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Using Machine Learning to Uncover Latent Research Topics in Fishery Models

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ABSTRACT

Modeling has become the most commonly used method in fisheries science, with numerous types of models and approaches available today. The large variety of models and the overwhelming amount of scientific literature published yearly can make it difficult to effectively access and use the output of fisheries modeling publications. In particular, the underlying topic of an article cannot always be detected using keyword searches. As a consequence, identifying the developments and trends within fisheries modeling research can be challenging and time-consuming. This paper utilizes a machine learning algorithm to uncover hidden topics and subtopics from peer-reviewed fisheries modeling publications and identifies temporal trends using 22,236 full-text articles extracted from 13 top-tier fisheries journals from 1990 to 2016. Two modeling topics were discovered: estimation models (a topic that contains the idea of catch, effort, and abundance estimation) and stock assessment models (a topic on the assessment of the current state of a fishery and future projections of fish stock responses and management effects). The underlying modeling subtopics show a change in the research focus of modeling publications over the last 26 years.

KEYWORDS



Topic models; latent Dirichlet allocation; fisheries science; fisheries models; research trends

1. Introduction

Global research efforts have increased significantly in recent years (Oecd, 2008), as has publication output within fisheries science (Aksnes and Browman, 2016). This growth has been partly driven by growing concerns about the state of fish stocks and the need to provide information for policy and decision makers globally. Since each fish stock is typically unique, and experimental approaches cannot be used to predict their response to fishing, it follows that the modeling and simulation of fisheries play a major role in providing management advice; these are among the most frequently used methods in fisheries science (Jarić et al., 2012). Models offer a feasible approach to the approximation of trends and processes, and they advance the understanding of fisheries and ecosystem dynamics (Angelini and Moloney, 2007) while guiding data collection and illuminating core uncertainties (Epstein, 2008). For this reason, and in contrast to common perceptions, a multitude of fisheries models is available besides standard stock assessment models, and these models take on many different shapes and forms depending on their method and purpose. Such models may include individual-based models to investigate fleet

behavior (Bastardie et al., 2014); Bayesian belief networks to better understand stakeholder viewpoints and perceptions (Haapasaari et al., 2012); or conceptual models to analyze fisheries from a socio-ecological complex adaptive system perspective (Ostrom, 2009; Partelow, 2015).

The frequent use of models and their wide range of applications, in combination with the growing global collections of scholarly literature, have led to an ever-increasing number of publications on the various types of models and approaches. As a result, scientists are suddenly faced with millions of publications, overwhelming their capacity to effectively use these collections and to keep track of new research (Larsen and von Ins, 2010). Online collections can be browsed and explored using keyword searches, through which publications can be collected manually; however, in addition to being time-consuming, the size and growth of the body of research often has the effect of limiting the possibility of identifying all the relevant literature. Another problem is that the underlying topic of an article is not readily available in most collections. Thus, the topic of an article – that is, the idea underlying the article, which may be shared with similar articles – cannot always be detected using

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keyword searches (Srivastava and Sahami, 2009). Given such challenges, an assessment of the field of fisheries models could reveal overlooked research topics, identify important changes in research directions (i.e., trends), assess the diversity of topics in publication outlets, and ultimately help in identifying new and emerging modeling topics. Furthermore, an improved understanding of fisheries modeling approaches could help researchers to more easily synthesize historical and current research developments.

The developments and trends in fisheries science and fishery models are usually assessed through reviews (e.g., Bjørndal et al., 2004; Prellezo et al., 2012) and bibliometric studies (Jarić et al., 2012; Aksnes and Browman, 2016). These types of studies have several limitations, such as taking into account only a limited number of publications (e.g., only 61 publications, Gerl et al., 2016); a limited time period (e.g., from 2000 to 2009, Jarić et al., 2012); a limited scope or very specialized focus (e.g., stock assessment methods, Cadrin and Dickey-Collas, 2015; bio-economic models, Prellezo et al., 2012; models of an ecosystem approach to fisheries, Plagányi, 2007; and models of the Celtic Sea, Minto and Lordan, 2014). Other limitations include proxies for full text such as titles (Jarić et al., 2012) and abstracts (Aksnes and Browman, 2016), and proxies for research topics such as one word per topic (Jarić et al., 2012; Aksnes and Browman, 2016). Most importantly, previous attempts to identify trends in fisheries and fisheries modeling are based on top-down approaches, in which research topics are predefined by the researcher (Debortoli et al., 2016), such as region, species, habitat, or study area. Such approaches are prone to human subjectivity; researchers may end up with different results (Urquhart, 2001), or the mapping of text features to categories may not be explicitly known (Quinn et al., 2010).

This study aims to overcome the limitations of previous approaches by applying a bottom-up approach in which research topics automatically emerge from the statistical properties of the documents. In doing so, the topics are automatically uncovered without prior human labeling, categorization, or predefined classification of publications, and they are thus not biased by researchers' top-down subjective choices. For this purpose, a probabilistic topic model algorithm called latent Dirichlet allocation (LDA) (Blei et al., 2003), which belongs to the field of unsupervised machine learning algorithms, was used to reveal research topics within the field of fisheries models that are published in peer-reviewed journals and have a strong focus on fisheries. Topic model algorithms can automatically uncover hidden or latent thematic structures (i.e., topics) from large collections of documents. The unsupervised nature of LDA allows documents to

“speak” for themselves, and topics emerge without human intervention. They have proven to be very useful in automatically identifying and interpreting scientific themes in relation to the journal's existing themes or categories (Griffiths and Steyvers, 2004).

By utilizing unsupervised machine learning, this study aims to provide comprehensive information on topical trends within fisheries modeling research for fisheries scientists and stakeholders. In particular, this study analyzes 22,236 full-text scientific publications published within the period from 1990 to 2016 in 13 top-tier fisheries journals. Thus, a unique dataset for the field of fisheries models was created, and topics in fisheries modeling and their underlying subtopics were identified to determine historical and current research interests. In addition, the species, areas, and methods occurring within the identified topics were assessed.

2. Methods

2.1. Latent Dirichlet allocation

The LDA model is a generative probabilistic topic model that represents documents (i.e., fisheries publications) as discrete distributions over K latent topics; each topic is subsequently represented as a discrete distribution over all the words (i.e., vocabulary) used. The words with high probability within the same topic are frequently co-occurring words, which can be seen as clusters or constellations of words that are often used to describe an underlying topic or theme (DiMaggio et al., 2013). In this way, LDA captures the heterogeneity of research ideas or topics within publications. The topics and their relative proportions within documents are hidden (i.e., latent) variables that LDA infers from the observable variables – that is, the words within the documents. The generative process behind LDA involves an imaginary random process, through which documents are created based on probabilistic sampling rules. The topics and their proportions are subsequently inferred from these generated documents by applying statistical inference techniques, such as variational and sampling-based algorithms (Blei and Jordan, 2006; Teh et al., 2006; Hoffman et al., 2010; Wang et al., 2011). LDA extends other popular topic model algorithms such as Latent Semantic Indexing (LSI) (Deerwester et al., 1990) and probabilistic Latent Semantic Indexing (pLSI) (Hofmann, 1999) while also overcoming their limitations. An explanation of LDA's generative process can be found in Appendix 1.

The LDA model makes two assumptions when analyzing and uncovering latent topics from documents. First, documents are represented as “bags of words” (i.e., unordered lists of words) in which the

word order is neglected. Although this is an unrealistic assumption, it is reasonable if the aim is to uncover semantic structures from text (Blei and Lafferty, 2006; Blei, 2012). Consider a thought experiment where one imagines shuffling all the words in a document. Even when shuffled, one might find words such as “population,” “size,” “virtual,” “minimum,” and “recruitment” and expect that the document deals with aspects of population dynamics. One of the core underlying principles of LDA is based on word co-occurrences, and a small number of co-occurring words is sufficient to resolve problems of ambiguity. Second, LDA assumes that the order in which documents are analyzed is unimportant (i.e., document exchangeability is assumed); however, at the end of the analysis, all documents are analyzed. As a result, LDA is unable to explicitly capture the evolution of topics over decades or centuries of work. This would require a more complicated and computationally expensive dynamic topic model (Blei and Lafferty, 2006), which is currently not feasible given the large dataset; however, this is a potential approach for future work. Document exchangeability is a limitation in the case of topics whose presentation in the literature has dramatically changed (e.g., in terms of the terminology used to describe the topic), but it still captures the phenomenon by which current literature builds upon previous literature. Nonetheless, the assumption of document exchangeability is especially problematic when analysing topics that span 50–100 years of research.

2.2. Topic interpretation

The topics emerge from the statistical properties of the documents and the statistical assumptions behind LDA. The topics are represented as discrete distributions over all the words, in which the top words (e.g., top 15) for each topic – that is, the words with the highest probability and those that more frequently co-occur together – provide insights into the semantic meaning of the topic. Topics are thus a reference to these probability distributions over words to exploit text-oriented intuitions. No epistemological claims are made beyond this representation. Furthermore, by no means is the topic distribution over words limited to these top 15 words; in fact, every word occurs in every topic, but with different probabilities. The topics are used to uncover the themes prevailing the documents, as well as the extent to which such themes are present in each document. In doing so, the main ideas of a publication can be extracted and used to track how they have developed over time. Note that the underlying topics and to what extent the document

exhibits these topics are not known in advance. These details are the output of the LDA analysis and emerge automatically from the statistical properties of the documents and the assumptions behind LDA.

