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AVALIAÇÃO DOS EFEITOS DAS MUDANÇAS CLIMÁTICAS GLOBAIS EM ESTOQUES PESQUEIROS COM DIFERENTES ESTRATÉGIAS DE VIDA

CAROLINE PEREIRA DE CAMPOS

MANAUS-AM

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Tese apresentada ao Programa de Pós-Graduação em Ciência Animal e Recursos Pesqueiros, da Universidade Federal do Amazonas, área de concentração Uso Sustentável de Recursos Pesqueiros Tropicais, linha de pesquisa Manejo e Conservação de Recursos Pesqueiros, para obtenção do título de Doutora em Ciência Animal e Recursos Pesqueiros.

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Ao meu pai, Carlos de Campos Junior (in memorian). Te amo para sempre, painho!

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"Eu tentei 99 vezes e falhei.
Mas na centésima tentativa eu consegui.
Nunca desista de seus objetivos,
mesmo que eles pareçam impossíveis,
a próxima tentativa pode ser a vitoriosa."
Albert Einstein

RESUMO

Os efeitos do aumento da temperatura decorrente das mudanças climáticas globais estão diretamente relacionados à sobrevivência dos peixes e, portanto, com sua mortalidade natural (M). Este parâmetro é um dos mais importantes na avaliação de estoques pesqueiros e considerar as incertezas nas estimativas de M é fundamental para o sucesso do gerenciamento desses estoques. Além disso, os padrões encontrados nas incertezas de M podem ser usados em abordagens mais holísticas, baseado nos agrupamentos de espécies com diferentes características de história de vida. Para modelar matematicamente essas incertezas, utilizou-se a Teoria dos Conjuntos Fuzzy para avaliar os efeitos do aumento da temperatura sobre M e, consequentemente, sobre o Rendimento por Recruta (Y/R) de peixes com diferentes estratégias de vida, considerando os cenários do IPCC (*Intergovernmental Panel on Climate Change*). Os modelos gerados confirmaram que o aumento da temperatura ocasiona um aumento em M e uma diminuição no Y/R para todas as espécies, entre o cenário atual e o cenário mais pessimista do IPCC. Além disso, espécies com características de história de vida oportunistas foram as que apresentam maior aumento de M, diminuição de Y/R e maiores incertezas de M e Y/R. Também foram estimados intervalos com possibilidades de rendimento máximo sustentável (MSY) e suas respectivas mortalidades por pesca (F_{MSY}), fornecendo pontos de referência biológicos (PRB) para a gestão pesqueira. As espécies com características de história de vida oportunistas apresentaram maior variação na diminuição de MSY. Como essas espécies são mais propensas ao risco, por apresentar maior incerteza, recomenda-se cenários mais conservadores na escolha de PRB's para essas espécies. Portanto, o presente estudo contribuiu para o gerenciamento pesqueiros abordando as incertezas inerentes aos efeitos das mudanças climáticas globais e no gerenciamento de estoques baseado nos agrupamentos de espécies com diferentes características de história de vida.

Palavras-chave: temperatura, lógica fuzzy, mortalidade natural, rendimento máximo sustentável, gerenciamento pesqueiro.

ABSTRACT

The effects of the increase in temperature due to global climate changes are directly related to fish survival and, therefore, with their natural mortality (M). This parameter is one of the most important in the fish stocks assement and considering the uncertainties in the estimates of M is fundamental for the success of the management of these stocks. In addition, the patterns found in the uncertainties of M can be used in more holistic approaches, based on groupings of species with different characteristics of life history. To mathematically model these uncertainties, the Fuzzy Set Theory was used to evaluate the effects of the temperature increase on M and, consequently, on the Recruit Yield (Y / R) of fish with different life strategies, considering the scenarios of the IPCC (Intergovernmental Panel on Climate Change). The generated models confirmed that the increase in temperature causes an increase in M and a decrease in Y / R for all species, mainly comparing the current scenario and the most pessimistic scenario of the IPCC. In addition, species with opportunistic life history characteristics were those with the greatest increase in M, decrease in Y / R and highest uncertainties in M and Y / R. Intervals with maximum sustainable yield possibilities (MSY) and their respective fishing mortality (FMSY) were also estimated, providing biological reference points (PRB) for fisheries management. Species with opportunistic life history characteristics showed greater variation in decreasing MSY. As these species are more prone to risk, due to their greater uncertainty, more conservative scenarios are recommended when choosing PRBs for these species. Therefore, the present study contributed to fisheries management by addressing the uncertainties inherent in the effects of global climate change and in stock management based on groupings of species with different characteristics of life history.

Keywords: temperature, fuzzy logic, natural mortality, maximum sustainable yield and fisheries management.

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SUMÁRIO

APRESENTAÇÃO

O aumento da temperatura média global da superfície do planeta, devido à elevação dos níveis de emissões de gases de efeito estufa (GEE), tem consequências biológicas ainda desconhecidas em sua totalidade (VAL, 2011). Para os organismos aquáticos, como os peixes, os efeitos das mudanças climáticas representado pelo aumento da temperatura provocam mudanças biológicas diretas sobre suas populações, que incluem mudanças na abundância, padrões de migração e distribuição geográfica. A nível de indivíduo, o aumento da temperatura implica nas respostas fisiológicas, que tem efeitos diretos sobre a mortalidade natural (M) de peixes (FREITAS et al., 2013; BARROS e ALBERNAZ, 2013; JEPPESEN et al., 2014; OJEA et al., 2017; ANDRADE et al., 2018; CAMPOS et al., 2018; VAL, 2019; OREMUS et al., 2020). Além disso, as mudanças climáticas causam alterações na abundância e produtividade pesqueira global já comprovado por diversos estudos (CHEUNG et al., 2010; SERPETTI et al., 2017; GAINES et al., 2018; CISNEROS-MATA et al., 2019; FREE et al., 2019), exacerbando os efeitos já negativos da pressão de pesca insustentavelmente alta que existe para alguns estoques (CISNEROS-MATA et al., 2019).

A Mortalidade Natural (M) é um parâmetro fundamental para entender a dinâmica das populações explotadas (KENCHINGTON, 2014) e para desenvolver procedimentos de conservação e manejo (CANALES et al., 2019). No entanto, a maioria dos modelos de avaliação de estoque pesqueiros assumem M constante para toda a população (DEROBA e SCHUELLER, 2013), sem levar em consideração o grande nível de incerteza que envolve a estimativa desse parâmetro (KENCHINGTON, 2014), devido a qualidade dos dados, dos métodos de estimação, da variação no tempo (CHEN et al., 2018) e das mudanças climáticas globais que, ao se juntarem às ameaças da sobrepesca, comprometem ainda mais os regimes de gestão (IPCC, 2014). Portanto, propagar as incertezas das estimativas de M induzidas pelo aumento da temperatura causado pelas mudanças climáticas é fundamental para o resultado da avaliação de estoque e, consequentemente, para os níveis de captura sustentáveis (BRODZIAK et al., 2011), sendo possível explorar cenários de gestão da pesca (SERPETTI et al., 2017). A incorporação dessas incertezas traz robustez ao modelo gerado quando este é baseado em metodologias que possibilitam a modelagem matemática da incerteza, como a Lógica Fuzzy (BARROS e BASSANEZI, 2010).

Os efeitos das mudanças climáticas podem afetar também fenômenos ambientais sazonais relacionados com o ciclo de vida dos peixes. Muitos aspectos da história de vida dos peixes estão relacionados ao clima em uma escala evolutiva, o que lhes confere alta ou baixa plasticidade (SLOMAN et al., 2006; VAL e ALMEIDA-VAL, 1995, VAL, 2011; JEPPESEN et al., 2014), dependendo da estratégia de vida de cada espécie (BLANCK e LAMOUROUX, 2007; ROPKE et al., 2017). Portanto, considerar as estratégias de vida de cada espécie é fundamental para reconhecer a amplitude e a intensidade de um fenômeno ambiental (BLANCK e LAMOUROUX, 2007; RÖPKE et al., 2017).

Nesse sentido, o objetivo geral da tese foi avaliar os efeitos das mudanças climáticas globais sobre estoques pesqueiros com diferentes estratégias de vida utilizando a Lógica Fuzzy. Para isso, foi feita uma revisão dos métodos de estimativa de Mortalidade Natural (M). Após, estimou-se a Mortalidade Natural (M) incorporando as variações e incertezas frente às mudanças climáticas globais e, posteriormente, incorporou-se essas incertezas de M na avaliação de estoques pesqueiros.

A tese é composta por três capítulos em forma de artigos. O **Capítulo I** apresenta uma revisão da produção científica sobre mortalidade natural de peixes e os métodos de estimativa mais utilizados, a partir de uma análise bibliométrica e sistemática. Portanto, além de conhecer os métodos existentes e os mais utilizados, bem como sua aplicabilidade, também identificou lacunas existentes sobre esse tema, ressaltando a importância de considerar novas abordagens, como a variação da temperatura dentro desses estimadores. O **Capítulo II** aplicou a Teoria dos Conjuntos Fuzzy para avaliar os efeitos das variações da temperatura, provocadas pelas mudanças climáticas globais, sobre a Mortalidade Natural (M) de peixes, considerando diferentes estratégias de vida. O **Capítulo III** incorporou as incertezas das taxas de Mortalidade Natural (M), estimadas no capítulo 2, partindo do pressuposto que essas incertezas são associadas às estratégias de vida das espécies explotadas. Além disso, apresentou as faixas de possibilidades para Rendimentos Máximo Sustentáveis (MSY’s), que fortalece as recomendações científicas sobre procedimentos de conservação e gestão desses estoques pesqueiros, como a definição de pontos de referência biológicos (PRB) que servem como ponto de partida para conselhos de capturas sustentáveis.

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CAPÍTULO I

NATURAL MORTALITY OF FISH: A REVIEW

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Natural mortality of fish: a review

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Abstract

Objetive. This paper analyzed the scientific production on natural mortality (M) in fish, in order to identify the most commonly used estimation methods.

Method. 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. In addition, the collaboration network of authors, institutions and countries was analyzed.

Results. 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. Only 20% of the authors wrote in co-authorship. The main research on the topic is concentrated in research institutes and universities in North America. Consequently, the USA and Canadawere the countries that conducted the most research related to the topic studied. Of the total papers, only 19 estimated M for 28 species, mostly marine fish from subtropical zones. Of these papers, 58% studied population dynamics and 42% made assessments of fish stocks. The most commonly used estimators were Hoenig and Pauly.

Conclusions. Given the results obtained, it is important to develop more sophisticated m ethods, 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

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 as accurate an estimate of M as possible, along with estimates of its uncertainty limits, is a key objective for stock status assessments.

According to Kenchington (2013), 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 (HEARN et al., 1998; FRUSHER and HOENIG, 2001; HIGHTOWER et al., 2001; LATOUR et al., 2003; POLLOCK et al., 2004; POLACHECK et al., 2006; HEWITT et al., 2007; BACHELER et al., 2009).

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.

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 (HOCHBAUM and WALTERS, 1984; BROWNIE et al., 1985; XU et al., 1995; QUINN and DERISO, 1999) and virtual population analysis (VPA) of multi-species (MAGNUSSON, 1995).

According to Kenchington (2013), 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} [Eq. 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 $Z \approx M$. However, Bayliff (1967) used this relationship specifically for Engraulidae [Eq. 2]. In the same year, Ursin (1967) developed an estimator based on catabolic and anabolic processes, and took weight into account [Eq. 3].

In the 1970s, 4 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 equation (1938), T_{max} and isometric growth [Eq. 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} [Eq. 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 [Eq. 6], though for the second, they applied a regression using data from 14 fish populations [Eq. 7].

The 1980s was the period in which most of the M estimators were described. Pauly's method (1980b) was the first of this decade and considered one of the main estimators of M to date (KENCHINGTON, 2013). A priori, Pauly (1978 and 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 and 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 and 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 [Eq. 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 [Eq. 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_∞) [Eq. 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 [Eq. 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 [Eq. 12]. The second was analogous to Pauly's estimator (1980b), although it was constructed on the basis of mechanistic reasoning and not empirical data [Eq. 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 [Eq. 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 [Eq. 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 [Eq. 16]. Djabali (1994) created an alternative version of Pauly's estimator (1980b) for Mediterranean Sea affixes, based on 56 teleost populations. However, the temperature was found to be non-significant throughout the Mediterranean surface water range [Eq. 17]. Jensen (1996) developed two estimators of M, the first took into account the relationship between M and t_m [Eq. 18] and the second between M and k [Eq. 19], and showed that measures resulted from an exchange between mortality and reduction when a species evolved to maximize its fertility throughout life. Lorenzen (1996) improved the Peterson and Wroblewski estimator (1984) and making specific relationships for affixes [Eq. 20]. Cubillos et al. (1999) made a change in the Hoenig estimator (1983), replacing T_{max} with $T_{95\%}$ (the age that fish reaches 95% of L_∞) [Eq. 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 [Eq. 22]. Frisk et al. (2001) developed their M estimator by making M/k ratios for 30 species of elasmobranchis [Eq. 23]. Jensen (2001) revised Pauly's estimator (1980b) and claimed that one of the data points used by him was wrong, therefore he repeated the regression analysis to eliminate the error [Eq. 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 [Eq. 25]. Griffiths and Harrod (2007) also revised Pauly's estimator (1980b) to generate their M estimator, using more advanced regression analyses and an expanded set of M estimates, removing the temperature effect [Eq. 26]. Jennings and Dulvy (2008) proposed an M estimator based on the effects of body size and temperature on fish life histories [Eq. 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 [Eq. 28]. However, Charnov et al. (2012) made a review of this last estimator, because they found errors of analysis, and made it simpler. Although Charnov et al. (2012) developed the new equation, the new estimator is known second estimator of Gislason (2010) [Eq. 29]. And finally, Kenchington (2013) used the same reasoning as Hoenig's estimator (1983), however added the recruitment age (t_c) to the equation [Eq. 30].

Kenchington (2013) 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 (2013) recommended that fishery scientists estimate M by more advanced methods whenever possible.

METODOLOGY

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).

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.

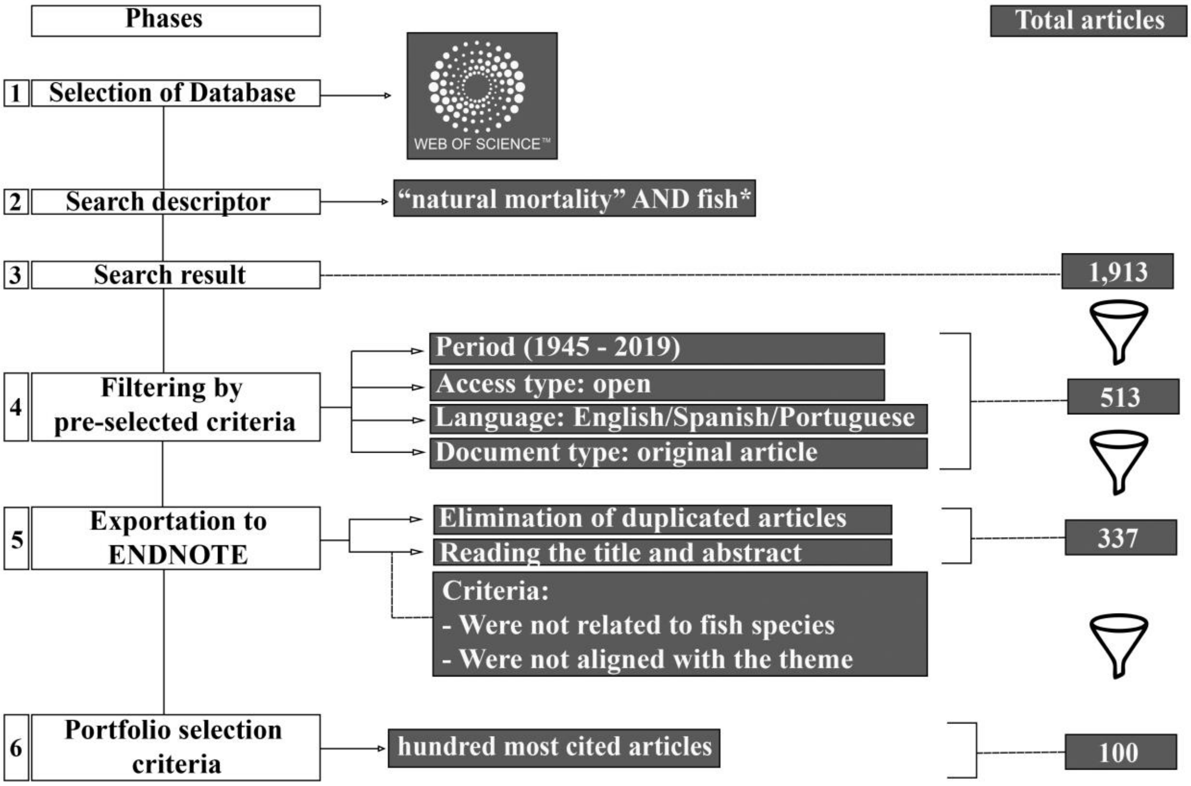

Figure 1. Selection process of the papers used to form the bibliographic portfolio

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).

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, coherence of the keywords for the identification of the most commonly used; and collaboration network analysis, obtained from the co-authorship relationships between authors, institutions and countries. 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 and collaboration network 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 and institution 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, 2016). 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.

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); method of estimating M; locality; type of environment (marine, estuarine or fresh water) and climatic zone.

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).

Bibliometrics

Degree of relevance of journals

Figure 2 shows the number of publications per year in the bibliographic portfolio. The observed trend is that every 1 or 2 years there is an increase in the number of papers published. However, the regularity of the publications occurred only from 1996, with occurrences in all years. The peak of publications occurred in the years 2011 and 2015.

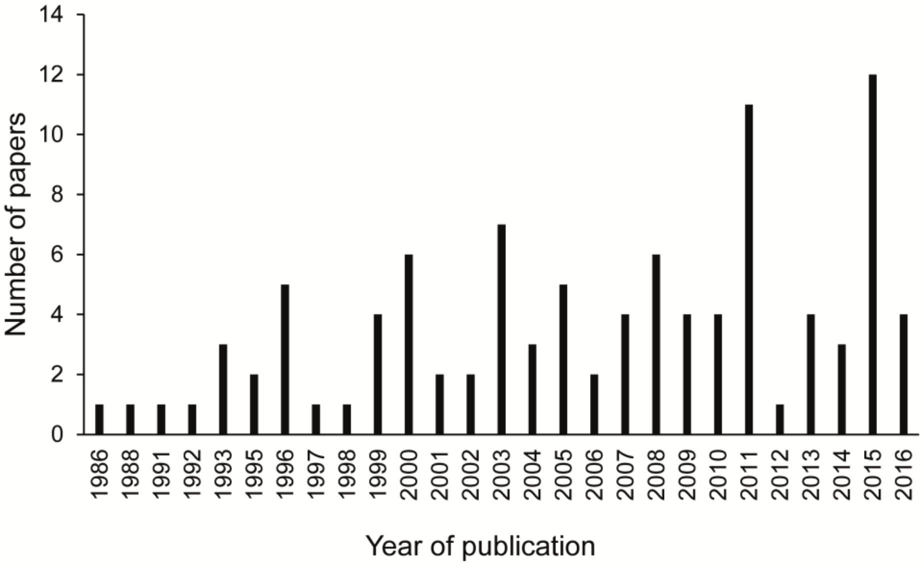

Figure 2. Period of publication of papers in the bibliographic portfolio

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.

