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Revisão do estado de conhecimento do beijupirá *Rachycentron canadum* (Linneaus, 1766) e o repovoamento na área marinha do Rio Grande do Norte, Brasil

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Dissertação apresentada ao Programa de Pós- Graduação em Oceanografia da Universidade Federal de Pernambuco, como requisito parcial para obtenção do título de mestre em oceanografia.

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RESUMO

O beijupirá (*Rachycentron canadum*) é uma espécie de peixe marinho de importância global, fundamental para a pesca e a aquicultura. Embora tenha recebido considerável atenção científica nas últimas décadas, revisões anteriores careciam de uma análise quantitativa de contribuições e motivações para a pesquisa. Este estudo realiza a primeira análise global de desempenho de pesquisa sobre *R. canadum* por meio da cienciometria, revelando um total de 577 documentos publicados entre 1964 e 2023, provenientes de diversos países e fontes. Apesar dos esforços de pesquisa em todo o mundo, alguns países dominam a maioria dos estudos, com tópicos relacionados à piscicultura marinha sendo o foco dos artigos mais citados. Alguns países fortemente envolvidos na captura de beijupirá direcionam uma parte substancial de sua produção científica para fontes relacionadas à piscicultura. Curiosamente, países com pesca significativa de beijupirá apresentam pouca ou nenhuma pesquisa associada. O aumento nas taxas de publicação desde os anos 2000 está alinhado com o crescimento na produção da piscicultura, indicando sua proeminência como o principal impulsionador de pesquisa para *R. canadum*. Após a análise bibliométrica, a avaliação de um projeto de repovoamento no litoral do Rio Grande do Norte utilizando o beijupirá foi realizada. Com a capacitação e participação dos pescadores artesanais da região foi possível diferenciar nas capturas peixes selvagens e recapturados da atividade de repovoamento. As análises investigaram o impacto do repovoamento na estrutura populacional do beijupirá e as relações com os ambientes marinhos. Foi realizada a soltura de 48.728 exemplares na costa do Rio Grande do Norte, sendo identificada a recaptura de 1.332 espécimes, representando 2,73% do total repovoado. A captura pós-repovoamento mostrou um aumento na frequência de exemplares capturados, assim como tamanhos significativamente menores, indicando proporções de jovens superiores as observadas na área de estudo em períodos anteriores ao repovoamento. A espécie apresentou segregação de tamanhos em relação as profundidades e geomorfologia dos substratos, onde os exemplares maiores preferem áreas mais profundas e substratos mais consolidados. Relações peso comprimento entre selvagens e repovoados demonstraram diferenças entre o crescimento em peso e comprimento para os dois grupos, com repovoados apresentando características próximas a isometria, embora as taxas de captura possam aumentar pós-repovoamento, a maioria dos beijupirás foram capturados ainda imaturos. O estudo destaca a necessidade de estratégias de manejo antes e após o repovoamento, incorporando contribuição dos pescadores em campanhas de conscientização. Além disso, destaca-se o papel do Conhecimento Ecológico Local no gerenciamento do repovoamento e pesca.

Palavras-chave: Bibliometria, Pesca Artesanal, Etnoecologia, Conservação, Manejo de estoques pesqueiros.

ABSTRACT

Cobia (*Rachycentron canadum*) is a marine fish species of global importance, crucial for both fisheries and aquaculture. Although it has received considerable scientific attention in recent decades, previous reviews lacked a quantitative analysis of contributions and motivations for research. This study conducts the first global analysis of research performance on *R. canadum* through scientometrics, revealing a total of 577 published documents between 1964 and 2023, originating from various countries and sources. Despite research efforts worldwide, a few countries dominate the majority of studies, with aquaculture-related topics being the focus of the most cited articles. Some countries heavily involved in cobia fishing direct a substantial portion of their scientific production toward aquaculture-related sources. Interestingly, countries with significant cobia fishing may have little or no associated research. The increase in publication rates since the 2000s aligns with the growth in aquaculture production, indicating its prominence as the primary driver of research for *R. canadum*. Following bibliometric analysis, an assessment of a restocking project on the coast of Rio Grande do Norte using cobia was conducted. With the training and participation of local artisanal fishermen, it was possible to differentiate betweenc wild and restocked cobia catch. The analyses investigated the impact of restocking on the population structure of cobia and its relationships with marine environments. A total of 48,728 specimens were released off the coast of Rio Grande do Norte, with 1,332 specimens identified as recaptured, representing 2.73% of the total restocked. Post-restocking catch displayed an increase in frequency of captured specimens, as well as significantly smaller sizes, indicating higher proportions of juveniles compared to periods before restocking in the study area. The species exhibited size segregation concerning depth and substrate, where larger specimens prefer deeper areas and more consolidated substrates. Length-weight relationships between wild and restocked specimens displayed differences in growth in weight and length for the two groups, with restocked specimens exhibiting characteristics close to isometry. Although catch rates may increase post-restocking, most cobia were captured still immature. The study emphasizes the need for management strategies before and after restocking, incorporating the contributions of fishermen in awareness campaigns. Furthermore, it highlights the role of Local Ecological Knowledge in restocking and fishing management

Keywords: Bibliometry, Artisanal fishery, Ethnoecology, Conservation, Fishing stock management.

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1. INTRODUÇÃO GERAL

A pesca e piscicultura de peixes marinhos são algumas das atividades de produção de alimento mais pertinentes na história, e provavelmente uma chave para a segurança alimentar no futuro (EINARSSON; ÓLADÓTTIR, 2020; NASH, 2010). Dentre os recursos pesqueiros utilizados nesse tipo de atividade, *Rachycentron canadum*, popularmente conhecido no Brasil como beijupirá ou cação-de-escama, é uma espécie que se destaca: a espécie possui um ciclo reprodutivo particularmente rápido e crescimento acelerado. Além disso, o beijupirá é um peixe de médio-grande porte, atingindo até 2 m de comprimento total e 60 kg de peso (BENETTI et al., 2021). É um predador oportunista, geralmente acompanhando outros grandes animais (e. g. arraias, tubarões e peixes de grande porte) e se alimentando de fauna exposta por perturbações causadas pelos grandes animais no sedimento e na coluna d'água (SHAFFER & NAKAMURA, 1989). Quando sozinho ou em grupos pequenos, geralmente está associado a estruturas fixas ou flutuantes, e até mesmo acima de recifes de coral. Isso torna o beijupirá um peixe com caraterísticas favoráveis ao consumo e suscetível a certas artes de pesca (ESTRADA et al., 2016; SHAFFER & NAKAMURA, 1989).

A espécie é historicamente pescada em todo o seu alcance geográfico (SHAFFER & NAKAMURA, 1989), e a partir dos anos 1990 esforços para o cultivo do beijupirá começaram em Taiwan e se popularizaram em países como China e Tailândia (BENETTI et al., 2021). Desde o final da década de 1990 até o ano de 2013, foram registradas mais de 43.000 toneladas de biomassa provenientes da produção da espécie (ESTRADA et al., 2016), com uma estimativa de 40.000 à 50.000 toneladas de produção por ano desde 2010 (BENETTI et al., 2021). Porém, a piscicultura do beijupirá também apresentou impactos negativos no Equador, onde indivíduos escaparam na natureza e hoje configuram uma espécie invasora na região (CASTELLANOS-GALINDO; MORENO; ROBERTSON, 2018). Tudo isso destaca a importância global do beijupirá e da pesquisa direcionada à essa espécie.

Tendo em vista as vantagens da espécie para a produção pesqueira, *R. canadum* possui grande potencial econômico no Nordeste do Brasil, onde sua exploração pesqueira já é presente (IGARASHI, 2018). Dentre as diversas formas de explorar o potencial da produtividade pesqueira, programas de repovoamento de recursos naturais podem ser especialmente sustentáveis (ASWANI; LEMAHIEU; SAUER, 2018). Esse tipo de reintrodução de indivíduos no ambiente se mostra altamente benéfico, tanto em relação à diversidade genética e tamanho populacional dos estoques (BIGNARDI et al., 2016), quanto em relação aos fatores socioeconômicos relacionados à produção pesqueira (LORENZEN; LEBER; BLANKENSHIP, 2010; TAYLOR et al., 2017). O beijupirá, sendo uma espécie com grande potencial para piscicultura e já historicamente explorada no Nordeste, possui grande potencial para a prática do repovoamento.

