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Review Article

Natural mortality of fish: a review

Mortalidade natural de peixes: uma revisão

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Abstract

This paper analyzed the scientific production on natural mortality (M) in fish, in order to understand the existing methods and identify the most commonly used ones. Research was carried out in the Web of Science database (WoS), using bibliometric and systematic analysis methods to evaluate scientific production using the following indicators: relevance of scientific journals, scientific recognition of papers, relevance of authors and co-occurrence of keywords. The bibliographic portfolio was composed of the hundred most cited papers of the WoS. The most relevant papers are reviews on the topic studied, which justifies the number of citations. The most cited researchers were the authors of the main estimators of M. The keywords of greatest occurrence were: natural mortality, growth and age. Of the total papers, only 19 estimated M for 28 species. Of these papers, 58% studied population dynamics and 42% made assessments of fish stocks. The most commonly used estimators were Hoenig (1983) and Pauly (1980b). Given the results obtained, it is important to develop more sophisticated methods, taking into account new approaches, such as temperature variation within this estimator, which was not observed in any of the methods.

Keywords: fish, fishery management, population parameters, bibliometry.

Resumo

Este artigo analisou a produção científica sobre a mortalidade natural (M) em peixes, com o objetivo conhecer os métodos existentes e identificar os mais utilizados. Foi realizada pesquisa na base de dados Web of Science (WoS), usando métodos de análise bibliométrica e sistemática para avaliar a produção científica por meio dos indicadores: relevância dos periódicos científicos, reconhecimento científico dos artigos, relevância dos autores e coocorrência de palavras-chave. O portifólio bibliográfico foi composto pelos cem artigos mais citados da WoS. Os artigos de maior relevância são revisões sobre o tema estudado, o que justifica o alto número de citações. Os pesquisadores mais citados foram os autores dos principais estimadores de M. As palavras-chave de maior ocorrência foram: mortalidade natural, crescimento e idade. Do total de artigos, apenas 19 estimaram M para 28 espécies. Desses artigos, 58% estudaram dinâmica populacional e 42% fizeram avaliações de estoques pesqueiros. Os estimadores mais utilizados foram os de Hoenig (1983) e Pauly (1980b). Diante dos resultados obtidos, ressalta-se a importância de desenvolver métodos mais inovadores, levando em consideração novas abordagens, como exemplo, a variação da temperatura dentro desse estimador, o que não foi observado em nenhum dos métodos.

Palavras-chave: peixes, manejo de pescarias, parâmetros populacionais, bibliometria.

1. Introduction

Population dynamics is the central component in fish stock assessment models, and is the only basis for quantitative advice for fisheries management (Hilborn and Walters, 1992). Natural mortality (M) is an essential parameter to estimate the productivity of stock, when considered in combination with the annual number of recruits, body growth rate and age of sexual maturity (Quinn and Deriso, 1999). Thus, obtaining an estimate of M, as accurate as possible, along with estimates of its uncertainty limits, is a key objective for stock status assessments.

According to Kenchington (2014), several methods try to calculate M using estimates made for other stocks of the same species, of similar species or predict M from age-based capture curves, characteristics of the species' life history, tagging and recapture, and ecological theories. More recently, many innovative approaches using electronic tagging and telemetry data promise to make direct and reliable estimates of M for a given stock (Pollock et al., 2004; Polacheck et al., 2006; Hewitt et al., 2007; Bacheler et al., 2009).

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However, estimating the natural mortality rate remains one of the greatest challenges for biologists and modelers in fishery sciences, due to the difficulties associated with estimating M in field experiments (Arriguín-Sánchez et al., 2012). Many of the methods only estimate total mortality, and as a result, natural mortality should be separated from fishing mortality to quantify the relative effects of fishing versus natural mortality (Brodziak et al., 2011). An incorrect specification or poor estimate of M can lead to a bias in estimated quantities using stock assessment methods, resulting in biased estimates of fishing benchmarks and catch limits, with the magnitude of the bias being influenced by life history and trends in fishing mortality (Johnson et al., 2015).

Therefore, knowing the existing and most used methods, as well as their applicability is fundamental to identify existing gaps on this theme. Given these considerations, the main objective of this study was to ascertain the level of scientific production in the area of Fishery Sciences, using a bibliometric and systematic analysis of natural fish mortality and the most commonly used estimation methods. This literature review may possibly pave the way for a better discussion about the different methods to estimate the natural mortality of fish, in addition to guiding future research in this field.