2.3. Creating the dataset

This paper aims to identify latent fisheries modeling topics from scientific research articles published in peer-reviewed journals specializing in fisheries. In this manner, the selection of publications was restricted exclusively to fisheries journals; therefore, it follows that some subjective choices were made to achieve this. All journals included in this analysis contain the term “fishery” or “fisheries” in their title and have an impact factor of 1.0 or higher. Additionally, the journal *The ICES Journal of Marine Science* was included, because it is part of the International Council for the Exploration of the Seas (ICES), which channels science-based advice to decision makers for sustainable fisheries, and fisheries models are an important focus of this journal. A total of 13 fisheries journals were included in the study (see Table 1). A time frame of 26 years, from 1990 to 2016, was chosen to allow for enough variation within publication trends. Due to difficulties with journal subscription rights and the fact that some journals started after 1990 (e.g., *Fish and Fisheries* was first published in 2000), coverage was incomplete for the complete time range of 26 years for a few journals. Documents that did not constitute a type of research article (e.g., book reviews, forewords, errata, conference reports, comments, policy notes, corrigenda, and letters) were discarded. In total, 22,236 full-text research articles from 13 top-tier fisheries journals were downloaded using automated download scripts, as well as by utilizing the available application programming interfaces (APIs) offered by the publishers. The use of full-text articles, in contrast to only using abstracts, has shown to increase topic quality and provide a more detailed overview of the latent topics permeating a document collection (Syed and Spruit, 2017). Table 1 provides an overview of the complete dataset utilized in this study.

The selection of fisheries journals and underlying fisheries publications comes with some limitations. First, some of the highly influential and most cited papers on fisheries models are published in high-impact journals such as *Nature*, *Science*, and *PNAS*. Although highly influential, such publications would constitute only a small number of our sample and would only marginally or even negligibly contribute to the overall number of 22,236 publications downloaded from fisheries journals for this study. Two other reasons exist to exclude such generic journals. The first reason is that including all publications published in such outlets would drastically

Table 1. Overview of the dataset (i.e., corpus): years represent the years for which documents (i.e., articles) are downloaded; IF, the journal's impact factor according to ISI Journal Citation Reports 2016; N , the number of documents; N/T , the percentage of journal articles in relation to the total number of articles; \bar{W} , the mean number of words within each document; Std. W, the estimated standard deviation of words within each document; and \bar{V} , the mean vocabulary size (number of unique words) within each document. The total number of documents is 22,236.

Journal	Years	IF	N	N/T	\bar{W}	Std.W	\bar{V}
Canadian Journal of Fisheries and Aquatic Sciences	1996–2016	2.44	4427	19.9%	4075.5	1305.5	1266.7
Fish and Fisheries	2000–2016	8.26	419	1.9%	5892.9	2801.4	1757.4
Fisheries	1997–2016	2.43	477	2.1%	3409.9	1633.2	1312.3
Fisheries Management and Ecology	1994–2016	1.51	1001	4.5%	2692.2	1135.7	955.5
Fisheries Oceanography	1997–2016	2.73	752	3.4%	3866.7	1353.8	1187.8
Fisheries Research	1995–2016	2.23	3610	16.2%	3204.4	1326.3	1064.4
Fishery Bulletin	1990–2016	1.51	1441	6.5%	3356.3	2037.0	1074.4
ICES Journal of Marine Science	1990–2016	2.63	3903	17.6%	3379.8	1378.7	1118.9
Marine and Coastal Fisheries	2009–2016	1.44	274	1.2%	4473.7	1363.8	1368.0
North American Journal of Fisheries Management	1997–2016	1.01	2517	11.3%	3288.9	1420.9	1036.6
Reviews in Fish Biology and Fisheries	1991–2016	3.22	659	3.0%	5799.8	3994.4	1750.1
Reviews in Fisheries Science & Aquaculture	1997–2016	2.03	375	1.7%	6185.6	6020.2	1737.3
Transactions of the American Fisheries Society	1997–2016	1.47	2381	10.7%	3887.8	1382.4	1202.7
		Total	22,236				

increase the number of uncovered topics, as fisheries make up a small portion of the publications in *Nature*, *Science* and *PNAS*. While one might be able to use keyword searches and include only those publications that match fisheries-related terms, this brings up the second reason to exclude such journals: publication filtering is based on the subjective choice of relevant keywords and is limited in terms of how publications are indexed and subsequently can be retrieved (e.g., title, abstract, or full text) from these journals. Through the inclusion of publications from only fisheries journals, such subjective choices and associated limitations are avoided.

The second limitation concerns the exclusion of non-fisheries-specialized journals in which fisheries-modeling-related publication might appear. Such journals focus on, but not limited to, the field of marine science (e.g., *Marine Policy* and *Advances in Marine Biology*), the field of coastal areas or zones (e.g., *Coastal Management* and *Ocean and Coastal Management*), the field of toxicology (e.g., *Environmental Toxicology and Pharmacology* and *Aquatic Toxicology*), and the field of modeling (e.g., *Environmental Modelling & Software* and *Ecological Modelling*), in addition to a number of other journals, such as *Developmental Dynamics*, *Bulletin of the American Meteorological Society*, *Environmental Science and Technology*, *Philosophical Transactions of the Royal Society*, *Environmental Health Perspectives*, *BioScience*, *Journal of Fish Biology*, and *Progress in Oceanography*. Some publications related to fisheries modeling approaches are published in these outlets, which is a potential limitation of this study. Again, filtering for fisheries modeling publications in these journals would be biased by the subjective choice of keywords and limitations due to indexing and retrieval functionalities. Consequently, publications with a focus on the novelty in modeling approaches,

which are commonly published in specialized modeling journals such as *Ecological Modelling*, were not assessed in this study. On the other hand, the modeling publications captured within the fisheries journals included in this study can potentially address other topics besides fisheries, such as climate change or habitat loss, which are likely to be included in the analysis of modeling publications.

The third limitation relates to the focus on peer-reviewed journals only. As a result, fisheries modeling research that appears in grey literature was excluded. As grey literature is not indexed in the same way as peer-reviewed studies, selecting only relevant grey literature would, again, introduce bias due to human subjectivity in the search and retrieval.

2.4. Preprocessing the dataset

Several important preprocessing steps were required to transform the documents into appropriate bag-of-word representations. First, each document was converted from PDF format into a plain-text representation. Image-based PDFs, mainly old documents from the 1990s, were converted using the Tesseract optical character recognition (OCR) library. Second, documents were tokenized, which involved creating individual words (e.g., from paragraphs and sentences); meanwhile, numbers, single characters, punctuation marks, and words with only a single occurrence were removed, since they bear no topical meaning. Additionally, words that occurred in $\geq 90\%$ of the documents were discarded due to their lack of distinctive topical significance (see Appendix 2). Boilerplate content, such as title pages, article metadata, footnotes, margin notes and so on, was also removed. The reference list of each article was maintained so as to allow for referenced

titles and names of authors to be part of the word distributions of topics. An advantage of this approach is that author names can be part of specific topics, but they can simultaneously introduce bias when the referenced articles have no direct link to the underlying topics. A standard English stop word list ($n = 153$) was used to remove words that serve only syntactical and grammatical purposes, such as *the*, *and*, *were*, and *is*. Finally, other than grouping lowercase and uppercase words, no normalization method was applied, such as stemming or lemmatization, to reduce the inflectional and derivational forms of words to a common base form (e.g., *fishing* and *fishery* to *fish*). Normalization reduces the interpretability of topics at later stages, as stemming algorithms can be overly aggressive and may result in unrecognizable words when interpreting topics. Stemming might also lead to another problem, as it cannot be deduced whether a stemmed word comes from a verb or a noun (Evangelopoulos et al., 2012). For these reasons, and considering that the interpretability of the topics at a later stage was considered to be highly significant, an extensive normalization phase was omitted.

2.5. Creating LDA models

The LDA models were created with the Python library Gensim (Rehurek and Sojka, 2010). The number of topics to be uncovered (i.e., K parameter) varied from 1 to 50, thus creating 50 different LDA models. The hyper-parameters for the LDA models, which affect the sparsity of the topics created and their relative proportions, were set to be symmetrical. Technically, since LDA is a Bayesian probabilistic model, the symmetrical hyper-parameters encode prior knowledge that a priori assign equal probabilities to topics within documents, and words within topics. The quality of each topic was calculated using a topic coherence measure to find the optimal value for K (analogous to finding the right number of clusters, e.g., K -nearest neighbors). A coherence measure calculates the degree of similarity between a topic's top N words. This provides a quantitative approach for assessing the interpretability of topics from a human perspective. As such, coherence measures aim to find coherent topics – a topic with top words *apple*, *pear*, and *banana* is more coherent than *apple*, *pear*, and *car* – rather than topics that are merely artefacts of the statistical assumptions behind LDA. The C_V coherence measure was adopted, since it has shown the highest accuracy of all available coherence measures (Röder et al., 2015). An elbow method was employed to find the K value with the best performing topic coherence score. A detailed description of the C_V coherence measure can be found in Appendix 3.

2.6. Identifying subtopics

For each modeling topic identified, a zoom-in was employed with the aim of uncovering underlying subtopics within each of the general modeling topics by applying an approach similar to that described above. These subtopics provide a more detailed deconstruction of the respective general modeling topics. A zoom-in is performed on a subset of the data consisting of documents that have the general modeling topic as the dominant topic. The dominant topic is defined as the topic with the highest relative proportion – that is, the topic that exceeds all other topic proportions within a document. Since documents are modeled as mixtures of topics, the dominant topic represents the primary topic of a document.

2.7. Labeling the topics

The LDA model outputs the uncovered topics as probability distributions over all the words used; when sorted, the top 15 words are used to label the topic semantically. Representing the words as probabilistic topics has the distinct advantage that each topic is now individually interpretable (Griffiths et al., 2007), compared to a purely spatial representation like the topic model of latent semantic analysis (Deerwester et al., 1990). As stated before, the distributions of words, and specifically the words with the highest probability within each topic, are used to describe an underlying theme; however, such themes are latent, and a semantic label that best captures those words needs to be attached. For example, a topic with the top 5 words *apple*, *banana*, *cherry*, *pear*, and *mango* describes the underlying theme of fruits and can be labeled as such.