Quando se trata de exploração pesqueira, especialmente no âmbito da pesca artesanal, o Conhecimento Ecológico Local (CEL) pode se mostrar útil para avaliar padrões biológicos e a dinâmica populacional de recursos pesqueiros e sua relação com as características oceanográficas do ambiente, muitas vezes provendo informações tão precisas quanto observações científicas in situ, e com obtenção mais rápida. Na verdade, um método integrativo entre as duas formas de obtenção de dados parece ser ideal (LIMA et al., 2017; SILVANO; VALBO-JØRGENSEN, 2008). Além disso, é importante avaliar formas de manter e utilizar esse tipo de conhecimento, que está em declínio e necessita de esforços ativos para continuar a ser valorizado (SILVANO & VALBO-JØRGENSEN, 2008).

O presente estudo desenvolveu um levantamento do estado de conhecimento do beijupirá em toda a sua área de distribuição por meio da cienciometria, apresentando as nações e autores que mais contribuíram, assim como as áreas de estudo e as interações entre os centros de pesquisa nas publicações relacionadas a espécie. Subsequentemente, um projeto de repovoamento do beijupirá desenvolvido no litoral do Rio Grande do Norte (região nordeste do Brasil) foi analisado. Os principais objetivos foram verificar a viabilidade da técnica de repovoamento para a espécie, considerando a sobrevivência, relações de crescimento de exemplares selvagens e repovoados em relação aos diferentes ambientes marinhos; analisar a estrutura populacional, frequência e abundância capturada antes e após o repovoamento. Para isso, foram utilizados dados de monitoramento pesqueiro prérepovoamento e possíveis publicações sobre o repovoamento do beijupirá em outras partes do Mundo. Os pescadores foram capacitados e incluídos no estudo para auxiliar na coleta de dados e diferenciar exemplares selvagens e repovoados nas atividades de suas pescarias, integrando dessa forma o CEL para analisar o efeito do repovoamento durante os anos subsequentes na população do beijupirá na costa do Rio Grande do Norte. Por fim, pretendeu-se fornecer subsídios para o repovoamento de peixes marinhos, contribuindo com sugestões para a conservação e gerenciamento do beijupirá na região nordeste do Brasil.

2. ARTIGO 1 - GLOBAL RESEARCH PERFORMANCE TRENDS AND KNOWLEDGE GAPS ON COBIA (*Rachycentron canadum*): A SCIENTOMETRIC PERSPECTIVE

Artigo submetido no periódico Reviews in Fish Biology and Fisheries em 25/04/2023, onde encontra-se em revisão.

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Declaration of competing interests

The authors declare no competing interests.

Author contributions

A. R. S. Jr.: Data curation, Investigation, Formal Analysis, Visualization, Writing – Original Draft. M. F. N.: Conceptualization, Supervision, Resources, Visualization, Writing – Review & Editing.

Abstract

Rachycentron canadum (cobia) is a marine fish species important to fisheries and aquaculture worldwide. The species has gathered scientific attention in the last decades, and today, a considerable body of knowledge exists on it. There are several reviews pertaining to different aspects of research, but a quantitative outlook has been lacking to identify contributors and motives for research on cobia. This study aims to present the first global research performance analysis on *R. canadum* through scientometrics. We found a total of 577 documents, published in the timespan of 1964 to 2023, from a variety of countries and sources. Although various countries have published studies on the species, a few countries concentrate the vast majority of research efforts. The most cited articles and the sources with most publications were mainly aquaculture-related. Some countries with high contribution to capture have a significant portion of their scientific production directed to aquaculture-related sources, while others have low scientific production in general. Some countries where the cobia fishery is present have had no research found at all. The boom in publication rate from the 2000s onwards exhibits a similar tendency to the rate of aquaculture production over the years, with aquaculture probably representing the main research driver for *R. canadum*. We recommend focusing additional scientific endeavors on wild cobia populations in countries where its fishery holds significance. Furthermore, we suggest that the currently existing aquaculture focus on the species may overshadow research interest on its fisheries.

Keywords: *Rachycentron canadum*; scientometrics; research drivers; fishery; aquaculture.

1. Introduction

Rachycentron canadum, commonly known as cobia, is a large, marine, unique teleost fish. It is found in the majority of coastal areas and has been a prominent species for global fisheries and aquaculture (Estrada et al. 2016). The first known documented report of cobia is its description as *Gasterosteus canadus* in Linneau's *Systema naturae* (Linné 1767), with some 17 synonymic classifications being made in the later centuries (Shaffer and Nakamura 1989). Although known for a long time, new information on the species seem to surface each year (Shaffer and Nakamura 1989; Estrada et al. 2016; Benetti et al. 2021).

Initially, a naturalistic approach to the study of this species was prevalent, with the main focus being the biology and ecology of cobia in its natural habitat. This viewpoint can be observed in the work of Shaffer & Nakamura (1989), which provided an in-depth synthetizing of the biological knowledge on *R. canadum* up until the 1980s. Biologically, cobia is a particularly interesting species, currently standing as monotypic in the Rachycentridae family, and lacking clear phylogenetic relatives. Among carangiform fishes, the external morphology of *R. canadum* makes the species bear resemblance to remoras (Echeneididae), although current evidence suggests that it is more closely related to the dolphinfishes (Coryphaneidae) (Harrington et al. 2016; Girard et al. 2020). The fish also lacks an air-bladder, displaying distinct movement patterns when compared to other teleosts (Fraser and Davies 2009). Its general shape and movement have made it, in some cases, resemble to a shark: in Northeastern Brazil, cobia is known as “cação-de-escama”, literally meaning “scaled-shark” (Filho 1992).

Uncommonly fast reproduction and growth rates have been observed in cobia populations (Franks and Brown-Peterson 2002), capable of growing up to 10 kg in one year (Estrada et al. 2016). Its good meat quality has been reported scientifically in the 1990s (Shiau 1999), and since then, the farming of cobia worldwide has gone up significantly, reaching more than 40.000 tonnes yearly since 2016, with China and Taiwan leading the species’ production (FAO 2022). In the last decades, the general focus of research involving cobia has shifted from a naturalistic approach to a more aquaculture-based approach, as the species’ started gaining attention due to its production-friendly characteristics (Benetti et al. 2021). The potential of cobia for aquaculture has been suggested in various regions, and efforts have been made to cultivate the species in places with a suitable climate, such as Brazil and the Caribbean (Benetti et al. 2007; Sampaio et al. 2011; Lima et al. 2018). However, the bulk of the species’ production has remained mainly in East Asia (FAO 2022). Benetti et al. (2021) have thoroughly reviewed advances in cobia aquaculture made in the last decades, highlighting the recent interest in the species and new developments in its production technology. The fishery for cobia is also significant globally, especially in the Middle East, South Asia and Southeast Asia, where the capture is mostly commercial, but also in the USA, where cobia constitutes a lucrative recreational fishery (Shaffer and Nakamura 1989).

Being a fast-growing, highly mobile, opportunistic carnivore, cobia has recently gathered attention due to its invasive potential. It traditionally occurs in all tropical and subtropical coastal areas of the World, except for the Mediterranean and Eastern Pacific (Shaffer and Nakamura 1989). The species has been reported as invasive in the Mediterranean as early as 1978 (Golani and Ben-Tuvia 1986), and new records have appeared since then in the region (Akyol and Ünal 2013; Crocetta et al. 2015; Ragkousis et al. 2020). In 2015, an escape of thousands of individuals from a cage culture in Ecuador has led to wild cobia being reported in the Eastern Pacific, with a high potential to become an invasive species (Castellanos-Galindo et al. 2016, 2018; Marín-Enríquez et al. 2022).

All of these characteristics have made *R. canadum* a species of great scientific interest, being the subject of various studies over the years. Benetti et al. (2021) points out that more than 500 studies have been published on the species up until 2021. The scientometric approach can be useful to assess the composition of such extensive literature, evaluating the countries, authors, sources and subjects that contribute to the research progress of a certain topic (Mingers and Leydesdorff 2015). This kind of knowledge can be extremely valuable as a way to identify what drives the research on a topic, the knowledge gaps, future implications, and help direct possible efforts to enrich the understanding and use of the topic (Ellegaard and Wallin 2015). Although some studies have reviewed various aspects of cobia research (Shaffer and Nakamura 1989; Fraser and Davies 2009; Hamilton et al. 2013; Estrada et al. 2016; Benetti et al. 2021), a quantitative, scientometric outlook has been lacking for the substantial body of literature that exists on the species. This study aims to use scientometric analysis to provide a quantitative global research performance assessment on the existing bibliography pertaining to *R. canadum*, identifying possible research drivers, knowledge gaps, and trends through time and between countries.

