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Global Analysis of Shallow Underwater Fish Observation Research: 70 Years of Progress, Persistent Geographic Biases and a Path Forward

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ABSTRACT

Marine ecosystems are increasingly threatened by overfishing, pollution, coastal development and climate change, underscoring the need for long-term, representative information on key fish populations and habitats to inform management and policy. Underwater fish observation (UFObs) techniques, such as Underwater Visual Census (UVC), stereo-Baited Remote Underwater Video (stereo-BRUV) and Remotely Operated Vehicles (ROVs), play a key role in sustaining long-term data collection. Despite technological advancements, gaps persist in understanding research focus, geographic distribution and methodological biases inherent in these methods. We conducted a scientometric analysis of 1443 peer-reviewed publications (1953–2023), employing natural language processing and network analysis to map the research landscape. We identified 15 knowledge clusters, including marine protected areas, apex predator conservation and reef ecosystems. Our findings reveal increasing use of BRUVS and ROVs in studies of marine protected areas and subsea infrastructure, while UVC remains prevalent in shallow coral reef research. Geographic representation

[Correction added on 9 March 2026, after first online publication: In author byline, the name Alejandro Perez Matus is replaced as 'Alejandro Pérez-Matus' and included the orcid id for this author in this version.]

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is skewed, with the field dominated by researchers based in Australia and the United States, and underrepresented in Africa and Southeast Asia. This imbalance highlights the need for more inclusive, globally coordinated monitoring and reporting. Our results underscore the urgency of standardising protocols within each observation method and developing interoperable reporting frameworks across techniques to maximise data comparability and foster international collaboration. Addressing these challenges will strengthen the field's capacity to inform global conservation strategies and support sustainable fisheries management.

1 | Introduction

Marine ecosystems have been undergoing progressive degradation for at least the past century, sparking concerns among policymakers, conservationists and scientists (Pandolfi et al. 2003; Ray and McCormick-Ray 2013; Abelson et al. 2020). In response, efforts to monitor and improve ocean biodiversity have intensified, with Underwater Fish Observation (UFObs) techniques becoming central to assessing fish populations and their habitats (Thurow et al. 2012; Mallet and Pelletier 2014; McGeady et al. 2023). As human activities such as overfishing, pollution, coastal development and climate change continue to exert pressure on marine ecosystems (Häder et al. 2020; Dulvy et al. 2021; Gissi et al. 2021; Worm and Lotze 2021), it is more critical than ever to establish representative and interoperable long-term datasets on key fish populations and their habitats to inform management and policy (Muller-Karger et al. 2018).

Historically, assessments of fish populations were restricted by the limited spatial extent of studies and available techniques, impeding the development of a global understanding of marine ecosystem health (Chatterjee 2017; Blasco et al. 2020; Ovando et al. 2022). They also generally emphasised extractive methods that can damage vulnerable populations and are counterproductive to conservation. However, technological advancements, capacity development and enhanced international collaboration have expanded the scale and scope of UFObs research (Thurow et al. 2012; Mallet and Pelletier 2014; McGeady et al. 2023). Techniques and approaches, such as the use of Baited Remote Underwater Video Systems (BRUVS) and Remotely Operated Vehicles (ROVs), now enable extensive and, critically, non-destructive data collection across diverse marine environments and depth ranges (McLean et al. 2017; Langlois et al. 2020; Jessop et al. 2022; see Table S5 for detailed descriptions of each technique). However, we have a poor understanding of the global distribution of research, priority research areas and the interoperability of collected data in the marine environment (Satterthwaite et al. 2021).

The growing body of UFObs research underscores the need for integrated, globally coordinated observation networks that can track spatiotemporal change and enable open data sharing to guide management (Muller-Karger et al. 2018). Such coordination is critical because many fish species undertake trans-boundary movements and cumulative pressures such as overfishing, habitat loss and rising temperatures act at scales that outstrip any single study site (Satterthwaite et al. 2021; Gissi et al. 2021). Global FinPrint's basin-scale reef-shark baseline (MacNeil et al. 2020), the Global Ocean Observing System's biological EOV framework (Moltmann et al. 2019), and Reef Life Survey's 50-nation volunteer protocol (Edgar et al. 2014) exemplify coordinated monitoring and highlight the remaining gaps that UFObs platforms can help bridge.

Understanding where UFObs fits within the global ocean-observation landscape is essential for pinpointing strengths, gaps and partnership opportunities. The Global Ocean Observing System's Essential Ocean Variable/Essential Biodiversity Variable (EOV/EBV) framework supplies a common yardstick for standardising observations globally. For fishes, the 'abundance and distribution' EOV identifies complementary census methods, including BRUVS, Underwater Visual Census (UVC), eDNA and acoustic telemetry, to generate globally comparable time-series (Muller-Karger et al. 2018). These harmonisation efforts dovetail with major policy drivers such as the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) and the '30 × 30' target, both of which demand high-quality, collaborative observations to inform management from reef to basin scale (Maestro et al. 2019; Ryabinin et al. 2019).

This study delivers a comprehensive, data-driven portrait of the UFObs literature, clarifying how research themes, methods and collaborations have evolved and where future gains in coverage and interoperability lie. Drawing from a comprehensive review of 1443 documents spanning 1953 to 2023, we use CorText (a computational platform for large-scale text analysis and network mapping) to conduct an epistemic mapping of the field (Breucker et al. 2016). The analysis traces the rise and shift of research topics, links observation techniques such as BRUVS, UVC and ROVs to the questions they address, and quantifies the geographic and institutional networks that drive knowledge production. Together, these results highlight key knowledge clusters, reveal leading and under-represented contributors and provide a forward-looking agenda to align UFObs science with global conservation and management needs.

2 | Methods

2.1 | Data Collection

We conducted an epistemic analysis of the UFObs research landscape using CorText (http://www.cortext.net), a computational platform specifically designed for large-scale text analysis and network mapping (Breucker et al. 2016). CorText's suite of scripts leverages techniques from information retrieval, natural language processing (NLP), scientometrics and network analysis to facilitate the handling and examination of extensive text corpora (Ziff 2013; Breucker et al. 2016; Shaffer et al. 2016).

To compile our text corpus, we performed systematic searches across Scopus, Web of Science and Google Scholar, utilising specialised queries tailored to each UFObs technique. These queries were executed across document titles, abstracts and keywords, employing logical operators, for instance by combining 'remotely operated vehicle' or 'ROVs' with 'fish' or 'fishes'. The specific UFObs techniques included in our searches were identified through preliminary scoping of the literature, expert knowledge and existing reviews of underwater observation methods (Thurow et al. 2012; Mallet and Pelletier 2014; McGeady et al. 2023).

Following data extraction, each document underwent a validation process to prepare the text for integration into CorText. Only peer-reviewed, primary research articles reporting original data were retained. We excluded grey literature, theses and review papers that did not present original UFObs data (the overall workflow for literature screening, data extraction and scientometric analysis is summarised in Figure S3). Documents that met the search criteria but failed to satisfy predefined inclusion standards were also removed.

Our inclusion criteria were strictly confined to documents that employed non-extractive, visual underwater observations as a methodology for quantitatively investigating fish. We therefore excluded extractive sampling methods (such as trawling, trapping or netting) as well as non-visual techniques such as environmental DNA (eDNA) and acoustic methods. While eDNA and acoustic techniques are rapidly evolving and valuable tools for biodiversity assessment, their methodological frameworks and data outputs differ fundamentally from the visual observation techniques that form the focus of this analysis. We also excluded studies focused solely on the physical environment. Furthermore, we limited our corpus to documents featuring data collected from coastal and nearshore environments shallower than 200 m (the full metadata for the final corpus is provided as Table S2).

2.2 | Term Extraction and Processing

We generated an initial lexicon of 2000 lexical units, encompassing both single- and multi-word terms extracted from the document abstracts. Using NLP methods available within CorText, we based term extraction on term associations and accounted for variations such as singular and plural forms, leading to the creation of individual lexical entities by their root words (Breucker et al. 2016). For example, from the sentence 'reef fish play a critical role in reef ecosystem function', we extracted terms such as 'reef fish' and 'reef ecosystem'.

We excluded terms pertaining to measurement units, geographical references, questionable expressions and species nomenclature, as well as methods for UFObs (which were treated independently). To mitigate language ambiguity, we systematically sorted and merged all synonymous terms. Following this refinement process, we retained 501 terms, which were then indexed against the text contained in the document abstracts.

In addition, we geocoded research contributions by extracting author affiliation data and mapping these to country-level identifiers. Author affiliation data were extracted from all authors listed on each publication, and for authors with multiple institutional affiliations, all listed affiliations were included in the analysis. Affiliations were geocoded to country level using CorText's automated geocoding script, which parses and normalises the institutional addresses listed in the publication metadata, classifies address components (such as city, region and country) and matches these components against reference geodatabases (OpenStreetMap, GeoNames, WhosOnFirst) to assign geographical coordinates. The 'Filtering organisation names' method was applied to prioritise less ambiguous geographical information (such as city and country names) and reduce false matches from multi-located institution names. In cases where addresses remained ambiguous or incomplete after automated processing, affiliations were manually verified using institutional websites and databases. It is important to note that these geocoded locations reflect where the researchers were based, not necessarily where the fieldwork occurred. As such, our geographic analysis represents the global distribution of research investment and institutional involvement, rather than the spatial footprint of the UFObs studies themselves.

2.3 | Co-Word Network Construction and Analysis

We constructed and examined networks based on the most frequently encountered entities in UFObs research (Table S1). This approach allowed us to identify key nodes and highlight their significance within the field. Networks were constructed using entities, such as terms and author affiliations, with links established based on a proximity measure that considered the frequency of their co-occurrence. This method revealed the interconnectedness of entities and their collective impact on the research landscape.

Our analysis employed two main types of proximity measures: direct and indirect. Direct measures, such as raw counts and chi-square statistics, focus on the co-occurrences between entities without altering their original statistical properties-for instance, the raw metric captures the total number of co-occurrences between two entities (Breucker et al. 2016; Shaffer et al. 2016). Indirect measures, like distributional metrics, consider all co-occurrences within the network when determining connections between nodes, offering a more nuanced understanding of the network structure.

We utilised raw metrics to create collaboration networks, emphasizing institutional affiliations and countries, thereby identifying which institutions frequently collaborate on UFObs research. Distributional metrics were employed to develop homogeneous networks, including co-word mapping, which helped us understand common themes and topics in the field. Chi-square metrics were used for heterogeneous networks, allowing us to explore the diversity and breadth of the research landscape.

To identify influential nodes within the network, we calculated betweenness centrality, a measure introduced by Freeman (1978), which highlights nodes that play a critical role in connecting different parts of the network (Freeman 2002).

2.4 | Clustering and Community Detection

To categorise related themes within the UFObs research to reveal dominant research areas and how they relate to each other through shared terminology and concepts, we conducted a co-word network analysis using the Louvain community detection algorithm, which is specifically designed to extract cohesive groups within large networks (Blondel et al. 2008). We also employed spatialisation techniques to optimise the arrangement of nodes on a two-dimensional plot, where proximity indicates the structural closeness of the clusters (Fruchterman and Reingold 1991).