To provide a semantically meaningful and logical interpretation of these probability distributions, a fisheries domain expert manually labeled the topics by close inspection of the top 15 high-probability words, together with an inspection of the document titles and content. Furthermore, to improve the labeling of the topics, the topics were visualized in a two-dimensional area by computing the distance between topics (Chuang et al., 2005) and applying multi-dimensional scaling (Sievert and Shirley, 2014). This two-dimensional topic representation aided in identifying similarities between topics and thus similarities between topic labels.

2.8 Calculating subtopical modeling trends

To gain insight into the subtopical temporal dynamics of the modeling subtopics, document topic proportions were aggregated into a composite topic-year proportion.

Such composite values provide insights into the prevalence of a modeling subtopic within a certain year, given all the publications within that year. It furthermore enables the analysis of changing topic proportions over the course of 26 years, as proportions increase or decrease for each subtopic and for each year. Additionally, to obtain insight into increasing and decreasing topical trends, a one-dimensional least square polynomial was fitted for different time intervals. The time intervals chosen were 1990–1995, 1995–2000, 2000–2005, 2005–2010, and 2010–2016, so as to allow for historical comparison. The polynomial coefficient is used as a proxy for the trend and defines the slope of the composite topic-year proportions for a range of years. Coefficients are multiplied by the number of years within each time interval to obtain the change measured in percentage points. Positive values indicate increasing or “hot” topics, and negative values indicate decreasing or “cold” topics. Color coding is used to represent the hot (i.e., red) and cold (i.e., blue) topical trends.

3. Results and discussion

3.1. General modeling topics

The optimal LDA model for the complete corpus ($N = 22,236$ documents) uncovered 31 general fisheries topics. The calculated coherence scores to obtain the optimal number of topics, referred to as the K parameter, can be found in Appendix 3. Among these general fisheries topics, two topics deal with the aspects of fisheries modeling. The publications dealing with these two modeling topics account for 12% ($N = 2761$ documents) of the total number of publications. The remaining 29 topics, which relate to other aspects of fisheries research, are listed in Appendix 4. A bibliometric analysis of trends in fisheries science found a higher proportion of publications employing models – around 30%, as estimated from publication titles and abstracts from a dataset containing 695 fisheries-related publications (Jarić et al., 2012). Several reasons can be offered to explain why these two percentages differ, such as the used time range and the selected journals; most importantly, the present paper identifies publications which predominantly deal with fisheries modeling aspects, in contrast to publications in which a modeling method is employed.

Figure 1 shows the top 15 words and their probabilities for the two modeling topics. The first modeling topic concerns catch-effort and abundance estimation methods and is, therefore, given the short name estimation models. It contains the words “catch,” “survey,” “sampling,” “effort,” and “sample” among its top 15 words. These words reflect the collection of both fisheries-independent data, which are usually gathered through survey and sampling

(1) ESTIMATION MODELS			(2) STOCK ASSESSMENT MODELS		
	word	prob.		word	prob.
	MODEL	.015		MODEL	.024
	ESTIMATES	.014		STOCK	.014
	CATCH	.012		MORTALITY	.014
	SURVEY	.008		POPULATION	.012
	SAMPLING	.008		RECRUITMENT	.011
	ESTIMATED	.008		MODELS	.010
	MODELS	.007		BIOMASS	.007
	ESTIMATE	.007		YEAR	.007
	DISTRIBUTION	.007		RATE	.007
	ABUNDANCE	.006		MANAGEMENT	.007
	MEAN	.006		PARAMETERS	.006
	EFFORT	.006		ASSESSMENT	.006
	SAMPLE	.005		FISHERIES	.006
	METHOD	.005		ESTIMATES	.006
	SIZE	.005		FISHING	.005

Figure 1. The two uncovered fisheries modeling topics (i.e., estimation models and stock assessment models) from the dataset containing 22,236 fisheries publications (1990–2016; 13 journals). The figure displays the topic label (top) and the top 15 high-probability words.

methods, and fisheries-dependent data (e.g., collected through logbooks), which commonly provide information on catch and effort. These and other obtained data feed into models in order to estimate intermediate parameters such as natural mortality rate or catchability (Hoggarth et al., 2006); this is a phase of research reflected in estimation models through the words “model,” “estimates,” “estimated,” and “estimate.” These types of models might also be called retrospective models, since they interpret the past based on collected data.

The second modeling topic concerns modeling approaches for the assessment of the current state of a fishery and future projections and is assigned the short name “stock assessment models.” It contains the words “stock,” “mortality,” “biomass,” “rate,” and “estimate,” which reflect the most commonly used indicators (i.e., fish catch, stock biomass, stock size, and fishing mortality; Hoggarth et al., 2006) to measure the status of the fishery and the state of the stock (Le Gallic, 2002). These indicators link to reference points, which give quantitative meaning to the goals and objectives set for a fishery (Jennings, 2005). Reference points are usually estimated through models that use stock and recruitment data, which is reflected in the words “stock,” “population,” “recruitment,” “management,” “parameters,” and “estimates” in stock assessment models. Together, indicators and reference points play a crucial role in fisheries management and can be used to give quantitative meanings to the objectives of a fishery (Hoggarth et al., 2006).

The distinction between these two topics shows how they are treated separately in fisheries research

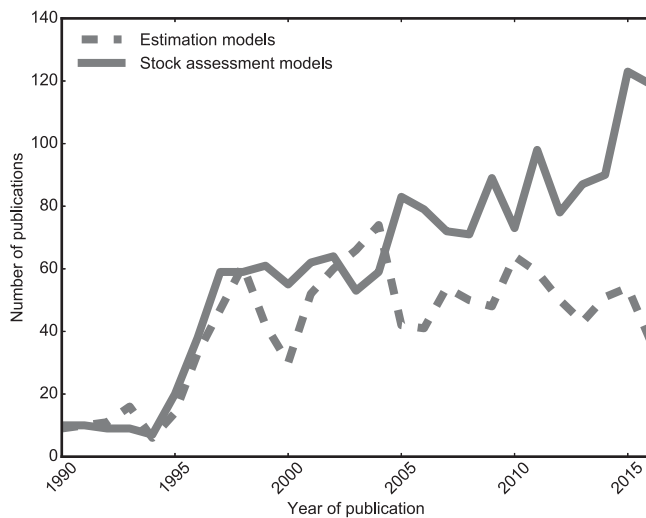


Figure 2. The number of publications per year for publications related to the topic estimation model and stock assessment model.

publications, whereas in practice (i.e., in fisheries stock assessments for management), these two topics are connected and combined into one model but reflect the different phases of the model development (Hoggarth et al., 2006). The distribution of publication frequencies for both general modeling topics is shown in Figure 2, which highlights the increased research interest in stock assessments models compared to estimation models. Additionally, the top five publications with the highest topic prevalence for each of the two modeling topics, indicating to what extent the content of a publication relates to the modeling topic, are shown in Table 2.

Interestingly, only the topics of estimation models and stock assessment models were uncovered (both of which focus on the ecological dimension of fisheries),

whereas topics on economic and social fisheries aspects were not found within the modeling publications. This finding might be a result of the selection of journals used in this study. Most of the included fisheries journals declare a multi-disciplinary or interdisciplinary scope, while some specifically include socioeconomic considerations and the human dimension as subjects of interest. Therefore, at least one social or economic modeling topic could be expected to be identified by the LDA model. Another reason for the absence of other modeling topics may be that fisheries are still perceived as a natural science. The ICES only recently established the Strategic Initiative on the Human Dimension (SIHD) “to support the integration of social and economic science into ICES work” (ICES, 2017), and the majority of the ICES workgroups still lack social science input (ICES, 2016). As a result, social scientists and economists may pursue publication of their models not in a journal related to fisheries, but rather in a journal related to their respective disciplines or having a broader scope, such as *Ecology and Society*, *Marine Resource Economics* or *Marine Policy*. Merit issues could also contribute to the topic bias. Different scientific disciplines receive publication merits for different journals, which is more often dependent on the index of a journal (e.g., Science Citation Index (SCI), Social Science Citation Index (SSCI), or International Scientific Index (ISI)) than on its impact factor. As a result, non-biological and non-ecological disciplines are less likely to use top-tier fisheries journals as publication outlets. This might, in turn, lead to low visibility of non-ecological models among fisheries stakeholders, because many fisheries journals such as *Fish and Fisheries* and *Fisheries Research* intend to reach fisheries managers, administrators, policy makers, and legislators.

Table 2. Publication title, year, and topic prevalence (in percentages) for the five publications with the highest topic prevalence for each general modeling topic.