2. Materials and methods

2.1 Data acquisition

The data acquisition was conducted through searches in the Elsevier's Scopus and Clarivate Analytics' Web of Science (WoS) databases on March 22, 2023. The search was performed on the same day for both databases in order to avoid bias due to database updating. Both Scopus and WoS have proven to have a widespread topic distribution, and both provide built-in tools for bibliometric data managing (AlRyalat et al. 2019). However, due to the predominance of scientific articles in these databases, the bibliography search can be limited, presenting a possibility of overlooking grey literature. Grey literature, despite having an evolving definition, is broadly thought to encompass a wide range of scientific material not published through conventional means, such as government documents, technical papers, and conference annals (Marzi et al. 2011), which could be relevant to meta-analysis. Older documents that may have metadata unavailable in most databases can also be neglected by such search. Nonetheless, older documents on cobia are relatively few and the present literature suggests a somewhat consistent type of study aimed at cobia before the 1970s (Shaffer and Nakamura 1989). Grey literature is an important aspect of scientific production (Conn et al. 2003), however, since cobia is already known to be a broadly studied species in commercial scientific publishing (Shaffer and Nakamura 1989; Benetti et al. 2021), the effects of overlooking grey literature are likely not as severe for *R. canadum* as in a meta-analysis for other less studied species. Thus, this study focused on peer-reviewed papers (Table 1).

Table 1. Number of documents by source type included in the final analysis.

Source type	**Nº of documents**
Article	542
Early access article	3
Proceeding paper article	3
Book chapter	2
Conference paper	3
Correction paper	1
Data paper	1
Editorial material	1

Erratum	1
Meeting abstract	2
Note	3
Proceedings paper	6
Review	9

The query focused on text mining encompassing the species' scientific name in the title, keyword, or abstract of publications. Thus, for both databases, the keywords utilized in the search were '*Rachycentron canadum*'. Data for cobia capture and aquaculture production by country was acquired from the United Nations Food and Agriculture Organization's (FAO) database available through the FishStatJ software (version 4.0.0) (FAO 2022).

2.2 Document selection

Out of the search results, a manual review of all titles and abstracts was performed in order to root out documents that could possibly not be relevant to the scope of the study. The most common cause of removal was due to studies being focused solely on the biology of parasites, where cobia was only the host from which the parasite was extracted. These studies provided no insight into *R. canadum*, and thus were found not relevant to the scope of this study. Another significant cause for removal was studies mentioning *R. canadum* in the abstract but not being aimed at the species. Cobia is an important model for aquaculture research (Benetti et al. 2021), and experimental studies on the species are often cited and used in the research for other species. Finally, a single study was found describing a fossil species belonging to the *Rachycentron* genus, and thus also removed (Figure 1).

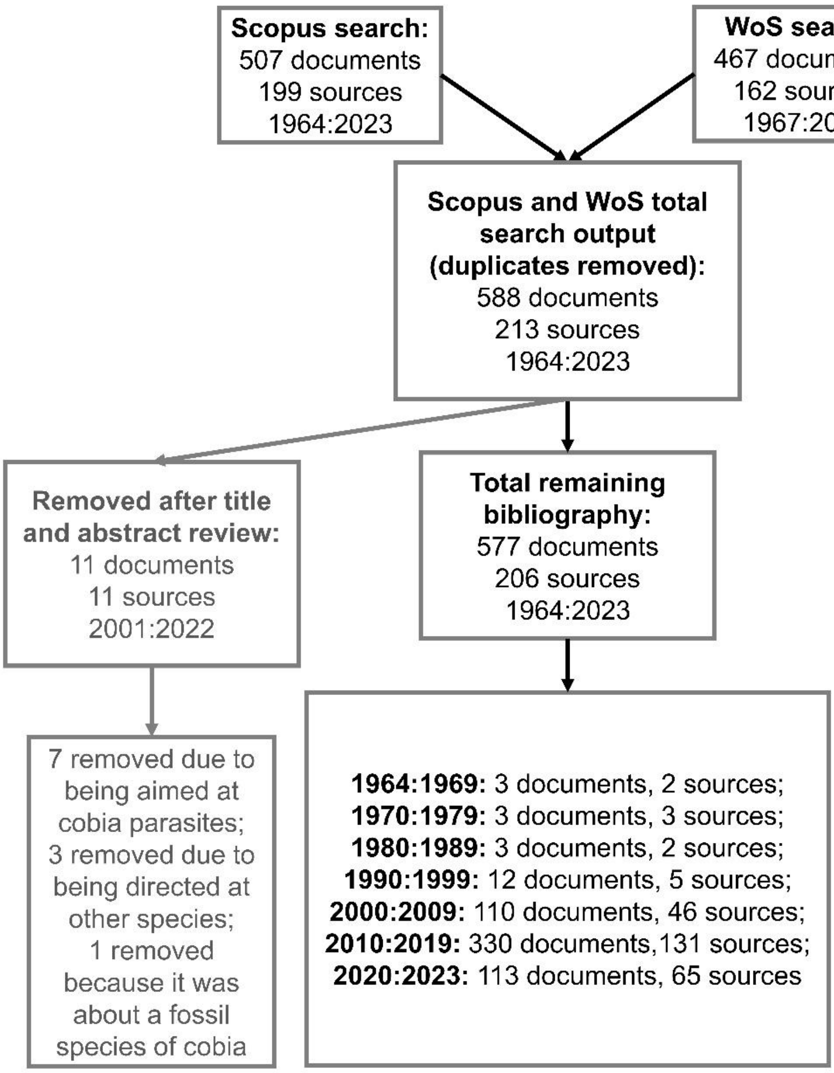

Figure 1. Flowchart of the selection process for the searches on *R. canadum*.

2.3 Data analysis

. The Scopus and WoS databases were merged and duplicate documents between them were removed. All further analysis were conducted utilizing the merged data. Bibliometric analysis was conducted to quantify the scientific production on *R. canadum*, identify the sources with most publications, the articles with most citations, and the most productive countries (identified by the country where the corresponding author is working out of). Document classification as single country publication (SCP) or multiple country publication (MCP) was based on whether all authors are working out of the same country or different countries. Terms like “fish”, “perciformes” and “rachycentron canadum” were considered noise as keywords for the purpose of addressing the research topics, and thus were removed from analysis. Keyword plus data, which is based on a WoS algorithm that extracts keywords from titles, was utilized for the trend topic analysis, as older publications tend not to have author keyword data. The *Bibliometrix* R package was employed to perform the bibliometric analysis (Aria and Cuccurullo 2017).

To assess differences in the number of publications before and after the 21st century, linear regressions of number of publications through time were used to identify trends. These timespans were chosen due to the reported surge of cobia aquaculture research interest and production in 1990s (Benetti et al. 2021). To compare the nature of temporal trends of scientific production in relation to aquaculture production and capture, locally estimated scatterplot smoothing was applied to those parameters in relation to time. Country collaboration was identified utilizing association strength normalization, a probabilistic measure of cooccurrence calculated by, in this case, the reason of two corresponding authors' countries cooccurrence by their occurrence in the whole dataset (Eck and Waltman 2009). The country collaboration clustering was assessed visually using visualization of similarities mapping (VOS) (Waltman et al. 2010). The clustering analysis and visualization was performed in VOSviewer (version 1.6.19) (van Eck and Waltman 2010). Data preparation and analysis was conducted in the R environment for statistical computing (R Core Team 2022)

3. Results

3. 1 Research performance

A total of 577 documents were found, from 206 sources, in the timespan of 1964 to 2023, with 1481 contributing authors. Most of the corresponding authors were from China (30%), followed by the USA (22.5%) and Brazil (17.9%). Five countries (China, USA, Brazil, India and Malaysia) amass more than 80% of all documents. China and the USA alone concentrate more than half (52.5%) of all publications. Out of the top ten countries, Brazil had the highest multiple country publications (MCP) (22), while Iran had the lowest (0). Norway was the country with the highest MCP to Article ratio (1), with all publications from the country being of international authorship (Table 2).

Table 2. Top ten corresponding author's countries for publications on R. canadum.

Country	Articles	SCP	MCP	%	MCP Ratio
China	173	164	9	0.3	0.052
USA	130	116	14	0.225	0.108
Brazil	103	81	22	0.179	0.214
India	43	41	2	0.075	0.047
Malaysia	17	11	6	0.029	0.353
Australia	9	6	3	0.016	0.333
Norway	8	0	8	0.014	1
United Kingdom	7	4	3	0.012	0.429
Iran	6	6	0	0.01	0
Vietnam	6	1	5	0.01	0.833

The Sankey diagram presents the pathway of authors' contribution to sources, considering the country from which the author is working (Figure 2). Sources and authors seem to have publications less concentrated in the top scientific producers than the countries. This indicates that most top authors work out a few countries, and most publications in the top sources come from the most dominant countries. However, most countries seem to contribute to a variety of sources.

In terms of country collaboration, the VOS mapping identified nine clusters (Figure 3). Brazil & the USA and Norway & Vietnam displayed the strongest collaboration links. The nature of collaboration connection between countries can be indirectly observed in the MCP numbers of countries. China only has three other countries in its cluster (Indonesia, Pakistan and Japan) and it is relatively isolated when it comes to collaboration. Naturally, China displayed the most SCP (164) and one of the lowest MCP to article ratio (0.052).