In our visualisations, node size corresponds to term frequency, while link thickness and distance between nodes represent the frequency of term co-occurrence. To maintain clarity and readability, we implemented a filter threshold depending on network size and link quantity to retain only the most relevant connections. The resulting clusters are depicted with unique colours, and the size of the circle surrounding each cluster is proportional to the number of documents containing the terms within. It is important to note that connections within a specific cluster are stronger than those between nodes from different clusters.

We carried out a matching process, associating each document in our corpus with the identified clusters. This enabled content-based labelling and facilitated the correlation of these clusters with the UFObs techniques used and the associated research institutions. The strength of these associations was evaluated through contingency matrices, considering the number of documents linked to each variable and calculating their correlation relative to a null model that assumes the independence of each distribution (Breucker et al. 2016).

To quantify the strength of association between observation methods and research themes, we constructed a contingency matrix using chi-square statistics. The matrix cross-tabulated each UFObs technique against the top 10 most frequently occurring thematic terms identified through co-word analysis. Each cell in the matrix represents the observed frequency of co-occurrence between a specific method and term, compared against a null model of independent distribution. Chi-square values were used to determine the direction and magnitude of deviation from independence, with cell size and colour in the visualisation (see Figure 8) corresponding to frequency and statistical strength, respectively.

2.5 | Temporal Evolution Analysis

To examine how research priorities and thematic focus have shifted over time in UFObs research, we performed a temporal analysis using alluvial diagrams and CorText's Epic Epoch method. This approach allowed us to identify trends in term usage, highlighting emerging and declining research themes.

We employed an alluvial analysis, as presented by Rule et al. (2015), to track fluctuations in term frequency over time (see Figure 4), complementing our bump chart visualisation (see Figure 5), which ranks key terms based on their prevalence within each period. Alluvial diagrams were then used to illustrate evolutions of the top 100 terms. Our corpus, spanning from 1953 to 2023, was divided into ten overlapping time periods to ensure smooth transitions between research themes (Rule et al. 2015). Each period was represented by vertical bars signifying distinct clusters, effectively capturing the emergence, continuity or decline of significant concepts.

The Epic Epoch method was used to detect significant shifts in research focus by identifying key terms that rose or declined in prevalence across time periods. This method allowed us to capture long-term patterns of thematic change in UFObs research (Breucker et al. 2016). This method involved three steps: identifying the most frequently occurring entities for each time period, creating timelines to display frequency trends associated with the selected terms, and using bump graphs to visualise dynamic changes in term frequency and ranking, thereby illustrating the transformation of the research landscape.

2.6 | Limitations

This analysis focused on large-scale patterns in UFObs research, using bibliographic data from major databases (Scopus, Web of Science and Google Scholar) and network analysis techniques. While these databases provide extensive coverage of peer-reviewed literature, our approach may underrepresent non-indexed, regionally focused or non-English publications, as well as older literature published prior to widespread digital indexing. This potential bias is particularly relevant for regions where scientific outputs are published in local journals or grey literature that is less visible in international databases. Additionally, bibliometric and network analyses capture thematic and collaborative trends but do not reflect the full depth of local ecological, socio-economic or cultural contexts that shape research priorities and outputs. As such, global analyses such as this should be complemented by targeted regional studies and local perspectives to provide a more complete understanding of the field.

3 | Results

3.1 | Corpus Overview and Publication Trends

A total of 1443 documents published between 1953 and 2023 were analysed (see Figure 1). This represents the final corpus after applying our inclusion criteria. The earliest document, from 1953, employed 'underwater television' for fish observation. Annual publication numbers remained low and sporadic until the 1990s, after which a steady increase was observed. By 2018, the field reached its most productive year, with over 100 documents published. The majority of these documents (91.8%) were journal articles, with the remainder comprising book chapters, conference proceedings and editorials.

Underwater Visual Census (UVC) emerged as the most frequently employed method, appearing in 570 documents. Baited Remote Underwater Video Systems accounted for 394 documents, followed by ROVs with 179, Remote Underwater Video Systems (RUVS; that is, without bait) with 121, Diver-Operated Video (DOV) with 93, Towed Video (TOWV) with 69 and AUVs with 17. As the field has evolved, these methods have become more widely adopted, reflecting technological advancements and increased accessibility.

Geographically, research output is dominated by a few countries. Australia accounted for the highest number of author affiliations ($n = 1341$), followed by the United States ($n = 795$), France

($n = 315$), the United Kingdom ($n = 290$) and Brazil ($n = 268$). Other notable contributors included Indonesia ($n = 253$) and South Africa ($n = 142$) (see Figure 2).

3.2 | Thematic Structure: Knowledge Clusters and Term Evolution

A total of 501 unique terms were extracted from the corpus and grouped into 15 distinct knowledge clusters using co-word network analysis (see Figure 3). The co-word network analysis revealed distinct patterns in node distribution and size across knowledge clusters. The 'Marine Reserves' cluster emerged as the most terminologically diverse, containing 78 nodes. While this cluster included frequently occurring terms with some large nodes (such as fisheries, management, MPAs and conservation), the majority of its nodes were small, indicating occasional rather than frequent term usage.

This cluster also contained a high degree of semantic overlap among spatial protection terms. Phrases such as 'Marine Protected Areas', 'Marine Reserves', 'Marine Parks' and 'no-take zones' frequently co-occurred and were grouped together based on their usage in the literature. These terms were not pre-categorised or treated as equivalent but clustered naturally according to how they were used by authors. This suggests that the field does not consistently distinguish between different types of spatial protection and instead reflects a convergence of terminology that may or may not align with formal designations.

In contrast, the 'Reef Ecosystems' cluster, despite comprising only 16 nodes, contained a high proportion of frequently occurring terms. Five of these nodes, including reef fish, coral reefs, fish communities and species richness, were notably large, suggesting this theme's research focuses intensively on a few core concepts rather than employing diverse terminology as in the 'Marine Reserves' cluster.

Several clusters exhibited notable independence in their terminology networks. Beyond the small but distinct 'Pool Ecosystems' (relating to intertidal rock pools) cluster, four major clusters demonstrated minimal terminology overlap with other themes: 'Marine Reserves', 'Reef Ecosystems', 'Subsea Pipelines' and 'Offshore & Gas Platforms'. This isolation may suggest that these represent specialised research areas characterised by distinct thematic vocabularies and focal areas.

Temporal analysis of these clusters (see Figure 4) showed notable shifts in research themes over the decades. Early research (1950s to 1980s) was characterised by fragmented topics and limited connectivity among themes, with less consistency in research topics between years. From the 2000s onward, there has been a convergence of research interests, with terms like 'Marine Protected Areas' (MPAs), 'reef ecosystems' and 'sharks' becoming more consistently prominent across publications.

It is important to note that some apparent changes in term prominence over time may reflect evolving language use rather than shifts in underlying research focus. For example, increased usage of 'MPA' in later decades coincides with a decline in 'marine reserve' and 'marine park', suggesting that the rise in some terms may reflect standardisation trends or shifting terminology rather than a conceptual reorientation. The bump graph (see Figure 5) illustrates these dynamics, showing an increase in the prevalence of terms such as 'MPAs', 'reef fish' and 'sharks', alongside a decline in terms like 'behaviour' and 'predators'.

3.3 | Knowledge Clusters and Associated UFObs Techniques

Each knowledge cluster was linked to specific observation techniques (see Figure 6). Through our content-based labelling process, where each publication was manually tagged with its underwater fish observation (UFObs) technique, clear associations emerged between methods and knowledge clusters. Baited Remote Underwater Video Systems (BRUVS) were linked to the 'Marine Reserves', 'Sharks, Rays and Skates' and 'Broad Scales' clusters, reflecting their use in targeting species attracted to bait and in studies related to conservation and management. Remotely Operated Vehicles (ROVs) and Autonomous Underwater Vehicles (AUVs) were primarily associated with the 'Subsea Pipelines', 'Offshore & Gas Platforms' and 'Mesophotic Depths' clusters, consistent with their application in infrastructure monitoring and deeper-water exploration.

Underwater Visual Census (UVC) was most strongly associated with the 'Reef Ecosystems' cluster, which included frequently occurring terms related to coral reefs, reef fish, fish communities and species richness. Additional associations for UVC included the 'Marine Reserves', 'Surface Water' and 'Oceanographic Data' clusters. Terminology related to spatial protection, including marine reserves, marine parks and marine protected areas, appeared across these clusters and frequently co-occurred with terms linked to fisheries and management.

Similarly, towed underwater video (TOWV) was strongly linked to studies focused on habitats and light-related themes, consistent with its design suitability for sedimentary environments. Remote underwater video systems (RUVs) were mainly connected to studies on seagrass habitats, predatory species and herbivores. These associations highlight the adaptability of observation methods to specific research contexts and objectives, reflecting both technological capabilities and ecological priorities (see Figure 7).

3.4 | Associations Between Observation Methods, Research Themes and Temporal Trends in Method Usage

The relationship between observation methods and thematic clusters was analysed using a contingency matrix (see Figure 8), which quantified the strength and direction of associations between specific underwater fish observation (UFObs) techniques and research themes. This analysis confirmed and sharpened patterns identified above. Underwater Visual Census (UVC) and BRUVS emerged as the most thematically distinct methods,