Tabela 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

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

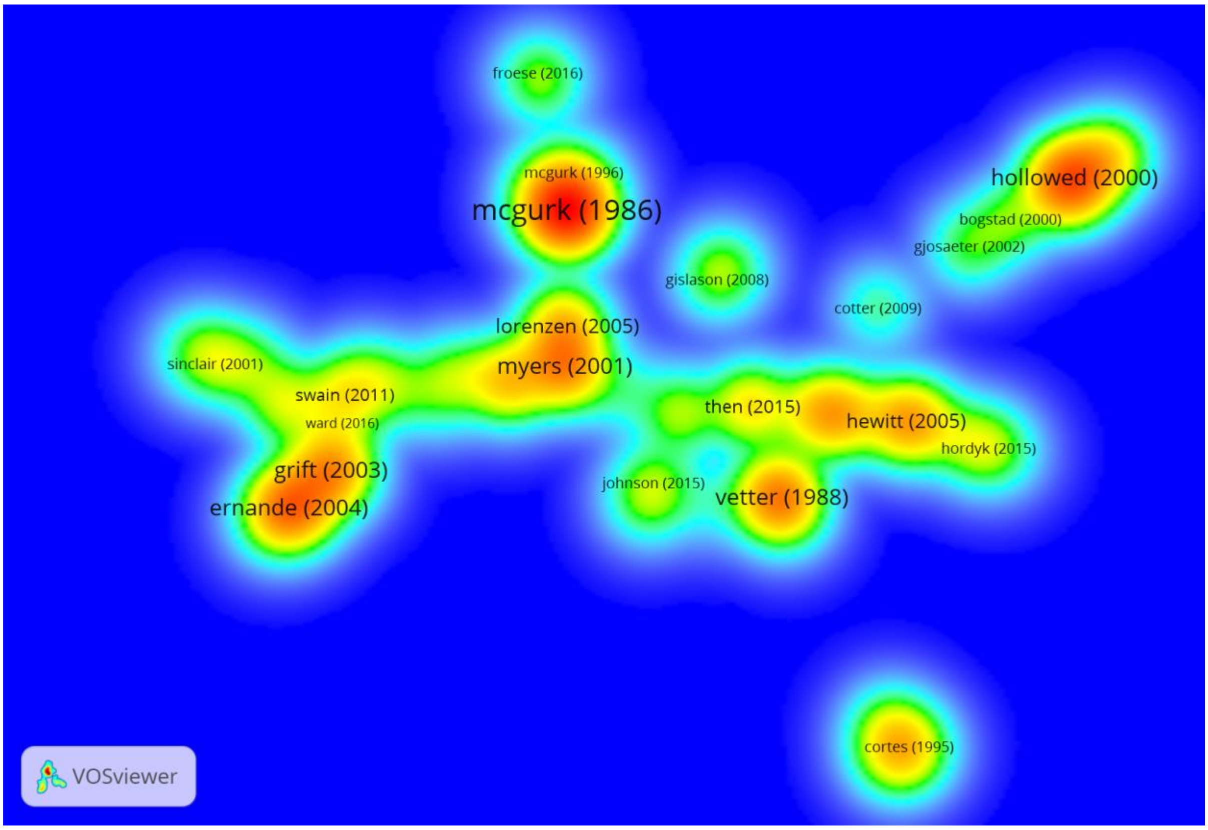

Figure 3.Heat map of the citation index by paper, from the bibliographic portfolio

McGurk (1986) studied the relationship between natural mortality of Roe and marine pelagic fish larvae and their spatial distribution. Verter (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 (2000) reviewed the application of multi-species models as tools to assess the impacts of fishing on marine communities.

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 (Table 2).

Table 2. Relevance of the authors according to the number of published papers

Author	Papers Published
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
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 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 4). 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.

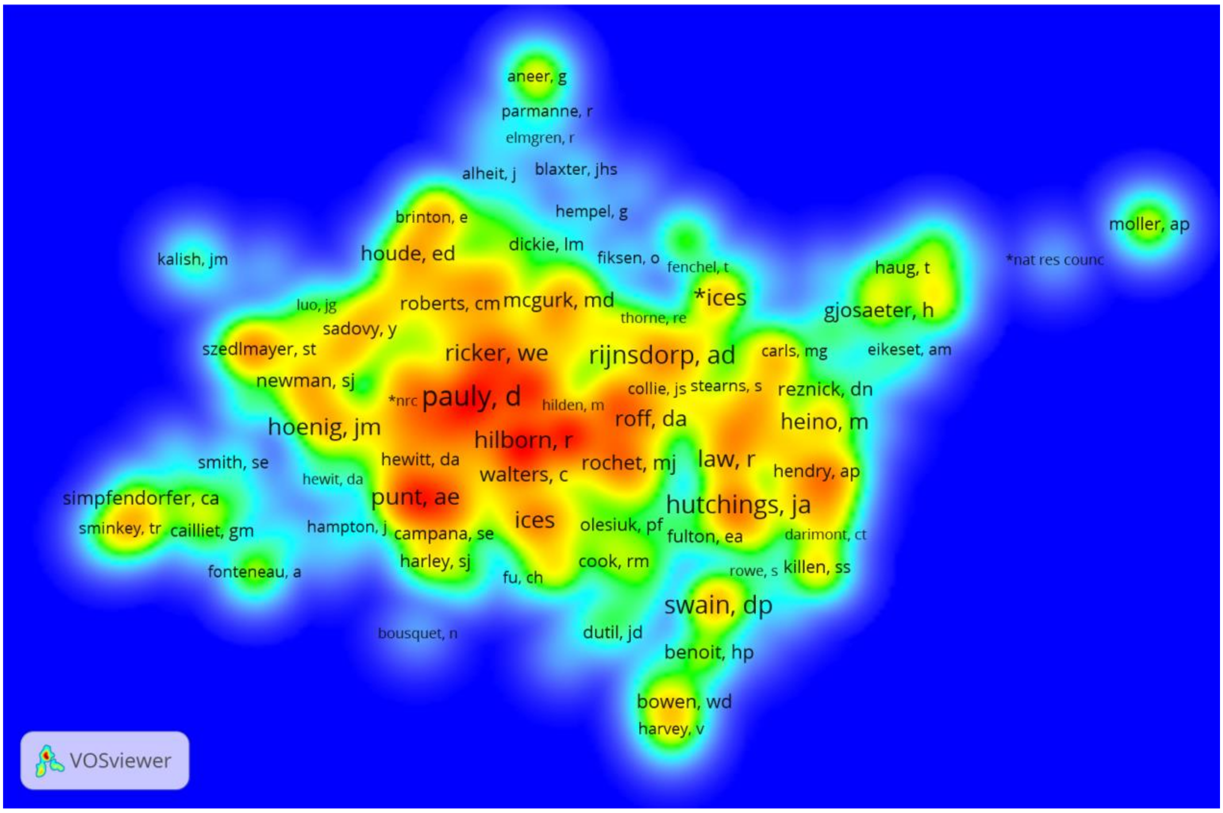

Figure 4. Heat map of authors co-citations from the bibliographic portfolio

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 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.

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 heat 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 5). 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.

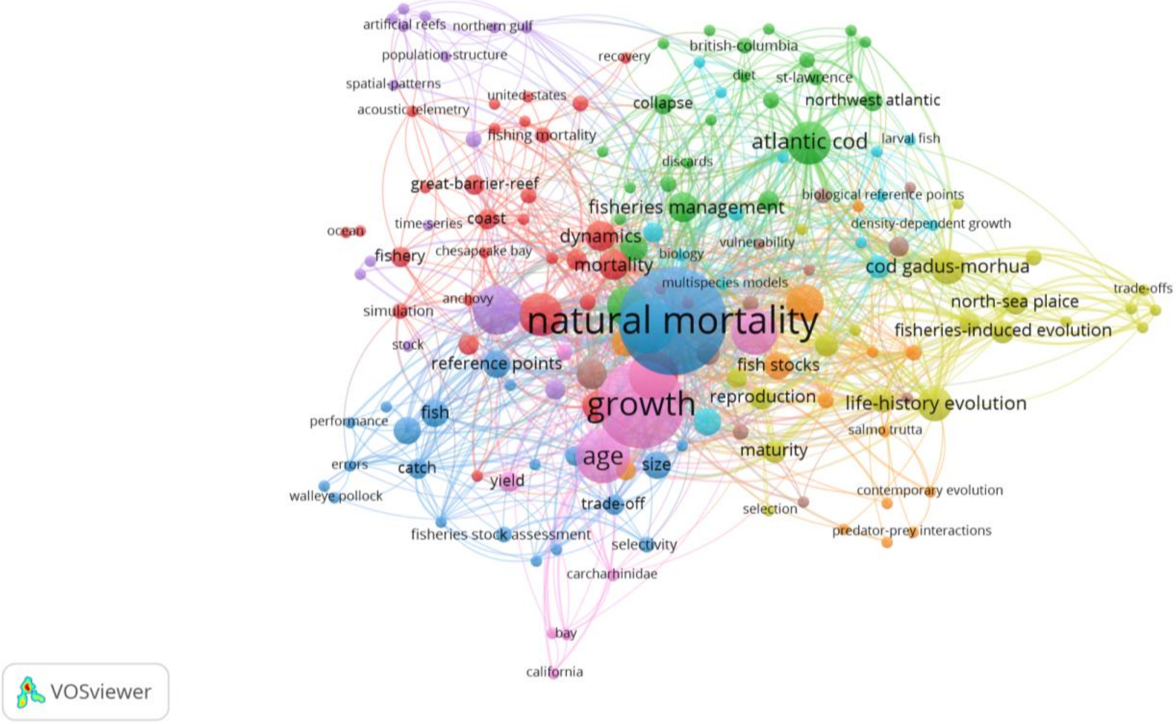

Figure 5. Bibliographic portfolio keyword co-occurrence map

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 (MYERS et al., 1997; GISLASON, 1999; 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.

Collaboration network

The term collaboration was used to indicate when two or more authors have at least one paper in common. Currently, collaborative publishing has become one of the requirements, and is therefore a way to measure scientific production. Scientific collaboration, as described in the literature, is related to co-authorship (VANZ and STUMPF, 2010; BUFREM, 2010), either through informal or formal interactions between scientists, but that at some point materialize in a product of science such as, for example, the scientific paper.

We identified 20 occurrences of co-authorship between authors, considering the minimum of two occurrences, grouped into three clusters. These authors published two papers each, except the author Ono, K., who published three. The authors who had the most interactions with other authors were Ono, K. and Punt, A., with 16 and 13 interactions, respectively.

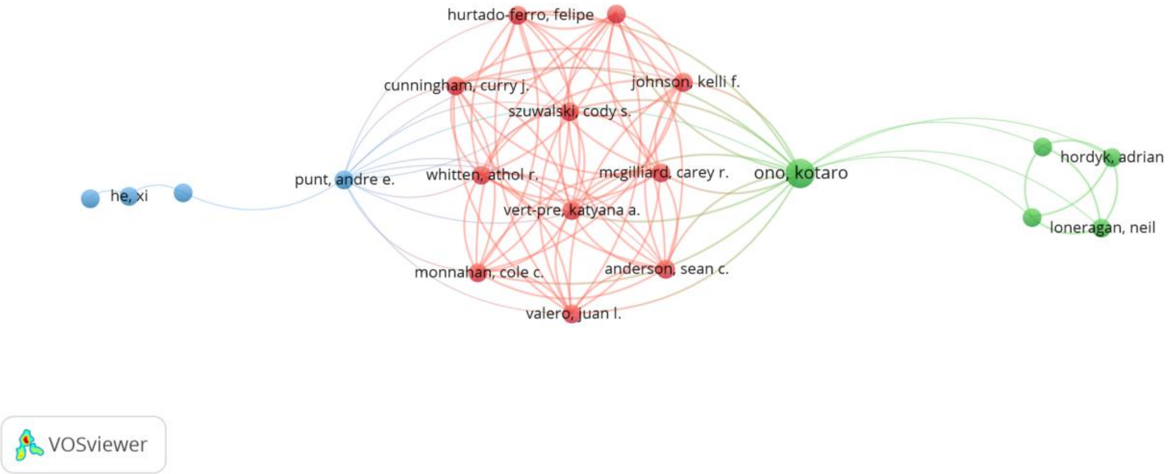

Figure 6. Collaboration network of authors of the bibliographic portfolio

As can be seen in Figure 6, these authors present themselves as a link between the networks of the ends (blue and green clusters) and the core network (red cluster), that is, both Ono and Punt are brokers in the network connecting the peripheral scientific communities.

For the analysis of co-authorship between institutions, the minimum of two occurrences of co-authorship between institutions was considered, which totaled 36 institutions, grouped into 6 clusters. The institutions with the highest number of interactions were Fisheries and Oceans Canada (7), National Oceanic and Atmospheric Administration (NOAA) (6), Institute of Marine Research Norway (6), University of British Columbia (6) and University of Washington (6) (Figure 7). Therefore, it can be verified that the main research on the topic is concentrated in the research institutes and universities of North America.

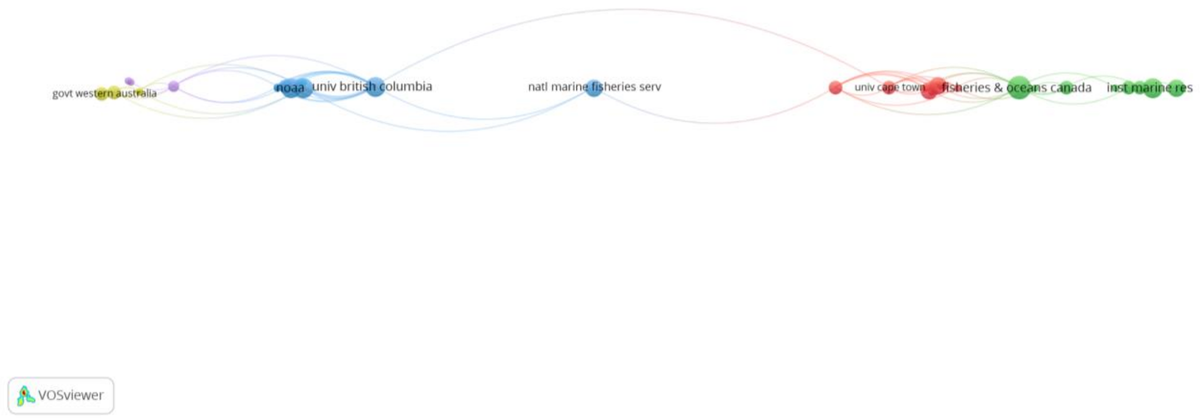

Figure 7. Collaboration network of the institutions in the bibliographic portfolio

The collaboration between countries network was composed of 7 clusters, which grouped the 34 countries that conducted research on the topic. Those with the highest number of interactions were the United States (37), Canada (23), Australia (16), Norway (15) and France (9) (Figure 8). With this analysis which corroborates with the analysis of co-authorship between institutions, it is evident that the United States and Canada were the countries that conducted the most research related to the topic studied.

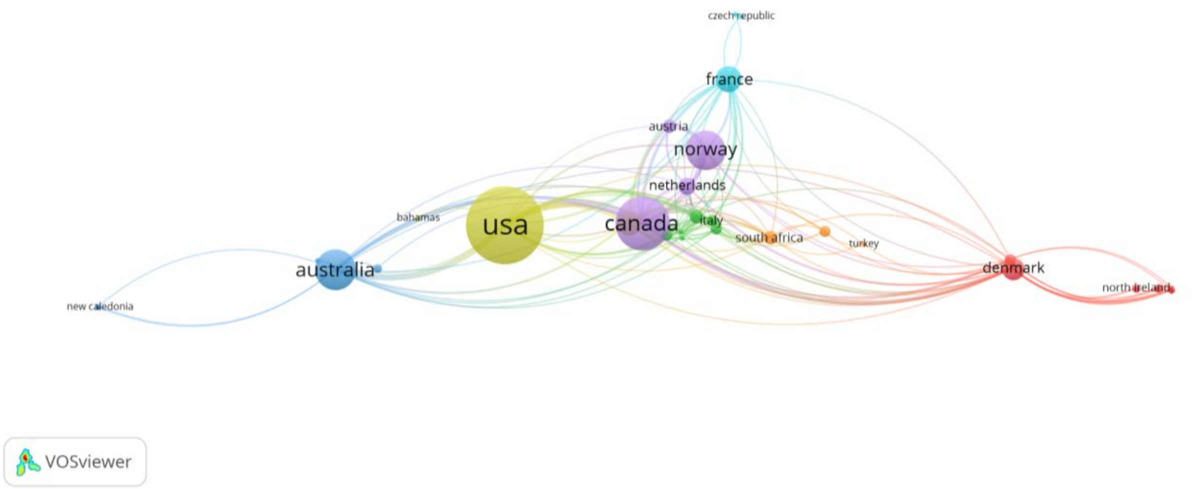

Figure 8. Collaboration network of countries that conducted research according to the bibliographic portfolio

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 94 papers, 81 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_o) and maximum age (T_{max}) (Table 3). For M estimates, the following estimators were used: Ricker (1975), Pauly (1980b), Hoenig (1983), Jensen (1996), 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. Some authors used more than one M estimator for the same species (Table 3). 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.

Table 3. Population parameters [asymptotic growth ($L\infty$), growth rate (k), age at zero length (t_0), maximum age (T_{max}), 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)

ID	Species	L_∞ (cm)	k (year^{-1})	t_0 (year)	T_{max} (year)	M (year^{-1})	T (°C)	Estimation method (M)
A05	*Stegastes nigricans* (Lacepède 1802)	17.50	0.37	-	-	**1.50**	25.0	Pauly (1980)
	Ctenochaetus striatus (Quoy and Gaimard 1825)	28.20	0.45	-	-	**1.00**		
	Caranx ignobilis (Forsskal 1775)	217.00	0.11	-	-	**0.20**		
A24	*Lutjanus campechanus* (Poey 1860)	-	-	-	54	**0.08**	-	Hoenig (1983)
A32	*Carcharhinus plumbeus* (Nardo 1827)	-	-	-	30	**0.11**	-	Hoenig (1983)
A34	*Rhizoprionodon terraenovae* (Richardson 1836)	108.00	0.36	-0.98	60	**0.07**	-	Hoenig (1983)
A35	*Pristipomoides multidens* (Day 1871)	59.80	0.19	-0.17	30	**0.10**	-	Hoenig (1983)
A38	*Carcharhinus obscurus* (Lesueur 1818)	374.40	0.04	-3.30	55	**0.09**	18.0	Pauly (1980)
		-	-	-		**0.10**	-	Hoenig (1983)
		-	-	-		**0.06**	-	Jensen (1996)
		-	-	-		**0.04**	-	Peterson and Wroblewski (1984)
	Carcharhinus plumbeus (Nardo 1827)	244.20	0.04	-4.80	40	**0.11**	24.0	Pauly (1980)
		-	-	-		**0.14**	-	Hoenig (1983)
		-	-	-		**0.10**	-	Jensen (1996)
		-	-	-		**0.08**	-	Peterson and Wroblewski (1984)
A41	*Gadus morhua* (Linnaeus 1758)	68.57	0.17	-0.65	17	**0.40**	-	Ricker (1975)
A42	*Sebastes jordani* (Gilbert 1896)	-	-	-	-	**0.26**	-	Regressão linear ponderada
A46	*Albula vulpes* (Linnaeus 1758)	67.58	0.26	-1.13		**0.30**	25.9	Pauly (1980)
A57	*Sebastes levis* (Eigenmann and Eigenmann 1889)	86.90	0.05	-1.94		**0.07**	-	Jensen (1997)
A70	*Galeocerdo cuvier* (Pérone Lesueur 1822)	-	-	-	-	**0.15**	-	Peterson and Wroblewski (1984)
		-	-	-	-	**0.32**	-	Lorenzen (1996)
		-	-	-	-	**0.50**	-	Chen e Watanabe (1989)
A73	*Epinephelus polyphekadion* (Bleeker 1849)	44.71	0.25	-0.14	22	**0.14**	-	Hoenig (1983)
A77	*Salmo trutta* (Linnaeus 1758)	68.00	0.16	-0.51	-	**0.39**	13.8	Pauly (1980)
		43.00	0.26	-0.30	-	**0.52**	15.8	
		39.00	0.25	-0.33	-	**0.54**	17.8	
A82	*Polyprion oxygeneios* (Schneider and Forster 1801)	89.00	0.24	-0.63	43	**0.09**	-	Hoenig (1983)
A86	*Lagodon rhomboides* (Linnaeus 1766)	30.10	0.31	-	-	**0.78**	24.0	Pauly (1980)
A89	*Etelis carbunculus* (Cuvier 1828)	-	-	-	43	**0.10**	-	Hoenig (1983)
	Etelis coruscans (Valenciennes 1862)	-	-	-	40	**0.10**	-	
	Etelis marshi (Jenkins 1903)	-	-	-	29	**0.14**	-	
	Pristipomoides filamentosus (Valenciennes 1830)	-	-	-	64	**0.06**	-	
A94	*Pinirampus pirinampu* (Spix and Agassiz 1829)	90.60	0.30	-0.41	-	**0.58**	26.0	Pauly (1980)
	Pseudoplatystoma fasciatum (Linnaeus 1766)	122.40	0.13	-0.90	-	**0.31**		
	Zungaro jahu (Ihering 1898)	172.00	0.13	-0.83	-	**0.28**		
	Pseudoplatystoma corruscans (Spix and Agassiz 1829)	149.70	0.13	-0.87	-	**0.29**		
A98	*Sardina pilchardus* (Walbaum 1792)	19.50	0.39	-0.48	-	**0.80**	-	Pauly (1980)
A100	*Latris lineata* (Forster 1801)	77.32	0.15	-1.46	43	**0.15**	-	Pauly (1980)
		-	-	-		**0.10**	-	Hoenig (1983)

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 9). As can be seen in Figure 9, the studies are concentrated in North America and Oceania.