The top five sources gathered 28,9% of all publications. The source with the most publications was Aquaculture (14%), with almost three times more articles than the source with the second most publications, Aquaculture Research (5,2%). Out of the top ten sources, five are related to aquaculture, two are related to fisheries, one to veterinary science, and one to immunology (Table 3).

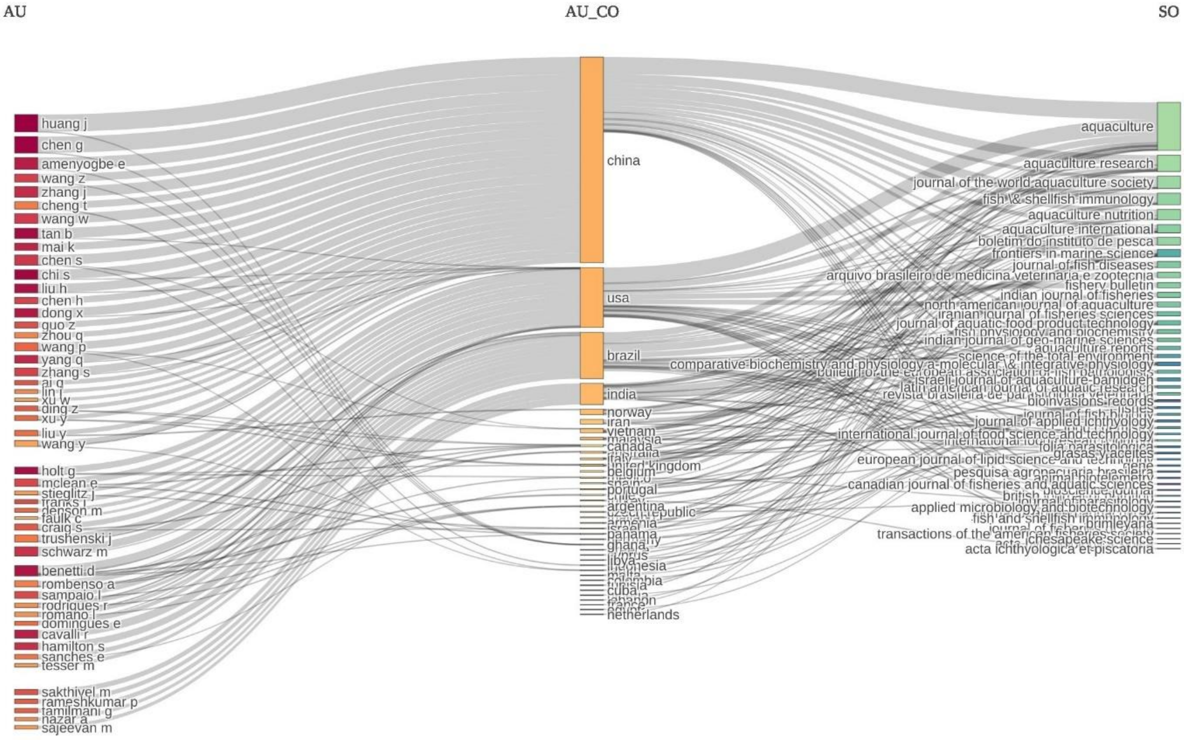

Figure 2. Sankey diagram containing the top 50 authors (AU), corresponding authors' country (AU_CO) and source (SO) on *R. canadum*. Bar thickness represents number of publications.

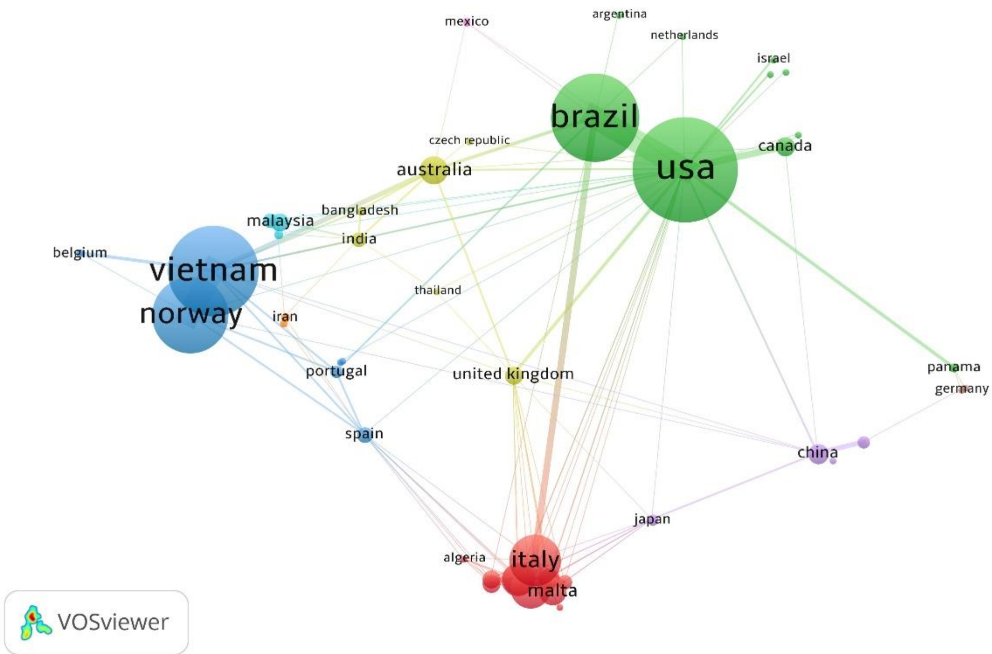

Figure 3. Country collaboration network utilizing VOS mapping for publications on *R. canadum*. Circle size represents total link strength. Circle size represents relative association strength.

Table 3. Top ten sources with the most articles on R. canadum.

Sources	Articles
Aquaculture	81
Aquaculture Research	30
Journal of the World Aquaculture Society	22
Aquaculture Nutrition	17
Boletim do Instituto de Pesca	17
Fish & Shellfish Immunology	15
Arquivo Brasileiro de Medicina Veterinária e Zootecnia	14
Aquaculture International	13
Fishery Bulletin	12
Indian Journal of Fisheries	12

3.2 Scientific production through time

The mean annual growth rate in scientific production for *R. canadum* was 2.38%. A spike in production occurred in 21st century, with 95.8% of all documents being published after the year 2000 (Figure 4). Before the turn of the century, the annual growth rate was -2.14%, while after, the annual growth rate was 8.76%. The rate of publication in the 20st century followed no trend ($R^2<0.06$), as publications were sparse and few. In the 21st century, a trend can be observed ($R^2=0.81$), with the number of publications tending towards growth through the years (Figure 5).

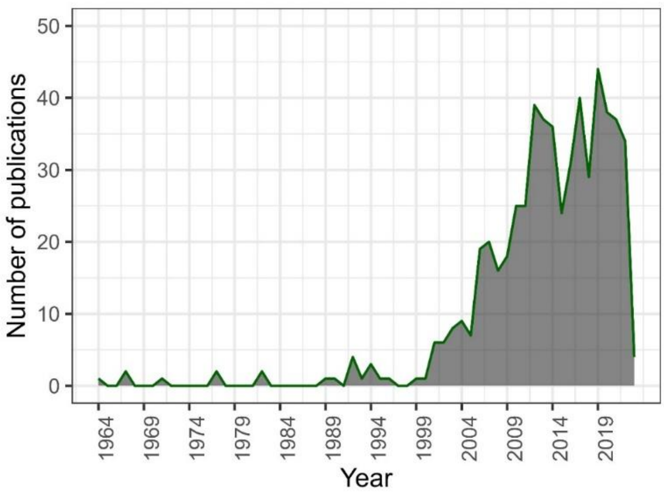

Figure 4. Annual scientific production for *R. canadum.*

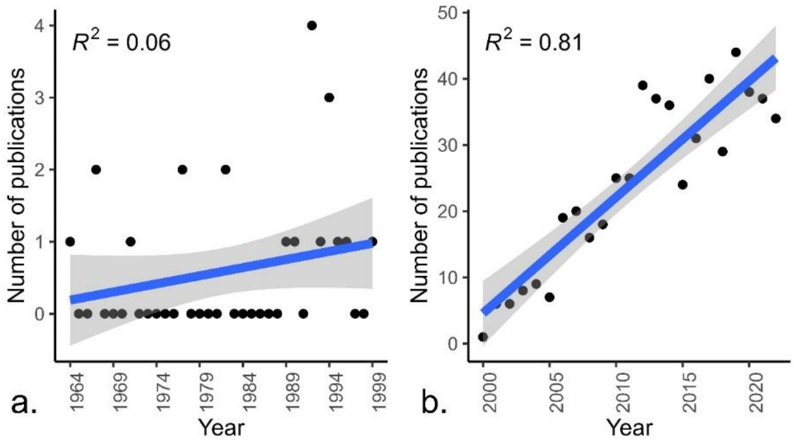

Figure 5. Trends in number of publications through time for the timespans for 1964:1999 (a) and 2000:2022 (b) on *R. canadum*.