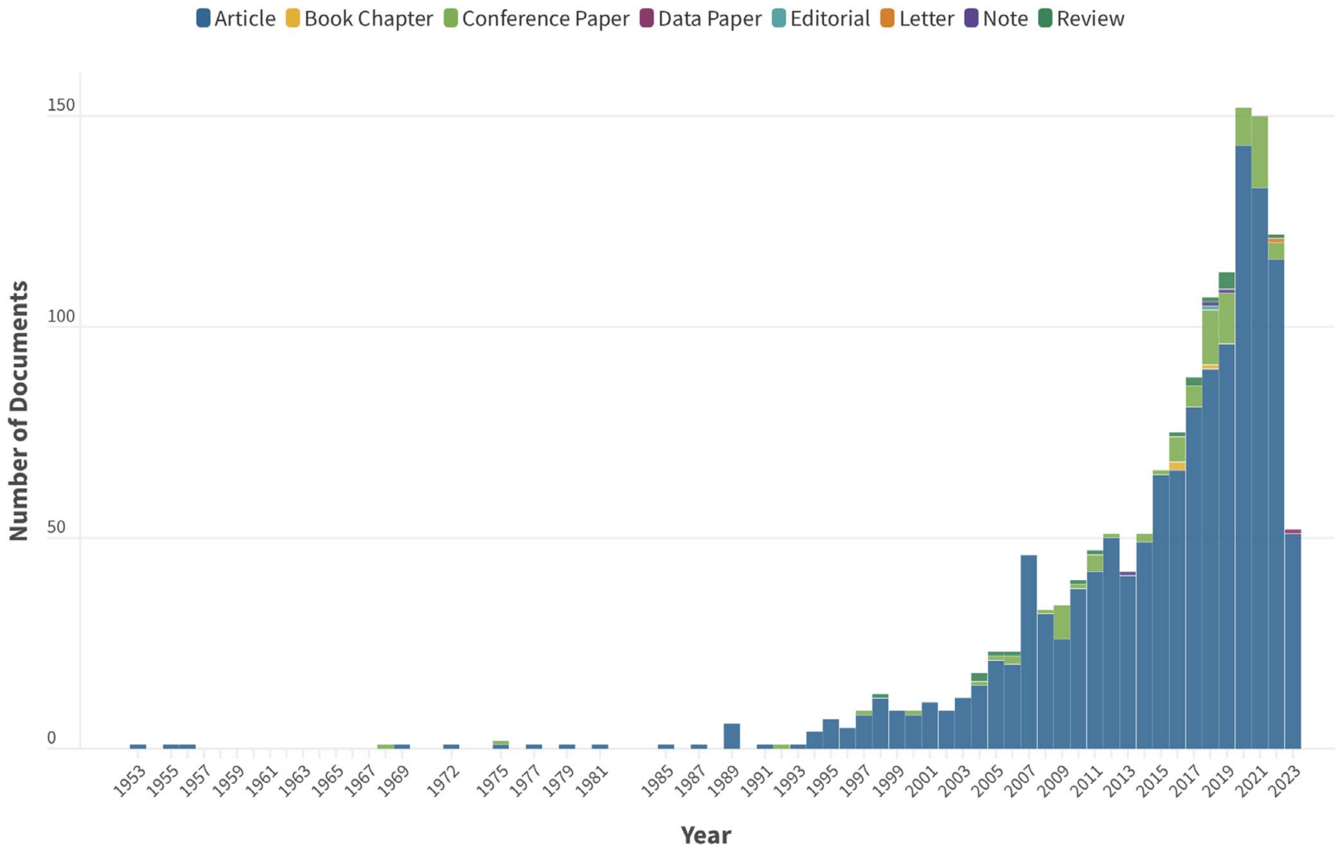

FIGURE 1 | Annual publication trends in underwater fish observation (UFObs) research from 1953 to 2023. This figure shows the number of publications per year, highlighting key growth periods over time Interactive link.

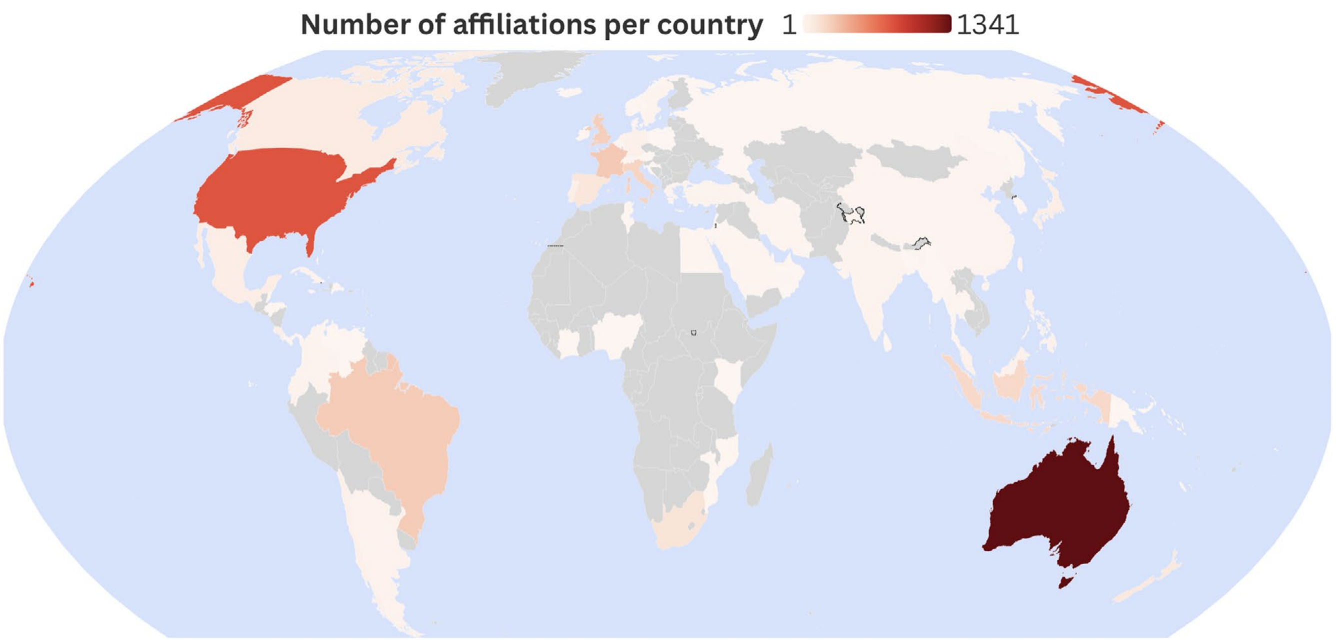

FIGURE 2 | Global distribution of research outputs in underwater fish observation (UFObs) techniques by country (1953–2023). This map presents the number of unique geocoded author affiliations by country (grey represents zero), illustrating the leading contributors to the field. These techniques include Underwater Visual Census (UVC), Baited Remote Underwater Video Systems (BRUVS), Remotely Operated Vehicles (ROVs), Remote Underwater Video Systems (RUVs), Diver-Operated Video (DOV), Towed Video (TOWV) and Autonomous Underwater Vehicles (AUVs) Interactive link.

with BRUVS strongly associated with shark-related and conservation themes, and UVC with reef fish and coral reef studies. Remote underwater video systems (RUVs) showed a positive association with reef-related themes where BRUVS were underutilised, while DOV, AUVs and ROVs exhibited broader or more specialised but weaker thematic correlations.

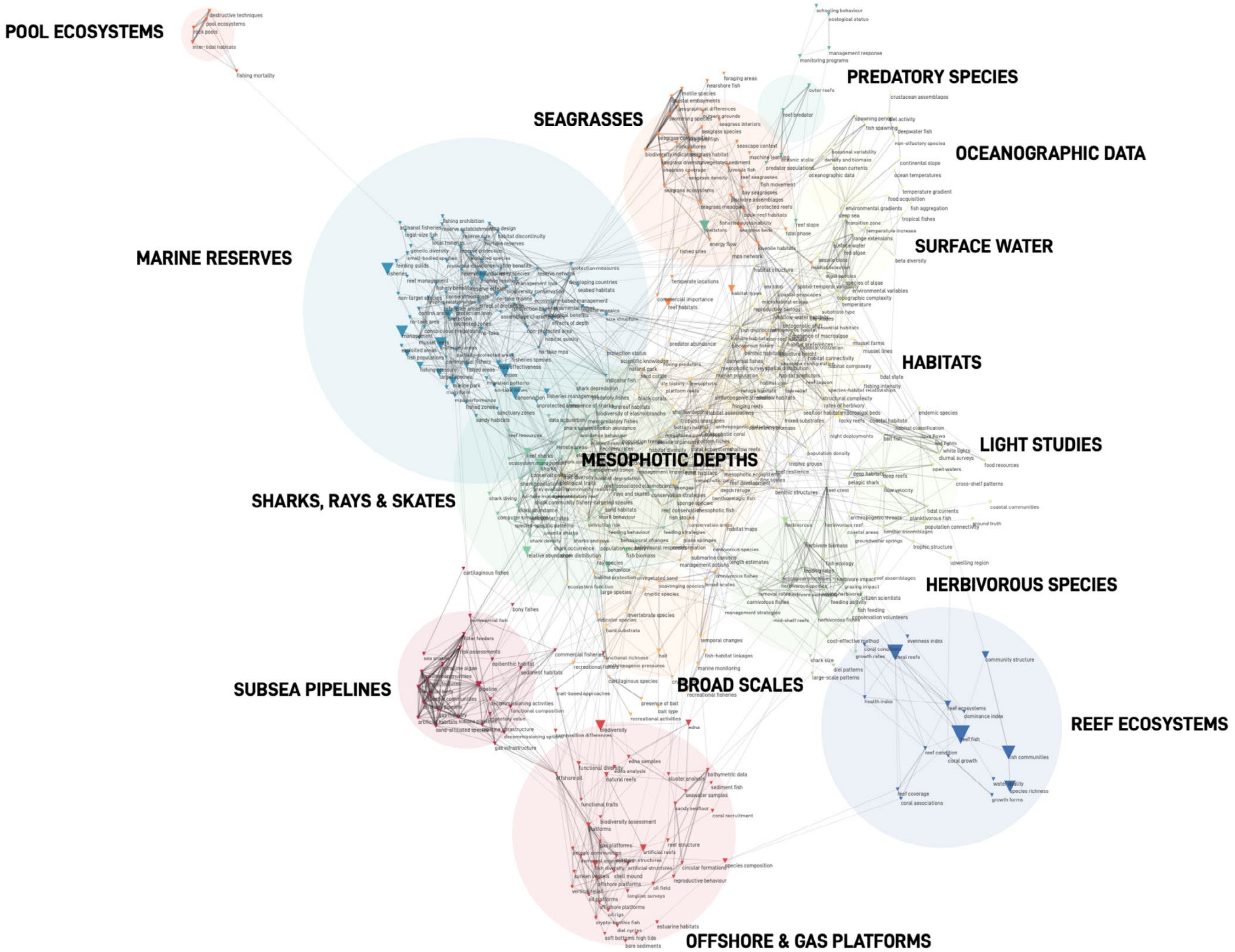

FIGURE 3 | Co-word network map illustrating the 15 knowledge clusters (shown in different colours) identified from the corpus of 1443 document abstracts. Each node represents a term, with the node size indicating term frequency. Edges (lines) between nodes reflect the term co-occurrence frequency in document abstracts, with thicker lines indicating more frequent co-occurrence. Larger clusters indicate dominant research themes in underwater fish observation research Interactive link.

The matrix also included several closely related terms such as 'Marine Protected Areas' (MPAs), 'protected areas', 'management' and 'conservation', which frequently co-occurred in association with BRUVS and UVC. These terms were treated as distinct entries in the analysis, based on how they were used in the original publications. Their close alignment highlights common thematic groupings but does not assume they are equivalent.

Temporal trends in the use of observation methods (see Figure 9) showed a steady decline in remote RUVs following their peak in the 1990s. In contrast, BRUVS and ROVs have seen a consistent rise in usage since the early 2000s.

3.5 | Geographic Contributions, Institutional Roles and Collaboration Networks

The analysis of geographic contributions and collaboration patterns revealed key insights into the global UFObs research landscape. The international collaboration network (see Figure 10) showed that the United States emerged as the leading contributor to the field, followed by Australia, the United Kingdom, France, Brazil and South Africa. Examination of international collaborations showed the strongest research partnerships between the United States and Australia (562 collaborations), followed by Australia and the United Kingdom (285), the United Kingdom and United States (241) and the United States and Brazil (204). Collaborative networks extended across Europe, Asia and South America, although regions such as Eastern Europe and Africa showed limited representation.