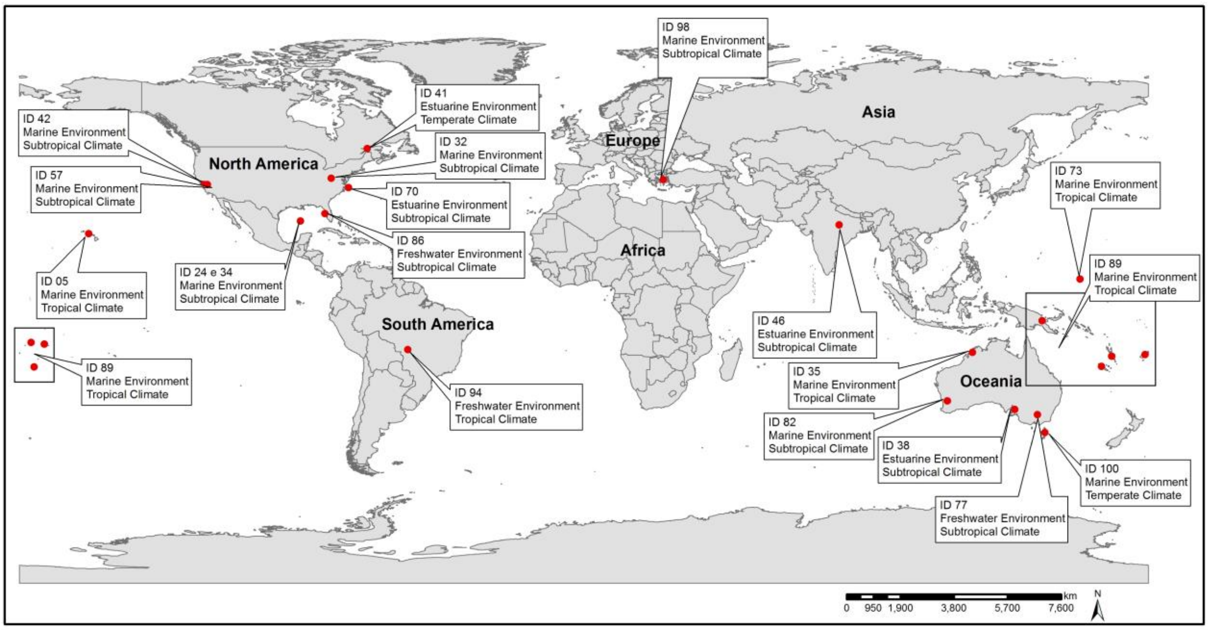

Figure 9. Distribution of studies, which estimated natural mortality in fish, by type of environment and climatic zone

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 importantance of developing more sophisticated methods can be noted. These methods should take into account new approaches, such as the temperature variation 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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APPENDIX A

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

Estimator	**Equation**	
Tanaka (1960)	$\mathrm{M} = -ln(P)/T_{MAX}$	[Eq. 1]
Bayliff (1967)	$\mathrm{Z} = 6.384/T_{MAX}$	[Eq. 2]
Ursin (1967)	$M_w \approx w^{-0.333}$	[Eq. 3]
Alverson and Carney (1975)	$\mathrm{M} = \frac{3k}{e^{k0.38T_{MAX-1}}}$	[Eq. 4]
Sekharan (1975)	$M \approx 4.6 / T_{MAX}$	[Eq. 5]
Rikhter and Efanov (1976)	$M = \frac{\beta k}{e^{k(t_m - t_0)}-1}$	[Eq. 6]
Rikhter and Efanov (1976)	$M = \frac{1.521}{t_m^{0.720}} - 0.155$	[Eq. 7]
Pauly (1980)	$log\, M = -0.0066 - 0.279\, log\, L_\infty + 0.6543\, log\, k +$ $0.4634 logT$ $log\, M = -0.0066 - 0.279\, log\, W_\infty + 0.6543\, log\, k +$ $0.4634 logT$	[Eq. 8]
Hoenig (1983)	$Z = 6.99 T_{MAX}^{-1.22}$	[Eq. 9]
Alagaraja (1984)	$M \approx 3.0 / T_\infty$	[Eq. 10]
Peterson and Wroblewski (1984)	$M_w \approx 1.28 w^{-0.25}$	[Eq. 11]
Roff (1984)	$M \approx 3 / t_m$	[Eq. 12]
Roff (1984)	$M = \frac{3kL\infty\left(\frac{1-lm}{L\infty}\right)}{l_m}$	[Eq. 13]
Ralston (1987)	$M = -0.00666 + 2.5k$	[Eq. 14]
Chen and Watanabe (1989)	$M_t = \frac{k}{1- e^{-k(t-t_0)}}\ , \mathrm{t} \leq t_s$ $M_t = \frac{k}{1- e^{-k(t-t_0)}}\ [1 - k(t - t_s)\ +\ 0.5k^2(t - t_s)^2], \mathrm{t} \geq t_s$	[Eq. 15]
Charnov and Berrigan (1990)	$M = 2.2 / t_m$	[Eq. 16]
Djabali (1994)	$log\, M = -0.0278 - 0.1172\, log\, L_\infty + 0.5092\, log\, k$ $log\, M = -0.0656 - 0.0302\, log\, W_\infty + 0.5280\, log\, k$	[Eq. 17]
Jensen (1996)	$M = 1.65 / t_m$	[Eq. 18]
Jensen (1996)	$M = 1.5k$	[Eq. 19]
Lorenzen (1996)	$M_w = 3.00 w^{-0.288}$	[Eq. 20]
Cubillos et al. (1999)	$M = 4.31 \left[t_0 - \frac{ln(0.05)}{k}\right]^{-1.01}$	[Eq. 21]
Groeneveld (2000)	$M = k\left(\frac{3L_\infty}{lm-3}\right)$	[Eq. 22]
Frisk et al. (2001)	$logM = 0.42\ lnk\ - 0.83$	[Eq. 23]
Jensen (2001)	$log\, M = 0.66\, log\, k + 0.45\, log\, T$	[Eq. 24]
Zhang and Megrey (2006)	$\mathrm{M} = \frac{\beta k}{e^{k(t_{mb} - t_0)}-1}$	[Eq. 25]
Griffiths and Harrod (2007)	$M = 1.406 w_\infty^{-0.096} k^{0.780}$	[Eq. 26]
Jennings and Dulvy (2008)	$M_w = w^{-0.25} e^{26.25 - 6960/(t+273)}$	[Eq. 27]
Gislason et al. (2010)	$lnMl = 0.55 - 1.61 lnl + 0.144 lnL_\infty + lnk$	[Eq. 28]
Gislason (2012)	$M_l = k\left(\frac{l}{L\infty}\right)^{-1.5} = k\left(\frac{L\infty}{l}\right)^{1.5}$	[Eq. 29]
Kenchington (2013)	$T_{MAX} = \frac{ln\{2n_e(1-e^{-z})+1\}}{z} + t_C$	[Eq. 30]

APPENDIX B

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

ID	Reference list
A01	McGurk, M. D. (1986). Natural mortality of marine pelagic fish eggs and larvae - role of spatial patchiness. *Marine Ecology Progress Series*, 34(3), 227-242.
A02	Vetter, E. F. (1988). Estimation of natural mortality in fish stocks - a review. *Fishery Bulletin*, *86*(1), 25-43.
A03	Hollowed, A. B., Bax, N., Beamish, R., Collie, J., Fogarty, M., Livingston, P., et al. (2000). Are multispecies models an improvement on single-species models for measuring fishing impacts on marine ecosystems? *Ices Journal of Marine Science*, *57*(3), 707-719.
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CAPÍTULO II

THE APPLICATION OF FUZZY LOGIC FOR ASSESSING THE EFFECTS OF GLOBAL CLIMATE CHANGE ON THE NATURAL MORTALITY OF FISH WITH DIFFERENT LIFE STRATEGIES

The application of fuzzy logic for assessing the effects of global climate change on the natural mortality of fish with different life strategies

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Abstract

The increase in temperature resulting from global climate change can directly affect the survival of fish and therefore population parameters such as natural mortality (M). The estimation of this parameter and the understanding of the uncertainties in its estimates are enormous challenges for studies that evaluate fish stocks. In addition, the effects of increases in temperature may be associated with life strategies. Therefore, the fuzzy set theory was used to evaluate the effects of temperature increase on the natural mortality of fish, considering different life strategies. The model generated confirmed that the increase in temperature causes an increase in M for all species, regardless of the life strategy. However, opportunistic species present greater uncertainties in estimates of M compared to equilibrium species. The patterns found in uncertainties of M associated with species groupings by life strategies can be used in holistic approaches for the assessment and management of recently exploited fisheries resources or for those with limited biological data.

Keywords: temperature, uncertainty, degree of memebership, equilibrium, seasonal and opportunistic.

INTRODUCTION

Climate change is considered to be the biggest and most complex environmental and socio-economic problem of the present day. The temperature increases on the surface of the planet are among the phenomena with greater predictability and with wide-ranging effects (IPCC, 2007). Global warming is the result of natural alterations in the climate system and human activities, which contribute to rising levels of greenhouse gas (GHG) emissions (MENDONÇA, 2006; IPCC, 2014). Scientific evidence indicates that anthropogenic emissions of GHGs are the main cause of the increase in temperature and the biggest culprit in relation to the current environmental imbalance, causing more than half of the observed increase in global average surface temperatures of the planet (CLEUGH et al., 2011; IPCC, 2014).

Temperature is an important environmental variable, and it is directly related to the survival of organisms (COSTA et al., 2012; RIBEIRO and NAVAS, 2012); mainly the survival of ectothermic animals such as fish (BAILLY, 2019). The effects on fish populations can be manifested through changes in abundance, migration patterns and geographical distribution (FICKE et al., 2007; FREITAS et al., 2013; ANDRADE et al., 2018; BAILLY, 2019; VAL, 2019). Oremus et al. (2020) made projections using global climate change scenarios in order to verify changes in the migration and distribution of 779 species of fish from each exclusive economic zone (EEZ), and concluded that tropical countries are more vulnerable to a potential loss of stocks of these species, since these migrate to cooler waters to maintain their thermal comfort. The effects of climate change can also affect seasonal environmental phenomena related to the life cycle of fish, and cause an impact on the breeding period and the behavior of fish.

The characteristics of the life history of freshwater and marine fish are distinct among species and, through studies that have performed comparisons, it has been possible to identify patterns that correspond to different life strategies (WINEMILLER, 1989; PONTON and MERONA, 1998; WINEMILLER and ROSE, 1992; ROPKE et al., 2017). The plasticity of species with different life strategies that depend on environmental variations has also been widely studied (BALON, 1975; WINEMILLER, 1989; WINEMILLER and ROSE, 1992; HENEBRY, 2011; ROPKE et al., 2017). Species with life strategies characterized as having a large size, high longevity, low growth rate and mortality are at a disadvantage in terms of temperature increase, due to their higher metabolic rate, and will likely face local extinction (ANDRADE et al., 2018). On the other hand, smaller species with lower trophic levels can benefit from the reduction of predators (WOODWARD et al., 2016). This shows that the effects of climate change on fish can be of a greater or lesser degree and can have distinct signs, depending on the life strategy of each species (BLANCK and LAMOUROUX, 2007; ROPKE et al., 2017).

With regard to the individual, the increase in temperature has direct effects on the natural mortality (M) of the fish. This parameter is one of the most important in the evaluation of fish stocks and it is essential in order to estimate the productivity of a fish stock (PUNT et al., 2021), but it is also one of the most difficult to estimate, due to limitations of data (ARREGUÍN-SÁNCHEZ et al., 2012; KENCHINGTON, 2014; PUNT et al., 2021). The magnitude of error, bias and variance in the estimation of this parameter can be substantial and can be affected by temporal and spatial effects (PUNT et al., 2021). However, uncertainty in estimates of M is essential in order to make robust assessments of the fish stock (BRODZIAK et al., 2011).

Most estimation methods for M consider only intrinsic factors of the species: length, maturation size, growth rate and age, without taking into account the influences of extrinsic factors, such as environmental variables (e.g., temperature) (KENCHINGTON, 2014), which can be determinants in population dynamics and are intrinsically variable (SAETHER et al., 2000). The only method of estimating M that takes into account intrinsic and extrinsic factors was proposed by Pauly (1980), who estimates M as a function of the Von Bertalanffy (1963) growth parameters and the average annual water temperature. It has been shown that the higher the temperatures, the higher the natural mortality rates in fish (SPARRE and VENEMA, 1997).

However, the effects of temperature increase, due to climate change, incorporate high variability, which is in part due to the intrinsic uncertainty of climate models and underlying scenarios (JEPPESEN et al., 2014). Thus, it is necessary to apply methodological approaches that incorporate variations and uncertainties in the estimation of parameters. In this sense, fuzzy logic and fuzzy set theory are presented as appropriate tools in the modeling of biological phenomena (BARROS and BASSANEZI, 2010). This theory was introduced by Zadeh (1965), with the idea of contrasting deterministic models to more flexible models, which enable mathematical modeling of uncertainty, besides mathematically formulating the subjectivity inherent to natural phenomena. Fuzzy logic has been used as a tool in several issues related to the biology of fisheries, such as assessing the vulnerability of marine species (CHEUNG et al., 2005), assessment of pelagic fishery ecosystems (PATERSON et al., 2007), classification of fishing areas (SYLAIOS et al., 2010), spatial management of marine fisheries (TEH and TEH, 2011), behavior of fishers in pelagic fisheries (WISE et al., 2012), stock-recruitment relations (YURRITA, 2014), parameter estimates of the relationship between weight and length (BITAR et al., 2014), dynamic of comptetion among species taking into account abiotic factors and fishing effort (SOUZA e BASSANEZI, 2018), and the fuzzy interactivity in the generalized model of von Bertalanffy (SOUZA e PRATA, 2019).

The estimation of the average annual water temperature, represented by a fuzzy number, would therefore enable an estimate of natural mortality that incorporates the variations and uncertainties in the face of global climate change. However, it should be recognized that the amplitude and intensity of the effects of environmental phenomena are species-specific (BLANCK and LAMOUROUX, 2007; ROPKE et al., 2017) and should be influenced by the life history characteristics of the species. Given the above, this study applied the fuzzy set theory in order to evaluate the effects of temperature variations caused by global climate change on the natural mortality (M) of fish species with different life strategies.

MATERIALS AND METHODS

Study area

The area covered in this study was the Brazilian tropical region, including continental and maritime areas (Figure 1). The main feature of the climate of the tropics is the high average monthly temperatures. However, factors such as latitude, altitude, circulation of air masses and global climate change can cause climate differentiation (IPCC, 2014).

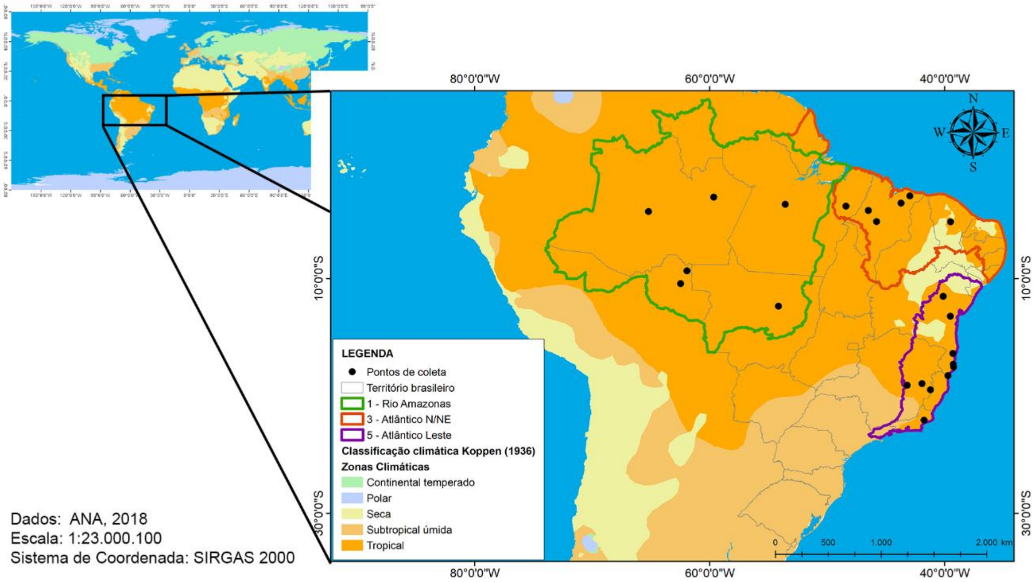

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Figure 1. Map of the Brazilian tropical zone, watersheds and temperature collection points (river monitoring stations)

Classification of life strategies of the target species

As an alternative to the concepts of r and k strategists (PIANKA, 1970) and based on mechanisms of trade-offs between reproduction, growth and survival of freshwater fish, Winemiller (1989) proposed a classification using three categories of life strategies: equilibrium, opportunistic and seasonal. The classification proposed by Winemiller (1989) gave rise to the triangular continuum of strategies model, which resulted from adaptive responses to environmental predictability and variability. Subsequently, Winemiller and Rose (1992), while studying freshwater and marine fish, confirmed this classification. Basically, these patterns of life strategies suggest that:

(1) Equilibrium strategists – These are fish with low growth rates and natural mortality, with a large body size, late first maturation, split spawning, large oocytes, low fecundity, broad reproductive period, relatively high longevity, parental care, which produce larger offspring in low quantities. Since they produce relatively few offspring, survival from the early stages must be high for these populations to prevail. These are species that live in relatively stable environments;

(2) Seasonal strategists – These are fish that exhibit migratory behavior, absence of parental care, growth rates and natural mortality from intermediate to high, with intermediate to large body size, first maturation is intermediate to late, small oocytes, high fecundity and short periods of reproduction. This strategy would be associated with both temporal and seasonal variations and, if these conditions are favorable, a synchronization in reproduction will occur, guaranteeing juvenile individuals greater chances of growth and survival, in addition to providing a rapid population replacement.