3.3 Keywords and topic trends

The research topics were assessed through the keywords used in the publications. The keywords with the most occurrence were generally terms addressing very broad topics, such as “fish”, “growth”, and “survival”. Another common type of keyword were other economically important fish species, such as “trout” and “atlantic salmon”. More specific terms among the most used keywords were “protein”, “lipid-levels”, “soybean-meal”, “aquaculture” and “quality” (Table 3), reflecting an aquaculture-oriented trend of studies on the species.

Table 3. Top 20 most used keywords in papers on *R. canadum*.

Words	Occurrences
Growth	75
rainbow-trout	61
Protein	42
juvenile cobia	38
fish-meal	32
trout oncorhynchus-mykiss	30
lipid-levels	29
Survival	29
Aquaculture	28
soybean-meal	27

growth-performance	25
Culture	22
atlantic salmon	21
Quality	21
Requirement	21
salmon salmo-salar	21
Replacement	20
Body-composition	19
Metabolism	18
sparus-aurata	18

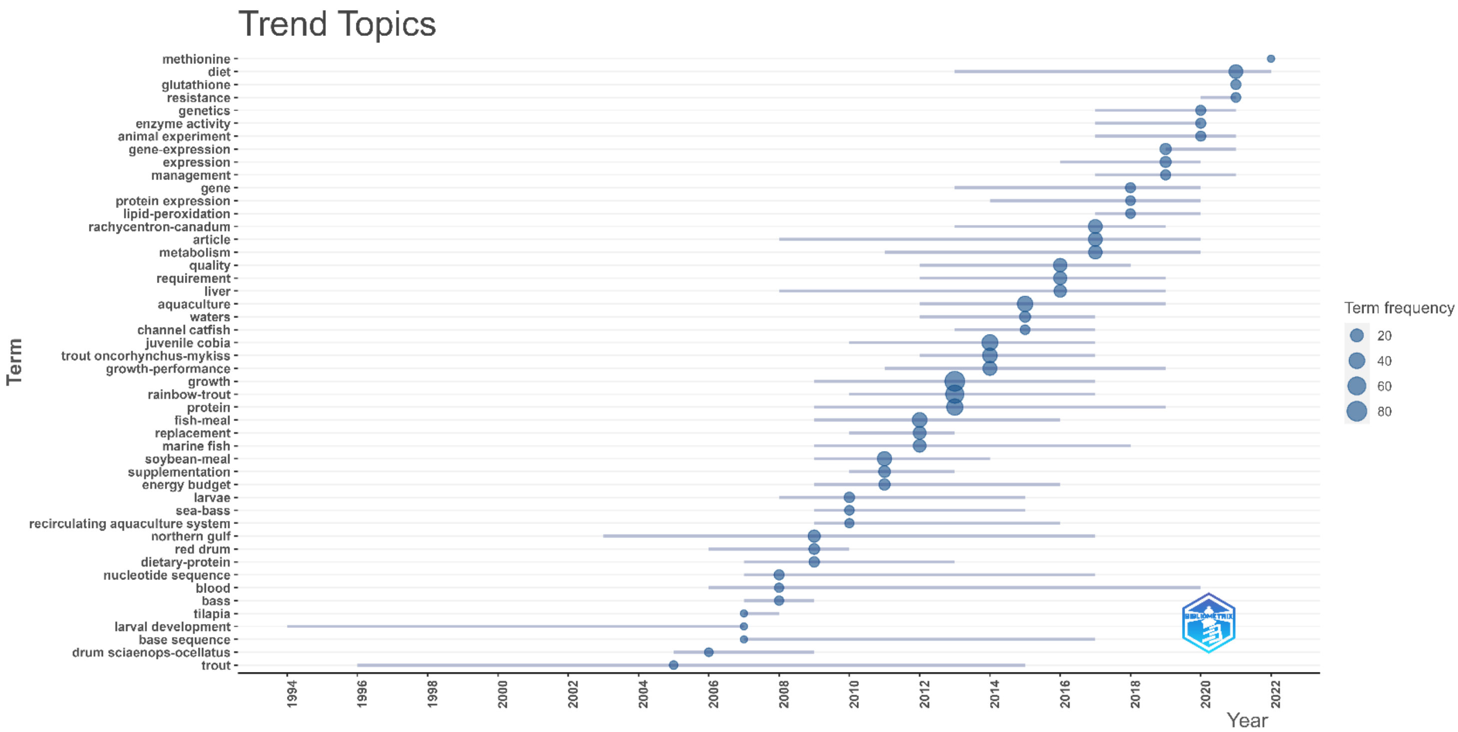

Figure 6. Trend topic analysis through time for publications on *R. canadum*

In earlier years, commonly used terms regarding cobia production were “supplementation”, “soybean-meal”, “dietary-protein” and “larval development”. In later years, terms such as “gene-expression”, “enzyme activity”, “glutathione” and “methionine” can be found. This suggests the research on the species has funneled into more specific topics over the years, with isolated aspects of the species’ development and diet being targeted. The term “northern gulf” was also prevalent for a long time, indicating that the Northern Gulf of Mexico region is especially targeted for studies on *R. canadum*. This was the only term in the trend topic analysis not referring to cage culture, physiology, genetics, or other species (Figure 6).

All of the ten most cited papers considered, in some way, aspects of cobia production. Most discussed dietary aspects of cobia farming (Chou et al. 2001, 2004; Zhou et al. 2004, 2012; Wang et al. 2005; Lunger et al. 2007; Salze et al. 2008), whereas parasitism in cobia aquaculture practices (Chi et al. 2003), physiology and metabolic pathways (Zheng et al. 2009), and a general aquaculture overview (Liao et al. 2004) were also discussed in the other top most cited papers (Table 4).

Table 4. Ten most cited papers on *R. canadum*.

Paper	**Total Citations**	**TC per year**
Wang, J. T., et al. "Effect of dietary lipid level on growth performance, lipid deposition, hepatic lipogenesis in juvenile cobia (*Rachycentron canadum*)." *Aquaculture* 249.1-4 (2005): 439-447.	259	13.63
Zhou, Q. C., et al. "Apparent digestibility of selected feed ingredients for juvenile cobia *Rachycentron canadum*." *Aquaculture* 241.1-4 (2004): 441-451.	206	10.3
Chou, R. L, Su, M. S. and Chen, H. Y. "Optimal dietary protein and lipid levels for juvenile cobia (*Rachycentron canadum*)." *Aquaculture* 193.1-2 (2001): 81-89.	177	7.7
Chou, R. L., et al. "Substituting fish meal with soybean meal in diets of juvenile cobia *Rachycentron canadum*." *Aquaculture* 229.1-4 (2004): 325-333.	173	8.65
Liao, I. C. et al. "Cobia culture in Taiwan: current status and problems." *Aquaculture* 237.1-4 (2004): 155-165.	165	8.25
Lunger, A. N., et al. "Taurine supplementation to alternative dietary proteins used in fish meal replacement enhances growth of juvenile cobia (Rachycentron canadum)." *Aquaculture* 271.1-4 (2007): 401-410.	158	9.29
Zheng, X., et al. "Physiological roles of fatty acyl desaturases and elongases in marine fish: characterisation of cDNAs of fatty acyl Δ6 desaturase and elovl5 elongase of cobia (*Rachycentron canadum*)." *Aquaculture* 290.1-2 (2009): 122-131.	148	9.87
Salze, G., et al. "Dietary mannan oligosaccharide enhances salinity tolerance and gut development of larval cobia." *Aquaculture* 274.1	139	8.69

(2008): 148-152.		
Zhou, Q., et al. "Effect of dietary vitamin C on the growth performance and innate immunity of juvenile cobia (Rachycentron canadum)." *Fish & Shellfish Immunology* 32.6 (2012): 969-975.	132	11
Chi, S. C., Shieh, J. R. and Lin, S. J. "Genetic and antigenic analysis of betanodaviruses isolated from aquatic organisms in Taiwan." *Diseases of Aquatic organisms* 55.3 (2003): 221-228.	131	6.24