The geographic evolution of research affiliations from 1953 to 2023, presented in Figure 11, highlighted an increasing diversity of contributing countries and institutions over time. Recent years have seen a rise in contributions from countries such as Brazil and Indonesia, which surpassed traditional contributors like France, Italy and South Africa in publication output. This growth reflects a broader geographic engagement in UFObs research.

To examine this shift more systematically, we analysed temporal trends in contributions from developed versus developing countries (see Figure S4). Overall, developing countries

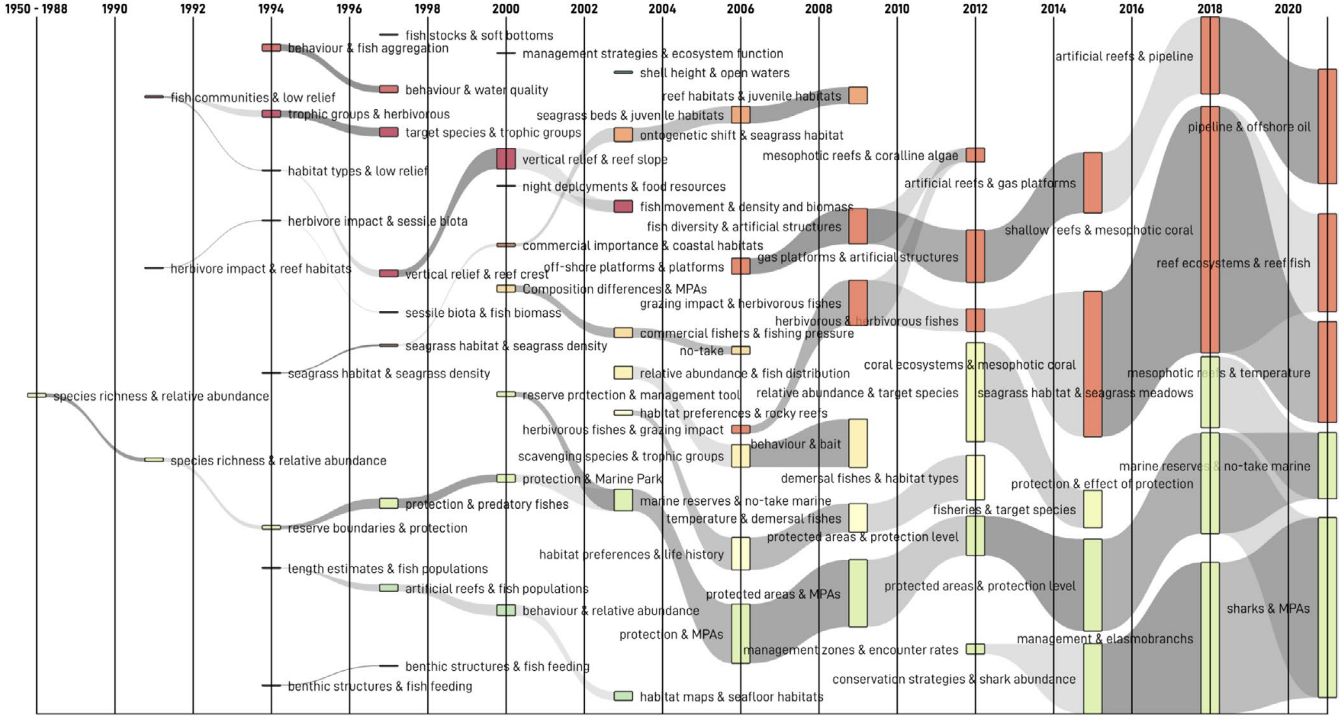

FIGURE 4 | Temporal evolution of research themes from the 1950s to 2023, illustrated as an alluvial diagram. The vertical bars represent distinct historical periods, with their width indicating the proportion of discourse during that time. The connecting flows indicate the degree of thematic continuity, with broader flows signifying themes that account for a larger proportion of discourse. Lines that remain connected over time form part of the same theme.

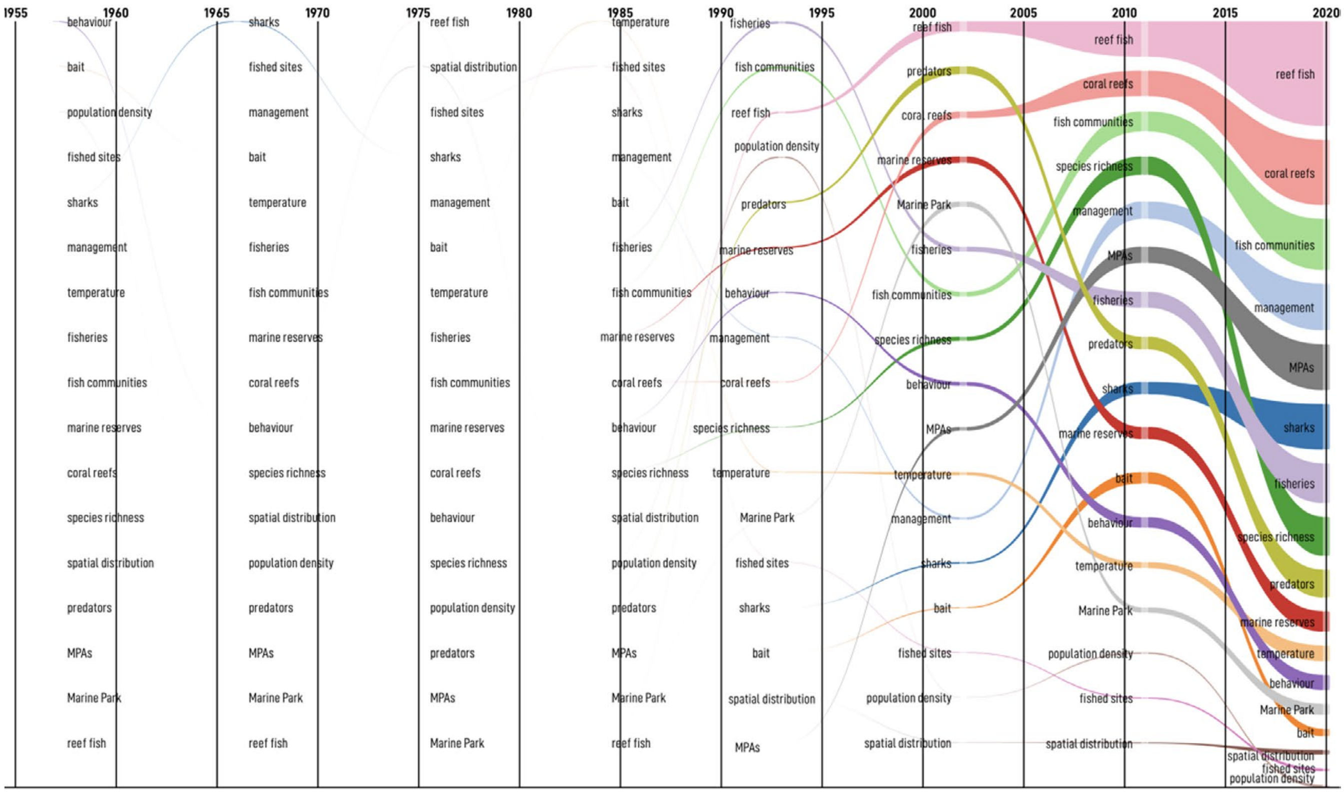

FIGURE 5 | Bump chart showing changes in the relative ranking of key research terms in underwater fish observation research from 1953 to 2023. Lines track the rank position of each term based on publication frequency, with the top line representing the most frequently used term at any given time. Only the top 15 most common terms across the entire time period are shown to enhance readability and highlight dominant research themes over time.

contributed 20.1% of publications ($n = 290$), whilst developed countries accounted for 79.9% ($n = 1153$). However, participation patterns changed dramatically over time. Before 2001, developing countries produced just 1.86% of publications on average. After 2001, this increased to 13.36%, representing an 11.5 percentage point increase ($p < 0.001$). The trend accelerated further post-2010, with developing countries averaging 17.79% of publications compared to 2.90% in earlier decades (14.9 percentage point difference, $p < 0.001$). In the most recent 5 years of the study (2018–2023), developing countries averaged 25.65% of publications, reaching a peak of 34.23% in 2023. Regression analysis confirmed a consistent growth trend of approximately 0.36 percentage points per year ($R^2 = 0.42$, $p < 0.001$), indicating that whilst developing countries remain underrepresented relative to their global population share, their participation in UFObs research is increasing steadily.

The increasingly collaborative nature of UFObs research is evidenced by temporal trends in authorship. The mean number of authors per publication increased significantly from 1.00 in the 1950s to 4.26 in the 2020s, representing a 326% increase over the 70-year period (linear regression: slope = +0.0901 authors/year, $r = 0.227$, $p < 0.001$; Figure S6). The most substantial growth occurred between the 1980s and 1990s (+78.9%), with sustained growth of approximately 30%–35% per decade since the 1990s. This trend reflects the field's evolution toward larger, multi-institutional collaborative research teams.

4 | Discussion

This study provides the first epistemic mapping of UFOb research, offering a high-level view of how the field has evolved in response to shifting scientific priorities, technological advances and conservation imperatives (Breucker et al. 2016). The widespread adoption of UFOb techniques, including UVC, BRUVS and ROVs, has contributed substantially to our understanding of the structure, functioning and resilience of reef fish populations across a range of marine ecosystems (Mallet and Pelletier 2014; Edgar et al. 2014; Stuart-Smith et al. 2013; MacNeil et al. 2020; Rolim et al. 2022; Harvey et al. 2021; Cheal et al. 2021). These tools have enabled global-scale baselines of biodiversity (Stuart-Smith et al. 2013), long-term assessments of marine protected area performance (Edgar et al. 2014), assessments of global shark conservation status (MacNeil et al. 2020) and mapping of functional traits in structurally complex reef systems (Rolim et al. 2022; Eggertsen et al. 2024).

However, the analysis also reveals notable gaps in the geographic distribution of research contributions, with researchers based in the Global South, particularly Africa, Southeast Asia and parts of South America, remaining significantly underrepresented (Ahmadia et al. 2021; Jarić et al. 2015; Veale et al. 2025). These geographic imbalances limit the field's ability to contribute comprehensively to knowledge generation, ecosystem monitoring and evidence-based policy at a global scale (Di Marco et al. 2017).