Modeling Topic	Title	Year	Prevalence
Estimation models	- Trawl survey based abundance estimation using datasets with unusually large catches.	1999	95.69%
	- Covariances in multiplicative estimates.	1999	94.35%
	- Use of simulation–extrapolation estimation in catch–effort analyses.	1999	93.90%
	- Reducing bias and filling in spatial gaps in fishery dependent catch per unit effort data by geostatistical prediction I methodology and simulation.	2014	92.23%
	- Confidence intervals for trawlable abundance from stratified-random bottom trawl surveys.	2011	90.48%
Stock assessment models	- The structure of complex biological reference points and the theory of replacement.	2009	99.37%
	- Analytical models for fishery reference points.	1998	98.50%
	- Implications of life-history invariants for biological reference points used in fishery management.	2003	98.14%
	- The estimation and robustness of FMSY and alternative fishing mortality reference points associated with high long-term yield.	2012	97.33%
	- Age-specific natural mortality rates in stock assessments: size-based vs. density-dependent.	2014	94.87%

(1) CATCH AND ABUNDANCE		(2) MORTALITY RATE (TAGS)		(3) ABUNDANCE (SURVEYS)		(4) RECREATIONAL FISHERIES		(5) PARAMETERS AND ESTIMATORS	
word	prob.	word	prob.	word	prob.	word	prob.	word	prob.
MODELS	.013	TAG	.016	SPATIAL	.015	CATCH	.023	ERROR	.011
CATCH	.011	MORTALITY	.014	SURVEY	.011	EFFORT	.015	ABUNDANCE	.010
ABUNDANCE	.008	RATES	.013	ABUNDANCE	.009	FISHING	.012	YEAR	.009
SPECIES	.007	TAGGING	.013	DENSITY	.009	SAMPLING	.012	STOCK	.007
YEAR	.006	RATE	.012	AREA	.009	SURVEY	.010	VARIANCE	.007
DEPTH	.006	TAGS	.009	ACOUSTIC	.007	ANGLERS	.008	CATCH	.007
EFFECTS	.005	TAGGED	.009	VARIANCE	.007	HARVEST	.007	POPULATION	.006
CPUE	.005	MOVEMENT	.008	SURVEYS	.006	SURVEYS	.007	MODELS	.006
VARIABLES	.005	REPORTING	.006	SAMPLING	.006	RATE	.007	INDEX	.006
SPATIAL	.004	MODELS	.006	DISTANCE	.005	ANGLER	.007	YEARS	.005
LONGLINE	.004	YEAR	.006	BIOMASS	.005	FISHERY	.006	ERRORS	.005
LINEAR	.004	FISHING	.006	RANDOM	.005	RECREATIONAL	.006	BIAS	.005
ENVIRONMENTAL	.004	RELEASE	.006	ESTIMATION	.004	DAY	.005	INDICES	.005
EFFECT	.004	PARAMETERS	.005	SEA	.004	VARIANCE	.005	SAMPLE	.004
RATES	.004	FISHERY	.005	KM	.004	LAKE	.005	REGRESSION	.004

(6) SAMPLING		(7) ABUNDANCE (SAMPLING)		(8) FISH DISTRIBUTION		(9) SPAWNING		(10) NET SELECTIVITY	
word	prob.	word	prob.	word	prob.	word	prob.	word	prob.
SAMPLING	.011	SAMPLING	.009	CATCH	.015	SPAWNING	.017	SELECTIVITY	.026
FISHING	.010	ABUNDANCE	.008	FISHING	.014	EGG	.014	MESH	.013
SPECIES	.010	POPULATION	.007	EFFORT	.013	EGGS	.012	LENGTH	.012
FISHERY	.009	BAYESIAN	.007	FISHERY	.013	PRODUCTION	.008	NET	.010
BYCATCH	.008	POSTERIOR	.007	CPUE	.011	DAY	.007	GILLNET	.009
CATCH	.008	PROBABILITY	.006	AREA	.011	STAGE	.007	SELECTION	.009
TRIP	.006	SPECIES	.006	COD	.011	BIOMASS	.006	CATCH	.008
TRIPS	.006	CATCHABILITY	.006	ABUNDANCE	.010	LARVAE	.006	GEAR	.008
OBSERVER	.006	MODELS	.006	CATCHABILITY	.009	SAMPLING	.005	CURVE	.008
VESSELS	.006	CAPTURE	.006	BIOMASS	.008	MORTALITY	.005	NETS	.007
EFFORT	.005	DENSITY	.006	STOCK	.006	DAILY	.005	CURVES	.007
SHRIMP	.005	PRIOR	.005	AREAS	.006	SAMPLES	.005	GILL	.006
LANDINGS	.005	SITES	.004	SEASON	.006	LARVAL	.005	PARAMETERS	.006
VESSEL	.004	PARAMETERS	.004	CRAB	.006	TEMPERATURE	.004	MM	.006
COMMERCIAL	.004	ELECTROFISHING	.004	RATES	.006	FEMALES	.004	RELATIVE	.006

(11) VESSELS AND FLEET		(12) TRAWL SURVEYS		(13) LENGTH AND GROWTH		(14) SALMON	
word	prob.	word	prob.	word	prob.	word	prob.
FISHING	.026	SURVEY	.021	LENGTH	.015	SALMON	.016
CATCH	.016	TRAWL	.019	GROWTH	.014	RIVER	.009
VESSEL	.012	SAMPLING	.013	PARAMETERS	.010	COUNTS	.007
EFFORT	.010	SPECIES	.011	SAMPLE	.008	SAMPLING	.007
VESSELS	.010	SURVEYS	.008	PARAMETER	.006	ABUNDANCE	.007
FISHERY	.008	BOTTOM	.007	SAMPLES	.006	RUN	.006
FLEET	.006	SAMPLE	.006	LIKELIHOOD	.006	SURVEY	.005
SPECIES	.006	TOW	.006	ERROR	.005	SPAWNING	.004
CPUE	.006	LENGTH	.006	MODELS	.005	POPULATION	.004
POWER	.005	EFFICIENCY	.005	STOCK	.005	YEARS	.004
AREA	.004	DESIGN	.005	FUNCTION	.005	CHINOOK	.004
YEAR	.004	AREA	.005	DISTRIBUTIONS	.004	COUNT	.004
MODELS	.004	CATCH	.005	ESTIMATION	.004	SAMPLE	.004
RATE	.004	DENSITY	.005	STANDARD	.004	STREAM	.004
INFORMATION	.003	TOWS	.005	SET	.003	ESTIMATOR	.004

Figure 3. The 14 uncovered subtopics from the documents ($N = 1124$) exhibiting the topic estimation models as the dominant topic. The figure displays the subtopic label (top) and the top 15 high-probability words.

3.2. Subtopics within estimation models

The zoom-in (i.e., the process of uncovering subtopics from general topics) on the general topic of estimation models ($N = 1124$ documents) identified 14 subtopics (see Appendix 3). Figure 3 provides an overview of the 14 estimation model subtopics, the top 15 words of the topics with their probabilities, and the manually attached label that best captures the semantics of the top words. Furthermore, a two-dimensional topic representation can be found in the topic similarity map in Figure 4A, showing the topic similarity with respect to the distribution of the words. The trends (i.e., the change in overall

topic proportion, in percentage points) and prevalence (i.e., the size of the overall topic proportion as a percentage) are presented in Figure 5A.

Most of the uncovered subtopics can be grouped. The principal group consists of the five subtopics focusing on the biological aspects of fisheries (i.e., catch and abundance, mortality rate (tags), fish distribution, spawning, and length and growth). This highlights the importance and scientific focus of the biological dimension in fisheries research. Catch and abundance shows the biggest overall increase over time (+15.46%) and had the largest proportion (14.84%) within the last six years (Figure 5A). Most of the other biological subtopics show very little variation over time, and some

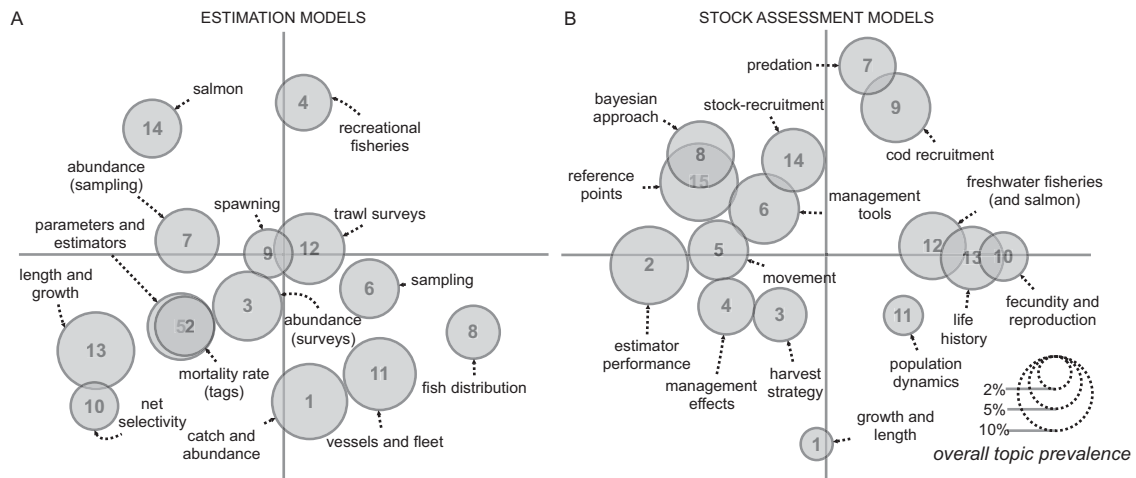


Figure 4. Topic similarity map that shows a two-dimensional representation (via multi-dimensional scaling). **A:** 14 estimation model subtopics. **B:** 15 stock assessment model subtopics. The distance between the nodes represents the topic similarity with respect to the distributions of the words (i.e., nodes closer together have more related word probabilities). The surface of the nodes represents the prevalence of the topic within the corpus.

only make a small contribution in terms of proportion (e.g., spawning), with only 3.82% overall topic proportion (Figure 5A). Length and growth showed the highest overall decrease over time (-14.04%), indicating a diminishing scientific interest. The subtopic of length and growth remained

relatively high in terms of topic proportion, with an average of 9.13% between 2010 and 2016, possibly because growth is an important parameter for stock assessments (Lorenzen, 2016; Maunder et al., 2016) and is also most frequently discussed in fisheries, as shown by a previous trend analysis