(3) Opportunistic strategists – these are fish with a small body size, early first maturation, small oocytes, low fecundity, prolonged breeding period, short life span and with little or no parental care. These characteristics are related to the ability of rapid colonization of environments marked by unpredictable temporal variations.

Species selected for the study

Species representing the different life strategies were selected according to the classification of Winemiller (1989) and Winemiller and Rose (1992). In addition, we sought to select species from freshwater and marine environments that present commercial importance. Based on these criteria, three freshwater and three marine species were selected, each representing a particular type of life strategy.

Representatives of freshwater environments:

Equilibrium Strategist: *Cichla temensis* (HUMBOLDT, 1821)

Order: Perciformes. Family: Cichlidae

The peacock bass, *Cichla temensis,* has its distribution restricted to the blackwater rivers and their tributaries in the basins of the Amazon River and Orinoco River. It has great importance in the diets of the riparian population, as well as in the ornamental fish trade and, especially, in sport fishing (SOARES et al., 2007). In 2003, the peacock bass represented 2.58% of the fishing production that was landed in the main ports of the state of Amazonas (RUFFINO et al., 2006) and in the middle Negro River region, and it was the third most landed fish in 2013 (INOMATA and FREITAS, 2015). It is characterized by a preference for lentic environments, edges of lakes and sandbanks in the main channel of rivers (GOULDING et al., 1980; WINEMILLER et al., 1997). *Cichla temensis* is a predator at the top of the chain, with a piscivorous habit and it differs among the 15 species of the genus *Cichla*, since it reaches larger sizes, which can be up to 80 cm and more than 11 Kg (WINEMILLER et al., 1997; Kullander and FERREIRA, 2006; MONTAÑA et al., 2007). The couple builds the nest and, one or both, take care of the offspring (BRAGA, 1952; ZARET, 1980; JEPSEN et al., 1999). It presents split spawning, with a long reproductive period and low fecundity (FONTENELE, 1950; WINEMILLER et al., 1997; JEPSEN et al., 1999; SOARES et al., 2007). It has low growth rates (k) and natural mortality (M), high values of theoretical maximum lengths ($L\infty$) and first maturation (L_{50}), as well as relatively high longevity (T_{max}) (Table 1).

Seasonal Strategist: *Prochilodus nigricans* (SPIX and AGASSIZ, 1829)

Order: Characiformes. Family: Prochilodontidae

The curimatã, *Prochilodus nigricans,* is found in the Amazon River and Tocantins River basins (CARVALHO and MERONA, 1986; CASTRO and VARI, 2003). It has significant commercial value, and is one of the most caught species in Brazilian continental waters (FERRAZ and BARTHEM, 2016; FERRAZ et al., 2012) and is predominant in the landings in Amazonian cities (BATISTA et al., 2012) in addition to its importance in subsistence fishing (ISAAC et al., 2015; ZACARKIM et al., 2015). This species inhabits large rivers, flooded forests, lakes and streams, and can be found at any time of the year, even if its abundance varies, due to the influence of seasonal fluctuations in the level of the rivers in the Amazon (Goulding, 1979; FARIAS et al., 2005). It performs trophic, reproductive and dispersal migrations throughout the year and feeds, basically, on organic debris and periphyton (SANTOS et al., 1984). Like other migratory fish that feed on detritus, it has access to an abundant source of energy (CASTRO and VARI, 2004; FLECKER, 1996), which contributes to the modulation of carbon flow and productivity of ecosystems (TAYLOR et al., 2006). It is a medium-sized species, between 35 and 50 cm long and is around 3 Kg in weight (SANTOS et al., 2006; ROPKE et al., 2017). It has high fecundity, small oocytes and short reproductive period (at the beginning of the rising water period) and does not provide parental care (LOUBENS and PANFILI, 1995; MOTA and RUFFINO, 1997; SILVA and STEWART, 2017; ROPKE et al., 2017). In addition, it presents high intermediate values of population parameters, such as growth constant (k), theoretical maximum length ($l\infty$), natural mortality (M) and first maturation length (L_{50}) (Table 1). Ropke et al. (2017) also classified *P. nigricans* as a seasonal strategist.

Opportunistic Strategist: *Triportheus angulatus* (SPIX and AGASSIZ 1829)
Order: Characiformes. Family: Characidae

A total of 16 species have been described for the genus *Triportheus,* in which 3 are well known, *Triportheus albus* (COPE, 1872)*, T. auritus* (VALENCIENNES, 1850) and *T. angulatus* (SPIX and AGASSIZ, 1829), and their occurrences are recorded in the basins of the Amazon, Tocantins and Orinoco Rivers (MALABARBA, 2004). In recent years, the demand and commercial interest for Amazonian fish species that are numerous, but of smaller size, has increased significantly. For example, in the 1970s, sardines were infrequently commercialized (PETRERE Jr., 1978; MERONA and Bittencourt, 1988), but in the past decade, there has been an increase in the volume of landings in the ports of Manaus and Manacapuru, Amazonas state, which has risen from 2% to 12% (RUFFINO et al., 2006; GONÇALVES and BATISTA, 2008). *Triportheus angulatus* is a pelagic fish that commonly lives near the surface and close to the banks of rivers and lakes. It has an omnivorous diet that includes insects, zooplankton, fruits and seeds, and it has been verified that, even under conditions of low oxygen concentrations, its feeding activity is not influenced, (YAMAMOTO et al., 2004), as it has the ability to modify its lower lips to absorb surface oxygen from water (MALABARBA, 2004).

Although *T. angulatus* is not considered a completely opportunistic species, it still has characteristics that approximate this type of life strategy, such as small body size, with a size that ranges between 20 and 24 cm (MALABARBA, 2004); low fecundity and single spawning (ARAÚJO et al., 2012); it does not provide parental care and presents high growth rates (k) and natural mortality (m), low values of theoretical maximum lengths (L∞) and first maturation lengths (L_{50}), as well as having a low life span (T_{max}) (Table 1).

Representatives of marine environments:

Equilibrium Strategist: *Cynoscion acoupa* (LACEPÈDE, 1801)

Order: Perciformes. Family: Sciaenidae

The red mullet, *Cynoscion acoupa*, has a wide distribution and occupies coastal waters from Panama, in Central America, to Argentina, in southern Latin America as well as most of the Brazilian coast (except in the extreme south of the country), both in marine and estuarine environments (CERVIGÓN, 1993). *Cynoscion acoupa* is the third most landed fish species in Brazil and has a high commercial value due to the quality of its meat and for its swim bladder, which is used as a raw material in the production of emulsifiers and clarifiers (BARLETTA et al., 1998; TORRES, 1999; WOLFF et al., 2000). *Cynoscion acoupa* is a species with nectonic, demersal and coastal habits that lives in shallow and brackish waters under the influence of estuaries and mangroves, which, for this species, are places of refuge, feeding and reproduction (SZPILMAN, 2011). It feeds mainly on fish and crustaceans (FERREIRA et al., 2016), and is a large species that can reach up to 130 cm in length and 20 Kg in weight (VANZOLINI, 1964; SZPILMAN, 2011). It has batch spawning, a long reproductive period and high fecundity (a common characteristic for marine species in equilibrium) (WINEMILLER and ROSE, 1992; ALMEIDA et al., 2016). It has low growth rates (k) and high values of theoretical maximum lengths (L∞) and first maturation lengths (L_{50}). Its longevity is considered as intermediate to high ($T_{máx}$) (Table 1).

Seasonal Strategist: *Lutjanus synagris* (LINNAEUS, 1758)

Order: Perciformes. Family: Lutjanidae

The lane snapper, *Lutjanus synagris*, has an area of occurrence that extends from North Carolina (USA) to southeastern Brazil (MANOOCH and MASON, 1984; FIGUEIREDO and MENEZES, 2000). It is an important fishing resource of tropical marine waters, due to its abundance and quality of meat, which gives it high commercial value (ALLEN, 1985; POLOVINA and RALSTON, 1987) and, as a result, it is the target of commercial, artisanal and sports fisheries (KLIPPEL and PERES, 2002; REZENDE et al., 2003, KLIPPEL et al., 2005). *Lutjanus synagris* is a species of demersal habits that lives in warm waters, and is often associated with rocky and coral bottoms, between the coastal zone and out to depths of about 400 m (MCEACHRAN and FECHHELM, 2005; PIMENTEL and JOYEUX, 2010). It feeds mainly on crustaceans and fish. Considered a medium-sized species, it can reach lengths of between 40 and 50 cm (FIGUEIREDO and MENEZES, 1980; ALMEIDA, 2000). It has batch spawning and high fecundity (GRIMES, 1987; SOUSA-JUNIOR et al., 2003; FREITAS et al., 2014). It presents intermediate to slow growth (k), as well as intermediate values of theoretical maximum lengths ($L\infty$) and first maturation (L_{50}), and is relatively long-lived (T_{max}) (Table 1). King and McFarlane (2003) concluded that species of the family Lutjanidae are seasonal strategists.

Opportunistic Strategist: *Sardinella brasiliensis* (STEINDACHNER, 1879)
Order: Clupeiformes. Family: Clupeidae

The Brazilian sardinella, *Sardinella brasiliensis*, is a species that is endemic to the southeastern coast of Brazil, and is found along the continental shelf, between Cabo de São Tomé, RJ and Cabo de Santa Marta Grande, SC (VALENTINI and CARDOSO, 1991; KATSURAGAWA et al., 2006). In terms of volume of production, it is the most important marine fishing resource in Brazil since it is the most commercialized and consumed fish in the country (PAIVA, 1997; MPA, 2013). Shoals occur near the surface, in water up to 80 m deep, and reduce their frequency as the depth increases (PAIVA and MOTTA, 2000). In the region where it occurs, specific oceanographic characteristics are observed, due to the periodic entry of infiltrations from the Central South Atlantic water. These waters act as a fertilization mechanism and provide a greater amount of plankton that favors the survival of the larvae of *S. brasiliensis* (MATSUURA, 1998; KURTZ and MATSUURA, 2001). It is a species of planktophagous feeding habits (SCHNEIDER and SCHWINGEL, 1999), of small size, ranging from 9 to 27 cm, with a high fertility rate, sequenced spawning and without parental care (SACCARDO and ROSSI-WONGTSCHOWSKI, 1991; CERGOLE and VALENTINI, 1994; CASTELLO, 2006; COSTA et al., 2018). In addition, it also presents a high natural mortality rate (M) and early maturation (L_{50}), with low values for theoretical maximum lengths ($L\infty$). Costa et al. (2018) also classified *S. brasiliensis* as an opportunistic strategist.

Data collection

Three data sets were obtained in order to estimate the fuzzy set of natural mortality (M): Von Bertalanffy (1963) growth parameters of species and annual average water surface temperature, which were used as input variables for the natural mortality equation (M) proposed by Pauly (1980), in addition to temperature estimates proposed by the Intergovernmental Panel on Climate Change (IPCC), which functioned as force variables in the modeling.

Growth parameters

The species selected for the study were defined and classified according to their life strategies. The growth parameters, L∞ (theoretical maximum length) and k (individual growth coefficient), of these species can be observed in Table 1.

Table 1. Population parameters of the species selected for the study. Asymptotic length

Nº	Species	L_∞ (cm)	k (year^{-1})	L_{50} (cm)	$T_{máx}$ (year)	Strategy	Environment
1	*Cichla temensis*	68.05	0.20	31.11	14.00	Equilibrum	Freshwater
2	*Prochilodus nigricans*	34.60	0.44	23.08	6.80	Seasonal	
3	*Triportheus angulatus*	26.78	0.77	16.30	3.89	Opportunist	
4	*Cynoscion acoupa*	142.90	0.13	42.07	10.00	Equilibrum	Marine
5	*Lutjanus synagris*	56.00	0.22	23.00	18.00	Seasonal	
6	*Sardinella brasiliensis*	23.68	0.26	15.80	10.73	Opportunist	

Source: 1 - Campos et al. (2015; 2020); 2 - Catarino et al. (2014), Camargo and Lima-Junior (2008); 3 - Prestes et al. (2010), Araújo et al. (2012); 4 - Oliveira et al. (2018; 2020), Almeida et al. (2016); 5 - Aschenbrenner et al. (2017); Freitas et al. (2014); 6 - Costa et al. (2018).

Average Annual Temperature

The National Water Resources Information System (SNIRH), whose organization, implementation and management is the responsibility of the National Water Agency (ANA. 2020), divides the national territory into eight large basins: 1 –Amazon River, 2 – Tocantins River, 3 – Atlantic (northern/northeastern stretch), 4 – São Francisco River, 5 – Atlantic (eastern stretch), 6 – Paraná, 7 – Uruguay, and 8 – Atlantic (southeastern stretch) (ANA, 2020). The temperature data concerning the watersheds 1, 3 and 5 (Figure 1), where the studies of estimation of growth parameters of the species were carried out (Table 2), were obtained and used in the modeling.

Table 2. Area of study of the target species and their respective watersheds of origin

Study Nº	Study area	Watershed
1	Rio Negro	1 - Amazon River
2	Rio Solimões	1 - Amazon River
3	Rio Solimões	1 - Amazon River

4	Baía de São Marcos	3 - N/NE Atlantic
5	Banco dos Abrolhos	5 - Eastern Atlantic
6	Costa do Itaipu	5 - Eastern Atlantic

IPCC scenarios

In 2014, the Intergovernmental Panel on Climate Change (IPCC) proposed four more simplified scenarios, but using a more complete system, known as RCPs (representative concentration pathways), which use the amount of energy absorbed (radiative forcing, in W/m^2) by greenhouse gases (GHG), during or near the end of the 21st century. RCP 2.6: mitigation scenario, which leads to a very low level of absorption; RCP 4.5 and RCP 6.0: stabilization scenarios and RCP 8.5: scenario with very high greenhouse gas emissions (Table 3) (IPCC, 2014).

Table 3. Features of the RCP scenario of the fifth IPCC report (AR5)

RCP	Radioactive Forcing	Concentration CO_2-equiv. (ppm)	Behavior	Rise in sea level (cm)	Elevation of T°C on the planet in 2100
2.6	Peak of < $3W.m^{-2}$ in 2100	490	Rising with a peak in 2040 and declining	26 - 55	0.3 – 1.7
4.5	Additional storage of $\approx 4.5W.m^{-2}$	650	Rising up to 2060 and stabilizing	32 - 63	1.1 – 2.6
6.0	Additional storage of $\approx 6W.m^{-2}$	850	Rising up to 2100 and stabilizing	33 - 63	1.4 – 3.1
8.5	Storage of $\approx 8.5W.m^{-2}$	> 1370	Rising up to 2100	45 - 82	2.6 – 4.8

Source: IPCC, 2014.

Data Analysis

Foundations of the fuzzy set theory

To understand the modeling process presented in this study, it is necessary to define concepts related to the theory of fuzzy sets. All concepts were defined according to Barros and Bassanezi (2010) and are detailed in Appendix I.

Estimation of Fuzzy Natural Mortality (M)

The fuzzy natural mortality estimate of each species was performed in two stages:

(i) Fuzzy Set Estimate for Average Annual Temperature:

For the fuzzification of average annual temperature, the normality of the data distribution was first verified using the Shapiro-Wilk normality test and its variance. Then, the average annual temperature was modeled as a fuzzy number, from a set of confidence intervals, based on the methodology of Buckley (2005).

Buckley (2005) suggests finding the confidence interval 100(1 - β) % for all $0.01 \leq \beta < 1$. Each of these intervals can be denoted by:

$$[\theta_1(\beta), \theta_2(\beta)]$$

The range is considered $[\theta^*, \theta^*]$ for $\beta = 1$, where θ^* it is the point estimate for the parameter θ, thus, there are intervals for $0.01 \leq \beta \leq 1$. These ranges define the fuzzy set $\hat{\theta}$ through its α-levels as follows:

$$[\hat{\theta}]^\alpha = [\theta_1(\alpha), \theta_2(\alpha)]$$

For $0 \leq \alpha < 0.01$, $[\hat{\theta}]^\alpha = [\theta_1(0.01), \theta_2(0.01)]$ was defined. With this, from the confidence intervals for a parameter θ, a fuzzy set for the average annual temperature was constructed whose α-cuts are those intervals. The fuzzy average annual temperature was estimated for each set of temperature data, according to the watershed of origin in the study area for each species.

For each IPCC scenario (RCP 2.6; RCP 4.5; RCP 6.0; RCP 8.5), a fuzzy average annual temperature was projected. The membership functions, used for each IPCC scenario, were assumed to be the characteristic function of the set of each temperature range, since it is believed that all values of this range have the same importance, since there is no evidence of differences.

(ii) Fuzzy Set for Natural Mortality

In each scenario, the fuzzy natural mortality was estimated by applying the Zadeh’s Extensions Principle (Zadeh, 1965) of the classical function proposed by Pauly (1980):

$$\ln(M) = -0.0152 - 0.279\ln(L\infty) + 0.6543\ln(k) + 0.463\ln(T)$$

where L∞, k and T denote theoretical maximum length, individual growth coefficient and average annual water surface temperature, respectively. The Python program was used for this analysis.

RESULTS

The fuzzy sets for the average annual temperature for the Amazon River basins (a), north/northeast Atlantic (b) and eastern Atlantic (c), which come from a 10-year historical series (2010-2020), can be observed in Figure 2. According to the data presented, it is observed that the Amazon River basin has a temperature range between 24 ºC and 32 ºC, while the northern/northeastern Atlantic basin has a temperature range of between 26 ºC and 33 ºC and the eastern Atlantic basin ranges between 19 ºC and 30 ºC. Taking into account the highest degree of membership, that is, 1 (one), the average temperature is 27.3 °C, 28.8 °C and 25.3 °C, for the northern/northeastern and eastern Amazon River basins, respectively.

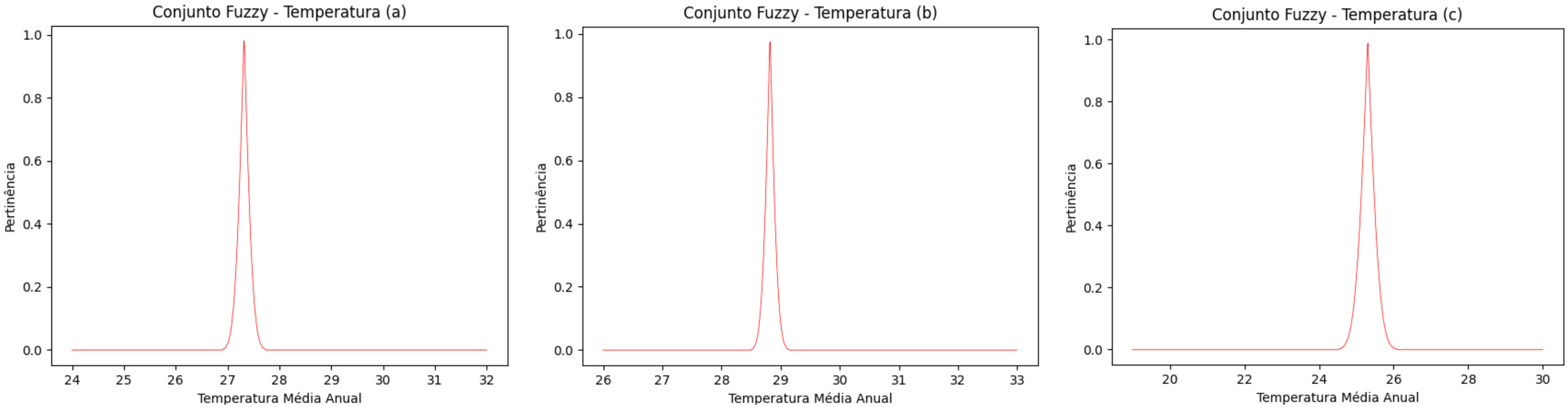

Figure 2. Fuzzy annual average temperature for the Amazon River (a), northern/northeastern Atlantic (b) and eastern Atlantic (c) basins

The Figure 3 below presents the distribution of possibilities of natural mortality (M) of fish, including the current scenario and for each scenario of the IPCC (Intergovernmental Panel on Climate Change), which represent the freshwater environment; *Cichla temensis* (a), *Prochilodus nigricans* (b) and *Triportheus angulatus* (c). The vertical axis on the left presents the possibilities of M. The bar on the right, in grayscale, presents the degree of membership, and the closer to 1 (one), the greater the pertinence of M. For the three species, it was possible to identify that there is a pattern of increasing the uncertainty of M with the increase in temperature. This uncertainty is most evident between scenarios C1 and C4. *Cichla temensis*, which presents strategy in equilibrium, presented the lowest degree of uncertainty of M among the freshwater species. Among these species, *Triportheus angulatus*, that presents characteristics of opportunistic species, presented the highest degree of uncertainty of M for all scenarios. *Prochilodus nigricans*, a seasonal species, presented an intermediate degree of uncertainty when compared to other freshwater species.