4.1 | From Foundational Exploration to Applied Conservation: Thematic and Collaborative Evolution in Underwater Fish Observation Research

Our analysis revealed 15 distinct knowledge clusters, reflecting the thematic evolution and interdisciplinary nature of UFObs research (see Figure 3). The emergence and composition of these clusters illustrate a broader shift in the field, from early ecological exploration toward research increasingly aligned with global conservation and sustainability priorities (Zyoud and Zyoud 2024). These thematic developments have been shaped by the maturation of the research community, advancements in observation technologies and the influence of funding structures and international policy frameworks (Jones et al. 2024). Early UFObs studies often focused on the sustainability of coral reef fisheries (Bohnsack 1983; Samoilys and Carlos 2000), whilst long-term monitoring of fish populations has remained a central but sometimes implicit objective, particularly in large-scale efforts such as the Global Coral Reef Monitoring Network (Jones et al. 2024). Whilst publication volume has increased substantially, our analysis suggests this growth reflects genuine field progression rather than simply repackaging existing ideas. The emergence of distinct knowledge clusters focused on previously understudied areas such as mesophotic depths, subsea infrastructure and the integration of conservation and fisheries science demonstrates substantive thematic expansion beyond the field's foundational ecology focus.

From the 1950s to the 1980s, UFObs research was characterised by fundamental ecological inquiries focused on documenting marine biodiversity and ecosystem dynamics. During this time, the field was in its infancy, with limited connectivity between researchers and a small, fragmented community generally working independently. Technological constraints further restricted the scale and scope of studies, resulting in a predominance of localised efforts. Foundational methods like UVC enabled important early insights but were often confined to specific regions or habitats, as reflected in the 'Marine Reserves' and 'Reef Ecosystems' clusters (see Figure 3). However, during the earliest phases of UFObs research (1950s–1970s), the absence of strong thematic cohesion across studies limited the field's capacity to contribute meaningfully to broader conservation and management strategies (McIntyre 1980).

By the 1980s, underwater observation research began transitioning toward applied science, supported by advancements in technology, increased funding and improved global connectivity (Schwing 2023; Robison et al. 2017; Moltmann et al. 2019). The introduction of remote techniques such as BRUVS, ROVs and AUVs enabled researchers to access previously unexplored environments and laid the foundation for addressing broader ecological questions, particularly when data were synthesised across programmes and regions. This shift coincided with a rapid expansion of Marine Protected Area (MPA) coverage globally (O'Leary et al. 2018), which likely contributed to increased demand for standardised, non-extractive monitoring tools to inform conservation policy and evaluate MPA performance. Assessing the effectiveness of MPAs, however, requires monitoring changes in ecological indicators over time,

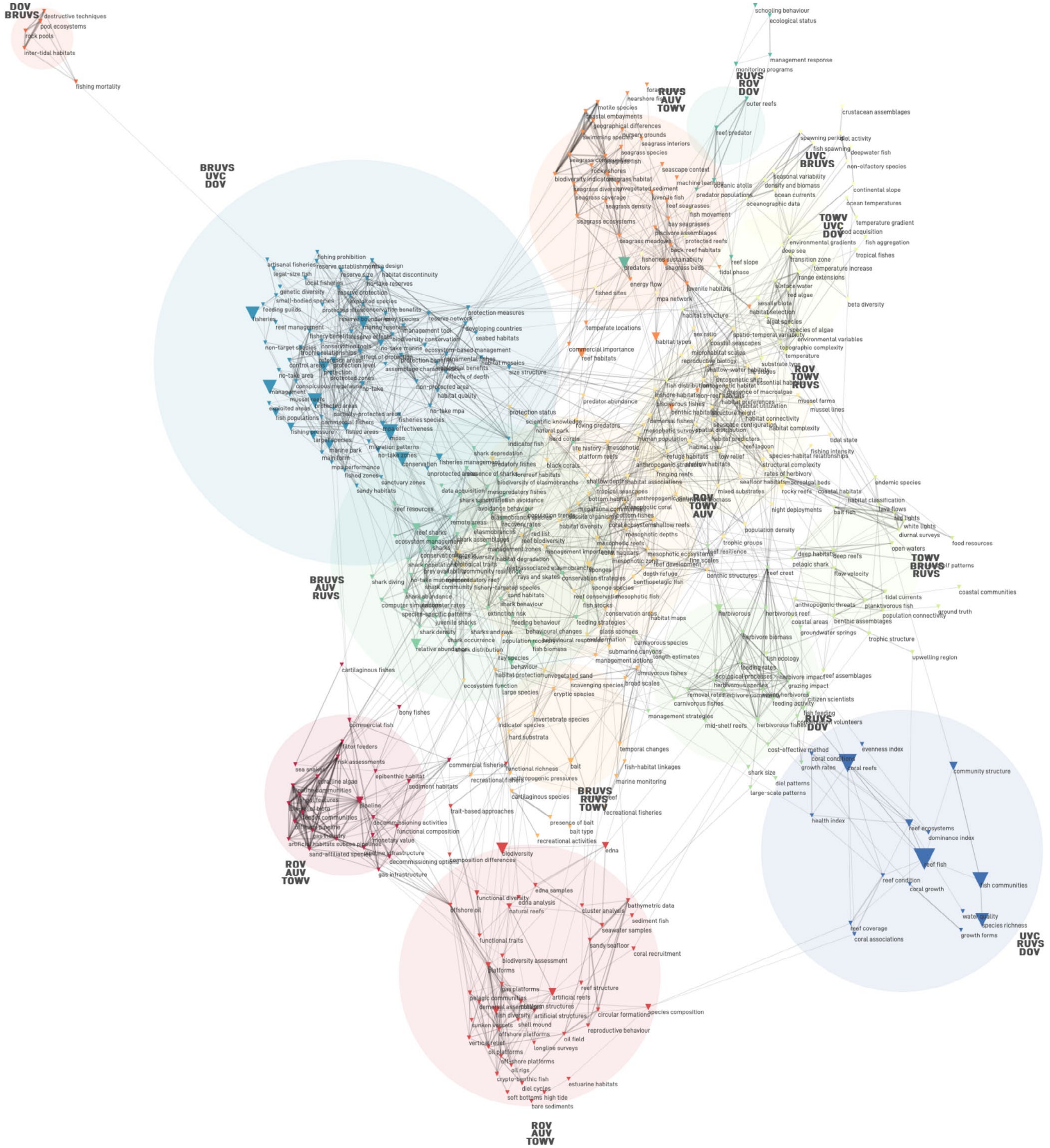

FIGURE 6 | Co-word network map illustrating the association between underwater fish observation (UFObs) techniques and the identified knowledge clusters. Nodes represent terms extracted from abstracts, with node size indicating term frequency. Edges (lines) denote co-occurrence relationships, with edge thickness representing the strength of co-occurrence within abstracts. Colours correspond to the same knowledge clusters identified in Figure 3 to maintain thematic consistency.

underscoring the importance of sustained, temporally resolved data collection. These developments are reflected in the prevalence of knowledge clusters such as 'Broad Scales' and 'Sharks, Rays and Skates' (see Figure 3), which signal a growing emphasis on biodiversity monitoring and the impacts of anthropogenic pressures (Mallet and Pelletier 2014; McGeady et al. 2023).

The thematic evolution of UFObs research also reflects shifts in global conservation priorities and the growing influence of funding structures. From the Millennium Development Goals (2000–2015) to the Aichi Biodiversity Targets (2011–2020) and the Sustainable Development Goals (2015–2030), global policy agendas have increasingly recognised the vital role of the

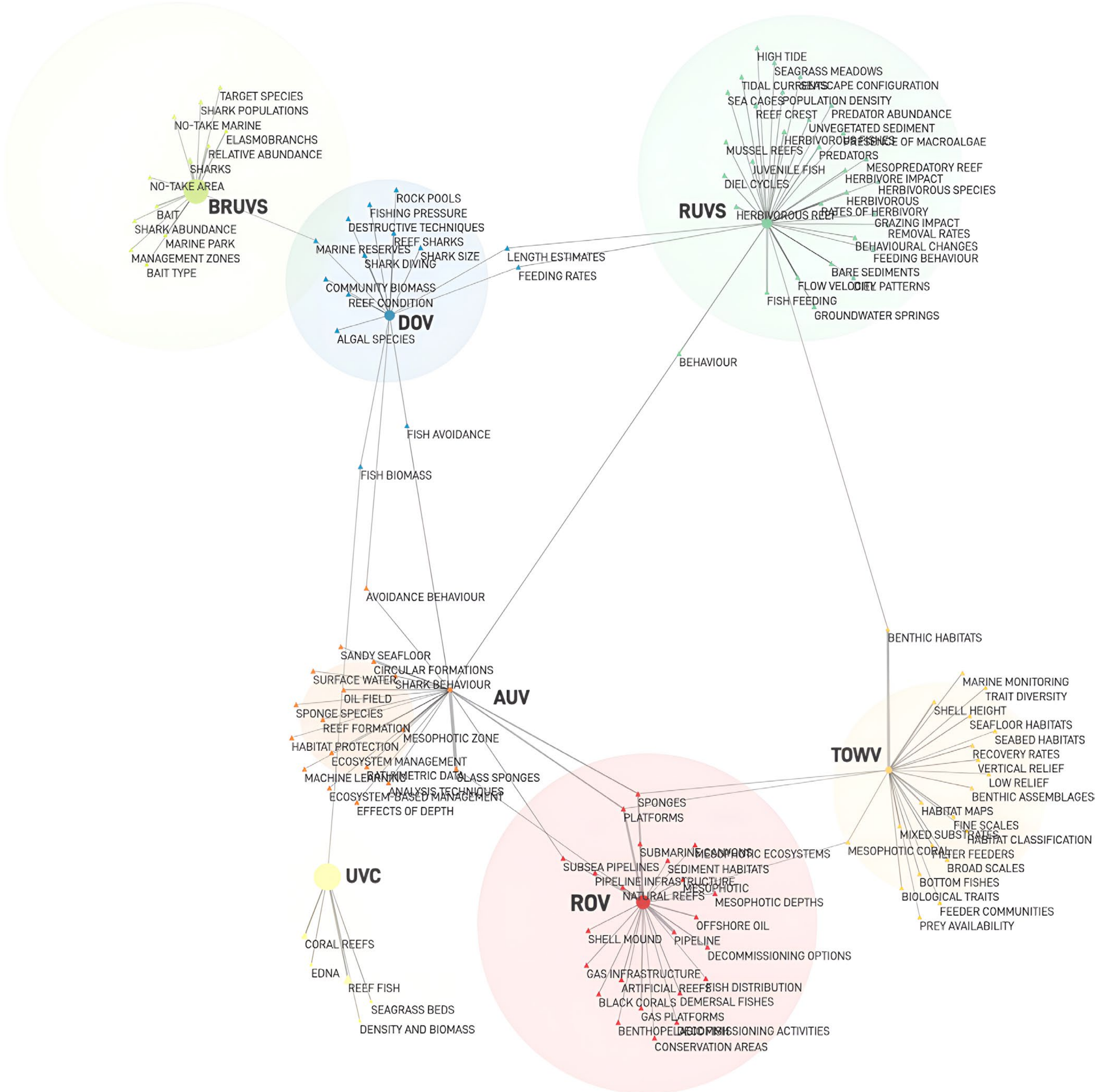

FIGURE 7 | Co-occurrence network showing the relationships between the primary observation methods and research themes. Each node represents an observation method (e.g., BRUVS, UVC, ROVs) or a research theme, with node size indicating the frequency of occurrence in the dataset. Edges (lines) between nodes indicate associations between methods and research themes. The number of nodes associated with each method reflects the breadth of thematic connections within the research landscape Interactive link.

ocean, marine reserves and coral reef ecosystems in achieving sustainable development and biodiversity conservation (Secretariat of the Convention on Biological Diversity 2010; United Nations 2015).