1.1. Estimators of natural mortality

Several approaches exist for estimating M, ranging from the most classical, such as the capture curve method (Beverton and Holt, 1956; Munro, 1982; Ricker, 1975; Csirke and Caddy, 1983), to the more contemporary marking and recapture experiments (Xu et al., 1995; Quinn and Deriso, 1999) and virtual population analysis (VPA) of multi-species (Magnusson, 1995).

According to Kenchington (2014), these approaches require a wide range of data and most require advanced scientific resources, along with supporting infrastructure and budgets, and are unavailable for most fisheries in the world. However, many authors, starting with Beverton (1963), sought simpler, less onerous and more pragmatic estimators for M. Based on this, this author divided the universe of approaches to estimate M into either "burdensome and information intensive", available for few fisheries or "pragmatic alternatives suitable for situations of limited information" and conducted a review of the estimators based on this last approach, while classifying the methods according to: age data, parameters of life history and ecological theory.

In order to provide M estimators for fisheries with limited data, this study describes them systematically and chronologically, presenting their main characteristics, as well as their equations (Appendix A).

The first of this group was described in the 1960s by Tanaka (1960). It is based on the maximum age observed (T_{max}) and it consists in determining the value of M, so that 100% (P) of the animals in the stock survive to age T_{max} (Equation 1). Some authors, such as Hewitt and Hoenig (2005), do not attribute this estimator to Tanaka (1960), but refer to it as the "golden rule"estimator. However, in that decade, Bayliff (1967) used a relationship described by Beverton (1963), who had observed a linear relationship between total mortality (Z) and the inverse of T_{max}, for various clupeids. Considering these stocks as being newly exploited, i.e., with little or no fishing mortality (F) and knowing that Z = M + F, he assumed that Z ≈ M. However, Bayliff (1967) used this relationship specifically for Engraulidae (Equation 2). In the same year, Ursin (1967) developed an estimator based on catabolic and anabolic processes, and took weight into account (Equation 3).

In the 1970s, four M estimators were developed, all based on age. Alverson and Carney (1975) used data from 63 fish populations, taking into account the growth constant (k) of the von Bertalanffy (1938) equation, T_{max} and isometric growth (Equation 4); Sekharan (1975) used the exponential M model for two tropical fish populations, assuming that, in the absence of exploitation, 1% of individuals would reach T_{max} (Equation 5); Rikhter and Efanov (1976) developed two estimators, both considering the same basic relationships as Alverson and Carney (1975), but related to the age of first sexual maturation (t_m), instead of T_{max} and considered allometric growth (β), for the first estimator (Equation 6), though for the second, they applied a regression using data from 14 fish populations (Equation 7).

The 1980s was the period in which most of the M estimators were described. Pauly's (1980b) method was the first of this decade and considered one of the main estimators of M to date (Kenchington, 2014). A priori, Pauly (1978, 1980a, b) took into account the studies of Beverton and Holt (1959), which observed the relationship between M and the growth constant (k) and that of Beverton (1963), and quantified this relationship for the first time, finding M/k for several clupeids. However, Pauly (1978, 1980a, b) developed a more complex version of this approach, developing an M estimator by means of multiple regression, with the independent variables k, L_∞ (asymptotic length) or W_∞ (asymptotic weight) and temperature of the water inhabited by the fish. The first published version (Pauly, 1978, 1980a) was based on 122 fish populations, and the definitive version (Pauly, 1980b), widely used in the last three decades, was based on data from 175 fish populations, mainly teleosts (Equation 8).

Another important estimator, also developed in the 1980s, is that of Hoenig (1983), which used the same approach as Bayliff (1967), but used 84 fish populations, of which 80 were teleosts. This method differs from Bayliff (1967) due to its broader base and addition of an exponential parameter (Equation 9). In the same study, the author developed M estimators for other aquatic organisms. The estimator by Alagaraja (1984) suggested a variant of the Tanaka estimator (1960), replacing the observed T_{max} with T_∞ (age at which a fish would reach its L_∞) (Equation 10). The estimator created by Peterson and Wroblewski (1984) took into account the theory that mortality rates are inversely related to body size in a wide variety of pelagic animals, then quantified this relationship, with the assumption that all deaths in these systems result from predation (Equation 11). The authors themselves do not recommend the use of this estimator for fishery management, because the relationships considered in the analyses were not exclusive to fish.

In the 1980s, Roff (1984) developed two M estimators; the first was an improvement on the estimators of Alverson and Carney (1975) and Rikhter and Efanov (1976), including broader parameters for fish life history (Equation 12). The second was analogous to Pauly's (1980b) estimator, although it was constructed on the basis of mechanistic reasoning and not empirical data (Equation 13). Ralston (1987) also used the studies of Beverton and Holt (1959) and Beverton (1963), on the M/k ratio, to estimate M, but specific to Lutjanid snappers and Serranid groupers, using data from 19 populations in an arithmetic mean regression (Equation 14). Chen and Watanabe (1989) developed an age-specific M estimator, which in addition to the high mortality expected at the beginning of life, would also show senescence at greater ages (Equation 15).