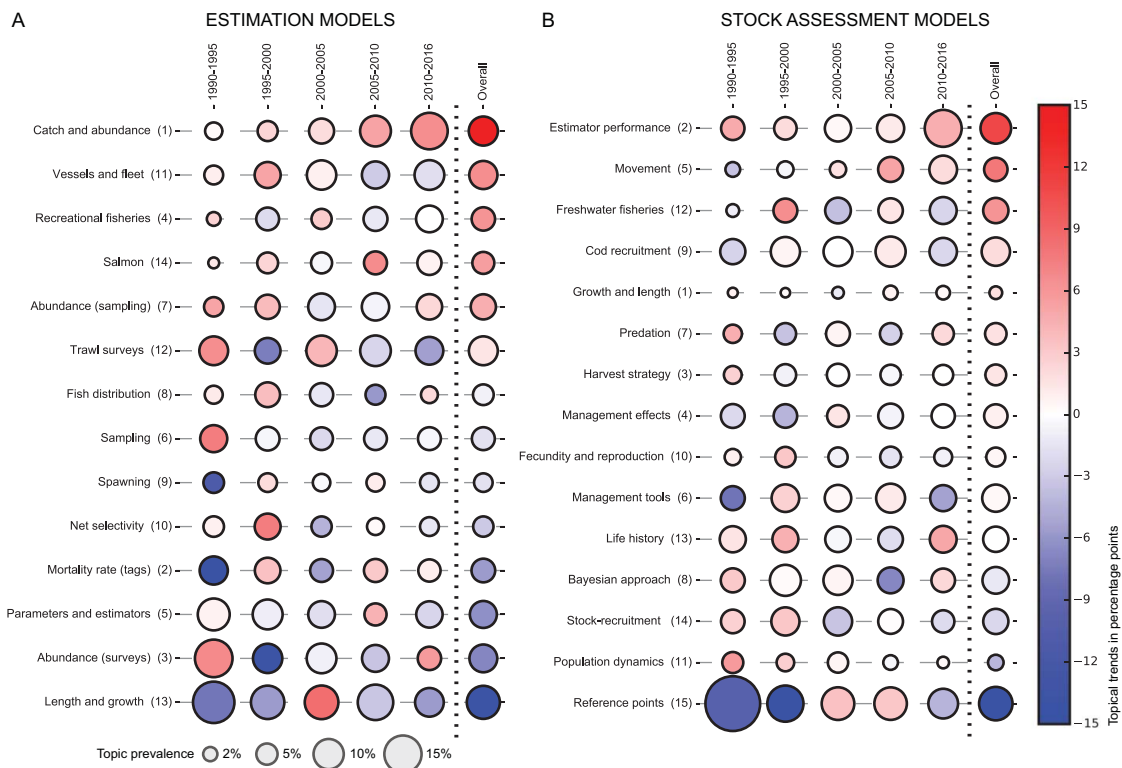


Figure 5. Trends in changing topic proportions for different time intervals for all subtopics. The left-hand side (A) displays the 14 uncovered estimation model subtopics. The surface of the node represents the topic prevalence within a certain time range and indicates how present a topic was within all the published material of that time frame. The colors indicate the trend in topic proportion (i.e., change in percentage points) and indicate whether a topic increased in popularity (hot topic) or decreased in popularity (cold topic) within that time frame. The right-hand side (B) displays the information for the 15 uncovered stock assessment model subtopics.

(Jarić et al., 2012). The subtopic of parameters and estimators relates more to the technical aspects of estimation modeling, but appears to be similar to the biological subtopic of mortality rate, as apparent from the similarity map (Figure 4A). Vessel and fleet showed a large topic proportion (between 8% and 10%) over the last 16 years (Figure 5A). Both the topic of vessel and fleet and that of net selectivity likely relate to biological considerations, but they could also hint at a slightly more economic perspective on industry (fleet) and gear-related matters; however, additional words such as “firm,” “prices,” or “market” would have to be present to confirm this hypothesis further. The four subtopics of abundance (survey), sampling, abundance (sampling), and trawl survey focus on survey and sampling, which are essential methods for gathering data and information on fisheries. In particular, information on catch and stock abundance is required by almost all stock assessment models (Hoggarth et al., 2006). These four subtopics account for a combined overall topic prevalence of 30.73%, indicating their importance to fisheries research. The subtopic of recreational fisheries refers to a type of fishery that differs in the estimation process compared to commercial fisheries, as it often employs surveys on anglers. This type of estimation process may refer not only to marine but also to freshwater fisheries. Recreational fisheries underwent an increase in topic proportion from 2.11% in the 1990–1995 period to 7.90% in the 2010–2016 period, indicating the growing importance of recreational fisheries assessments in fisheries science. The increased importance of recreational fishing on the commercial fish stocks (Griffiths and Fay, 2015) is in line with the observed trend in this study. Apart from recreational fisheries, no other types of fisheries (e.g., small-scale, artisanal, or commercial fisheries) were identified by the topic model. The distance of recreational fisheries from the other subtopics in the similarity map may explain this, as authors writing about recreational fisheries use distinctive words that are different from the discourse on other types of fisheries. Another possible explanation may be that there are more studies on recreational fisheries than on other types of fisheries. Salmon is the only topic that focuses on one particular species. The similarity map shows how the topic of salmon differs within the words used, indicating the particularity and specialized research niche of the topic (Figure 4A). Salmon showed a positive trend (+5.61%) over the study period; however, this result is in conflict with previous research that showed a diminishing research interest in the species (Jarić et al., 2012). This could be due to the increasing effort within aquaculture and the growing economic importance of the species over the period (FAO, 2016) that separates this study from that of Jarić, Cvijanović, Knežević-Jarić, and Lenhardt (2012).

Within the top 15 words of the subtopics, important subjects such as species and names/methods can be identified.

Three subtopics contain species names (i.e., “shrimp” in sampling, “cod” and “crab” in fish distribution, and “salmon” and “chinook” in salmon). Methods mentioned within the subtopics of estimation models are “regression” in parameters and estimators and “Bayesian” in abundance (sampling). Parameters for fish stock assessments can be estimated through the least square method, represented in the form of regression analysis; however, maximum likelihood methods are now preferred, as they allow for a better specification in the form of errors in the models. Bayesian methods are commonly used to incorporate uncertainty into management advice, but this could also involve other methods such as maximum likelihood, bootstrapping, or Monte-Carlo modeling (Hoggarth et al., 2006). The two methods “regression” and “Bayesian” do not reflect the current diversity of modeling methods, nor necessarily the most conventional models used in fisheries assessments today, but they seem to have a strong association with the two topics of parameters and estimators and abundance (sampling). Note that references to names of species and methods highlight the importance and relation of such words within a specific topic – technically, they co-occur more frequently to describe the latent topic – but are by no means mutually exclusive (i.e., methods and species can occur in different subtopics simultaneously). They provide information from a topical perspective (i.e., a high-level decomposition of the document into clusters of co-occurring words), but fail to address on what basis such species and methods are linked within a specific topic.

3.3. Subtopics within stock assessment models

The zoom-in on the topic of stock assessment models ($N = 1637$ documents) revealed 15 subtopics (see Appendix 3 for the calculated topic coherence scores). Figure 6 provides an overview of the 15 subtopics, the top 15 words with their probabilities, and the label attached to each topic. The topic similarity for these subtopics can be found in Figure 4B. The subtopic trends and prevalence are displayed in Figure 5B.

Most of the subtopics of stock assessment models evolve around biological aspects and processes (i.e., growth and length, movement, predation, cod recruitment, fecundity and reproduction, population dynamics, life history, and stock recruitment). The majority of these subtopics show a slight increase over the study period (Figure 5B); together, these subtopics have an overall topic proportion of 42.91%, which shows their consistent importance within fisheries science and fisheries management (Hilborn and Walters, 1992). Within the biological subtopics, predation stands out as the only subtopic that refers to “interaction,” “multi-species,” and the “ecosystem.” The subtopic of predation increased by 4.67% during the period from 1990 to 1995

(1) GROWTH AND LENGTH		(2) ESTIMATOR PERFORMANCE		(3) HARVEST STRATEGY		(4) MANAGEMENT EFFECTS		(5) MOVEMENT	
word	prob.	word	prob.	word	prob.	word	prob.	word	prob.
GROWTH	.017	SELECTIVITY	.011	FISHING	.008	FISHING	.013	SPATIAL	.008
MM	.007	BIOMASS	.010	CATCH	.007	CATCH	.011	TUNA	.007
ABALONE	.006	RECRUITMENT	.010	CRAB	.007	LENGTH	.010	MOVEMENT	.006
LENGTH	.006	CATCH	.010	BIOMASS	.006	EFFORT	.006	FISHING	.006
HARVEST	.005	ERROR	.007	SHARK	.006	LANDINGS	.004	TAGGING	.006
PARAMETER	.004	ESTIMATION	.006	LOBSTER	.006	GULF	.004	RATES	.006
ABUNDANCE	.004	RELATIVE	.006	RECRUITMENT	.004	CATCHES	.004	DISTRIBUTION	.005
BASS	.004	BIAS	.006	MEAN	.004	SOUTH	.004	ABUNDANCE	.005
MEAN	.004	PERFORMANCE	.005	SHARKS	.004	YIELD	.003	TAG	.005
INDIVIDUAL	.004	FISHING	.005	FLOUNDER	.004	BIOMASS	.003	INFORMATION	.004
LAKE	.003	PUNT	.005	ABUNDANCE	.004	STUDY	.003	AREA	.004
MAXIMUM	.003	TRUE	.005	GROWTH	.003	REFERENCE	.003	SURVEY	.004
ENHANCEMENT	.003	SURVEY	.005	MATURE	.003	ESTIMATE	.003	ATLANTIC	.004
RELEASE	.003	SIMULATION	.005	RATES	.003	STOCKS	.003	CATCH	.004
STUDY	.003	ASSESSMENTS	.005	MALE	.003	EXPLOITATION	.003	ASSUMED	.003