Philanthropic funding has played a critical role in driving research toward practical conservation outcomes, while government funding has increasingly aligned with these global initiatives (Brooks et al. 2006; Abelson et al. 2020). This alignment is evident in applied research clusters such as 'Marine Reserves' and 'Broad Scales' which focus on ecosystem management and biodiversity reporting. Similarly, the industrialisation of the seafloor, exemplified by the 'Subsea Pipelines' and 'Offshore & Gas Platforms' clusters, reflects a response to the environmental challenges associated with expanding offshore infrastructure and exploration (McLean et al. 2017, 2020; Schramm, Harvey, et al. 2020; Schramm, Marnane, et al. 2020).

Since the early 2000s, UFObs research has become increasingly characterised by a more cohesive and collaborative global community. Advances in digital communication and institutional capacity have facilitated rapid data sharing and

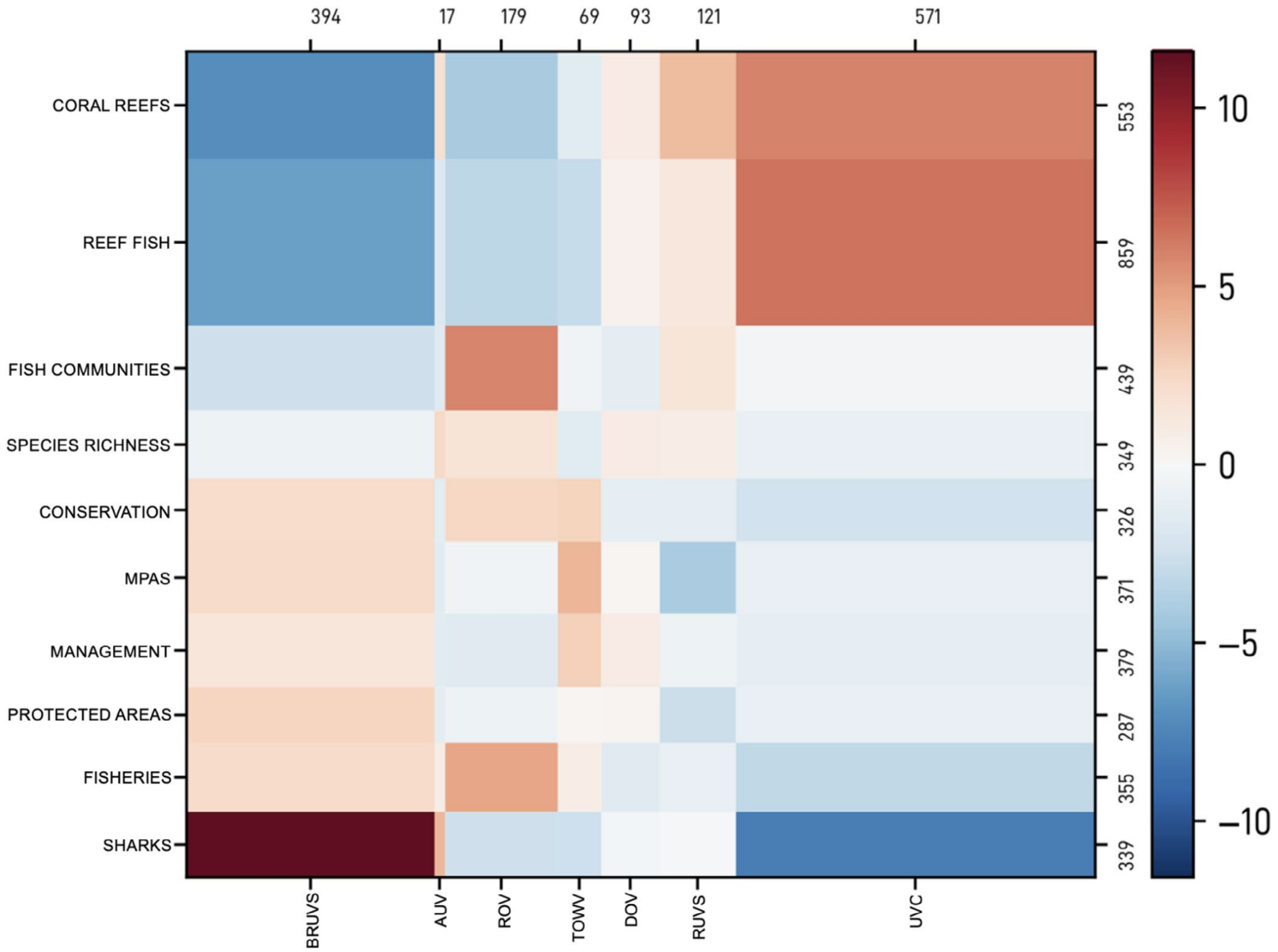

FIGURE 8 | Contingency matrix illustrating the degree of correlation, measured using chi-square statistics, between UFObs techniques (*x*-axis) and the top 10 terms (*y*-axis) extracted from bibliographic information. The values on the right *y*-axis indicate the total number of publications containing each term. Cell size represents the number of documents contributing to each correlation, while the colour scale indicates the strength and direction of the association between observation methods and thematic clusters.

multidisciplinary studies, enabling researchers to address a diverse set of ecological, conservation and resource management challenges at broader spatial and thematic scales (Lubchenco and Petes 2010; Harvey et al. 2021). The growing research community, supported by robust international networks, has contributed to a balance between applied conservation studies and fundamental ecological inquiries (Ovando et al. 2022; Muller-Karger et al. 2018). Central to both is the capacity to monitor changes in fish populations and ecosystem structure over time, which remains a key requirement for evaluating ecological dynamics and the effectiveness of management interventions (Satterthwaite et al. 2021; McGeady et al. 2023; Dulvy et al. 2021). For instance, knowledge clusters like ‘Reef Ecosystems’ and ‘Sharks, Rays and Skates’ continue to explore ecological processes while increasingly informing policy and management practices (figure 3; Cheal et al. 2021; MacNeil et al. 2020). Other clusters, such as ‘Mesophotic Depths’ and ‘Seagrasses’, address knowledge gaps in understudied habitats, reflecting the field's responsiveness to emerging challenges (Bond et al. 2020; Nalmpanti et al. 2023; Stefanoudis et al. 2023).

4.2 | Technological Advancements and Methodological Standardisation

Technological progress has greatly widened the scope of UFObs research, moving it from basic observational tools to a diverse suite of sophisticated approaches (Mallet and Pelletier 2014; McGeady et al. 2023). Early devices such as towed-underwater video (TOWV) appeared before SCUBA but were only widely adopted once digital video and compact action cameras improved usability and cost-effectiveness (Schramm, Harvey, et al. 2020; Schramm, Marnane, et al. 2020). Remotely Operated Vehicles (ROVs) likewise existed from the 1960s, yet broad uptake for ecological research followed later advances in manoeuvrability, affordability and reliability (McLean et al. 2020; Meyer et al. 2019). By contrast, SCUBA-based UVC was embraced rapidly thanks to its low capital costs, flexible sampling designs, and the ease of adapting terrestrial transect methods to the benthos (Bell et al. 1985; Harvey et al. 2001).

Traditional, diver-based UVC remains central to coral reef science because it offers species-level inventories and direct counts

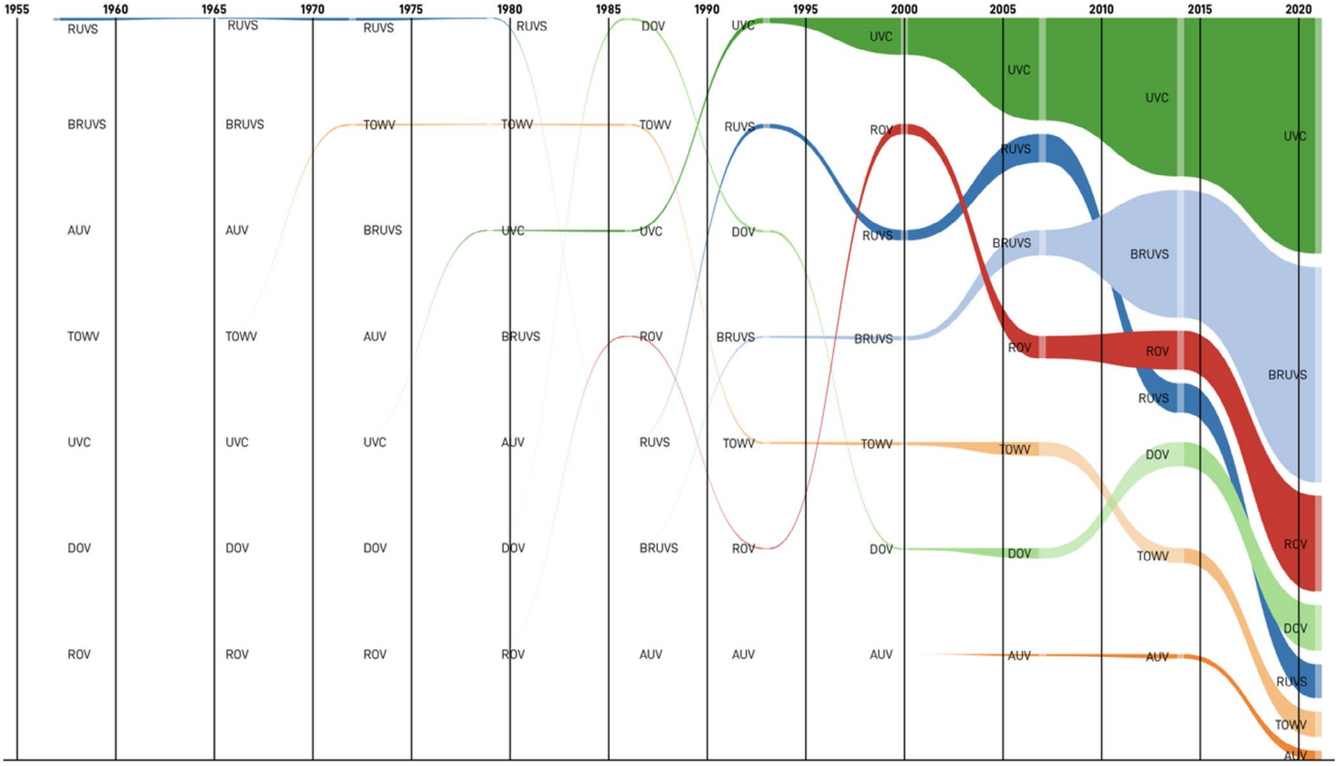

FIGURE 9 | Bump graph displaying rank changes in the use of underwater fish observation (UFOb) techniques over time, including the rise in Baited Remote Underwater Video Systems (BRUVS) and Remotely Operated Vehicles (ROVs), and the gradual decline in Remote Underwater Video Systems (RUVS) use.

in structurally complex habitats (Samoilys and Carlos 2000; Cheal et al. 2021; Jessop et al. 2022; Nalmpanti et al. 2023). Limitations including depth restrictions, diver effects, observer variability and detectability biases (MacNeil et al. 2008; Bernard et al. 2013) are balanced by advantages such as in situ habitat assessment and recording of interspecific interactions (Harvey et al. 2001; Langlois, Chabanet, et al. 2006; Langlois, Harvey, et al. 2006; Edgar et al. 2004; Samoilys 1988). Consequently, UVC's long temporal coverage exerts a legitimate pressure to retain comparable protocols in time-series monitoring (Sweatman et al. 2008).