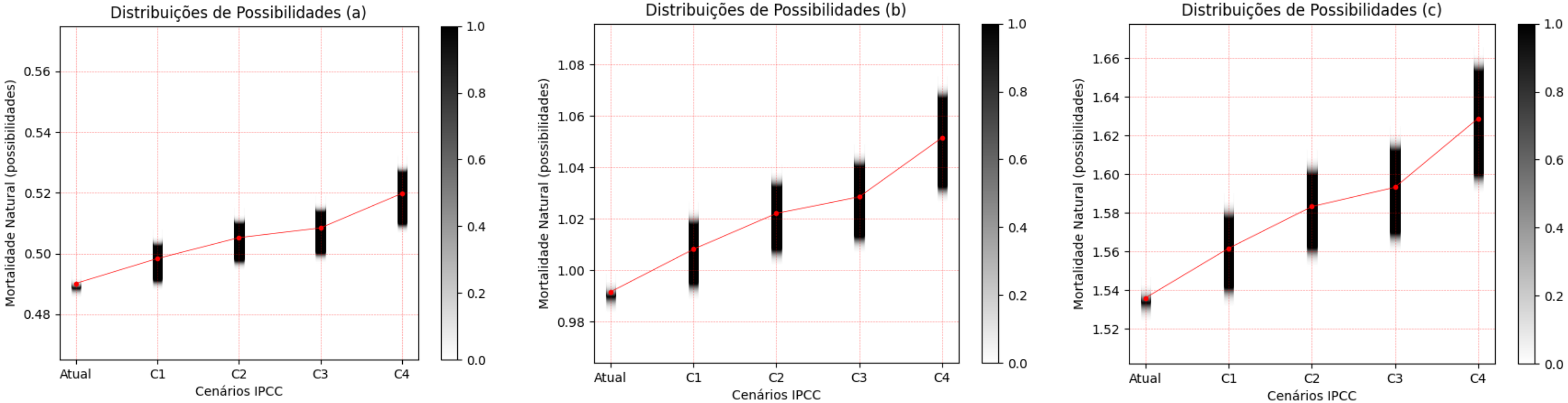

Figure 3. Distribution of possibilities of natural mortality (M) for *Cichla temensis* (a), *Prochilodus nigricans* (b) and *Triportheus angulatus* (c) and their degree of membership (vertical bar on the right), for each IPCC (Intergovernmental Panel on Climate Chang) scenario, after the application of the Zadeh extension. (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

The current distribution of possibilities of natural mortality (M) for each scenario of the IPCC (Intergovernmental Panel on Climate Change) and its degree of membership (membership value) for the fish *Cynoscion acoupa* (a), *Lutjanus synagris* (b) and *Sardinella brasiliensis* (c), which represent the marine environment, is illustrated in Figure 4. In the same manner as was presented for the freshwater species, the observed pattern is an increase in the uncertainty of M with the increase in temperature for the three species, and this is more evident between scenarios C1 and C4. When the life strategies were compared, *Cynoscion acoupa*, an equilibrium strategist, presented the lowest degree of uncertainty between the species. This increased for *Lutjanus synagris*, which is a seasonal strategist, and *Sardinella brasiliensis*, an opportunist, presented the highest degree of uncertainty of M, among the species.

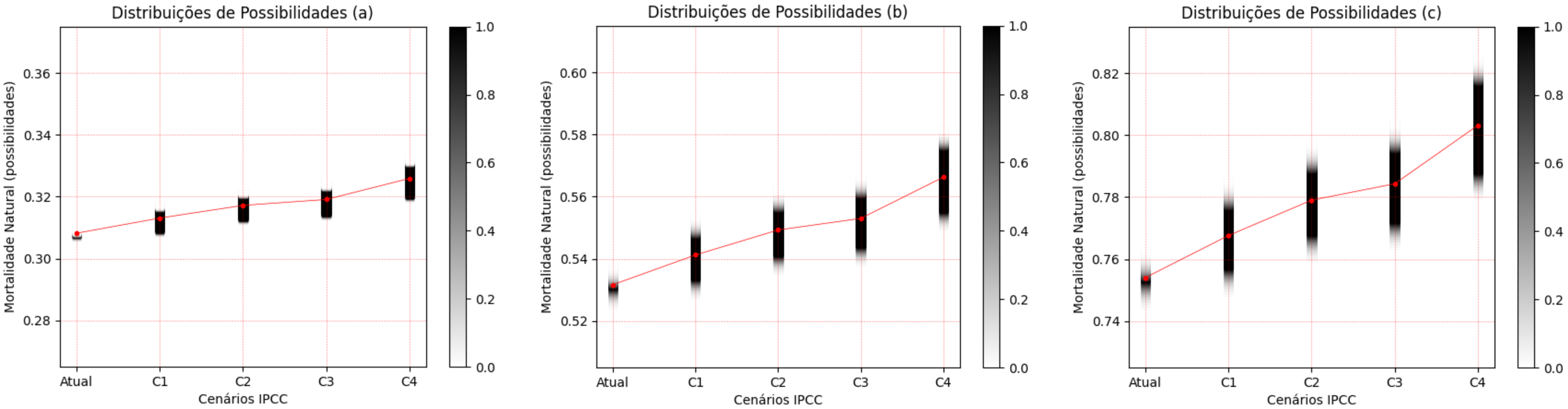

Figure 4. Distribution of possibilities of natural mortality (M) for *Cynoscion acoupa* (a), *Lutjanus synagris* (b) and *Sardinella brasiliensis* (c) and their degree of membership (vertical bar on the right), for each IPCC scenario (Intergovernmental Panel on Climate Change), after applying the Zadeh's Extension Principle. (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

Considering a degree of membership greater than or equal to 0.05, the distribution of the possibility of M for each species and for each IPCC scenario can be observed in Table 4.

Table 4. Natural mortality possibilities (M) for each target species in the study and IPCC (Intergovernmental Panel on Climate Change) scenarios, considering a degree of relevance greater than or equal to 0.05

Species	Current	C1	C2	C3	C4	Strategy	Environment
Cichla temensis	0.48	0.49 - 0.50	0.51	0.49 - 0.51	0.50 - 0.53	Equilibrium	Freshwater
Prochilodus nigricans	0.98 - 0.99	0.99 - 1.02	1.00 - 1.03	1.01 - 1.04	1.03 - 1.07	Seasonal	
Triportheus angulatus	1.52 - 1.54	1.53 - 1.58	1.55 - 1.60	1.56 - 1.62	1.59 - 1.66	Opportunist	
Cynoscion acoupa	0.30	0.31	0.31	0.31	0.33	Equilibrium	Marine
Lutjanus synagris	0.52 - 0.53	0.52 - 0.55	0.53 - 0.56	0.54 - 0.56	0.55 - 0.58	Seasonal	
Sardinella brasiliensis	0.74 - 0.76	0.75 - 0.78	0.76 - 0.79	0.76 - 0.80	0.78 - 0.82	Opportunist	

It was possible to identify a general pattern associated with estimates of M, which resulted from IPCC scenarios, and two patterns related to the interactions between the life strategy and the type of environment inhabited by the species. There is an effect of the rise in temperature, which is predicted in the IPCC scenarios, on the uncertainty of estimates of natural mortality that is not linked to the environment and the life strategy of the species. The uncertainty of M increases gradually from one scenario to another, and is consistently higher in C4 for all species. However, the variation in the uncertainty is not constant between species with different life strategies. Species in equilibrium have lower uncertainty in estimates of M in all scenarios. Seasonal species present estimates of M with intermediate values of uncertainty. While, opportunistic species or with characteristics that come close to the opportunistic strategy, such as *T. angulatus*, exhibit the greatest uncertainties in the estimated M values for all scenarios, and the variation in the increase in natural mortality is slightly greater for these species. Apparently, species that inhabit freshwater systems have a higher degree of uncertainty of M when compared to marine species.

DISCUSSION

The difficulty in estimating natural mortality is associated with the amount of factors that influence it and the complexity of taking into account all or most of these factors in the estimation process. To minimize this problem, Brodziak et al. (2011) suggested considering the relative influence of intrinsic versus extrinsic factors and using the estimated distribution of M to provide a more accurate approximation of parametric uncertainties. Our model used temperature as a key factor, which can influence both the increase in baseline natural mortality rates (in the ratio of metabolic rate and body mass - intrinsic factor), as well as the additional natural mortality beyond the baseline (as an isolated environmental factor and in interaction with other environmental factors - extrinsic factor). Therefore, this can be considered a more robust model compared to the models that have already been used in the attempt to incorporate the uncertainties of M, but that do not combine the 2 groups of factors that affect M or do not use a force variable that can influence the intrinsic and extrinsic factors (HAMEL, 2011; MACCALL, 2011; PUNT et al., 2021).

The relationship between the metabolic rate and body mass adjusted for habitat temperature may be affected. The physiology of fish is directly related to temperature, which has an inverse relationship with the amount of dissolved oxygen in the aquatic environment (FICKE et al., 2007; LIMA et al., 2016). Therefore, the increase in temperature and the reduction of oxygen level lead to an increase in metabolic rate, an increase in physiological stress, and an imbalance in biochemical functions as a result of changes in body temperature, as well as an increase in the mortality rate of eggs, larvae and adult fish, thus changing the structure, composition and population dynamics of the species (FREITAS et al., 2013; BARROS and ALBERNAZ, 2013; ROPKE et al., 2017). Due to the allometric scale of metabolism (WOODWARD et al. 2016), large species that have a long life and slower life cycles, i.e., species that have a life strategy in equilibrium, such as C*ichla temensis* and *Cynoscion acoupa*, are at a disadvantage when compared to smaller species, due to their higher metabolic rates and are more likely to face local extinction (WOODWARD et al., 2016; ANDRADE et al., 2018).

The increase in temperature may also cause additional natural mortality in the target species of the study, due to adverse environmental events. Many natural populations experience short-term mortality events in the form of diseases or environmental episodes that can operate beyond the baseline M (BRODZIAK et al., 2011). The effects of climate change due to an increase in temperature may vary by region and cause adverse environmental events, such as hydrological, oceanographic alterations, as well as climatic extremes (MARENGO et al., 2009). One reason that would explain the additional natural mortality of freshwater species, which in this study are Amazonian species (*Cichla temensis, Prochilodus nigricans* and *Triportheus angulatus*), would be the extreme events in the Amazon region, such as extreme flooding and droughts (MARENGO et al., 2007, 2009; ZUANON, 2008; BARROS and ALBERNAZ, 2013;

ROPKE et al., 2017). The marine species (*Cynoscion acoupa*, *Lutjanus synagris* and *Sardinella brasiliensis*) may have been affected by impacts on coastal circulation patterns such as coastal resurgences and South Atlantic central water infiltrations (GARCIA et al., 2003, 2004; DIAZ and ROSENBERG, 2008; VIEIRA et al., 2008; GRUBER, 2011).

The patterns observed in the increase in natural mortality (M) for each species, according to each IPCC scenario, corroborate with the characteristics of these scenarios presented in the fifth IPCC report (AR5). Scenario C1 corresponds to a mitigation scenario, with projections of an elevation of T°C on the planet from 0.3 to 1.7. Scenario C4 corresponds to the highest rates of M, and is a scenario with projections of elevation of T°C of 2.6 to 4.8. Scenarios C2 and C3 are stabilization scenarios (IPCC, 2014) and were clearly observed in our results. In a recent study, Dahlke et al. (2020) analyzed 694 freshwater and marine fish species from all climate zones and concluded that 60% of fish species may not survive if climate warming reaches the worst-case scenario, i.e., increasing by round 4 °C. However, for a more optimistic scenario, with an increase of up to 1.5 °C, only 10% of the species surveyed would be at risk in the next 80 years.

The uncertainties and variability of estimates of M observed in this study are directly related to the life strategies of each species. Many aspects of the life history of fish are related to climate on an evolutionary scale, which gives them high or low plasticity, i.e., the ability to adapt to natural changes in their habitats (SLOMAN et al., 2006; VAL and ALMEIDA-VAL, 1995, VAL, 2011; JEPPESEN et al., 2014). However, the climate changes that are currently underway are occurring at a higher rate than the adaptation rates, and it is necessary to understand, from the aspects of the life history of a species, if the species has the potential to deal with these changes in the environment (VAL, 2011; DAHLKE et al., 2020; SUNDAY, 2020), since life history traits are the underlying determinants for population responses to environmental forces (KING and MCFARLANE, 2003).

Several studies have been carried out that relate the characteristics of the life history of fish species to temperature in the face of climate change. Studies comparing lake fish from temperate and tropical regions along latitudinal gradients have shown that fish species from lower latitudes are often smaller, grow faster, mature earlier, have a shorter life expectancy, and allocate less energy for reproduction than species from higher latitudes (GRIFFITHS, 1997; BLANCK and LAMMOUROUX, 2007; TEIXEIRA-DE MELLO et al., 2009; JEPPESEN et al., 2010; MEERHOFF et al., 2012; BRUCET et al., 2013). Jeppesen et al. (2014) conducted a literature review and synthesized the expected changes in the main characteristics of fish life history of inland water systems. In a temperature gradient, species with opportunistic life history characteristics showed greater plasticity compared to species in equilibrium. It has also been shown that the influence of temperature is greater and more significant, both positively and negatively, for fish populations with opportunistic characteristics (faster growth, early age of sexual maturity and shorter life expectancy), than fish with slower life histories, such as species in equilibrium (FREE et al., 2019).

King and McFarlane (2003) analyzed the life history characteristics of 42 commercially important fish species from the west coast of Canada. The authors grouped the species by life strategies and made inferences in responses to environmental conditions for fisheries management purposes. They concluded that equilibrium strategists are able to withstand only low or moderate rates of capture, since they have low fecundity and late maturation and, therefore, are not able to recover as quickly as other fish after population reduction by fishing and, because they have low growth rates, their population dynamics have a very low variability. As seasonal strategists are relatively long-lived, they are able to benefit from this by ensuring a relatively long reproductive cycle, which minimizes the risk that periods of unfavorable environmental conditions might result in the loss of a stock. However, these species exhibit lower variability in abundance and were classified as having a steady-state population pattern. Opportunists occupy habitats not only with a high degree of variability, but also with large energy resources, so their population responses tend to be large in amplitude. These species were classified as having cyclic, irregular or spasmodic population patterns and, within an environmental regime, their abundance is dynamic, in other words, by increasing or decreasing over time and, over the regime periods, they presented population patterns of high amplitude of variability.

These studies corroborate with our results in regards to the variability and uncertainties in the possibilities of natural mortality (M) and, consequently, in regards to population dynamics. The increase in temperature has less influence and, therefore, a lower degree of uncertainty of M for strategists in equilibrium (*Cichla temensis* and *Cynoscion acoupa*) in regards to climate change. The seasonal strategists (*Prochilodus nigricans* and *Lutjanus synagri*s) presented an intermediate and/or stationary degree of uncertainty of M and the opportunists or with characteristics that come close to the opportunistic strategy (*Triportheus angulatus* and *Sardinella brasiliensis*) presented the highest degree of uncertainty of M. This suggests that the adaptation and plasticity of fish species in order to deal with current climate changes, associated with life strategies, follow a gradient of temperature and natural mortality (M), in addition to a general behavior in the variability of the population dynamics, as can be seen in Figure 5.

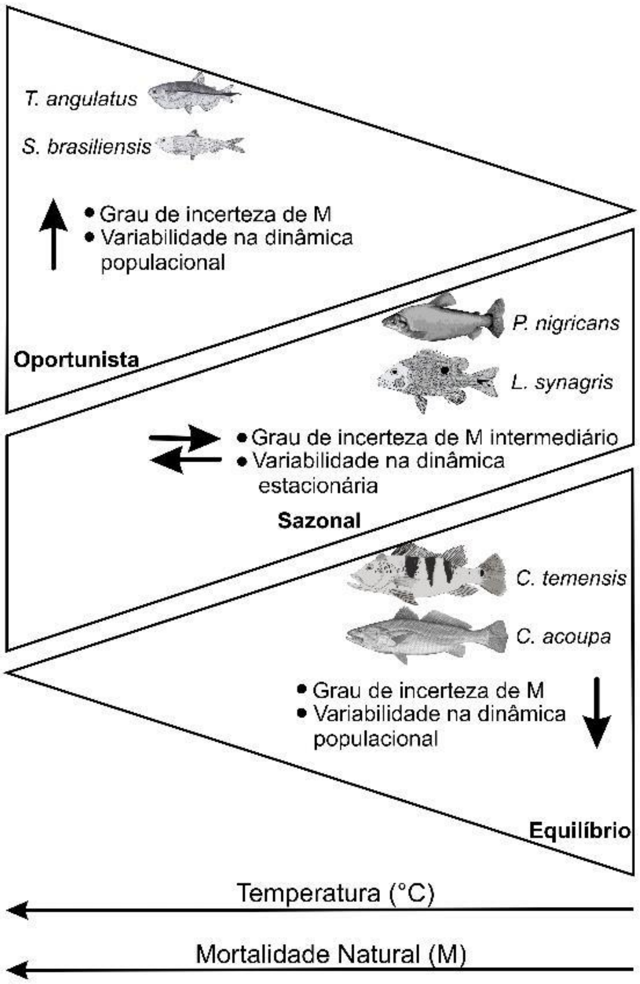

Figure 5. Expected behavior according to the characteristics of the life history of fish according to a gradient of temperature (°C) and natural mortality (M) (adapted from Jeppesen et al., 2014)

The magnitude of natural mortality (M) is directly related to the productivity of the stock, the yields that can be obtained, the optimal exploitation rates, the types of management and the reference points (BRODZIAK et al., 2011), in addition to being one of the most sensitive parameters of fish stock assessment models (KING, 1995). Therefore, it is essential to use M estimates that incorporate variations and uncertainties in the face of global climate change. In addition, the patterns found in uncertainties of M associated with species groupings by life strategies can be used in more holistic approaches to the assessment and management of recently exploited fishery resources or those with limited biological data.

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APPENDIX I

The difference between classical theory and fuzzy set theory begins in the concept of pertinence of an element to a set. In the classical logic of sets, the concept of pertinence of an element to a set is well defined. The degree of membership is expressed mathematically by the characteristic function, the definition of which is given below.