Six M estimators were developed in the 1990s. Charnov and Berrigan (1990), based theirs on simple empirical relationships between M and age of first sexual maturation (t_m) from the works of Beverton and Holt (1959) and Beverton (1963). They did not suggest its application in the M estimate, but Hewitt et al. (2007) deduced and explained the estimator (Equation 16). Djabali et al. (1994) created an alternative version of Pauly's (1980b) estimator for Mediterranean Sea affixes, based on 56 teleost populations. However, the temperature was found to be non-significant throughout the Mediterranean surface water range (Equation 17). Jensen (1996) developed two estimators of M, the first took into account the relationship between M and t_m (Equation 18) and the second between M and k (Equation 19), and showed that measures resulted from an exchange between mortality and growth reduction when a species evolved to maximize its fertility throughout life. Lorenzen (1996) improved the Peterson and Wroblewski (1984) estimator and making specific relationships for affixes (Equation 20). Cubillos et al. (1999) made a change in the Hoenig (1983) estimator, replacing T_{max} with $T_{95\%}$ (the age that fish reaches 95% of L_∞) (Equation 21).

In the decade from 2000-2010, Groeneveld (2000) claimed to have extracted the basis of his estimator from Beverton and Holt (1959), although these authors did not present evidence for their claim and still confirmed that their application generated estimates that can not be replicated using the values of the parameters (Equation 22). Frisk et al. (2001) developed their M estimator by making M/k ratios for 30 species of elasmobranchis (Equation 23). Jensen (2001) revised Pauly's (1980b) estimator and claimed that one of the data points used by him was wrong, therefore he repeated the regression analysis to eliminate the error (Equation 24). Zhang and Megrey (2006) merely revised the estimator of Alverson and Carney (1975), with changes in the type of growth and age, and presented a more generalized version (Equation 25). Griffiths and Harrod (2007) also revised Pauly's (1980b) estimator to generate their M estimator, using more advanced regression analyses and an expanded set of M estimates, removing the temperature effect (Equation 26). Jennings and Dulvy (2008) proposed an M estimator based on the effects of body size and temperature on fish life histories (Equation 27).

More recently, Gislason et al. (2010) adjusted their M estimator in a model that allowed M to vary with individual length, as well as with L_∞ and k (Equation 28). However, Charnov et al. (2013) made a review of this last estimator, because they found errors of analysis, and made it simpler. Although Charnov et al. (2013) developed the new equation, the new estimator is known second estimator of Gislason et al. (2010) (Equation 29). And finally, Kenchington (2014) used the same reasoning as Hoenig's (1983) estimator, however added the recruitment age (t_c) to the equation (Equation 30).

Kenchington (2014) applied each of these estimators to 13 examples of fish resource populations and came to the conclusion that they do not provide accurate estimates for all species, are not accurate enough for use in analytical models of stock assessments, and some of these estimators perform so poorly that they have no practical utility.

All mathematical models of the dynamics of fish stocks include M and do not explicitly require any specific form for this parameter, it may be constant or vary in any way. But since M proved extremely difficult to measure directly, it is almost always considered a specific constant for any stock being modeled (Vetter, 1988). However, M is far from constant for many fish stocks and this variability is extensive enough to be ignored. Vetter (1988) suggested that analyses of fish stock dynamics need much stricter estimates of M variability within fish stocks, and Kenchington (2014) recommended that fishery scientists estimate M by more advanced methods whenever possible.

2. Metodology

2.1. Methodological framework

The analysis of the portfolio was performed through bibliometry, followed by systematic analysis of the papers. Bibliometric analysis is performed from 'metric studies', as an analysis tool for evaluating the information produced based on quantitative resources. Therefore, the bibliometric analysis started from the process of quantitative evidence of the statistical data of a defined set of papers (bibliographic portfolio), for the management of information and scientific knowledge of a given subject, carried out through the counting of documents (Kobashi and Santos, 2008). With regard to systemic analysis, this is a research methodology used to describe and interpret the content of a class of documents and texts that, through such analysis, can lead to systematic, qualitative or quantitative descriptions (Moraes, 1999). This was performed from the full reading of the texts selected in the bibliographic portfolio. Thus this has a result that allows the researcher to comprehend the state of the art of the subject in question. The systematic search is replicable, transparent and scientific, in addition, it allows the identification of gaps, as well as the identification of the knowledge produced, that is, what is known and, consequently, it is also possible to identify what is not known (Inomata et al., 2015).