(6) MANAGEMENT TOOLS		(7) PREDATION		(8) BAYESIAN APPROACH		(9) COD RECRUITMENT		(10) FECUNDITY AND REPRODUCTION	
word	prob.	word	prob.	word	prob.	word	prob.	word	prob.
FISHING	.017	BIOMASS	.015	PARAMETER	.008	COD	.022	SPAWNING	.018
EFFORT	.011	PREDATION	.014	DISTRIBUTION	.008	RECRUITMENT	.013	EGG	.015
HARVEST	.011	PREY	.012	BAYESIAN	.007	SEA	.010	REPRODUCTIVE	.014
CATCH	.008	ECOSYSTEM	.010	PRIOR	.007	FISHING	.007	FECUNDITY	.014
YIELD	.008	FISHING	.009	POSTERIOR	.007	NORTH	.006	SURVIVAL	.013
AREA	.007	PREDATOR	.008	UNCERTAINTY	.007	STOCKS	.006	LIFE	.009
AREAS	.006	FOOD	.007	SERIES	.006	SPAWNING	.006	EGGS	.008
BIOMASS	.006	TROPHIC	.006	ERROR	.005	ATLANTIC	.005	LARVAL	.008
OPTIMAL	.005	MULTISPECIES	.006	PROBABILITY	.005	HERRING	.005	PRODUCTION	.008
TARGET	.005	PREDATORS	.006	PROCESS	.005	ENVIRONMENTAL	.005	RECRUITMENT	.008
CONTROL	.004	COMMUNITY	.006	DISTRIBUTIONS	.005	SSB	.004	STAGE	.007
POLICY	.004	CONSUMPTION	.006	FUNCTION	.005	TEMPERATURE	.004	POTENTIAL	.006
RECRUITMENT	.004	ABUNDANCE	.005	LIKELIHOOD	.004	CHANGES	.004	LARVAE	.006
LEVEL	.004	INTERACTIONS	.004	INFORMATION	.004	BALTIC	.004	MATURITY	.006
LEVELS	.004	SEA	.004	EXAMPLE	.004	POPULATIONS	.004	EFFECTS	.006

(11) POPULATION DYNAMICS		(12) FRESHWATER FISHERIES (AND SALMON)		(13) LIFE HISTORY		(14) STOCK-RECRUITMENT		(15) REFERENCE POINTS	
word	prob.	word	prob.	word	prob.	word	prob.	word	prob.
GROWTH	.013	LAKE	.012	GROWTH	.041	RECRUITMENT	.016	FISHING	.011
SHRIMP	.012	SALMON	.011	LENGTH	.015	PACIFIC	.010	BIOMASS	.010
RECRUITMENT	.009	RIVER	.011	LIFE	.008	STOCKS	.008	REFERENCE	.008
BAY	.006	POPULATIONS	.009	INDIVIDUALS	.006	ENVIRONMENTAL	.008	CATCH	.008
OYSTER	.006	SURVIVAL	.009	HISTORY	.006	SALMON	.008	STOCKS	.007
SEA	.005	RATES	.007	RATES	.005	ABUNDANCE	.006	RECRUITMENT	.007
FISHING	.005	TROUT	.007	MEAN	.005	SARDINE	.006	POINTS	.006
ABUNDANCE	.004	HABITAT	.006	MATURATION	.005	ANCHOVY	.005	YIELD	.006
TEMPERATURE	.004	ABUNDANCE	.005	INDIVIDUAL	.005	SERIES	.005	MSY	.005
SQUID	.004	DENSITY	.005	BERTALANFFY	.004	SPAWNING	.005	SSB	.005
MM	.004	HARVEST	.005	BODY	.004	BIOMASS	.005	PRODUCTION	.004
POPULATIONS	.004	LAKES	.004	POPULATIONS	.004	CLIMATE	.004	EFFORT	.004
BIOMASS	.004	ADULT	.004	CM	.004	VARIABILITY	.004	SEA	.003
RATES	.003	CHINOOK	.003	ECOLOGY	.004	RICKER	.004	FMSY	.003
ANIMALS	.003	RECRUITMENT	.003	MATURITY	.004	MEAN	.004	MAXIMUM	.003

Figure 6. The 15 uncovered subtopics from the documents ($N = 1637$) exhibiting the topic stock assessment models as the dominant topic. The figure displays the subtopic label (top) and the top 15 high-probability words.

(Figure 5B), which reflects the increased scientific awareness of predator–prey interaction and model implications in the early 1990s (e.g., Yodzis, 1994). The topic proportion of predation shows a positive trend, as it rose from 3.75% in the period of 1990–1995 to 5.07% in the period of 2010–2016; this might indicate the increased attention of the scientific community to an ecosystem approach to fisheries and the implementation of multi-species and ecosystem considerations within stock assessments, modeling frameworks, and management advice (Maynou, 2014; Möllmann et al., 2014; Gaichas et al., 2017). The four subtopics of harvest strategy, management effects, management tools and reference points all concern management measures and effects, but they mainly address biological components such as “recruitment,” “abundance,” and “biomass.” Reference points

shows the strongest overall negative trend of all subtopics (−26.55%), indicating that the popularity of this topic among fisheries scientists has decreased over the years. Nevertheless, the topic of reference points still makes up a relatively large proportion, 9.82% (Figure 5B); this is the second largest proportion in the period of 2010–2016 after estimator performance, which has a 15.19% topic proportion within the same period. This highlights the continuity of research on reference points from the 1990s to the present day (Caddy and Mahon, 1995; Caddy, 2004; Froese et al., 2017). The subtopic of estimator performance shows the highest increase (+11.11%) within the overall study period (i.e., 1990–2016) and makes up a large proportion within the last six years of the time frame, from 2010 to 2016 (15.19%); this finding could be related to the increased

overall importance of models in fisheries science (Jarić et al., 2012). The subtopic of freshwater fisheries shows an overall positive trend (+6.28%), even though freshwater fisheries habitats have been found to be less studied than marine fisheries (Jarić et al., 2012). The topic proportion of freshwater fisheries rose over the study period, from 1.82% in 1990–2000 to 8.08% in 2010–2016 (Figure 5B). The importance of freshwater fisheries in areas such as Africa and India may explain the increase in research efforts within this field (FAO, 2016).

From the top 15 words (Figure 6), related subjects were identified, such as regions, species, and names/methods. The two marine regions mentioned are “Atlantic” and “Pacific,” possibly because these are some of the world’s major fishing areas (FAO, 2016). The various species names found within the top 15 words, such as “cod,” “herring,” and “anchovy,” cover many of the commercially important species in marine capture production (FAO, 2016). These results stand in stark contrast to a bibliometric study on trends in fisheries science, which found virtually no research on many commercially important species (Aksnes and Browman, 2016); however, these results were based on word frequencies in publication titles and abstracts, which may not mention the species of concern. This finding highlights the strength of the full-text LDA analysis. Other mentioned species, such as “abalone,” “lobster,” and “shark,” may have high probabilities for occurrence in the subtopics because they represent species of great economic value and also are often a focus of conservation efforts (Turpie et al., 2003; Simpfendorfer and Dulvy, 2017).

Several names within the words of the subtopics refer to a method named after a scientist, e.g., “Bayesian,” “Bertalanffy,” “Ricker,” and “Punt,” which could be a direct consequence of the inclusion of the reference list in the analysis. The subtopic of Bayesian approach indicates the importance of this methodology in fishery science and for fisheries models. A Bayesian approach can be used for stock assessments and decision analysis and resembles an improved way of fitting models to data and decision-making (Hoggarth et al., 2006). The scientists von Bertalanffy and Ricker both made substantial contributions to fisheries science – von Bertalanffy in metabolism and growth (von Bertalanffy, 1957) and Ricker in the computation and interpretation of computational statistics of fish populations (Ricker, 1975). Their methods are still applied today in the form of growth models (Allen, 1966; Piner et al., 2016) and in stock-recruitment models (Baker et al., 2014). The author Punt has not developed any particular method that takes his name; however, his name may occur within the top 15 words due to his significant contribution to research and his publications on estimator performance and data

standardization, as well as his many citations by other scientists within the field. Although Punt is, relatively speaking, a newcomer compared to some of the early influential researchers in the field (e.g., Hjort, Beverton, and Holt), the occurrence of his name is perhaps a result of the timeframe examined, or it may indicate that the names of senior scientists and methods have become somewhat common knowledge and are therefore not always explicitly stated or cited.

4. Conclusions

The aim of this paper was to uncover fisheries modeling topics from 22,236 scientific publications from 13 peer-reviewed fisheries journals. Additionally, subtopics from general modeling topics were uncovered to provide insights into their developments and trends over the last 26 years. Overall, two main fisheries modeling topics were identified: estimation models and stock assessment models. This study demonstrates that research in the field of fisheries modeling shows a shift of scientific focus in topics and subtopics over the last 26 years. Stock assessment models are outperforming estimation models, and their underlying subtopics have moved from length and growth to catch and abundance, and from reference points to estimator performance over the last 26 years. Economically important species and areas show a high presence within the modeling subtopics.

Both general modeling topics focus primarily on the biological aspects of fisheries; however, since this study was limited to publications in 13 fisheries journals, other topics in fisheries modeling (e.g., with a focus on social, management or economic aspects of fisheries) may well exist in publications of other journals. Possible disciplinary merit issues and the remaining understanding of fisheries as a natural science discipline might further limit fisheries journals to models with an ecological focus, despite their multi-disciplinary scope.

In conclusion, this novel machine learning approach revealed interesting insights into the topical trends of a large dataset of models published in fisheries journals. This approach enables researchers to identify research topics and shifts in research focus, and it provides a bigger picture that captures the main ideas prevailing scientific publications.