<u>Definition (1) [Characteristic Function]</u>: given a set *A* in a universe *U*, an element belongs to or does not belong to that set and cannot be partially contained:

$$\chi_A(x) = \begin{cases} 1 & \text{se } x \in A \\ 0 & \text{se } x \notin A \end{cases}$$

However, there are cases where the degree of membership between elements and sets is not accurate, or rather, it is not known whether an element actually belongs to a set or not. Zadeh (1965) proposed a broader characterization, and generalized the characteristic function so that it could assume an infinite number of values in the interval [0.1].

<u>Definition (2) [Fuzzy Set]</u>: A fuzzy set *A* in a universe *U* is characterized by a membership function $\varphi_A : U \rightarrow [0,1]$. The membership value $\varphi_A(x)$ indicates the degree of pertinence of *x* in *A*, where $\varphi_A(x) = 0$ and $\varphi_A(x) = 1$ indicate the non-pertinence and complete pertinence of *x* to the fuzzy set *A*, respectively. The fuzzy set *A* can be represented by a set of ordered pairs:

$$A = \{(x, \varphi_A(x)), \text{ with } x \in U\}$$

<u>Definition (3) [Support of a Fuzzy Set]</u>: Given a fuzzy set *A* in a universe *U*, the support of *A*, denoted by supp(*A*), is the (classical) subset of *U* defined by supp(*A*) = $\{x \in \mathrm{U} : \varphi_A(x) > 0\}$. In general terms, supp(*A*) is the classical set of all elements that have a certain (non-zero) degree of pertinence in *A*.

<u>Definition (4) [α-level]:</u> Let *A* be a fuzzy subset of *U* defined by the relevance function $\varphi_A : U \rightarrow [0.1]$ and $\alpha \in [0.1]$. The α-level of *A*, denoted by $[A]^\alpha$, is the classic subset of *U* defined by:

$$[A]^\alpha = \{x \in U : \varphi_A(x) \geq \alpha\} \text{ for } 0 < \alpha \leq 1$$

Definition (5) [Fuzzy Number]: A fuzzy subset *A* is called a fuzzy number when the universe set in which φ_A is defined is the set of the real numbers R and satisfy the following conditions:

(i) all the α-levels of *A* are non-empty, with $0 \leq \alpha \leq 1$;

(ii) all the α-levels of *A* are closed intervals of R;

(iii) supp$A = \{x \in R : \varphi_A(x) > 0\}$ is limited.

Definition (6) [Zadeh's Extension Principle]: Let $f : X \to Z$ and *A* be a fuzzy subset of *X*. The Zadeh's Extension of *f* is the function $\hat{f}$ which, applied to *A*, provides the fuzzy subset $\hat{f}(A)$ of *Z*, whose membership function is defined as:

$$\varphi_{\hat{f}(A)}(z) = \begin{cases} \sup\limits_{f^{-1}(z)} \varphi_A(x) & if\ f^{-1}(z) \neq \emptyset \\ 0, & if\ f^{-1}(z) = \emptyset \end{cases}$$

where $f^{-1}(z) = \{x; f(x) = z\}$, it is called the pre-image of z.

CAPÍTULO III

INCORPORAÇÃO DAS INCERTEZAS DA MORTALIDADE NATURAL (M) FRENTE AS MUDANÇAS CLIMÁTICAS GLOBAIS NA AVALIAÇÃO DE ESTOQUE DE PEIXES COM DIFERENTES ESTRATÉGIAS DE VIDA

Incorporação das incertezas da Mortalidade Natural (M) frente as mudanças climáticas globais na avaliação de estoque de peixes com diferentes estratégias de vida

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Resumo

Incorporar as incertezas das estimativas de Mortalidade Natural (M), decorrentes das mudanças climáticas globais, é fundamental para a avaliação de estoques pesqueiros e, consequentemente, para o sucesso do gerenciamento desses estoques. Portanto, esse estudo incorporou as incertezas de M, devido as mudanças climáticas globais, partindo do pressuposto que essas incertezas são associadas às estratégias de vida das espécies explotadas. Para modelar matematicamente essas incertezas, utilizou-se a teoria dos conjuntos fuzzy. Nossos resultados apontaram uma diminuição do rendimento por recruta (Y/R) para todas as espécies, com diminuição gradual entre o cenário atual e o cenário mais pessimista do IPCC (*Intergovernmental Panel on Climate Change*). Além disso, o modelo gerou intervalos de rendimento máximo sustentável (MSY) e suas respectivas mortalidades por pesca (F_{MSY}), fornecendo pontos de referência biológicos (PRB) para a gestão pesqueira. As espécies com características de história de vida oportunistas apresentaram maior variação na diminuição de MSY. Como essas espécies são mais propensas ao risco, por apresentar maior incerteza, recomenda-se cenários mais conservadores na escolha de PRB's para essas espécies. Portanto, o presente estudo contribuiu para o gerenciamento pesqueiros abordando as incertezas inerentes aos efeitos das mudanças climáticas globais e no gerenciamento de estoques baseado nos agrupamentos de espécies com diferentes características de história de vida.

Palavras-chave: rendimento máximo sustentável, pesca, mortalidade por pesca, gerenciamento pesqueiro.

INTRODUÇÃO

Os modelos de avaliação de estoques pesqueiros identificam o estado de explotação dos estoques naturais e estimam níveis ótimos para sua explotação sustentável, propiciando o desenvolvimento de estratégias para evitar o colapso do estoque devido a níveis excessivos de intensidade de pesca (SPARRE e VENEMA, 1997). Esses modelos requerem dados biológicos da população provenientes dos parâmetros de crescimento e das taxas de mortalidade. Os modelos matemáticos utilizados assumem, como premissas básicas, suposições que metodologicamente ou biologicamente nem sempre são cumpridas, como amostras aleatórias, recrutamento constante de ano a ano, distribuição dos indivíduos em coortes discretas e mortalidade constante ao longo do tempo (KING, 1995, SPARRE e VENEMA, 1997), gerando vícios e/ou erros (distorções) nos resultados obtidos. As incertezas que envolvem a avaliação dos estoques pesqueiros podem dificultar a tomada de decisão acerca das capturas futuras.

A mortalidade natural (M) é um dos parâmetros-chave para o entendimento da dinâmica de populações pesqueiras explotadas (KENCHINGTON, 2014). Nos modelos de avaliação de estoques pesqueiros, M é parte da mortalidade total incidente sobre o estoque (QUIROZ et al., 2010; KENCHINGTON, 2014), e sua estimação é fundamental na definição dos níveis de mortalidade por pesca que o estoque pode suportar e que constituirão as bases para propostas de manejo (GAERTNER, 2015). A estimativa de M envolve algumas incertezas substanciais que interferem na avaliação do estoque pesqueiro, resultantes da qualidade dos dados, dos métodos de estimação, da variação no tempo (CHEN et al., 2018) e das mudanças climáticas globais que, ao se juntarem às ameaças da sobrepesca, comprometem ainda mais os regimes de gestão pesqueira (IPCC, 2014).

Essas incertezas afetam os resultados da avaliação do estoque, enviesam a estimativa de mortalidade total e, via de consequência, reduzem ou aumentam a estimativa da produção total da população (DUTIL e LAMBERT, 2000). Sendo assim, a variação e a incerteza sobre M devem ser explicitamente consideradas na avaliação e nas variáveis de gestão de estoque (por exemplo, Rendimento Máximo Sustentável). Devendo, se possível, agregá-las ao modelo com a finalidade de mensurar o risco biológico associado à incerteza (QUIROZ et al., 2010; WHITLOCK et al., 2012). Por exemplo, uma incerteza mais alta em M poderia se traduzir em um *buffer* maior entre a captura biológica permitida e a captura no nível de sobrepesca (BRODZIAK et al., 2011).

Schrank (2007) argumentou que o nível de incerteza associado à pesca vem dificultando a eficiência das estratégias de manejo pesqueiro.

Na literatura encontram-se algumas ferramentas para o tratamento das incertezas. Dentre essas cita-se o uso da lógica fuzzy juntamente com a teoria dos conjuntos fuzzy (CHEUNG et al., 2005; PATERSON et al., 2007; SYLAIOS et al., 2010; TEH e TEH, 2011; WISE et al., 2012; YURRITA, 2014; BITAR et al., 2014), que possibilitam a modelagem matemática da incerteza, além de formular matematicamente a subjetividade inerente aos fenômenos naturais, para tentar fazer previsões coerentes (BARROS e BASSANEZI, 2010).

Além disso, os padrões encontrados nas incertezas de M podem ser usados em abordagens mais holísticas para a avaliação e gestão dos recursos pesqueiros recentemente explorados ou com dados biológicos limitados (KING e MCFARLANE, 2003). Uma maneira de abordar essas lacunas de informação é caracterizar agrupamentos de espécies explotadas comercialmente com base em características da história de vida conhecidos e usar esses agrupamentos para caracterizar as tendências dos níveis produção sustentável de espécies em várias escalas de tempo (KING e MCFARLANE, 2003). Cenários de manejo conceituais baseados em características da história de vida podem ser usados para o manejo de espécies recentemente explotadas.

Diversos estudos já avaliaram a incerteza da mortalidade natural de peixes (QUIROZ et al., 2010; GAERTNER, 2015; LEGAULT e PALMER, 2016; CHEN et al., 2018) e o impacto das mudanças climáticas na produção pesqueira global (CHEUNG et al., 2010; SERPETTI et al., 2017; GAINES et al., 2018; CISNEROS-MATA et al., 2019; FREE et al., 2019). No entanto, não há relatos na literatura de uma avaliação de estoques pesqueiros relacionando esses fatores. Diante disso, o objetivo desse estudo foi incorporar as incertezas da Mortalidade Natural (M), devido as mudanças climáticas globais, usando a lógica fuzzy, partindo do pressuposto que essas incertezas são associadas às estratégias de vida das espécies explotadas. A análise aqui proposta faz recomendações científicas sobre procedimentos de conservação e gestão desses estoques pesqueiros.

MATERIAL E MÉTODOS

Coleta de dados

Foram selecionadas espécies com diferentes estratégias de vida, agrupadas em: estrategista em equilíbrio, sazonal e oportunista, de acordo com a classificação de Winemiller (1989) e Winemiller e Rose (1992). Além disso, buscou-se selecionar espécies de ambientes de água doce e marinho e que apresentassem importância comercial. As espécies representantes de ambientes de água doce foram: *Cichla temensis* (estrategista em equilíbrio), *Prochilodus nigricans* (estrategista sazonal) e *Triportheus angulatus*, que apesar de não ser considerada uma espécie completamente oportunista, ainda assim, apresentam características que se aproximam desse tipo de estratégia de vida. As espécies representantes de ambientes marinhos foram: *Cynoscion acoupa* (estrategista em equilíbrio), *Lutjanus synagris* (estrategista sazonal) e *Sardinella brasiliensis* (estrategista oportunista).

Os parâmetros populacionais de cada espécie, que serviram como dados de entrada para a estimativa do Conjunto Fuzzy de Rendimento por Recruta (Y/R) foram extraídos da literatura. Para cada espécie, buscou-se extrair os parâmetros de um único estudo, para evitar possíveis erros de viés metodológico. Alguns parâmetros não estavam acessíveis, mas a partir dos dados disponíveis, foi possível estimá-los. Na Tabela 1 apresenta-se os dados consolidados para os parâmetros populacionais disponíveis na literatura (em preto) e os estimados neste estudo (em vermelho). Foram utilizados os Conjuntos Fuzzy da Mortalidade Natural (M) para cada cenário do IPCC, estimados no Capítulo 2.

Tabela 1. Parâmetros populacionais das espécies selecionadas para o estudo para estimativa do Conjunto Fuzzy de Rendimento por Recruta (Y/R)

Nº	Espécie	Tc/Tr (anos)	W∞ (gr)	k (ano^{-1})	b	$T_{\text{máx}}$ (ano)	Estratégia	Ambiente
1	*Cichla temensis*	1,88	5037,63	0,20	3,232	14,00	Equilíbrio	Água Doce
2	*Prochilodus nigricans*	0,78	967,45	0,44	2,720	6,80	Sazonal	
3	*Triportheus angulatus*	0,39	350,36	0,77	2,859	3,89	Oportunista	
4	*Cynoscion acoupa*	0,73	16112,66	0,13	3,028	10,00	Equilíbrio	Marinho
5	*Lutjanus synagris*	0,91	2200,00	0,22	2,890	18,00	Sazonal	
6	*Sardinella brasiliensis*	0,56	180,33	0,26	3,130	10,73	Oportunista	

Fonte: 1 - Campos et al. (2020); 2 - Catarino et al. (2014); 3 - Prestes et al. (2010); 4 - Oliveira et al. (2020); 5 - Aschenbrenner et al. (2017); 6 - Costa et al. (2018).

Análise de dados

O modelo para o Rendimento por Recruta (Y/R) Fuzzy incorporou estimativas para os parâmetros populacionais do modelo. Os parâmetros t_r, t_c e W∞ foram estimados por não estarem disponíveis na literatura. Os parâmetros Z e F, mesmo que disponíveis na literatura, estão diretamente relacionados com a Mortalidade Natural (M) e como adotamos um conjunto $\widetilde{M}$ fuzzy para M, foi necessário estimá-los com a utilização de operações com conjuntos fuzzy.

Parâmetros Populacionais

Idade de Recrutamento à pesca (t_r) / Idade de primeira captura (t_c)

As idades de recrutamento (t_r) e primeira captura (t_c) foram computadas usando uma adaptação da equação de crescimento de von Bertalanffy (KING, 1995; SPARRE e VENEMA, 1997):

$$t_r = t_0 - \left(\frac{1}{k}\right) \cdot ln\left(1 - \frac{L_r}{L_\infty}\right) \qquad (1)$$

$$t_c = t_0 - \left(\frac{1}{k}\right) \cdot ln\left(1 - \frac{L_c}{L_\infty}\right) \qquad (2)$$

Onde:

k := coeficiente de crescimento individual;
L∞ := comprimento máximo teórico;
Lc := comprimento de primeira captura;
Lr := comprimento médio de recrutamento.
t_0 := idade teórica no comprimento zero

O parâmetro t_0 foi considerado zero, uma vez que esse parâmetro não tem conotação biológica, sendo uma correção matemática para o ajuste da curva (SPARRE e VENEMA, 1997).

Para o comprimento de primeira captura (Lc) e o comprimento médio de recrutamento (Lr) assumiu-se Lc = Lr com base na menor classe de comprimento que está plenamente representada na captura (KING, 1995; SPARRE e VENEMA, 1997).

Peso máximo assintótico (W∞)

O peso máximo assintótico (W∞) foi estimado de acordo com a equação abaixo (SPARRE e VENEMA, 1997):

$$W_\infty = a * {L_\infty}^b \qquad (3)$$

Onde:

L∞ := comprimento máximo teórico;

a e b := parâmetros da relação peso-comprimento.

Mortalidade Total (Z) / Mortalidade por Pesca (F)

Na modelagem da Mortalidade Total (Z) adotou-se os possíveis valores para F (de 0 a 6, dependendo da espécie). Sendo a mortalidade total (Z) a soma da mortalidade natural (M) e mortalidade por pesca (F), tem-se que (SPARRE e VENEMA, 1997):

$$Z = M + F \tag{4}$$

Para o cálculo da Mortalidade Total Fuzzy ($\tilde{Z}$), a componente mortalidade natural (M) da equação (4) foi tratada como um Número Fuzzy e a operação soma foi estendida para soma de números fuzzy. Dessa forma os alfa-níveis do conjunto $\tilde{Z}$ foram obtidos conforme o Teorema 2.4[1] de Barros e Bassanezi (2010): $[Z]^{\alpha} = [M]^{\alpha} + [F]^{\alpha}$. O tratamento para F foi crisp, logo $[F]^{\alpha} = F$.

Conjunto Fuzzy para Rendimento por Recruta (Y/R)

No modelo proposto para estimativa do rendimento fuzzy $\tilde{Y}(t)$ considerou-se t ≥ Tc, pois é quando o estoque pesqueiro começa a sofrer captura. Se valor de R denota o recrutamento da espécie, então a expressão $\tilde{Y}/R(t)$, expressa o rendimento fuzzy por recruta no instante t. Para avaliar o comportamento desse rendimento, ao final do ciclo de vida da espécie, considerou-se t ∈ [tc,tf], onde tc corresponde a idade de primeira captura e tf a idade ao final do ciclo.

O problema de valor inicial (clássico) com variação de rendimento a ser resolvido seria o seguinte:

$$\begin{cases} \dfrac{dY}{dt} = FN(t)W(t) \\ Y(t_c) = Y_0 \end{cases} \tag{5}$$

Onde:

N(t) := número de indivíduos sujeitos a captura ($t \geq t_c$)

W(t) : = peso médio do indivíduo no instante t

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[1] Teorema 2.4: Os alfa-níveis do conjunto fuzzy A + B são dados por: $[A + B]^{\alpha} = [A]^{\alpha} + [B]^{\alpha}$, para todo α ∈ [0, 1].

Y(t) := rendimento obtido do estoque pesqueiro.

F := taxa de mortalidade por pesca

Y_0 := rendimento no instante t = t_c

Seja H: $[t_c,t_f] \to F(\Re)$ a função definida por $H(t) = FN(t)W(t)$, sendo $F(\Re)$ o universo dos conjuntos fuzzy dos números reais. Supondo H contínua, é possível garantir que o problema (5) (BARROS, 1997) possui solução única definida por:

$$Y(t) = Y_0 + \int_{t_c}^{t} H(t)dt \tag{6}$$

Com o uso das expressões $N(t) = Re^{-M(Tc-Tr)}e^{-Z(t-Tc)}$, sendo R := número de indivíduos iniciais da coorte e $W(t) = W\infty\,(1 - e^{-k(t-t_0}))^3$, verifica-se que a solução do problema de valor inicial (5), calculada em T_f, satisfaz:

$$Y(T_f) = g(F, \Gamma) \tag{7}$$

Na equação (7), Γ é o vetor de parâmetros ($\Gamma \in R^5$), $\Gamma = (R, M, k, W_\infty$ e $b)$, presentes na função H, em que R, M, k, W_∞ e b denotam o número inicial de indivíduos da coorte, a mortalidade natural, a taxa de crescimento, o peso assintótico e parâmetro alométrico, respectivamente. Esses parâmetros bioecológicos são inerentes às espécies. A solução original por Beverton e Holt (1957), como apresentada na equação (8), assumiu b = 3. No entanto, como b varia com as condições ambientais, esse parâmetro não pode ser assumido sempre como igual a 3 (BRAGA, 1997) e a solução nesse trabalho, para b ≠ 3 foi obtida por Métodos Numéricos.

$$Y/R = F * exp^{[-M(Tc-Tr)} * W\infty * [\left(\frac{1}{z}\right) - \left(\frac{3S}{Z+k}\right) + \left(\frac{3S^2}{Z+2k}\right) - \left(\frac{3S^3}{Z+3k}\right) \tag{8}$$

Onde:

Y/R := rendimento por recruta;

F := mortalidade por pesca;

M := mortalidade natural;

Tc := idade de primeira captura;

Tr := idade de recrutamento;

W∞ := peso máximo assintótico;

Z := mortalidade total;

k := coeficiente de crescimento individual;

$S = \ exp^{[-k(Tc-t_0)]}$.

O interesse do estudo é a solução do modelo (5), supondo que M é um conjunto fuzzy. Em geral avalia-se $Y(t_f)$ variando-se F e identificando o Rendimento Máximo Sustentável (MSY). Essa estratégia será mantida com a hipótese de que M é definido como um conjunto fuzzy. Retornando à equação (7), podemos tomar o quociente por R, resultando em:

$$\frac{Y(T_f)}{R} = \frac{g(F,\Gamma)}{R} = h(F,\Gamma) \tag{9}$$

A equação (9) sugere um valor para o rendimento por recruta em função do parâmetro F. A representação gráfica para $Y(T_f)/R$ está ilustrada na Figura 1.