2.2. Selection of the bibliographic portfolio

The selection process of the papers, used to form the bibliographic portfolio, was divided into 6 steps and can be observed schematically in Figure 1. The survey was conducted between July and October 2019.

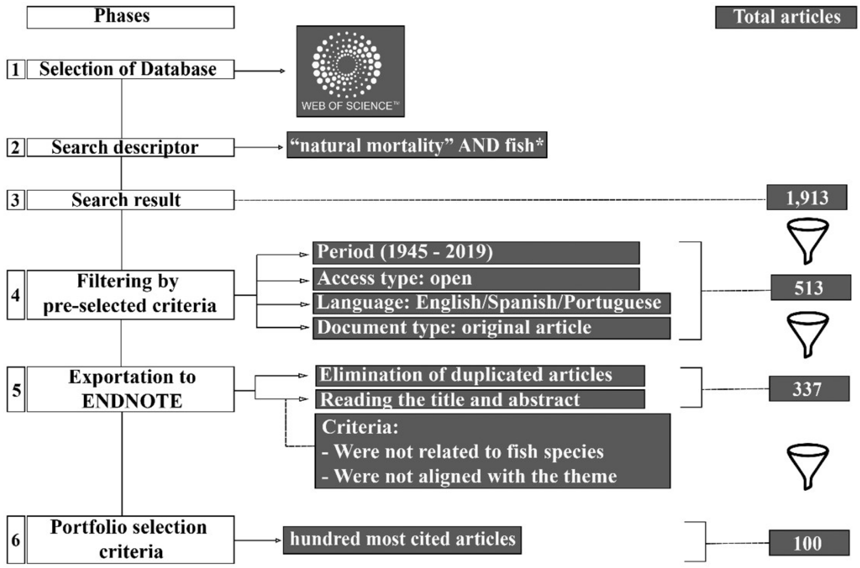

Figure 1. Selection process of the papers used to form the bibliographic portfolio.

The first step was the choice of the database. The selected database was the main collection of Web of Science (WoS), because it is multidisciplinary, and allows the integration of relevant sources for systematic bibliographic research and also indexes only the most cited journals in their respective fields, in addition to being one of the largest databases of abstracts and bibliographic references of peer reviewed, scientific literature (Costa and Zoltowski, 2014). The second step was the definition of search descriptors ("natural mortality AND fish*"). These terms were chosen in order to identify the papers that related natural mortality with fish, the target taxonomic group. The descriptors were defined in English, because it was intended to identify the international visibility of papers. The third step was the search, which identified 1,913 papers. The fourth step was the application of pre-selected criteria filters, where the following was defined: period - the entire time interval of the database (1945-2019); type of access (free), language the papers were published in (English, Spanish and Portuguese) and the type of document (full paper). After this filtering, 513 papers were identified. The fifth step was the export of these papers to a bibliographic reference management software. The software used was the Endnote Web, which is available on the WoS base. In this step, duplicate papers were excluded and, after reading the titles and abstracts, those that were not aligned with the theme "natural mortality" and those that did not correspond to fish were also excluded. By the end of this stage, 337 papers had been detected. The sixth step was the selection of the portfolio, defined from the 337 papers selected in the previous step, using the criterion of the 100 most cited papers in the WoS (Appendix B).

2.3. Bibliometric and systematic analysis

The systematic bibliometric analysis was used to analyze the following aspects: the degree of relevance of the journals, measured by the number of papers published in the jornal, by the SCImago Journal Rank (SJR), which is a measure of the influence of scientific journals using both the number of citations received by a journal and the importance or prestige of the journals where the citations occur, and the quartile in which the set of journals classified according to the SJR, and is divided into four equal groups, where Q1 comprises the one-quarter of the journals with the highest values, and the Q2, Q3, and Q4, are the following quartiles in descending order; the degree of recognition of scientific papers, as measured by the citation index; the degree of author relevance, which is measured by the number of papers published and the contents of the co-citations of the authors; and coherence of the keywords for the identification of the most commonly used. Therefore, a set of information was formed that allowed us to plan, execute and perform data analysis in an efficient and effective way.

As for the representation of metadata which came from the systematic search, we used VOSviewer software, version 1.6.11. Created in 2010 by the Centre for Science and Technology Studies of the University of Leiden (The Netherlands), it is a free software that compiles network maps based on data extracted from scientific production. With the help of the VOSviewer the analysis of the information of word co-occurrence was performed, through the generation of matrices, which served as the basis for the elaboration of network maps (Inomata et al., 2019).