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Appendix 1

Generative Process of LDA

The generative process of LDA is described below:

1. For each topic
 - a. Draw a distribution over all the words, $\beta_K \sim \text{Dir}(\eta)$
2. For each document
 - a. Draw a distribution over topics $\theta_d \sim \text{Dir}(\alpha)$ (per-document topic proportion)
 - b. For each word in the document
 - i. Draw a topic $z_{d,n}$ from θ_d (per-word topic assignment)
 - ii. Draw a word $w_{d,n}$ from that topic

Each topic is a multi-nomial distribution over all the words and arises from a Dirichlet distribution $\beta_k \text{Dir}(\eta)$. Additionally, each document is represented as a distribution over the topics and arises from a Dirichlet distribution $\theta_d \sim \text{Dir}(\alpha)$. The Dirichlet parameter η defines the smoothing of the words within topics, and α defines the smoothing of the topics within documents. The per-word topic assignment $z_{d,n}$ is the topic drawn from the per-document topic proportions (Step 2a) for the n -th word in the d -th document. The joint distribution of the observed words w_D and the hidden variables β_K (topics), θ_D (document topic proportions), and z_D (word topic assignments) becomes:

$$\begin{aligned}
 & p(\beta_K, \theta_D, z_D, w_D) \\
 &= \prod_{k=1}^K p(\beta_k | \eta) \prod_{d=1}^D p(\theta_d | \alpha) \prod_{n=1}^N p(z_{d,n} | \theta_d) \\
 & \quad p(w_{d,n} | z_{d,n}, \beta_{d,k})
 \end{aligned} \tag{1}$$

The per-word topic assignment $z_{d,n}$ depends on the per-document topic proportion θ_d it draws a topic for each word from the previously drawn per-document topic proportion. As a result, the generative process creates documents that contain multiple topics in varying proportions. The drawn word $w_{d,n}$ depends on the per-word topic assignment $z_{d,n}$ (it draws a word from the previously drawn topic) and all the topics β_K (the probability of $w_{d,n}$ (row) is retrieved from $z_{d,n}$ (column) within the $K \times V$ topic matrix).

Equation 1 shows the joint probability of all the hidden and observed variables and the encoded statistical assumptions underlying LDA. The process now is to infer the hidden variables from the observed variables in order to obtain the topics and topic proportions per document. The inference is based on the conditional probability of the hidden variables given the observed words, also known as the posterior distribution (see Equation 2). Moreover, this inference can be viewed as a reversal of the generative process, and it tries to identify the structure likely to have generated the data.

$$p(\beta_K, \theta_D, z_D | w_D) = \frac{p(\beta_K, \theta_D, z_D, w_D)}{p(w_D)} \tag{2}$$

Unfortunately, the posterior is intractable to compute (Blei et al., 2003) due to the denominator. The marginal probability $p(w_D)$ is the sum of the joint distribution over all instances of the hidden structure and is exponentially large (Blei, 2012). The computational problem now is to estimate the posterior distribution using statistical inference techniques. Several methods exist, such as variational and sampling-based algorithms, for achieving a sufficiently close approximation of the true posterior (Blei and Jordan, 2006; Teh et al., 2006; Hoffman et al., 2010; Wang et al., 2011). Variational methods place a family of probability distributions onto the latent structure and aim to find the distribution closest to the true posterior, measured with, for example, Kullback–Leibler (KL) divergence. Sampling-based inference is a repeated sampling process, generally using one variable at a time while fixing the other variables, until the process converges; the sample values will have the same distribution as if they came from the true posterior. An example of sampling-based inference is the Gibbs sampler (Griffiths and Steyvers, 2004), a Markov chain Monte Carlo (MCMC) algorithm. It is important to note that both variational and sampling-based approaches provide similarly accurate results (Asuncion et al., 2012).

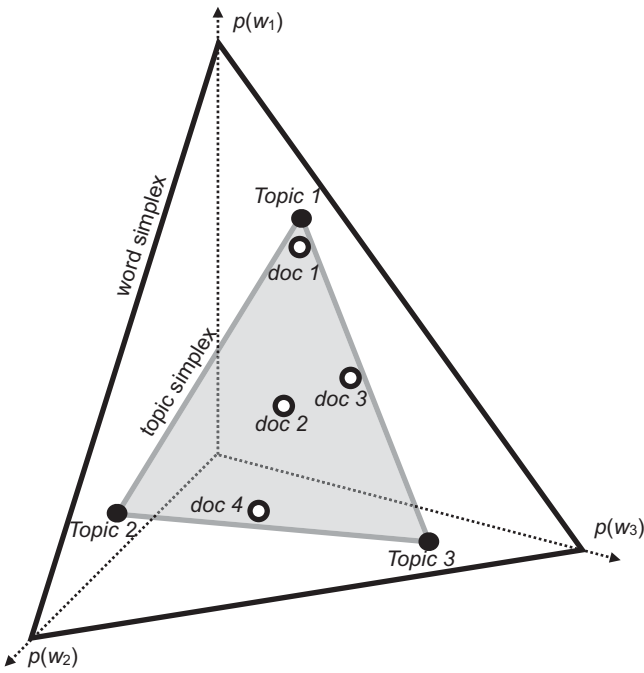


Figure 7. Geometric interpretation of LDA, showing a $(V-1)$ -dimensional word simplex with $V = \{w_1, w_2, w_3\}$, in which every point on the simplex represents a discrete distribution of word probabilities. A point closer to one of the corners indicates that more probability mass is placed on that word. Similarly, within the word simplex a topic simplex can be found, in which a topic represents some probability distribution over all the words (three words in this example). The documents, represented as distributions over topics, are placed within the $(K-1)$ -dimensional topic simplex. As such, each document is represented as a discrete probability distribution over K topics, which in this example is three.

Figure 7 displays a simplified geometric interpretation of LDA. The vocabulary V contains just three words (w_1, w_2, w_3) and is represented as a $(V-1)$ -dimensional word simplex. In reality, the word simplex contains many dimensions, as the vocabulary can easily contain thousands of words. The word simplex relates to all the probability distribution of words. Similarly, Figure 7 illustrates how the topics, modeled as distributions of the vocabulary, are positioned within the word simplex. The example shows three topics T , represented as a $(T-1)$ -dimensional topic simplex. The documents, modeled as distributions over the topics, are points on the topic simplex. For example, Document 1 deals almost entirely with Topic 1; Document 2 exhibits all three topics in equal proportions; and Document 3 has equal proportions of Topics 1 and 3 but none of Topic 2. Note that this only holds if the topic simplex is defined by a uniform Dirichlet distribution that assigns equal probability mass to all topics. The shapes of the Dirichlet distributions within the word simplex and topic simplex are given by η and α , respectively.

Appendix 2

See Table 3

Table 3. The words that occurred in $\geq 90\%$ of the documents and that are thus eliminated from the study. Words that occur in almost every document have no significant topical distinctiveness, and including them would cause these words to dominate every topic. N is the number of publications.

Dataset	N	Words
Overall	22,236	of, and, for, to, the, in, with, is, from, as, this, that, on, are, at, be, an, or, not, was, have, these, were, which, also, between, been, than, all, other, it, more, has, their, but, two, used, research, however, only, can, one, both, each, most, data, when, study, using, such, into, some, number, they, during, where, analysis, there, time, different, high, fish
Estimation models	1124	with, from, as, is, in, of, and, this, for, be, the, to, are, an, at, on, each, not, that, used, or, which, data, was, between, all, also, than, these, more, were, can, two, using, it, number, have, methods, when, but, where, been, fish, both, one, other, however, fisheries, only, if, analysis, their, has, based, because, estimated, such, estimates, different, estimate, use, research, total, some, there, same, size, over, distribution, mean, values, time, then, most, would, into, large, they, new, small, model, could, similar, given, within, study, three, first, those, method
Assessment models	1637	from, an, as, is, in, on, of, and, this, that, for, the, to, be, are, with, not, at, or, have, which, used, it, than, between, also, can, when, these, more, fish, all, where, but, was, however, has, fisheries, other, data, been, two, using, model, research, only, were, such, population, one, each, if, analysis, both, based, values, time, their, some, most, because, different, stock, would, models, there, number, over, management, given, marine, year, size, parameters, into, years, use, methods, first, value, dynamics, mortality, they, assessment, new, biological, then, same, rate, could, estimates, estimated, high, natural, fishery, similar, available, approach, those, should, large, total, its, will, we, species

Appendix 3

Calculating Model Quality

C_V uses four stages to arrive at an overall topic score: (1) segmentation of the topic's top N words into pairs; (2) probability calculations of individual words or pairs of words; (3) calculation of a confirmation measure that captures the agreement of pairs; and finally (4) aggregation of individual confirmation measures into an overall topic coherence score.

- (1) The first step is to segment the data into word subsets to calculate the degree of support between two subsets. C_V segments each word in W with every other word in W , where W is the set of a topic's top 15 words. This segmentation creates pairs, S , where the left subset is $W' \in W$ and the right subset is $W^* \in W$. All pairs are formally defined as $S = \{(W', W^*) \mid W' = \{w_i\}; w_i \in W; W^* = W\}$. For example, if $W = \{\text{salmon, catch, tag}\}$, then one pair might be $S_i = (W', W^*)$ as $W' = \{\text{salmon}\}$ and $W^* = \{\text{salmon, catch, tag}\}$.
- (2) The probabilities of single words $p(w_i)$ and the joint probability of two words $p(w_i, w_j)$ can be estimated using Boolean document calculation – that is, the number of documents in which w_i or (w_i, w_j) occurs divided by the total number of documents. A Boolean document, however, ignores the frequencies and distances of words. C_V incorporates a Boolean sliding window in which a new virtual document is created for each window of size $s = 110$ (Röder et al., 2015) when sliding over the document, with one word token per step. For example, a document d_1 with w words results in the virtual documents $d'_1 = \{w_1, \dots, w_{110}\}$, $d'_2 = \{w_2, \dots, w_{111}\}$, etc. In contrast to a Boolean document, a Boolean sliding window tries to capture word token proximity to some degree.
- (3) For every $S_i = (W', W^*)$ a confirmation measure ϕ is calculated that indicates how strongly W^* supports W' and this confirmation measure is based on the similarity of W' and W^* in relation to all the words in W . To calculate this similarity, W' and W^* are represented as context vectors (Aletras and Stevenson, 2013) as a means to capture the semantic support for all the words in W . These vectors are denoted by $\vec{v}(W')$ and $\vec{v}(W^*)$ and are created by pairing them to all words in W , as exemplified in Equation 3:

$$\vec{v}(W') = \left\{ \sum_{w_i \in W'} \text{NPMI}(w_i, w_j)^y \right\}_{j=1, \dots, |W|} \quad (3)$$

Given the running example of $W = \{\text{salmon, catch, tag}\}$, this can be demonstrated with the pair $S_i = (W', W^*)$ as $W' = \{\text{salmon}\}$ and $W^* = \{\text{salmon, catch, tag}\}$. One of these context vectors is $\vec{v}(W') = \vec{v}(\text{salmon})$, now represented as $\vec{v}_{\text{salmon}} = \{\text{NPMI}(\text{salmon, salmon})^y, \text{NPMI}(\text{salmon, catch})^y, \text{NPMI}(\text{salmon, tag})^y\}$.

