic ecology, community structure, and biogeography. Second, the dissimilarity analyses indicate limited integration among several major research themes, pointing to fragmentation between ecological, management, and human-dimension perspectives. Third, key ecosystem-level processes, such as flood pulse dynamics and functional extinction and ecosystem consequences, although consistently present, have received relatively lower emphasis over time, reflecting uneven thematic attention rather than complete absences in knowledge.

Together, these patterns highlight concrete priorities for future research, including stronger integration between ecological and socio-environmental approaches, greater cross-thematic synthesis, and more balanced attention to underrepresented processes that underpin the functioning of Amazonian freshwater systems. Addressing these priorities will be essential for advancing a more holistic understanding of fish ecology in the region.

Although regionally focused, the Amazon is a globally significant freshwater system, and the thematic patterns identified here offer insights into broader tendencies in freshwater biodiversity research, particularly regarding how research agendas prioritise themes and integrate ecological and social dimensions. By providing a reproducible and transparent synthesis of long-term research trajectories, this study contributes directly to global freshwater biodiversity conservation agendas and emerging international initiatives such as the Freshwater Biodiversity Framework.

Author Contributions

J.V.P.: conceptualization, data curation, formal analysis, investigation, methodology, software (lda modelling), validation, visualisation, writing – original draft preparation (lead), writing – review and editing; O.J.L.: formal analysis, methodology, supervision (supporting), validation, visualisation, software (LDA modelling), writing – review and editing; V.G.: conceptualization, methodology, supervision (lead), validation, visualisation, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Simplified flow diagram illustrating the identification, screening, and selection of studies included in the analysis. **Table S1:** Textual content of the articles used in the topic modelling (LDA). Each record was generated by concatenating the title, abstract, and author-supplied keywords (when available). **Table S2:** Dissimilarity matrix based on the topic weight matrix (W-matrix), where rows represent documents and columns correspond to topic probabilities derived from the posterior distribution of the LDA model. **Table S3:** Complete RBO-based stability matrix and corresponding summary statistics for the 20 replicated LDA models. **Table S4:** Full list of articles included in the study. **Table S5:** List of the two articles most strongly associated with each of the 13 topics, identified by the highest document–topic posterior probabilities from the LDA model.