The maps show items that are indicated by a tag: author in the case of co-authoring maps; and, words, for co-occurrence maps, and are presented in circular format. For each item, the size of the tag and circle may vary, that is, the greater the weight or frequency of these items the larger the tags and circles will be. With regard to the colors used in the representations of the VOSviewer software, the color of the item is defined by the cluster or group to which a particular item belongs, thus, the closer the items, the stronger their relationship (Van Eck and Waltman, 2019). In addition, the VOSviewer software also allows representation by means of a heat map, in which the more intense the color, the greater concentration of the publications at this point.

2.4. Analysis of methods used to estimate natural mortality (M) in fish

To analyze which are the most used methods for estimating M according to the bibliographic portfolio, an Excel spreadsheet was prepared, where the following information was extracted: species; population parameters: maximum asymptotic length (L_∞), growth constant (k), age at zero length (t_0), maximum age (T_{max}), when estimated and natural mortality (M); and method of estimating M (Appendix C).

3. Results

The bibliographic portfolio was composed of the hundred most cited papers of the Web of Science database, after going through several stages of selection, therefore, they are presented in order of citation. Each paper received an identification number (ID), ranging from A01 to A100 (Appendix B).

3.1. Bibliometrics

3.1.1. Degree of relevance of journals

The journals with the highest number of papers published were: Ices Journal of Marine Science, Fishery Bulletin and Marine Ecology Progress Series, two of high quality and one of medium quality, according to SJR and quartile indicators, as can be observed in Table 1. However, it can be noted that the Evolutionary Applications, Journal of Applied Ecology and Proceedings of The Royal Society B: Biological Sciences, with fewer publications, are also high-quality journals.

3.1.2. Degree of scientific recognition of papers

The citation index of the papers aimed to identify the number of times each paper was cited in other research. The most cited papers can be observed in the table containing the portfolio (see Appendix B), which is arranged in order of citation. The following papers are highlighted: *Natural mortality of marine pelagic fish eggs and larvae - role of spatial patchiness*; *Estimation of natural mortality in fish stocks - a review;* and *Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems?*, with 321, 198 and183 citations, respectively.

Figure 2 shows the most cited papers represented by their authors – McGurk (1986), Vetter (1988) and Hollowed et al. (2000). Of the most cited papers, two of them are reviews on the topic studied, which can justify the number of citations.

McGurk (1986) studied the relationship between natural mortality of Roe and marine pelagic fish larvae and their spatial distribution. Vetter (1988) reviewed the methods used to estimate M for fish stocks, the sensitivity of common fishing models to the values chosen for M, and the evidence that refutes the assumption that a constant value of M may be an adequate approximation of M in single fishing stocks. Hollowed et al. (2000) reviewed the application of multi-species models as tools to assess the impacts of fishing on marine communities.

3.1.3. Degree of relevance of the authors

The portfolio was composed of 343 authors, distributed among main authors and co-authors. Among these, those who published from three papers on the topic were highlighted: Dieckmann, U. (4); Gislason, H. (4); Swain, D. P. (4); Heino, M. (3); Jorgensen, C. (3); Methot, R. D. (3); Newman, S. J. (3); Ono, K. (3); Punt, A. E. (3); Rochet, M. J. (3); Stenseth, N. C. (3) and Valero, J. L. (3).

As for the authors' co-citations, 863 occurrences were identified, taking into account the minimum of 2 occurrences for this analysis, i.e., when the author was

Table 1. Most relevant journals identified in the research, according to the number of published papers, the Scimago Journal Rank (SJR) indicator and respective quartilhes.

Journal	Papers Published[a]	SJR	Quartile
Ices Journal of Marine Science	33	1.59	Q1
Fishery Bulletin	19	0.59	Q2
Marine Ecology Progress Series	12	1.28	Q1
Canadian Journal of Fisheries and Aquatic Sciences	5	1.23	Q1
Aquatic Living Resources	4	0.40	Q3
Evolutionary Applications	3	2.17	Q1
Journal of Applied Ecology	2	2.73	Q1
Mediterranean Marine Science	2	0.90	Q1
Plos One	2	1.10	Q1
Proceedings of The Royal Society B: Biological Sciences	2	2.72	Q1

[a]Occurrence of two or more papers.

cited at least twice. The researcher Pauly, D. was the most cited, with 67 citations, followed by Ricker, W. and Hilborn, R., with 36 citations each, and Hoenig, J. and Punt, A., with 31 citations each (Figure 3). It is observed that among the most cited researchers are, precisely, the authors of the main estimators of M in fish and, therefore, consolidated in the literature on the topic addressed, ensuring that the portfolio, as well as the analyses, presented an alignment with the objective of the study.