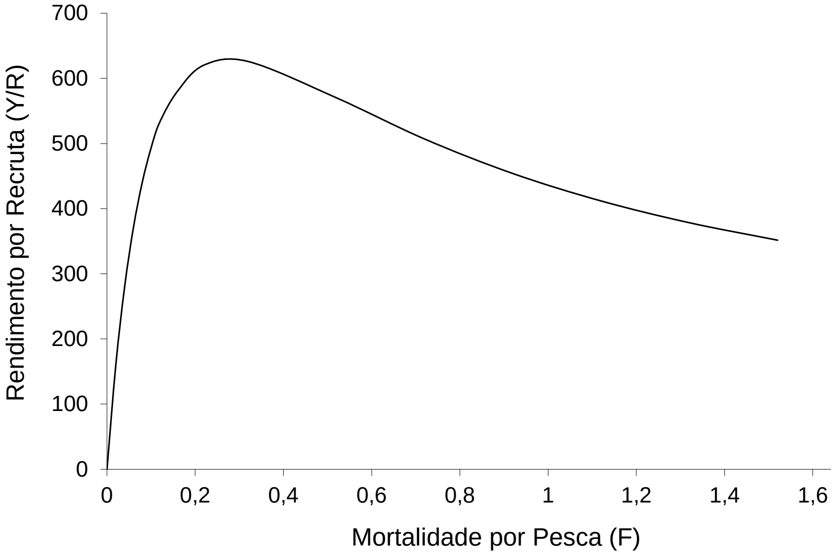

Figura 1. Representação gráfica do Rendimento por Recruta em função da Mortalidade por Pesca (F)

Agora, seja Y_t (Y_0, M) a família de soluções, dadas pela equação (6), que dependem do parâmetro M e da condição inicial Y_0. A investigação para solução do problema de valor inicial (5), no caso em que $\widetilde{M}$ é um conjunto fuzzy para mortalidade natural M, considerou o seguinte modelo de Equação Diferencial Fuzzy:

$$\frac{dZ}{dt} = \widehat{H}(t,\widetilde{M}) \qquad Z(t_c) = Y_0 \tag{10}$$

Na equação (10), $\widehat{H}$ denota a Extensão de Zadeh para função H, a expressão à esquerda é a derivada de Hukurara (MARKOV, 1978) e Z uma função definida por

Z:[t_c,t_f] → $F(\Re)$. A demonstração para existência de solução do problema (10) e aprofundamento sobre o tema podem ser encontradas em (BARROS, 1997; CECCONELLO, 2010).

Para computação dos alfa-níveis para solução fuzzy da equação (10) recorreu-se novamente à Extensão de Zadeh, sobre a solução de (5). Se $Y_t(Y_0, M)$ é solução determinística de (5), então pelo Teorema 2.1[2] de Barros e Bassanezi (2010), os alfa-níveis da solução fuzzy $Z_t(Y_0, \widetilde{M})$ de (10), são obtidos como segue: $[Z_t(Y_0, \widetilde{M})]^\alpha = [\hat{Y}_t(Y_0, \widetilde{M})]^\alpha = Y_t(Y_0, [\widetilde{M}]^\alpha)$, sendo $\hat{Y}_t$ a Extensão de Zadeh para solução Y_t. Essa última igualdade permite a análise do conjunto fuzzy para o rendimento, com base nos alfa-níveis de $\widetilde{M}$ (Figura 2). E dessa forma podemos avaliar diversos cenários.

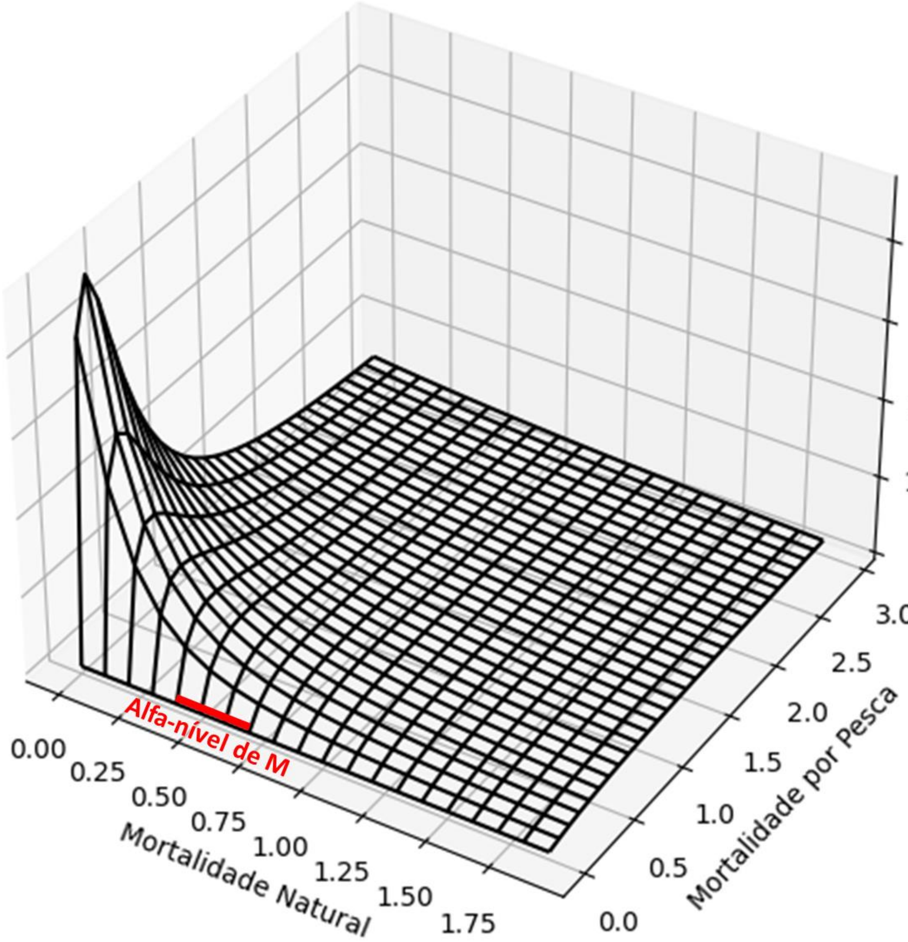

Figura 2. Representação gráfica do Rendimento por Recruta em função da Mortalidade Natural (M) e Mortalidade por Pesca (F), com destaque ao alfa-nível de M

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[2] Teorema 2.1: Sejam $f : X \to Z$ uma função contínua e A um subconjunto fuzzy de X. Então, para todo $\alpha \in [0, 1]$ vale: $[\hat{f}(A)]^\alpha = f([A]^\alpha)$.

RESULTADOS

A estimativa do Rendimento por Recruta (Y/R) Fuzzy, com a incorporação da Mortalidade Natural (M) Fuzzy, apresentou dois padrões, para todas as espécies alvo do estudo, decorrentes dos cenários do IPCC (*Intergovernmental Panel on Climate Change*): (i) O Y/R diminui gradativamente do cenário atual para o cenário C4 e (ii), de forma inversa, as incertezas nas estimativas de Y/R aumentam e ficam mais evidentes no cenário C4 (Figuras 3 e 4). Foi possível identificar também dois padrões nas estimativas de Y/R, que representam interações entre a estratégia de vida e o tipo de ambiente habitado pela espécie. Espécies em equilíbrio apresentaram incerteza menor nas estimativas de Y/R em todos os cenários do IPCC. As espécies sazonais apresentam estimativas de Y/R com valores intermediários de incerteza. Enquanto, as espécies com características de história de vida oportunistas exibem as maiores incertezas nos valores estimados de Y/R para todos os cenários. Aparentemente, espécies marinhas apresentam maior grau de incerteza de Y/R comparadas com as espécies que habitam sistemas de água doce.

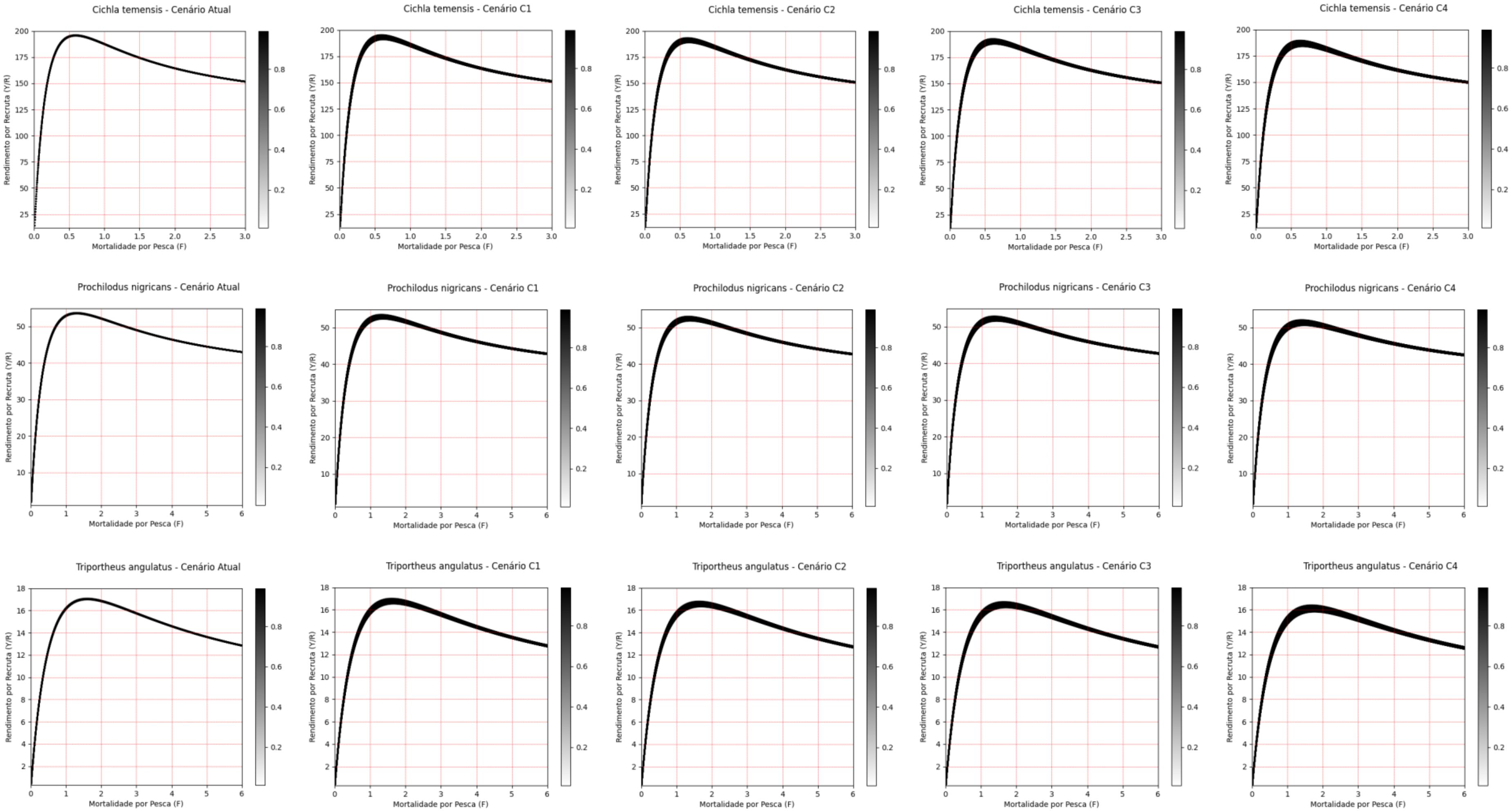

Figura 3. Rendimento por Recruta (Y/R), com a incorporação da Mortalidade Natural (M) Fuzzy, para *Cichla temensis*, *Prochilodus nigricans* e *Triportheus angulatus* e seu grau de pertinência (barra vertical à direita), para cada cenário do IPCC (*Intergovernmental Panel on Climate Change*), após a aplicação da Extensão de Zadeh. (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

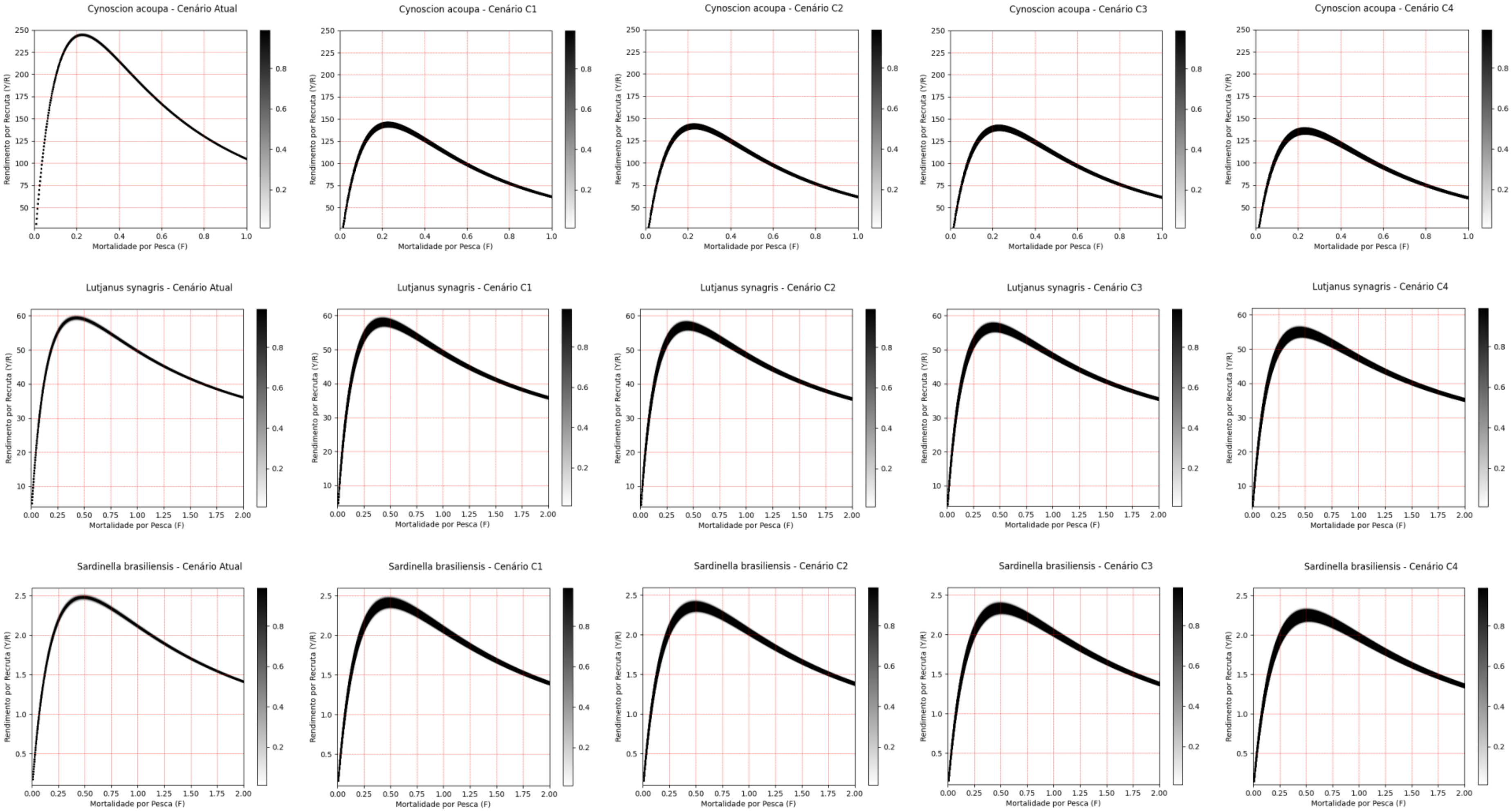

Figura 4. Rendimento por Recruta (Y/R), com a incorporação da Mortalidade Natural (M) Fuzzy, para *Cynoscion acoupa*, *Lutjanus synagris* e *Sardinella brasiliensis* e seu grau de pertinência (barra vertical à direita), para cada cenário do IPCC (*Intergovernmental Pannel on Climate Change*), após a aplicação da Extensão de Zadeh (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

As possibilidades de Rendimento Máximo Sustentável (MSY), para cada cenário do IPCC, tanto para espécies que habitam ambiente de água doce como marinho são apresentadas nas Tabelas 2 e 3, respectivamente. Para essa análise, foram considerados três alfa-níveis para a estimativa de MSY. Um alfa-nível menos conservador (0,01), que apresenta mais possibilidades, um moderado (0,4) e um mais conservador (0,8), com menos possibilidades. Para cada nível é apresentada a faixa de possibilidades de MSY com suas respectivas mortalidades por pesca (F), onde o MSY_1 corresponde ao menor valor de MSY (cor vermelha) e F_1 a respectiva mortalidade por pesca que proporciona MSY_1. O MSY_2 corresponde ao maior valor de MSY (cor azul) e F_2 a respectiva mortalidade por pesca que proporciona MSY_2. Ambos dentro da faixa de possibilidades para determinado alfa-nível escolhido. Em termos práticos, supondo que um tomador de decisão do gerenciamento pesqueiro esteja diante das possibilidades apresentadas para MSY, ele poderá ser otimista se escolher o MSY_2 ou pessimista, escolhendo o MSY_1 e seus respectivos F's.

Apesar de MSY_2 ser sempre maior que MSY_1, F_2 é sempre menor que F_1. Ou seja, dentro da faixa de possiblidades para MSY, ao escolher o MSY_1, a pesca estaria retirando menos do que seria biologicamente possível apesar de ter intensidade de pesca maior. Como esse foi um padrão para todas as espécies, foi escolhida uma espécie para representar graficamente esse padrão (Figura 5).

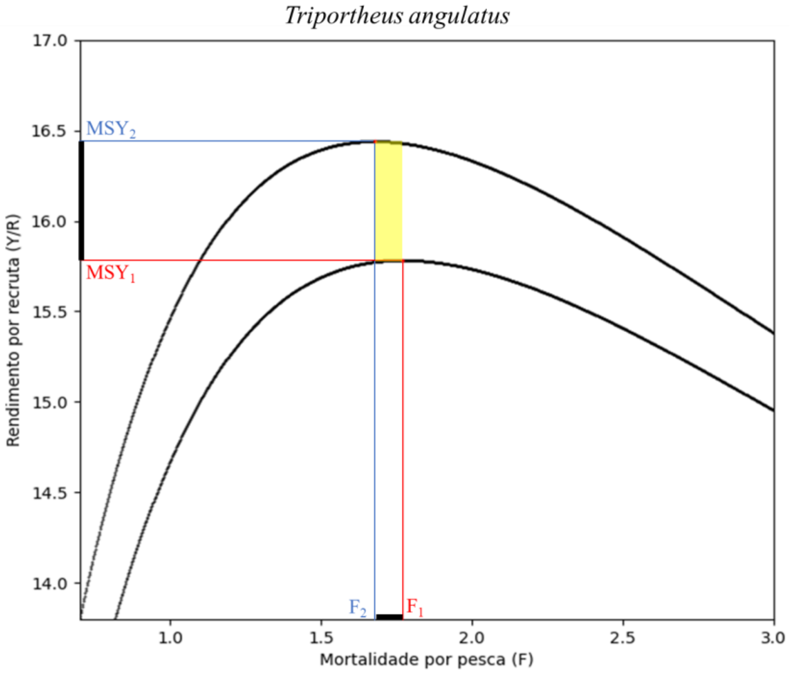

Figura 5. Faixa de possibilidade de Rendimento Máximo Sustentável (MSY) (caixa amarela), com limites inferior (MSY_1) e superior (MSY_2) e suas respectivas Mortalidade por Pesca (F_1 e F_2), para *Triportheus angulatus*, considerando um alfa-nível de 0,01

A variação de F (Δ F) foi mais sutil para espécies em equilíbrio. Portanto, a escolha de um cenário mais ou menos conservador, ou seja, um alfa-nível maior ou menor, deve ser considerado principalmente para espécies sazonais e com características oportunistas, visto Δ F é maior para essas espécies (Tabelas 2 e 3).