3.4 Scientific production, fisheries, and aquaculture

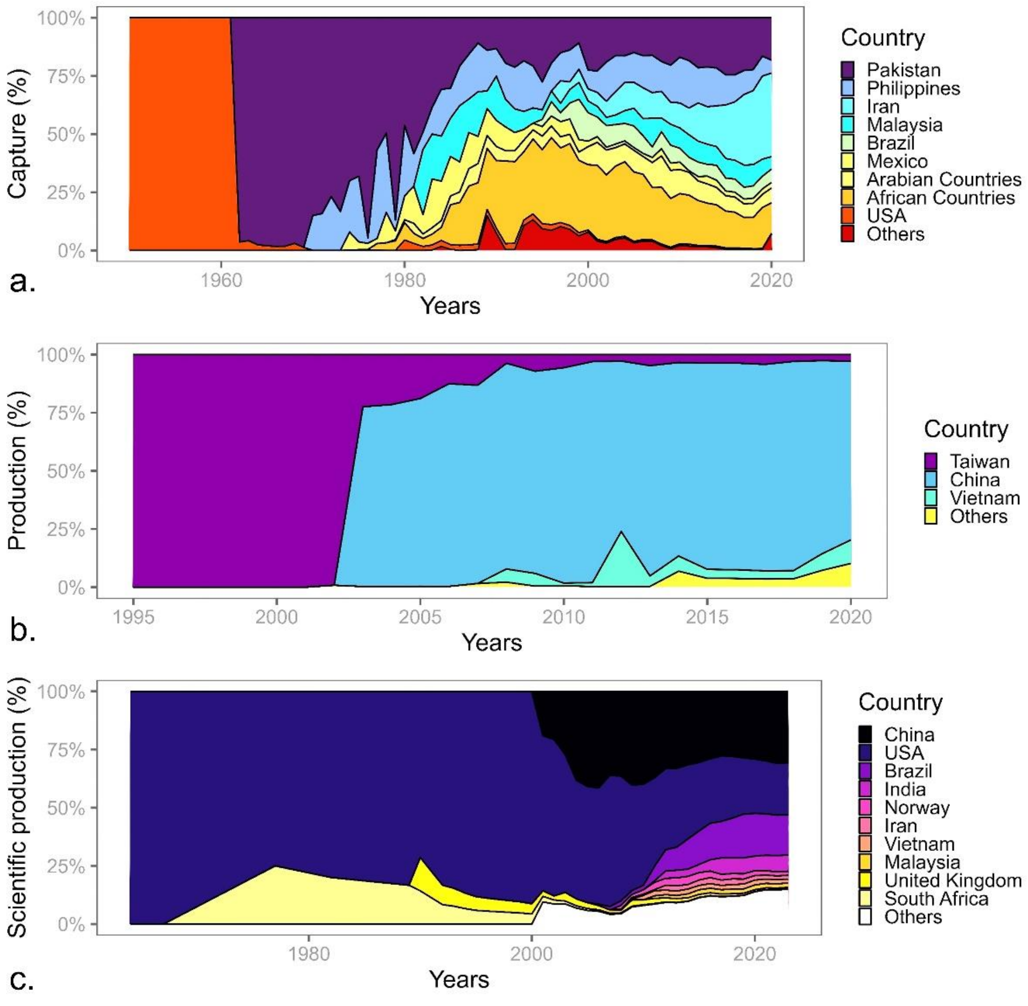

Figure 7. Time series of countries' relative contribution (%) to total capture (a), aquaculture production (b), and scientific production (c) for *R. canadum* worldwide.

Up until the early 2000s, Taiwan was responsible for practically all production of farmed cobia, but since then, China surpassed it as the main producer, being responsible for the vast majority of the species' aquaculture efforts to this day. Taiwan remains contributing steadily to the species' production, and after 2005, Vietnam also became a significant producer of cobia, with other countries such as Brazil and the Bahamas adopting the practice, though at a much smaller scale. However, in terms of cobia fishery, the contribution of countries to the species' capture is more evenly distributed in relation to its aquaculture production. The USA was dominant in the United Nations' Food and Agriculture Organization (FAO) records as far back as the 1960s, when Pakistan started making a significant contribution to the capture and surpassed the USA. The main producers for the species (China, Taiwan and Vietnam) are not among the most significant fisheries. While the main producers are in East Asia, the fishery for cobia is present worldwide. The trend in scientific production seems to resemble the trend in aquaculture production as opposed to fishery capture (Figure 8).

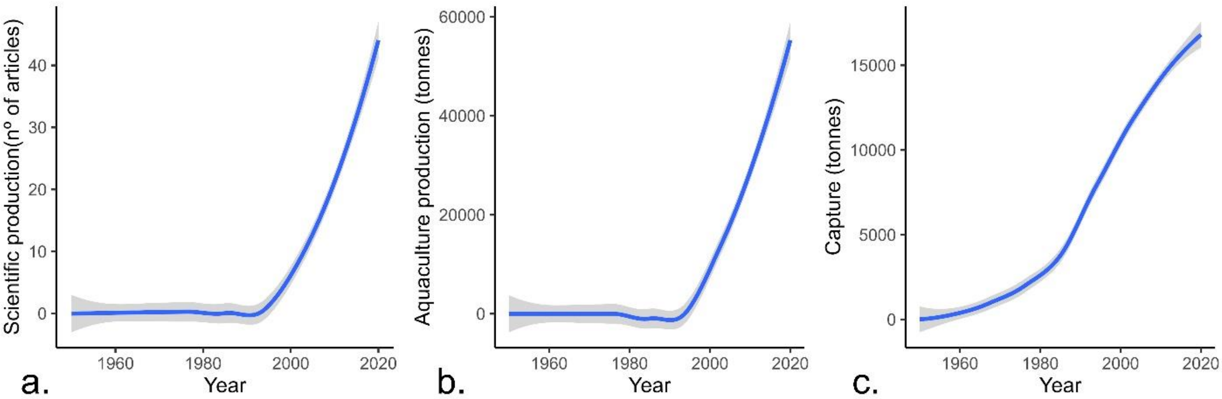

Figure 8. LOESS representation of temporal trends in scientific production (a), aquaculture production (b) and capture (c) for *R. canadum*.

4. Discussion

4.1 Science and production panorama

Overall, a moderate number of articles have been published on *R. canadum*. However, when compared to other economically important finfish species, the scientific production for cobia is small. Species like the Atlantic salmon (*Salmo salar*) and the rainbow trout (*Oncorhynchus mykiss*) have had upwards of 1500 articles published on them up until 2011 (Nikolic et al. 2011). This is probably due to freshwater fish farming dominates global aquaculture, with finfish mariculture producing less output in most places (Zhang et al. 2022), and the production for these species (especially salmonids) being much more well established in relation to cobia, which displays potential globally but it is still concentrated in a few regions (Benetti et al. 2007, 2021; FAO 2022).

The high potential of cobia for aquaculture has been discussed in a number of articles: in the Taiwan Province of China (Su and Liao 2000), the Americas and Caribbean in general (Benetti et al. 2007), Vietnam (Nhu et al. 2011) and Brazil (Sampaio et al. 2011). While the production for the species is consolidated in a few regions (FAO 2022), in most suitable countries it is still mainly small scale. The prevalence of the USA in the earlier years is probably due to the popular recreational cobia fishery in the country. However, the fishery for the species in countries like Pakistan, the Philippines and Iran is mainly commercial, and thus tends to have higher capture in number.

Today, China and Vietnam are the countries with the highest aquaculture yield for cobia, with China being the most scientifically productive country for the species' research. This is also true for the some of the countries with the highest capture yield, such as Iran, Malaysia, and Brazil. Countries like Pakistan and the Philippines represent some of the biggest fisheries for cobia but have relatively low scientific production. A possible explanation for this is the tendency of developing countries to have lesser scientific output in relation to more economically developed countries, alongside the internal policy of countries' research investment (Rodríguez-Navarro and Brito 2022). This is also likely why scientific networks are common between developing countries and more economically developed countries, as collaborations provide a way to obtain more resources to conduct research in emergent nations (Banerjee 2017). This pattern could explain the strong link between Brazil & the USA and Vietnam & Norway for cobia research.

4.2 Aquaculture as a research driver

Regarding temporal trends, there seems to be a correlation between scientific production and aquaculture, even more so than scientific production and capture. The aquaculture production for cobia appears to dictate the species' scientific production. This is probably the case as opposed to scientific production setting the path for aquaculture, because even though the earliest publications on the species were mainly on its ecology, the most used keywords, most cited articles and trend topics are almost all aquaculture-related. Furthermore, The earliest large scale operations for cobia farming started in the early 1990s (Liao et al. 2004), whereas the major boom in scientific production began in the late 1990s.