Pauly, D., known for his studies of human impacts on global fisheries, is currently a researcher at the Institute for the Oceans and Fisheries at The University of British Columbia and his main lines of research are Aquatic Ecosystems, Ichthyology and Fisheries Management. Ricker, W., who died in 2001, was one of the founders of Fishery Science and is known for the "Ricker model", which is used to study stock and recruitment in fishing, but he was also internationally recognized as an entomologist and

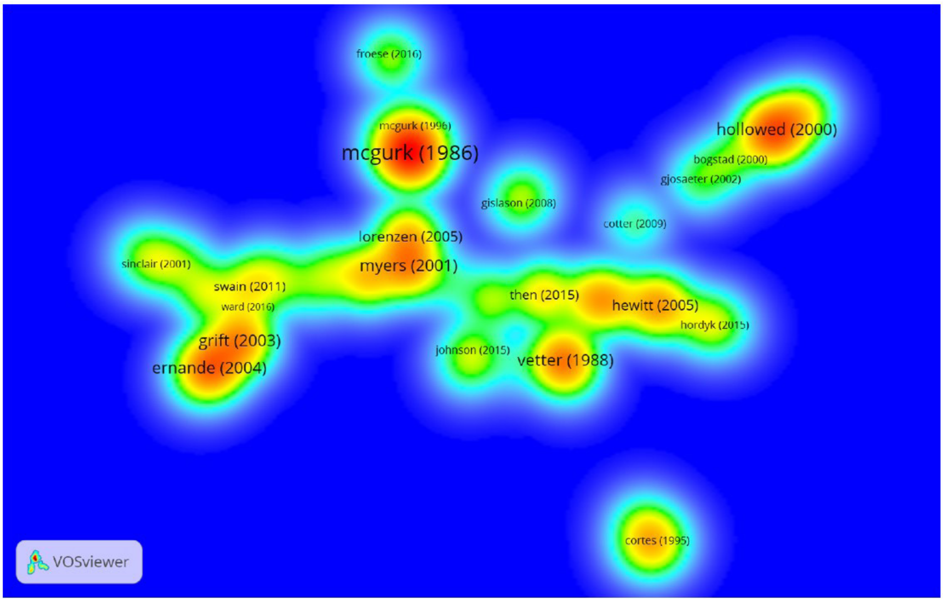

Figure 2. Heat map of the citation index by paper, from the bibliographic portfolio.

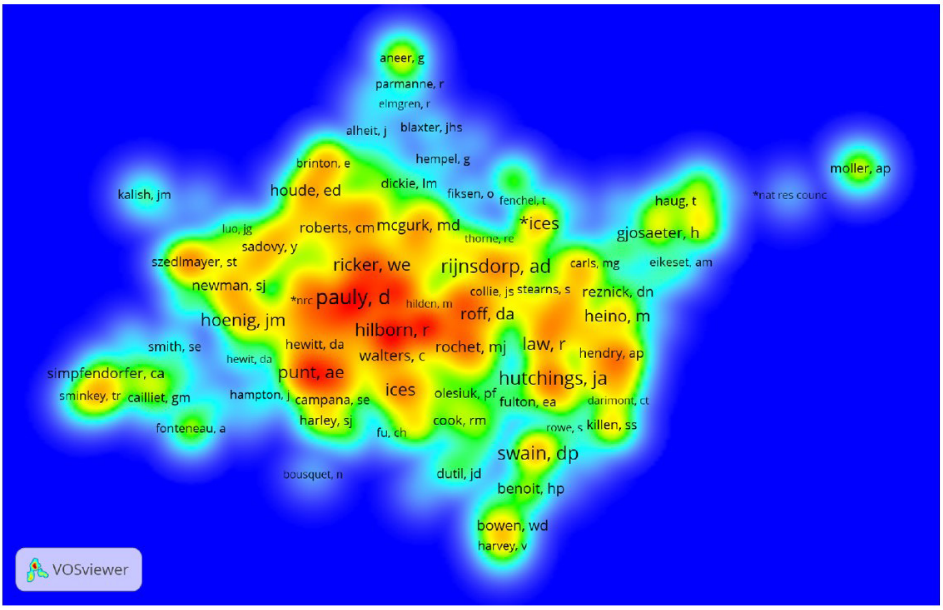

Figure 3. Heat map of authors co-citations from the bibliographic portfolio.

scientific editor. Hilborn, R. is a professor at the School of Aquatic and Fishery at the University of Washington, and develops research in the areas of management and conservation of natural resources, evaluation of fish stocks and modeling, as well as advising several international fishery commissions and agencies.