Para todas as espécies, independente do ambiente que habitam, observa-se que com a diminuição do MSY, de um cenário para outro, a variação do MSY (Δ MSY) aumenta, ou seja, há maior incerteza na estimativa de MSY em cenários com maiores incertezas na Mortalidade Natural (M). No entanto, a variação relativa da diminuição de MSY do cenário atual para o cenário C4 é maior para espécies com características oportunistas, tanto de água doce quanto marinhas, independente do alfa-nível (Tabelas 2 e 3).

Tabela 2. Possibilidades de Rendimento Máximo Sustentável (MSY) para espécies que habitam ambiente de água doce, considerando diferentes alfa-níveis, para cada cenário do IPCC (*Intergovernmental Panel on Climate Change*). (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

AMBIENTE			ÁGUA DOCE																	
ESPÉCIE			*Cichla temensis*						*Prochilodus nigricans*						*Triportheus angulatus*					
		Alfa-Nível	MSY_1	F_1	MSY_2	F_2	Δ MSY	Δ F	MSY_1	F_1	MSY_2	F_2	Δ MSY	Δ F	MSY_1	F_1	MSY_2	F_2	Δ MSY	Δ F
CENÁRIOS	**Atual**	**0,01**	194,944	0,596	196,344	0,588	1,400	0,008	53,387	1,316	53,861	1,294	0,474	0,022	16,934	1,616	17,124	1,594	0,190	0,022
		0,40	195,404	0,594	195,867	0,590	0,463	0,004	53,545	1,310	53,701	1,302	0,156	0,008	16,997	1,608	17,060	1,600	0,063	0,008
		0,80	195,569	0,592	195,701	0,592	0,132	0,000	53,599	1,306	53,643	1,304	0,044	0,002	17,018	1,606	17,037	1,604	0,018	0,002
	C1	**0,01**	190,680	0,620	195,536	0,592	4,856	0,028	52,289	1,372	53,651	1,304	1,363	0,068	16,494	1,670	17,040	1,604	0,546	0,066
		0,40	191,101	0,618	195,075	0,594	3,974	0,024	52,431	1,364	53,493	1,312	1,062	0,052	16,550	1,662	16,977	1,610	0,426	0,052
		0,80	191,246	0,616	194,911	0,596	3,665	0,020	52,483	1,362	53,439	1,314	0,956	0,048	16,571	1,660	16,955	1,614	0,384	0,046
	C2	**0,01**	188,571	0,634	193,454	0,604	4,883	0,030	51,748	1,402	53,108	1,330	1,360	0,072	16,276	1,700	16,823	1,628	0,548	0,072
		0,40	188,969	0,630	193,006	0,606	4,037	0,024	51,882	1,394	52,960	1,338	1,078	0,056	16,330	1,692	16,762	1,636	0,432	0,056
		0,80	189,109	0,630	192,847	0,608	3,738	0,022	51,931	1,392	52,907	1,340	0,975	0,052	16,350	1,690	16,742	1,638	0,392	0,052
	C3	**0,01**	187,439	0,640	192,689	0,608	5,250	0,032	51,458	1,418	52,912	1,340	1,454	0,078	16,160	1,714	16,744	1,638	0,584	0,076
		0,40	187,830	0,638	192,257	0,610	4,427	0,028	51,589	1,412	52,765	1,348	1,176	0,064	16,212	1,708	16,685	1,646	0,473	0,062
		0,80	187,968	0,638	192,099	0,612	4,132	0,026	51,635	1,408	52,713	1,350	1,078	0,058	16,231	1,706	16,664	1,648	0,433	0,058
	C4	**0,01**	183,808	0,666	189,783	0,626	5,976	0,040	50,524	1,476	52,157	1,380	1,633	0,096	15,784	1,770	16,441	1,678	0,657	0,092
		0,40	184,168	0,664	189,370	0,628	5,202	0,036	50,646	1,468	52,019	1,388	1,373	0,080	15,832	1,762	16,385	1,684	0,553	0,078
		0,80	184,298	0,662	189,229	0,630	4,932	0,032	50,690	1,464	51,969	1,390	1,279	0,074	15,850	1,760	16,365	1,688	0,515	0,072

Tabela 3. Possibilidades de Rendimento Máximo Sustentável (MSY) para espécies que habitam ambiente marinho, considerando diferentes alfa-níveis, para cada cenário do IPCC (*Intergovernmental Panel on Climate Change*). (C1 = RCP 2.6; C2 = RCP 4.5; C3 = RCP 6.0; C4 = RCP 8.5, IPCC, 2014)

AMBIENTE			MARINHO																	
ESPÉCIE			*Cynoscion acoupa*						*Lutjanus synagris*						*Sardinella brasiliensis*					
		Alfa-Nível	MSY$_1$	F$_1$	MSY$_2$	F$_2$	Δ MSY	Δ F	MSY$_1$	F$_1$	MSY$_2$	F$_2$	Δ MSY	Δ F	MSY$_1$	F$_1$	MSY$_2$	F$_2$	Δ MSY	Δ F
CENÁRIOS	**Atual**	**0,01**	243,100	0,228	245,897	0,226	2,797	0,002	58,510	0,434	60,221	0,424	1,711	0,010	2,435	0,490	2,525	0,480	0,090	0,010
		0,40	244,020	0,228	244,946	0,226	0,926	0,002	59,068	0,432	59,636	0,428	0,568	0,004	2,464	0,488	2,494	0,484	0,030	0,004
		0,80	244,341	0,228	244,603	0,226	0,262	0,002	59,267	0,430	59,435	0,428	0,168	0,002	2,475	0,486	2,483	0,484	0,009	0,002
	C1	**0,01**	234,479	0,230	244,281	0,228	9,802	0,002	56,426	0,448	59,806	0,426	3,380	0,022	2,326	0,506	2,503	0,482	0,177	0,024
		0,40	235,338	0,230	243,339	0,228	8,001	0,002	56,923	0,446	59,228	0,430	2,305	0,016	2,352	0,502	2,473	0,486	0,120	0,016
		0,80	235,645	0,230	243,020	0,228	7,375	0,002	57,103	0,444	59,029	0,432	1,927	0,012	2,362	0,500	2,462	0,488	0,101	0,012
	C2	**0,01**	230,170	0,232	240,089	0,228	9,919	0,004	55,399	0,456	58,730	0,434	3,332	0,022	2,273	0,514	2,447	0,490	0,173	0,024
		0,40	230,989	0,232	239,207	0,228	8,218	0,004	55,873	0,452	58,184	0,436	2,311	0,016	2,298	0,510	2,418	0,494	0,120	0,016
		0,80	231,288	0,230	238,875	0,228	7,587	0,002	56,047	0,452	57,998	0,438	1,952	0,014	2,307	0,508	2,408	0,494	0,102	0,014
	C3	**0,01**	227,844	0,232	238,562	0,228	10,718	0,004	54,854	0,460	58,340	0,436	3,486	0,024	2,245	0,518	2,426	0,492	0,181	0,026
		0,40	228,653	0,232	237,687	0,228	9,034	0,004	55,314	0,456	57,807	0,440	2,493	0,016	2,269	0,514	2,398	0,496	0,129	0,018
		0,80	228,948	0,232	237,377	0,230	8,429	0,002	55,478	0,456	57,623	0,440	2,145	0,016	2,277	0,512	2,389	0,496	0,111	0,016
	C4	**0,01**	220,329	0,234	232,660	0,230	12,331	0,004	53,106	0,474	56,857	0,446	3,751	0,028	2,156	0,532	2,349	0,502	0,193	0,030
		0,40	221,085	0,234	231,813	0,230	10,728	0,004	53,522	0,470	56,361	0,450	2,839	0,020	2,176	0,528	2,323	0,506	0,147	0,022
		0,80	221,350	0,234	231,513	0,230	10,163	0,004	53,677	0,470	56,186	0,450	2,509	0,020	2,184	0,526	2,314	0,508	0,130	0,018

DISCUSSÃO

Os resultados mostraram que os efeitos de mudanças climáticas globais refeltem nos parâmetros populacionais, no caso a Mortalidade Natural (M) de peixes e, consequentemente, sobre os rendimentos das capturas de estoques pesqueiros. Esses efeitos evidenciaram a diminuição nos rendimentos das capturas e nos níveis de rendimento máximo sustentável (MSY) em todos os cenários do IPCC (*Intergovernmental Panel on Climate Change*), já comprovados em diversos estudos (CHEUNG et al., 2010; SERPETTI et al., 2017; GAINES et al., 2018; CISNEROS-MATA et al.; 2019; FREE et al., 2019; PLAGÁNYI, 2019). Medir o impacto do aquecimento global na produção pesqueira e na captura máxima sustentável (MSY) para uma determinada pescaria é uma abordagem promissora (FREE et al., 2019). Embora às vezes criticado, o MSY é o limite de captura sustentável para a Convenção da ONU sobre o Direito do Mar, Objetivo de Desenvolvimento Sustentável da ONU e muitos outros acordos de pesca, porque maximiza o potencial de abastecimento dos recursos pesqueiros a longo prazo (LARKIN, 1977; BRITTEN et al., 2016; FREE et al., 2019).

Análises globais de 915 estoques pesqueiros apresentaram mudanças no MSY global (média ponderada) em 1,0%, -1,5%, -5,0% e -25,0% até 2100, sob os cenários RCPs 2.6, 4.5, 6.0 e 8.5, respectivamente (GAINES et al., 2018). No entanto, os autores relatam que essas mudanças modestas no MSY global, sob os três RCPs mais baixos, mascaram uma enorme variação nas mudanças entre os estoques, pois enquanto alguns estoques se extinguem (MSY diminui em 100%), outras aumentam em mais de 35% sob o RCP 6.0. No geral, aproximadamente 41%, 53%, 66% e 91% dos estoques globais experimentam um declínio projetado no MSY total até 2100 sob os RCPs 2.6, 4.5, 6.0 e 8.5, respectivamente. Serpetti et al. (2017) avaliaram o impacto das mudanças climáticas em estoques pesqueiros de importância comercial, considerando unidades populacionais esgotadas e crescentes, comparando os cenários de *status quo*, rendimento máximo sustentável (MSY) e MSY adicionado dos cenários do IPCC. Observaram que a captura apresentou uma diminuição geral em todos os cenários do IPCC em comparação com o cenário “MSY”. Isso sugere que os estoques serão afetados com o aumento da temperatura em decorrência das mudanças climáticas globais, independente do estágio de explotação do estoque, crescente ou em declínio.

Os efeitos da diminuição nos níveis de rendimento máximo sustentável (MSY) também estão relacionados com as diferentes estratégias de vida de estoques explotáveis. Cisneros-Mata et al. (2019) analisaram os impactos, em função de mudanças climáticas, esperados na produtividade de 25 estoques pesqueiros, que correspondem a mais de 70% do total de desembarques do México. Os autores verificaram que a maioria dos estoques (84%) deverá apresentar declínios no potencial máximo de captura comparado ao rendimento máximo sustentável (MSY) inicial, ao longo de um horizonte de tempo de 30 anos. Os declínios variaram entre -1% e -44%. Dentre as espécies estudadas, estão *Cynoscion othonopterus* (com diminuição de -2,5%), pertencente ao mesmo gênero de *Cynoscion acoupa*; *Lutjanus peru* (com diminuição de -21%), pertencente ao mesmo gênero de *Lutjanus synagris*; e *Sardinops sagax* (com diminuição de -24%), pertencente à mesma família de *Sardinella brasiliensis*. Free et al. (2019) mediram os efeitos do aumento da temperatura na produtividade de 235 populações globais de peixes e invertebrados, correspondentes a aproximadamente 33% da captura global relatada. Os autores usaram o modelo gerado para retransmitir mudanças induzidas pela temperatura no MSY e estimaram uma diminuição de 4,1% do MSY combinado de todas as populações. Além disso, relacionaram a influência da temperatura com as características da história de vida das espécies e observaram que, apesar de serem espécies que respodem mais rápido às mudanças, a temperatura afeta mais as espécies com características oportunistas (crescimento mais rápido, idade precoce de maturidade sexual e expectativa de vida mais curta), do que estrategistas em equilíbrio. Esses estudos corroboram com nossos resultados quanto aos aspectos da história de vida, que evidenciaram uma maior variação relativa na diminuição de MSY para espécies com características oportunistas. Além disso, as maiores incertezas de rendimento por recruta (Y/R) se apresentaram para esse grupo de espécies. Isso poderia ser explicado pela maior plasticidade (JEPPESEN et al., 2014) e alta amplitude de variabilidade nos padrões populacionais dessas espécies, pois ocupam habitats com alto grau de variabilidade e com grandes recursos de energia e, por consequência, suas respostas populacionais tendem a ser grandes em amplitude (KING e MCFARLANE, 2003).

A mortalidade natural (M) é um parâmetro com influência nos modelos de rendimento por recruta, que opera simultaneamente e continuamente com a mortalidade por pesca (F) para produzir a mortalidade total (Z), que determina as reduções na abundância da população ao longo do tempo. No entanto, a mortalidade natural é notoriamente difícil de estimar e os modelos de rendimento por recruta, usados em avaliação de estoques, são sensíveis ao valor escolhido de M (PASCUAL e IRIBARNE, 1993; QUINN E DERISO, 1999; QUIROZ et al., 2010). O efeito da especificação incorreta de M na avaliação de estoque foi investigado por vários autores (ULLTANG, 1977; SIMS, 1984; LAPOINTE et al., 1992; AANES et al., 2007; CHEN et al., 2018; PUNT et al., 2021). Além disso, estimativas errôneas de M irão influenciar os cálculos de rendimentos máximos sustentáveis (MSY’s) (QUIROZ et al., 2010). Por exemplo, Pope e Garrod (1973) analisaram a sensibilidade do MSY dos estoques de bacalhau aos valores escolhidos para M. Os autores demonstraram que, subestimando o M em 50%, superestimaria o F necessário para gerar um MSY (F_{MSY}) em 67%. Enquanto, superestimando M em 50%, subestimaria o F_{MSY} em 50%. No entanto, os valores de M foram assumidos de forma arbitrária por Pope e Garrod (1973), enquanto nossa análise partiu de valores de M estimados com base em cenários do IPCC, usando lógica fuzzy que incorpora as incertezas das estimativas. A inclusão das incertezas das estimativas de M nas avaliações de estoque pesqueiros, com base em metodologias que possibilitam a modelagem matemática da incerteza, como a Teoria do Conjuntos Fuzzy (BARROS e BASSANEZI, 2010), demonstrou ser uma estratégia promissora. Outros estudos já incorporaram as incertezas de M em avaliação de estoque (QUIROZ et al., 2010; GAERTNER, 2015; LEGAULT e PALMER, 2016; CHEN et al., 2018). Mas o presente estudo é o primeiro a incorporar as incertezas de M relacionadas as mudanças climáticas globais.

Avaliações de estoque são usadas para definir os pontos de referência biológicos (PRB) que servem como ponto de partida para conselhos de capturas sustentáveis. Um dos PRB's largamente aplicados tem sido a taxa de mortalidade que maximiza o rendimento sem levar ao risco de sobrepesca, ou seja, a taxa de mortalidade que permite o rendimento máximo sustentável (MSY) – referida como F_{MSY} (MATEUS e PENHA, 2007). Selecionar um PRB para um estoque é sempre uma troca que tenta equilibrar o risco de pesca excessiva (e possivelmente colapso do estoque) se o F_{MSY} for definido muito alto, com o risco de perda de rendimento se o F_{MSY} for definido muito baixo (HART, 2013). Nossos resultados sustentam um intervalo de F_{MSY} $[F_2,F_1]$ que possibilita um faixa de valores para MSY $[MSY_2,MSY_1]$, sugerindo que esse intervalo $[F_2,F_1]$ contenha os pontos de referência biológicos (PRB) para as espécies estudadas. Além disso, como os dados apresentaram um padrão, também seria possível inferir em uma abordagem mais holística, extrapolando esses PRB's para os agrupamentos de espécies por estratégias de vida. No entanto, para essa abordagem holística, deve-se tomar algumas precauções. Segundo Chen et al. (2018), quanto maior a incerteza de M em modelos da avaliação de estoques, maiores são os riscos de pesca excessiva, implicando que o risco de sobrepesca deve ser assumido prioritariamente com uma grande incerteza de M. Espécies com características oportunistas apresentaram as maiores incertezas nas variações de MSY e, portanto, estão mais propensas ao risco. Nesse caso, é necessário tomar decisões mais conservadoras na escolha dos cenários de gestão para espécies com essa estratégia de vida.

Este estudo projetou os impactos das mudanças climáticas nas estimativas de rendimentos de estoques pesqueiros, que é um passo fundamental para prever mudanças nas taxas de capturas futuras, fornecendo pontos de referência biológicos. Dessa forma, contribuiu para o gerenciamento pesqueiros abordando as incertezas inerentes aos efeitos das mudanças climáticas globais. Esses resultados também poderão auxiliar no gerenciamento de estoques de peixes com dados limitados, diante de uma abordagem holística baseado nos agrupamentos de espécies com diferentes características de história de vida.

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CONCLUSÃO

Este trabalho avaliou os efeitos das mudanças climáticas globais em estoques pesqueiros com diferentes estratégias de vida, com base em quatro cenários do IPCC (Intergovernmental Panel on Climate Change), utilizando a lógica fuzzy para modelar as incertezas inerentes a essas mudanças. A aplicação da Teoria dos Conjuntos Fuzzy possibilitou estimar os efeitos das variações da temperatura, provocadas pelas mudanças climáticas globais sobre a Mortalidade Natural (M) de peixes e, consequentemente, a avaliação de estoques pesqueiros, com a incorporação das incertezas de M.

No primeiro capítulo, fizemos uma revisão sobre a Mortalidade Natural (M) em peixes. Nesta revisão foi possível identificar vários padrões e relações a partir dos indicadores bibliométricos utilizados e conhecer os métodos existentes de estimativa de M para dados limitados. A partir disso, foi possível inferir sobre a importância de desenvolver métodos mais sofisticados ou fazer análises sobre esses métodos, levando em consideração novas abordagens, como exemplo, a variação da temperatura dentro desse estimador, o que não foi observado em nenhum dos métodos.

No segundo capítulo, foi possível verificar as variações e incertezas da Mortalidade Natural (M) frente às mudanças climáticas globais sobre estoques pesqueiros com diferentes estratégias de vida. Essas incertezas foram mais evidentes para espécies com características oportunistas. Como M é um parâmetro fundamental nos modelos de avaliação de estoque, recomendamos que essas incertezas sejam incorporadas nesses modelos, sempre que possível.

No terceiro capítulo, projetamos as incertezas da Mortalidade Natural (M) frente as mudanças climáticas nas estimativas de rendimentos de estoques pesqueiros com diferentes estratégias de vida. Os resultados obtidos mostram claramente que essas incertezas variam para espécies com diferentes estratégias de vida e, novamente, as espécies com características oportunistas foram as que apresentaram maior variação e incertezas nos rendimentos. Portanto, nossos resultados poderão servir de base para o gerenciamento de estoques de peixes com dados limitados, diante de uma abordagem holística baseado nos agrupamentos de espécies com diferentes características de história de vida. Além disso, geramos cenários com diferentes possibilidades de rendimentos com suas respectivas mortalidades por pesca. Esses dados poderão ser utilizados como pontos de referência biológicos e, dessa forma, contribuir para o gerenciamento pesqueiros abordando as incertezas inerentes aos efeitos das mudanças climáticas globais.