The fishery for cobia appears earlier in FAO records in relation to aquaculture, and while lesser in production, it is more widespread globally. Some of the more significant contributors to the species' capture, like Iran, Pakistan, Malaysia, India and the USA, have a number of articles on stock assessment and population ecology in general (Salari Aliabadi et al. 2008; van der Velde et al. 2010; Ganga et al. 2012; Darden et al. 2014; Nurul Amin et al. 2016; Maharshi et al. 2017; Babatunde et al. 2018; Perkinson et al. 2019; Sajeevan and Madhusoodana Kurup 2020; Raza et al. 2022; Aciole Barbosa et al. 2022). Countries like Brazil, however, display little information on its wild cobia population (Hamilton et al., 2019; Hamilton et al., 2021), despite being one of the top contributors to capture, but play a huge role on fish farming publications for the species. To this date, the various Sub-Saharan African countries where the cobia fishery is present have had one article found with scientific efforts directed towards its stocks (Darracott 1977).

4.3 Knowledge gaps and future potential

Fisheries and aquaculture practices can be important activities for poverty alleviation and food security (Béné et al. 2016), and more research towards the development of these activities for cobia in developing countries could prove successful, given its suitability for fish farming. In these countries, fishery is an overlooked subject when it comes to scientific interest for the species. Proper stock assessment and population dynamics studies can be highly beneficial to help direct sustainable fisheries (Walters and Martell 2002). More efforts to understand wild cobia stocks could not only provide more sustainable and productive models for the species' fisheries, but also represent a means to direct monitoring and populational control in areas where the fish is invasive, such as the East Pacific (Castellanos-Galindo et al. 2016).

In developing countries where the cobia fishery is significant but scientific production is low, more studies on the present cobia stocks as well as economic aquaculture feasibility could prove both profitable and socially beneficial. In countries where the cobia fishery is consolidated but its aquaculture is not (i. e. Brazil, Iran, Pakistan), the small scale fish farming practices already present could prove helpful as a way to enhance the current stocks (Taylor et al. 2017), taking advantage of these regions' suitability for the species' farming. Furthermore, enriching an already established economic activity is more cost-effective than to start new activities from scratch, and in the case of cobia, could help drive a new scientific interest in the species' already existing fishery practices in addition to its aquaculture potential. In this study, no publications on *R. canadum* restocking or stock enhancement efforts were found.

5. Conclusion

In general, *R. canadum* is a widely studied species, with a body of literature that mostly encompasses aquaculture-related knowledge. The potential of the species for this practice has been scientifically discussed in a number of regions, and even though only a few countries have adopted cobia fish farming at a large scale, articles on its production technology are published worldwide. The fishery for the species is present in various countries, however, research on wild populations and fishing stocks are still localized, and there is a lack of scientific knowledge for wild cobia in various regions where its fishery is present. More efforts to understand cobia fishery and to use its aquaculture potential for stock enhancement could be highly beneficial, especially in regions where the species' farming is unavailable at a larger scale. The scientific attention for the species seems to have been heavily focused on its aquaculture potential, while the already present fisheries may be overlooked.

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3. ARTIGO 2 - SHORT-TERM EFFECTS OF RESTOCKING ON COBIA *Rachycentron canadum* (LINNEAUS, 1766) POPULATIONS IN NORTHEASTERN BRAZIL: THE IMPORTANCE OF ARTISANAL FISHERMEN'S LOCAL ECOLOGICAL KNOWLEDGE

Artigo submetido no periódio Aquatic Conservation: Marine and Freshwater Ecosystems em 18/10/2023, onde encontra-se em revisão.

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Declaration of competing interests

The authors declare no competing insterests.

Data availability statement

The data that support the findings of this study are available from the project administrators, M. F. N and J. E. L. O., upon request.

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Abstract

1. Due to its high commercial value, cobia (*Rachycentron canadum*) is an important species to Brazilian fisheries, with a stronger presence in the northeastern region due to the prevalence of the artisanal fleet. In order to recover these heavily exploited stocks, a restocking project was developed by the Federal University of Rio Grande do Norte, with funding from the federal government. This project included the larviculture, rearing and release of tagged fry in the coastal region of the Rio Grande do Norte state. However, the tagging proved unsuccessful, but local artisanal fishermen were able to distinguish between wild and restocked fish based on general morphology and catch composition.

2. This study explores the impact of restocking on cobia catch and size composition based on artisanal fishermen knowledge, and its implications for marine resource conservation.

3. Size was significantly smaller in post-restocking catch than in pre-restocking. Weight was significantly different between wild and restocked fish, but Total Length was not. Length-weight relationships highlighted allometric differences between wild and restocked fish, further corroborating fishermen classification. The results suggest that while catch might be higher after restocking, cobia is mostly caught immature, representing a possible setback for the restocking population increase.

4. We propose that cobia restocking should be followed by fishery management strategies pre and post-restocking. Further, we advocate for including fishermen input in pre-restocking awareness campaigns and emphasize the role of Local Ecological Knowledge. Overall, cobia restocking holds promise for conservation measures through sustaining fisheries, but it requires careful consideration and comprehensive management.

Keywords: Artisanal fishery, Citizen Science, Aquaculture, Fishery management, Sustainability, Marine Resources.

1. Introduction

Fisheries and aquaculture are some of the most relevant food sources in human history, representing activities of extensive historical and social importance (Finegold, 2009), and potentially a key to food security in the future (Einarsson & Óladóttir, 2020;

Liu et al., 2018). Although different, these are not isolated activities, as there is evidence of direct connection between them, both economically and ecologically (Clavelle et al., 2019; Kitada, 2018).When it comes to market interactions, the aqua feed market relies on fishery derived products (e. g. fishmeal and fish oil), and the increase of total fish supply by aquaculture practices lowers fish product prices and reduces pressure on overexploited species (Natale et al., 2013). Ecologically, aquaculture can cause environmental degradation in its surrounding habitats, altering fish community compositions and fishery productivity (Wiber et al., 2012; Zhao et al., 2021), but it can also increase fishery productivity when targeting the replenishment of fisheries (Taylor et al., 2017). The latter is the case in restocking and stock enhancement, where fish are reared with the objective of being released in the wild in order to improve self-sustaining populations or to replenish depleted stocks (Bell et al., 2006; Lorenzen et al., 2010).

Restocking and stock enhancement can be highly sustainable to fisheries, providing socio-economic benefits to a wide range of stakeholders (Taylor et al., 2017), and increasing size and genetic diversity of fish populations (Bignardi et al., 2016). With the World's marine fisheries in decline (Palomares et al., 2020; Pauly and Zefller, 2016) and little progress being made to address this problem in most countries (Ye & Gutierrez, 2017), solutions that implement aquaculture in fishery management hold promising potential to maintain sustainability in fisheries (Lorenzen et al., 2010). Restocking and stock enhancement programs have already proven successful in improving the state of fish populations in countries like Japan (Kitada & Kishino, 2006), Australia (Loneragan et al., 2013) and China (Chen et al.g, 2015).

Among the various species with potential for restocking and stock enhancement, *Rachycentron canadum*, commonly known as cobia, is a teleost fish that stands out due to its production-friendly characteristics (Benetti et al., 2021), being a strong candidate for aquaculture practices worldwide (Benetti et al., 2007; Nhu et al., 2011; Su & Liao, 2000). *R. canadum* is a coastal pelagic species (Hamilton et al., 2013), naturally present in tropical and subtropical waters of all oceans, with the exception of the Eastern Pacific (Shaffer & Nakamura, 1989). Fish farming for the species is already consolidated in a few countries, with an estimated production of 40 to 50 thousand tonnes per year since 2010 (Benetti et al., 2021; FAO, 2022). Although the main focus of the species' human use and research has been aquaculture, the fishery for cobia is also important, with an estimated yearly capture of 13 to 16 thousand tonnes from 2010 to 2020 (FAO, 2022). In Northeastern Brazil, where the cobia fishery has been historically present (Nóbrega et al., 2015), the favorability of the species for fish farming has been discussed with remarkable potential(de Bezerra et al., 2016; Igarashi, 2018). The Rio Grande do Norte Coastal and Interior Native Species Restocking Project (REPOVOA) took advantage of this aquaculture potential to conduct a restocking project in the coast the Rio Grande do Norte state (RN). The REPOVOA project saw to the rearing and release of more than 40 thousand live fry, marked with plastic tags to distinguish between wild and farmed individuals when eventually captured. However, the tagging method proved difficult to assess, and the identification of the captured fish's origin relied mostly on the fishermen's knowledge.