The contingency matrix (see Figure 8) shows UVC clustering with shallow, reef-associated themes, while BRUVS align more closely with studies of predatory fishes and resource management across broader depth ranges (Langlois et al. 2020; Jessop et al. 2022). Stereo-Baited Remote Underwater Video Systems (Stereo-BRUVS) now underpin many broad-scale surveys of mobile or diver-averse species, delivering length and biomass data suitable for fisheries assessment (Harvey et al. 2021; Schramm, Harvey, et al. 2020; Schramm, Marnane, et al. 2020). Baited Remote Underwater Video Systems eliminate the need for divers, reduce logistical and regulatory hurdles, and can be deployed by small teams with limited training, which is an important consideration for regions with constrained resources (Cheal et al. 2021). However, the labour required for video annotation and the need for specialised software can limit throughput. A further critical limitation is the difficulty in determining the precise area sampled by BRUVS, as the area of attraction varies with environmental conditions, bait type and species behaviour. This uncertainty precludes the calculation of area-standardised metrics such as density or community productivity, limiting their direct application in fisheries assessment frameworks that require such measures (Harvey et al. 2021; Langlois et al. 2020).

The association between remote underwater video systems (RUVs, without bait) and studies on seagrass habitats, predatory species and herbivores reflects a distinct methodological consideration. By avoiding both bait attraction and diver presence, RUVs allow researchers to observe natural habitat associations and ecological processes such as herbivory and predation without the confounding effects these stimuli can introduce (Langlois, Chabanet, et al. 2006; Langlois, Harvey, et al. 2006).

Remote Underwater Video Systems (ROVs) and AUVs have extended UFObs into mesophotic reefs and industrial seascapes such as pipelines and offshore platforms (Bond et al. 2020; McLean et al. 2020; Meyer et al. 2019). Originally designed for industry inspection, ROVs are increasingly repurposed for ecological monitoring in deep, structurally complex settings (McLean et al. 2020). Lower-cost models now permit quantitative fish surveys (Fernandes and Brierley 2002; Monk et al. 2019), yet broader adoption is still hindered by equipment cost, technical training needs and the absence of agreed ecological survey protocols (Schramm, Harvey, et al. 2020; Schramm, Marnane, et al. 2020). Video footage collected by ROVs during industrial operations (such as oil and gas infrastructure inspections or environmental surveys) remains difficult to access and is inconsistently archived, so the true scale of ROV-derived ecological information is likely underestimated.

Comparative studies continue to refine method performance and encourage harmonisation (Jessop et al. 2022; Bouchet

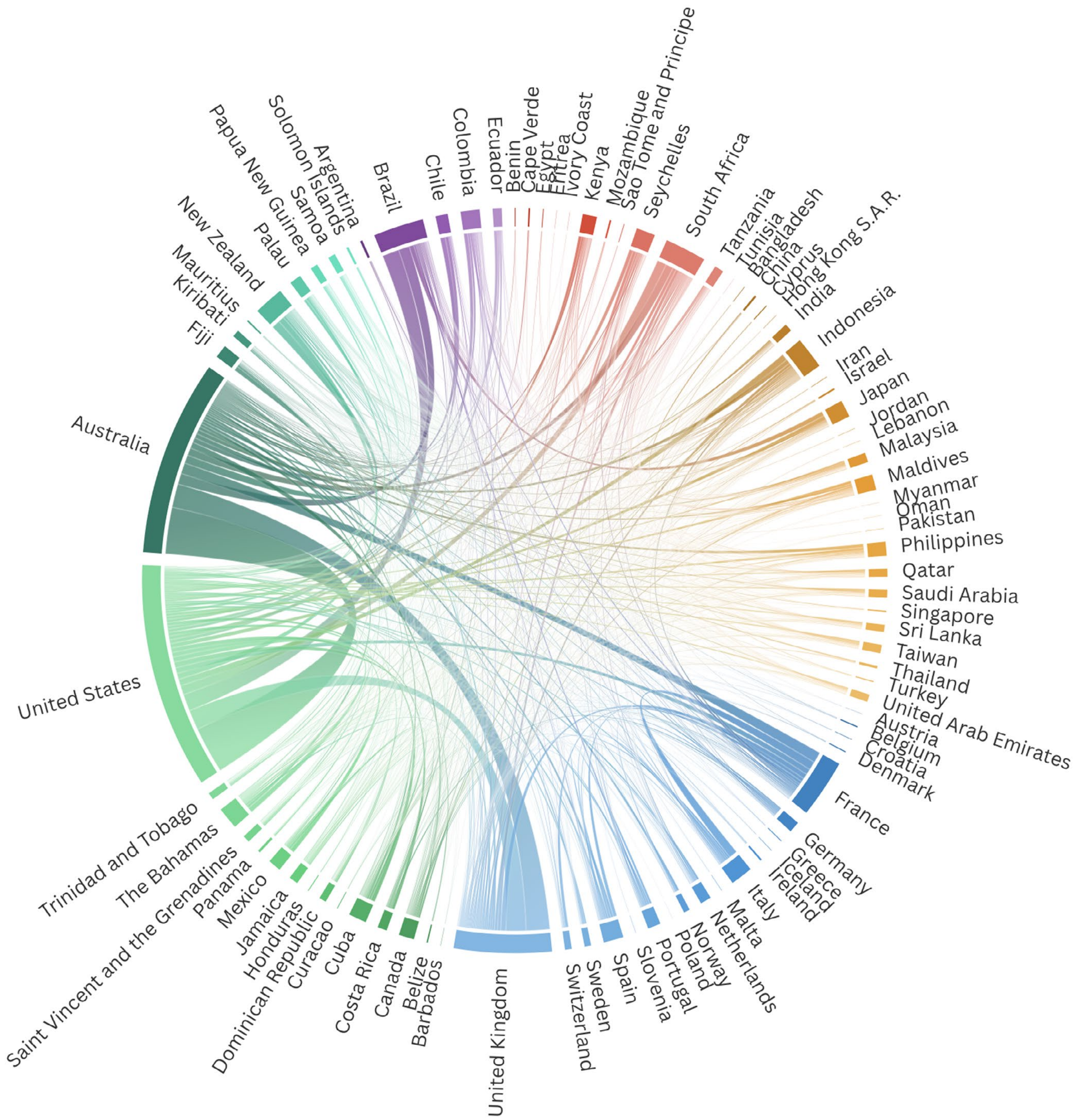

FIGURE 10 | Chord diagram illustrating the international collaboration network among top contributing countries in underwater fish observation (UFObs) research. The arc length represents the total number of collaborations per country, and the thickness of the chords reflects the frequency of collaborations between countries Interactive link.

et al. 2018; Przeslawski and Foster 2020). Inter-method calibration remains a priority. Goetze et al. (2019) showed that biomass estimates from stereo-DOV and UVC can be standardised, and similar frameworks are being explored for BRUVS-UVC comparisons. When sampling designs converge, such as transects used in both UVC and DOV, conversion factors can extend long-term datasets and improve interoperability across methods.

Growing methodological diversity also complicates cross-study syntheses when protocols differ. The lack of universally accepted standard operating procedures (SOPs) for ROV surveys, in particular, limits comparability. Recent initiatives to develop SOPs for BRUVS, DOVs and UVCs provide a strong foundation, but community consensus on ROV guidelines is still needed (Muller-Karger et al. 2018; Goetze et al. 2019; Williams et al. 2018; Edgar and Stuart-Smith 2014).

International collaborations and network initiatives remain critical levers for achieving methodological alignment. GOOS, OBIS and the Ocean Best Practice System (OBPS) foster data sharing, capacity building and the codification of best practices (Grassle and Stocks 1999; Moltmann et al. 2019; Buttigieg et al. 2019;

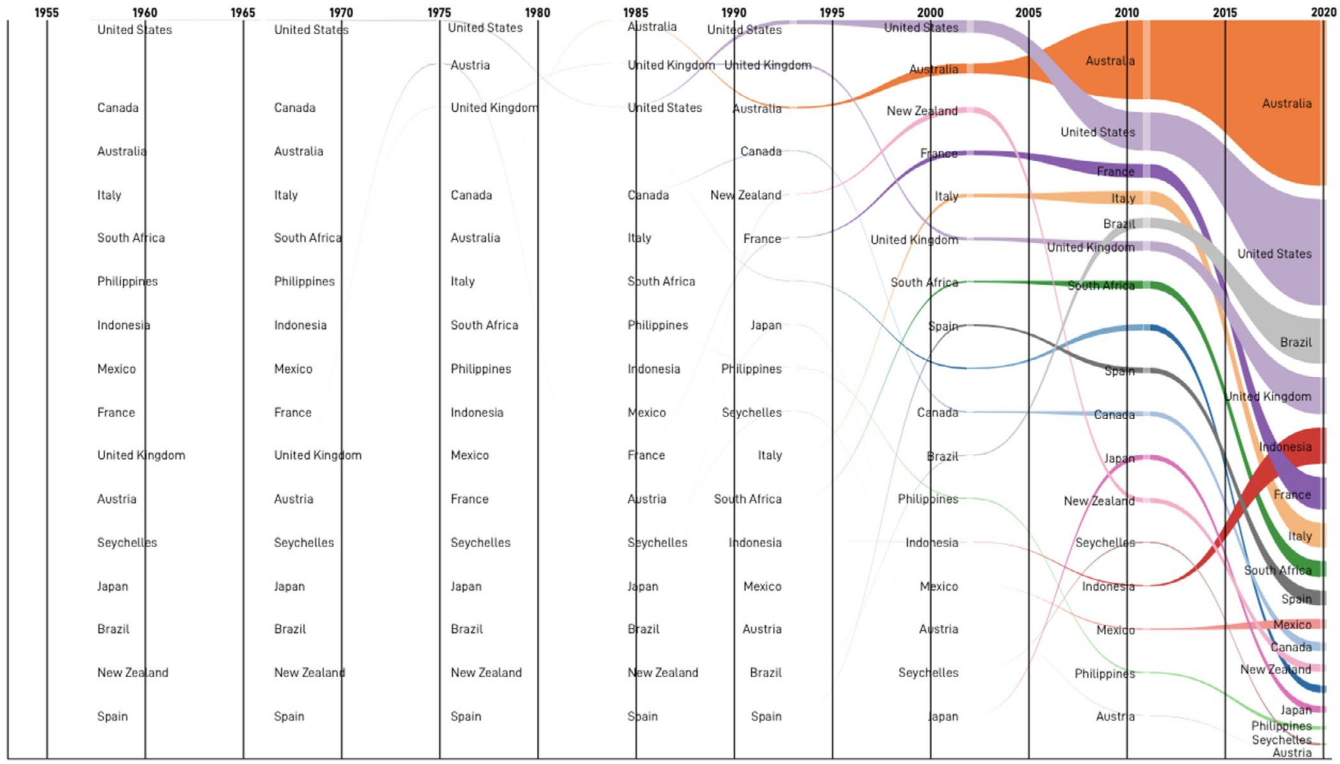

FIGURE 11 | Evolution of scientific outputs by country in underwater fish observation (UFObs) research from 1953 to 2023. This figure shows the proportional growth and ranking of the top 16 contributing countries over time.