3.1.4. Most used keywords

The occurrence of keywords related to the topic, in addition to those used as search descriptors (natural mortality and fish), was estimated using the criterion of a minimum of two occurrences in the database publications. 160 keywords were identified, which were grouped into 9 clusters. In the keyword co-occurrence map, it is observed that the keywords that most often occurred were: natural mortality, with 37 occurrences and 122 interactions; growth, with 28 occurrences and 94 interactions; and age, with 15 occurrences and 60 interactions (Figure 4). It is evident that the term natural mortality would be the most common, because it was the search term in the databases. However, the keywords of greater occurrence demonstrate an alignment between the descriptors used in this research with those of the bibliographic portfolio. It is worth noting that the keywords are chosen by the author in order to represent the content of the text and are usually related to the object of study used in conducting the research.

It is also possible to see that the clusters are connected, forming a dense network, the terms of which are related. For example, studies on fish growth and age are related (pink cluster), since they are indispensable parameters for the study of population dynamics of fish stocks (Sparre and Venema, 1997). Analyzing the green cluster, it is observed that Atlantic cod is highly correlated with the terms collapse and fisheries management. Most likely, this was because the cod collapsed in the early 1990s (Swain, 2011) and many studies were conducted to manage this important fishery resource (Butterworth and Rademeyer, 2008; Swain, 2011; Zemeckis et al., 2014; Eero et al., 2015). Just as it was observed in the yellow cluster, there was a high occurrence of cod gadus-morhua, which is also the Atlantic cod, evidencing that this is a highly-studied species.

3.1.5. Methods used to estimate natural mortality (M) of fish

After reading the entire bibliographic portfolio (100) it was found that one paper was not found in full on the web and three did not study fish, it is not possible to verify at the time of selection of the portfolio, since both the title and the abstract, indicated that the study object was fish, however, in this case, it was crustaceans. Of the remaining 96 papers, 77 used M indirectly, i.e., estimated by other studies. As our aim was to verify which methods were used to estimate M, only studies that estimated this parameter directly, (a total of 19 papers) were considered.

The papers considered in this analysis applied the estimates of M to discover the population dynamics and make assessments of fish stocks. Of these, 58% estimated parameters for understanding population dynamics and 42% of the papers evaluated stocks. Natural mortality rates were estimated for a total of 28 species, but not all estimated other population parameters, such as maximum asymptotic length (L_∞), growth constant (k), age at zero length (t_0) and maximum age (T_{max}) (Appendix C). For M estimates, the following estimators were used: Ricker (1975), Pauly (1980b), Hoenig (1983), Jensen (1996),

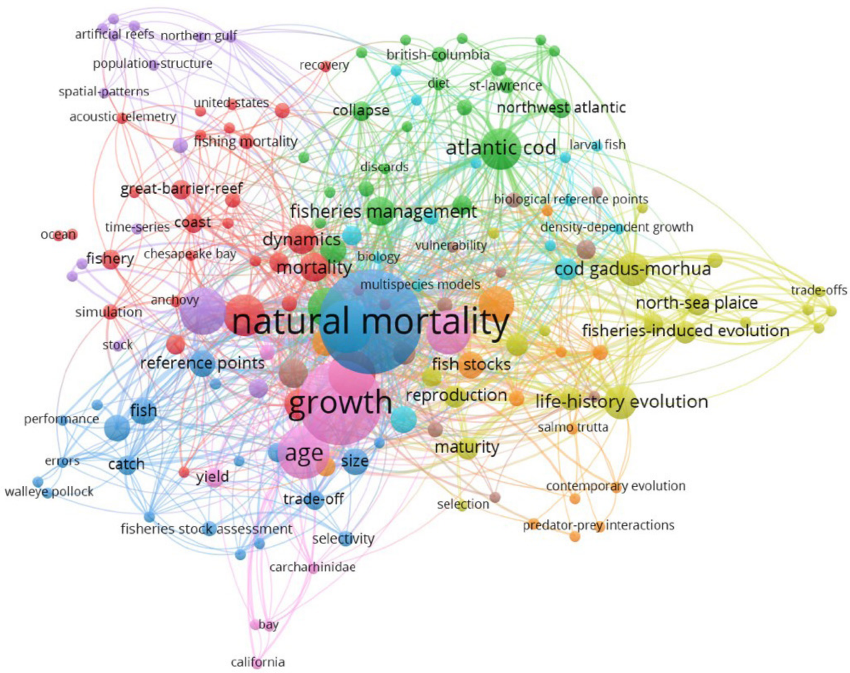

Figure 4. Bibliographic portfolio keyword co-occurrence map.