The coherence between the individual words w_i and w_j is calculated using normalized pointwise mutual information (NPMI), as expressed in Equation 4. In

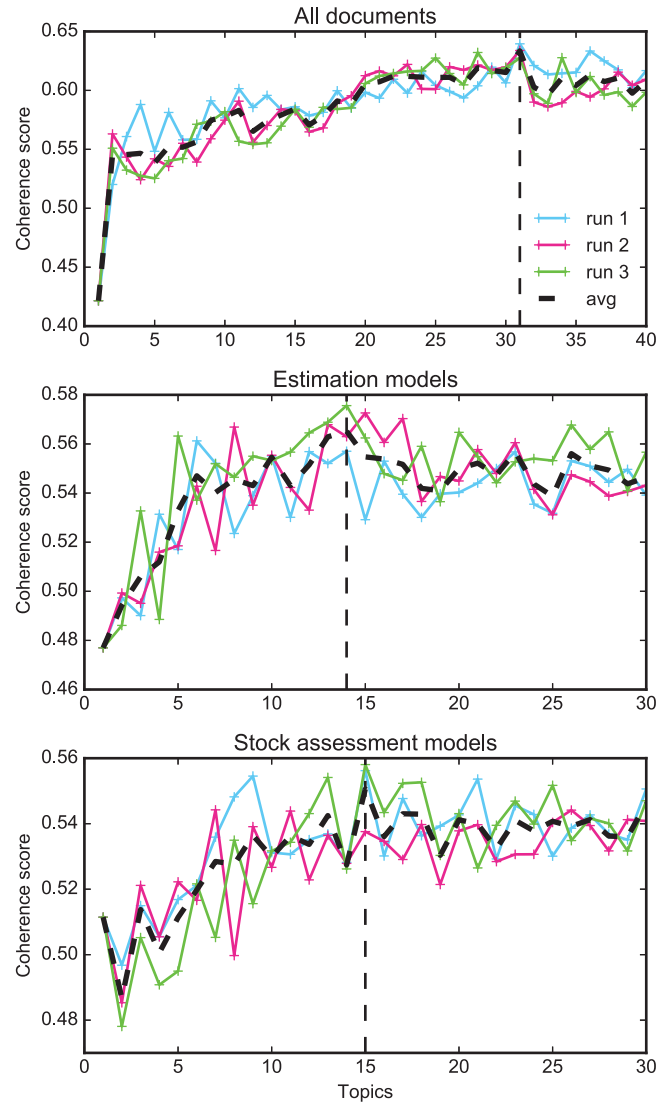


Figure 8. Calculated coherence scores (y-axis) for the number of topics (x-axis) (i.e., K parameter) for three different runs. The average coherence score is calculated by averaging the scores over all three runs for the same K parameter. The figures represent the following: A: all documents ($N = 22,236$); B: documents that exhibit the topic estimation models as the dominant topic ($N = 1124$); C: documents that exhibit the topic stock assessment models as the dominant topic ($N = 1637$).

contrast to pointwise mutual information (PMI), NPMI shows a higher correlation with human topic ranking data (Bouma, 2009). Additionally, $\varepsilon = 10^{-12}$ (Stevens et al., 2012) is used to account for logarithms of zero, and γ is used to place more weight on higher NPMI values.

$$\text{NPMI}(w_i, w_j)^\gamma = \left(\frac{\log \frac{P(w_i, w_j) + \varepsilon}{P(w_i) \cdot P(w_j)}}{-\log(P(w_i, w_j) + \varepsilon)} \right)^\gamma \quad (4)$$

Within a pair $S_i = (W^p, W^*)$, utilizing all context vectors $\vec{v}(W^p)$, denoted here as \vec{u} , and utilizing all context vectors $\vec{v}(W^*)$, denoted here as \vec{w} , the cosine vector similarity ϕ_{S_i} is calculated in order to obtain the confir-

mation measure of the pair $S_i = (W^p, W^*)$. The cosine vector similarity is expressed in Equation 5.

$$\phi_{S_i}(\vec{u}, \vec{w}) = \frac{\sum_{i=1}^{|W|} u_i \cdot w_i}{\|\vec{u}\|_2 \cdot \|\vec{w}\|_2} \quad (5)$$

- (4) Finally, the arithmetic mean of all confirmation measures is taken to obtain the overall coherence score of a topic.

The calculated topic coherence scores can be found in Figure 8.

Appendix 4

See Table 4.

Table 4. The top 15 words (i.e., the words with highest probability) for each of the 31 uncovered general fisheries topics. Topics in bold (i.e., 4 and 9) are the identified modeling topics used in the analysis of this paper, with 4 being the topic estimation models and 9 being the stock assessment models.

Topic	Top 15 words
1	crab, crabs, lobster, eel, eels, size, traps, mm, lobsters, trap, american, anguilla, blue, females, fishery
2	salmon, hatchery, chinook, river, wild, atlantic, survival, coho, sockeye, juvenile, oncorhynchus, fisheries, smolts, pacific, steelhead
3	river, species, sampling, electrofishing, colorado, fishes, chub, capture, population, suckers, sucker, abundance, reach, sites, site
4	model, estimates, catch, survey, sampling, estimated, models, estimate, distribution, abundance, mean, effort, sample, method, size
5	genetic, populations, population, river, loci, samples, among, structure, individuals, microsatellite, within, stock, alleles, diversity, sample
6	prey, larvae, growth, larval, food, predation, size, feeding, diet, juvenile, zooplankton, abundance, mm, predator, rates
7	red, reef, gulf, species, snapper, florida, marine, mexico, reefs, fishes, shrimp, coral, habitat, artificial, drum
8	atlantic, bay, striped, tuna, bass, flounder, estuary, north, marine, new, river, carolina, chesapeake, estuaries, estuarine
9	model, stock, mortality, population, recruitment, models, biomass, year, rate, management, parameters, assessment, fisheries, estimates, fishing
10	species, variables, environmental, sites, lakes, assemblages, community, water, assemblage, richness, communities, diversity, index, models, spatial
11	cod, sea, atlantic, north, species, herring, size, cm, trawl, length, stock, area, mesh, baltic, fishing
12	fisheries, management, fishing, fishery, catch, economic, marine, effort, fishers, species, recreational, information, anglers, use, new
13	habitat, water, flow, use, depth, river, velocity, substrate, channel, areas, sites, site, area, movement, spawning
14	spawning, females, eggs, egg, males, female, reproductive, male, fecundity, sex, maturity, mature, stage, size, development
15	species, sharks, bycatch, shark, catch, longline, fishery, fisheries, fishing, gear, hooks, caught, hook, cm, atlantic
16	mortality, tag, tagged, tags, tagging, release, survival, released, movement, rates, fisheries, studies, capture, effects, transmitters
17	lake, lakes, perch, michigan, yellow, walleye, great, fisheries, northern, walleyes, mean, ontario, journal, consumption, population
18	growth, length, mm, size, otoliths, body, ages, otolith, cm, mean, years, first, weight, differences, lengths
19	temperature, water, growth, effects, swimming, treatment, energy, levels, temperatures, experiment, activity, body, effect, experiments, experimental
20	sea, squid, mediterranean, distribution, area, anchovy, species, waters, larvae, sardine, marine, spawning, shelf, temperature, mackerel
21	bass, largemouth, reservoir, river, species, lake, catfish, smallmouth, fisheries, shad, water, management, reservoirs, white, black
22	species, fishes, freshwater, carp, new, native, river, water, aquaculture, crayfish, populations, introduced, conservation, tilapia, many
23	species, dna, genetic, gene, mtdna, samples, molecular, mitochondrial, sequence, haplotypes, infection, atlantic, identification, disease, sequences
24	acoustic, depth, vertical, water, bottom, surface, ts, distribution, speed, range, target, density, measurements, night, behaviour
25	otolith, otoliths, sr, marine, river, ratios, samples, water, differences, juvenile, chemistry, isotope, freshwater, values, campana
26	fishing, marine, species, fisheries, areas, sea, area, fishery, catch, australia, effort, total, south, effects, coastal
27	river, sturgeon, dam, chinook, columbia, lower, passage, migration, salmon, downstream, steelhead, upstream, juvenile, spawning, dams
28	trout, brook, rainbow, brown, lake, sea, fry, lamprey, river, stocking, lampreys, salvelinus, arctic, streams, stocked
29	water, concentrations, phytoplankton, production, concentration, samples, nutrient, sediment, carbon, total, food, values, biomass, organic, levels
30	stream, trout, streams, creek, habitat, cutthroat, sites, reaches, river, effects, brook, temperature, watershed, abundance, aquatic
31	sea, pacific, marine, species, climate, ocean, north, alaska, rockfish, change, ecosystem, changes, abundance, temperature, california