Pearlman et al. 2019, 2021). Australia's nationally coordinated field manuals illustrate how regional efforts can feed into global frameworks, with several manuals now progressing toward endorsement through GOOS and OBPS (Przeslawski et al. 2023). Such alignment is essential for tracking temporal change, integrating diverse datasets and ensuring that UFObs outputs remain comparable and policy-relevant across scales.

4.3 | Geographic Imbalances: Underrepresentation of Critical Regions

Our analysis revealed significant geographic imbalances in research output, with Australia, the United States and the United Kingdom emerging as the most prolific contributors. These nations benefit from relatively substantial funding, well-resourced research institutions, advanced infrastructure and/or extensive coastlines with high marine biodiversity (Edgar et al. 2014). In contrast, regions such as Africa, Eastern Europe and parts of Asia are underrepresented despite their rich marine ecosystems and significant conservation challenges. Limited financial resources, inadequate institutional support and geopolitical factors often hinder the ability of these regions to contribute proportionally to global marine research efforts (Pendleton et al. 2014). The persistent underrepresentation of research from developing nations within the Global South, particularly in Africa, is not only a function of limited funding and infrastructure but also reflects historical and systemic inequalities in scientific investment and collaboration (Veale et al. 2025; Samoilys et al. 2025).

However, temporal analysis reveals encouraging trends in developing country participation. Since 2001, contributions from developing countries have increased significantly from less than 2% to over 13%, with further acceleration post-2010 reaching nearly 18% on average. Most recently (2018–2023), developing countries have averaged 25.65% of publications, peaking at 34.23% in 2023. This represents a statistically robust growth trend of approximately 0.36 percentage points per year ($R^2 = 0.42$, $p < 0.001$), suggesting that barriers to participation are gradually being addressed, particularly in countries like Brazil and Indonesia, which now rank among the top contributors globally. Despite this progress, developing countries remain significantly underrepresented relative to their global population share and the extent of marine biodiversity within their waters.

The underrepresentation of these nations has critical implications for global marine sustainability and conservation objectives. Knowledge gaps about local ecosystems reduce the effectiveness of international conservation initiatives, particularly in biodiversity hotspots where tailored, context-specific strategies are essential (Di Marco et al. 2017; Jarić et al. 2015). For example, the lack of regionally driven research can result in conservation policies that fail to account for unique ecological characteristics, cultural practices or socio-economic constraints (Turner et al. 2024). This absence also limits the ability to establish baselines or detect early signs of ecological change in underrepresented regions, compounding vulnerabilities in areas already facing significant threats such as overfishing, habitat degradation and climate change impacts (Ray 2023). Moreover, the lack of local monitoring and data can enable overexploitation by external actors, such as distant-water fishing fleets operating with limited oversight, further undermining the sustainability of local marine resources.

This imbalance can result in research outputs representing Western-centric perspectives, prioritising ecological frameworks, methodologies and management approaches that may not align with regional contexts (Frazão Santos et al. 2018; Ray 2023). These perspectives frequently overlook local ecological knowledge, socio-economic factors and the specific conservation needs of underserved regions (Turner et al. 2024). For example, a management strategy that is effective in the coral reefs of Australia might not translate to the culturally and economically distinct settings of Southeast Asia or West Africa. While the substantial research and funding invested in well-studied regions such as Australia have generated valuable knowledge that can inform global conservation practice, there is an urgent need to increase investment, capacity and research effort in underrepresented regions to ensure that solutions are locally relevant and equitable. Without such efforts, there is a risk of imposing ineffective or unsustainable approaches that fail to account for regional socio-ecological contexts (Pendleton et al. 2014; Frazão Santos et al. 2018).

To address these biases, it is essential to foster equitable collaboration and capacity-building initiatives that empower underrepresented regions to lead and contribute to research efforts. Initiatives such as Challenger 150, which is supporting global capacity-building and inclusive participation in deep-sea science, provide an encouraging model for how this can be achieved (Howell et al. 2020).

Strengthening partnerships between developed and developing nations, promoting locally driven research and long-term monitoring, and increasing access to funding and resources can help bridge these gaps (Jarić et al. 2015). Furthermore, incorporating diverse perspectives and integrating traditional ecological knowledge into scientific research can enrich global understanding and lead to more effective, inclusive conservation strategies (Di Marco et al. 2017).

4.4 | Power Dynamics in International Collaborations: Impact on Knowledge Production

Collaboration networks in underwater fish observation (UFObs) research are predominantly centred on developed nations, with key institutions in Australia and the United States emerging as central nodes. These networks facilitate knowledge exchange and resource sharing, but are often characterised by imbalances that favour established research communities whilst limiting contributions from underrepresented regions (Bourdieu 1975; Aksnes and Browman 2016; Albert and Kleinman 2011). Such patterns reinforce existing geographic biases and constrain the diversity of perspectives shaping the field, reducing its capacity to develop globally relevant conservation strategies (Pendleton et al. 2014).

Well-established international collaborations such as the Global FinPrint project and BRUVS-based monitoring efforts in Brazil have demonstrated effective models for equitable partnerships, combining standardised methods with local capacity building and leadership (MacNeil et al. 2020; Rolim et al. 2019, 2022; Reis-Filho et al. 2019; Pimentel et al. 2020). However, the concentration of research output among a few developed nations can create 'collaborative silos' where collaboration intensifies within established networks without expanding to broader connectivity (Leahey 2016; Saetnan and Kipling 2016). The dramatic increase in authorship over time (from 1.00 authors per publication in the 1950s to 4.26 in the 2020s; Figure S6) demonstrates the field's shift toward collaborative research models. Yet this growth must be examined critically alongside the geographic patterns described above (see Section 3.5).

Whilst multi-author publications have become the norm, the persistence of developed-country dominance in authorship networks suggests that increased collaboration alone does not guarantee equitable participation or knowledge co-production. Researchers from regions such as Africa or Southeast Asia may struggle to access these networks due to funding constraints, limited resources or language barriers, reducing their ability to influence the global research agenda (Jarić et al. 2012; Edgar et al. 2014; Turner et al. 2024). In some cases, this dynamic fosters extractive practices such as parachute science, where researchers from the Global North conduct studies in underrepresented regions without meaningful engagement with local scientists or institutions (de Vos and Schwartz 2022; Cambronero-Solano et al. 2023; Johri et al. 2021).

These disparities are compounded by the emphasis on publishing in high-impact journals and reliance on citation metrics, which disproportionately disadvantage researchers from developing countries where access to such journals and funding opportunities are limited (Jarić et al. 2012; Aksnes and Browman 2016; Frazão Santos et al. 2018). Limited educational infrastructure, access to specialised training and mentorship further hinder the ability of researchers from underrepresented regions to produce publications meeting international standards (Jones and Bailey 2007; Uwizeye et al. 2022; Sawyer 2004).

Addressing these disparities requires fostering inclusive collaboration networks and actively engaging researchers from underrepresented regions through capacity-building initiatives, equitable access to funding and collaborative frameworks (Grassle and Stocks 1999; Muller-Karger et al. 2018). Global networks such as GOOS and OBIS have demonstrated the potential to enhance data sharing and methodological alignment (Moltmann et al. 2019; Buttigieg et al. 2019; Muller-Karger et al. 2018), whilst initiatives such as the Ocean Best Practices System could further support standardised protocols and enable greater participation from Global South researchers (Pearlman et al. 2021). By addressing these entrenched power dynamics and fostering equitable research practices, the UFObs research community can enhance the diversity and inclusivity of its global knowledge base, ensuring that conservation strategies are informed by diverse regional perspectives and ecological contexts.

5 | Conclusion

Over the past 70 years, UFObs research has evolved from localised, foundational studies to a globally interconnected field addressing urgent conservation priorities. The integration of advanced technologies and international collaboration has expanded the scope of research, enabling a deeper understanding of fish populations and their habitats. This study highlights how these advancements have contributed to the emergence of key knowledge clusters and the evolution of thematic priorities, reflecting the field's responsiveness to pressing ecological challenges.

Despite this progress, our analysis reveals significant geographic and methodological disparities that limit the global impact of UFObs research, constraining opportunities to develop a comprehensive understanding of species distributions and movements, and to monitor and assess networks of protected and managed areas. These imbalances restrict the field's ability to contribute fully to knowledge generation, ecosystem monitoring and evidence-based policy at a global scale. Addressing these disparities requires targeted efforts to enhance representation from underrepresented regions, establish standardised methodologies for monitoring temporal change, and foster equitable collaboration. Initiatives such as the United Nations Decade of Ocean Science for Sustainable Development and the '30 × 30' target underscore the importance of high-quality, inclusive research and monitoring to inform policy and management strategies across all scales.

The next phase of UFObs research should harness emerging technologies and interdisciplinary partnerships to accelerate progress and broaden participation. Artificial intelligence and computer vision offer transformative potential for automated species identification and behaviour analysis, reducing the technical barriers that currently limit research capacity in under-resourced regions. Cross-sector collaborations between academic institutions, government agencies, NGOs and local communities can facilitate technology transfer, capacity building and co-production of knowledge that is both scientifically rigorous and locally relevant. Establishing open-access platforms for sharing standardised protocols, training resources and analytical tools will further democratise participation and ensure that UFObs research becomes truly global in both scope and contribution.

Looking ahead, the field must leverage its collective expertise to address these challenges and strengthen its global research network. By prioritizing inclusivity, methodological consistency and open access to data and outputs, UFObs research can play a pivotal role in safeguarding marine ecosystems and supporting sustainable management practices.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information provided with the manuscript. The full corpus metadata is provided as Table S2.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Table S1:** Top 100 indexed terms used in co-word analysis. **Table S2:** Complete corpus metadata. **Figure S3:** Workflow for epistemic analysis of UFObs research. **Figure S4:** Temporal trends in research contributions from developed and developing countries. **Table S5:** Descriptions, applications and key references for the seven Underwater Fish Observation (UFObs) techniques analysed in this study. **Figure S6:** Temporal trends in co-authorship patterns for underwater fish observation research publications (1953–2022).