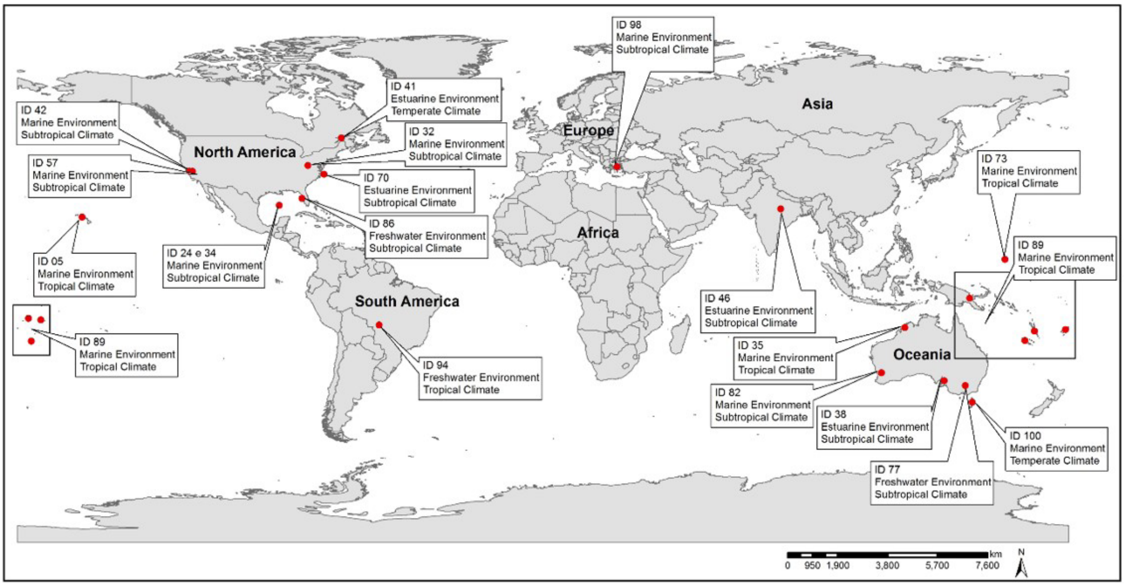

Figure 5. Distribution of studies, which estimated natural mortality in fish, by type of environment and climatic zone.

Peterson and Wroblewski (1984), Chen and Watanabe (1989), Lorenzen (1996) and paper A42 estimated M based on the equation $N_t = n_{0.} e^{-MT}$, adjusted by a weighted linear regression of $Log_e(N_T)$ in function of T.

Considering M estimators as either 'burdensome and information intensive' or 'pragmatic alternatives suitable for situations of limited information,' 18 papers estimated M based on the approach 'pragmatic alternatives suitable for situations of limited information,' and only paper A41 estimated M based on the approach 'burdensome and information intensive. Some authors used more than one M estimator for the same species (Appendix C). The most commonly used estimators were Hoenig (1983) and Pauly (1980b), with 10 and 9 uses, respectively. The first based on maximum age data (T_{max}) and the second on life history parameters.

As for the type of Environment, 16 studies were carried out with marine species and only three studies were carried out for freshwater species (3). The climatic zone that prevailed was the subtropical zone, with 12 studies, followed by the tropical Zone (5) and temperate zone (2) (Figure 5). As can be seen in Figure 5, the studies are concentrated in North America and Oceania.

4. Conclusions

In this review, it was possible to identify several patterns and relationships from the bibliometric indicators, such as the main journals, the main authors on the subject, as well as the collaboration network that works on the investigation of natural mortality (M) in fisheries. In addition, it was possible to discover which M estimators were most used by the authors who comprised the bibliographic portfolio. Given the results obtained from the review of the M estimators, the importance of developing more innovative methods can be noted. These methods should take into account new approaches, such as the temperature variation or other environmental parameters relevant to the populations within this estimator, which was not observed in any of the methods.

It is noteworthy that, for the elaboration of the sample analyzed in the bibliometric and systematic study, this study adopted as a criterion the publications that had the descriptors "natural mortality and fish" mentioned in the subject field. However, it is possible that some papers adhering to the topic may eventually not have been selected.

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Supplementary Material

Supplementary material accompanies this paper.

Appendix A. Natural mortality (M) estimators in fish for limited data.

Appendix B. Portfolio selected from the Web of Science database concerning natural mortality in fish, with its respective Identification Number (ID) and in order of most cited.

Appendix C. Population parameters [asymptotic growth ($L\infty$), growth rate (k), age at zero length (t0), maximum age (Tmax), natural mortality (M) temperature of the water surface (T)] and methods of estimating M of the species extracted from the bibliographic portfolio, with their identification number (ID).

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