Local fishermen can provide essential information about aquaculture, fisheries and the relation between both in the form of Local Ecological Knowledge (LEK) (Gianelli et al., 2021; Sáenz-Arroyo & Revollo-Fernández, 2016; Wiber et al., 2012). LEK can be useful as a way to evaluate biological patterns and population dynamics of fishery resources, especially in data-poor fisheries, where funding, time or interest for research and management is often limited (Beaudreau & Levin, 2014; Lopes et al., 2019). In fact, an integrative method between the two forms of data acquisition seems to be ideal to assess information that is relevant to local stakeholders (Lima et al., 2017; Silvano and Valbo-Jørgensen, 2008). Furthermore, it is important to evaluate ways to consciously maintain and utilize this type of knowledge, which is in decline and requires active efforts to continue to be valued (Aswani et al., 2018). Considering that, this study aims to provide an assessment of restocking effectiveness, survival and size composition for cobia populations in the context of the REPOVOA restocking project in northeastern Brazil through an integrative approach utilizing LEK.

2. Materials and methods

2.1 Restocking and tagging

Between 2014 and 2015, the REPOVOA project for *R. canadum* was carried out on the coast of Rio Grande do Norte (RN), Brazil, involving the production and release of 48,728 live fry in the coastal area of the municipalities of Macau, Rio do Fogo, and

Baía Formosa (Figure 1), in depths ranging from 3 to 15 m in sand, mud and gravel bottom regions. Fry was reared by the company Camanor Produtos Marinhos LTDA, operating in the municipality Canguaratema, RN. Locally captured wild cobia were used for the restocking broodstock production, ensuring minimal genetic divergences between wild and restocked populations. The larviculture and rearing followed standard protocols for cobia production set by the company.

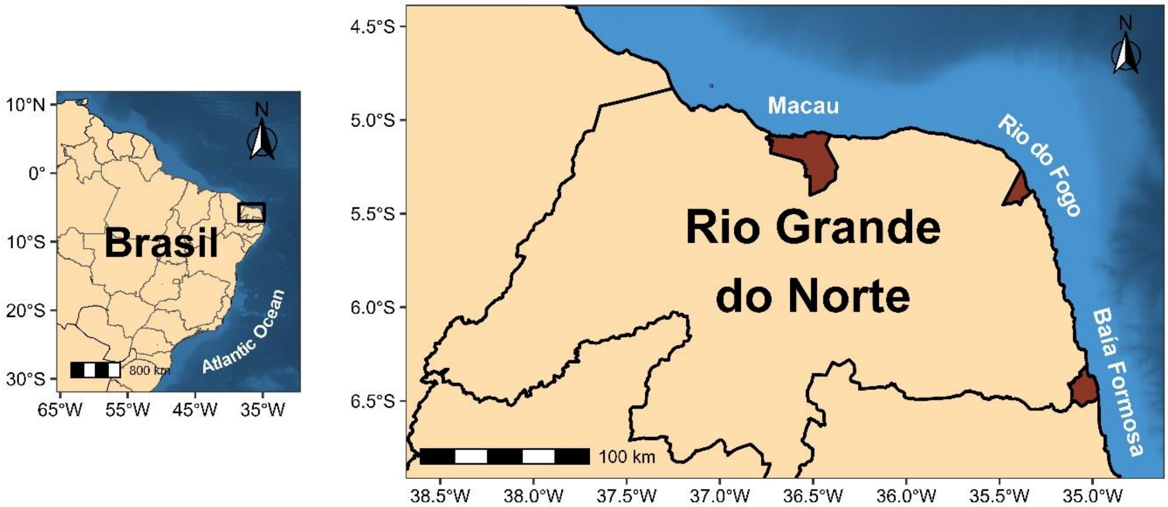

Figure 1. Release locations of reared cobia by the REPOVOA restocking project.

The tagging of reared individuals was carried out at an average age of 70 days of age for the fish, shortly before the release. Plastic tags with different colors were chosen for each release locality: blue for the municipality of Baía Formosa, black for Rio do Fogo, and transparent for the municipality of Macau. Using a tag gun, the tags were inserted into the fish's muscle region just under the first dorsal fin, ensuring no interference with the fry's swimming ability and easy identification of the fish's origin during recapture. Tagging and release activities began in July 2014 and were completed in August 2015. During each tagging period, the total number fry was divided among the regions. Fluctuations in survival rates during egg fertilization and larviculture influenced the difference in the number of released fry in the locations (Table 1). All of the 48,728 fry were tagged, and biometric measurements were performed on 2200 fry before release (Figure 2).

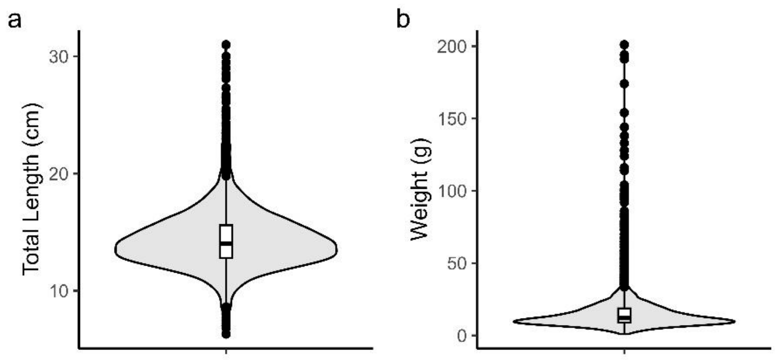

Figure 2. Violin plot of total length (a) and weight (b) of fry prior to the release.

Table 1. Number and age of released fry for each municipality.

Age (days)	nº released	Release date (d.m.y.)	Municipality
71	676	24.07.2014	Baía Formosa
78	2.663	02.09.2014	Baía Formosa
66	2.437	09.09.2014	Baía Formosa
70	4.352	15.01.2015	Rio do Fogo
53	4.500	28.03.2015	Macau
60	7.000	02.04.2015	Rio do Fogo
67	7.000	10.04.2015	Baía Formosa
63	6.600	01.08.2015	Rio do Fogo e Macau
101	1.500	29.08.2015	Baía Formosa
76	6.000	28.08.2015	Rio do Fogo
76	6.000	28.08.2015	Rio do Fogo

2.2 Artisanal fishermen awareness and data obtaining

Technical visits were conducted to fishing communities in the North and South coast of Rio Grande do Norte, in the municipalities of Macau, Rio do Fogo, and Baía Formosa, to make the restocking known and collect information about the current catch of the species in their respective region. A brief questionnaire was implemented for the fishermen, regarding the catch, sizes, weights, and the usual catch locations for cobia.

For each region, local fishermen or individuals responsible for monitoring fishing fleets' landings were registered, as well as fisheries' owners with easy access to the landings. The collectors were instructed to sample all cobia specimens. These registered collaborators received prior training on note taking and collecting scientific data and were provided with adequate tools to record catch location, depth, substrate type, fishing gear (net, line or spearfishing), fish length, weight, and tag color. The weight of captured cobia was recorded using scales commonly used at fisheries. To collect the cobia catch and related data, monthly visits to fisheries in the release locations were conducted between January 2015 and October 2018.

Up to 2018, a total of 1,530 individuals were captured, with 1,332 being considered recaptured of restocked individuals (2.73% of total released). Out of the catch, only one individual was captured with the presence of a plastic marker. However, fishermen were able to distinguish between wild and restocked individuals through LEK-based observations. LEK is an important aspect of fisheries management in northeastern Brazil, and local fishermen are familiar with both wild and released farmed fish (Viana et al., 2021). According to them, cobia caught in groups and with similar size likely originate from aquaculture, as well as stockier, larger cobia in relation to their length. Cobia is known to be a generally solitary fish, except for spawning aggregations (Richards, 1967; Shaffer & Nakamura, 1989), and being caught in groups of same-sized individuals is perceived as an odd behavior, present in farmed fish. Due to a lack of continuity in fisheries statistics for this region, assessing differences in *R. canadum* populations pre and post restocking can be challenging, as biometric and catch-related data for cobia is scarce. Biometric data for cobia in northeastern Brazil is available from the Live Resources Sustainability Potential of the Exclusive Economic Zone (REVIZEE) project, from the Brazilian Ministry of Environment (MMA) (Lessa et al., 2018). In this study, fork length data of 127 specimens caught off northeastern Brazil, captured between 1998 and 2000, were utilized (figure S1).

Finally, 554 individuals had available biometric data, and 421 individuals had available biometric, substrate type, fishing gear and capture depth data available. Length of first maturity data was obtained by converting FL reported by Hamilton et al. (2021) for cobia in northeastern Brazil utilizing linear regression with the FL available in the REPOVOA project.

2.3 Analyses

To assess possible differences in cobia pre and post restocking, and between wild and restocked populations, Permutational Multivariate Analysis of Variance (PERMANOVA) was utilized (Anderson, 2017). PERMANOVA can be useful as a univariate analysis for historical fisheries data, as this type of data tends to be highly asymmetric and different in size and availability (Anderson, 2017; Gray, 2022). Thus, PERMANOVA (α = 0.05) was performed to test differences in Fork Length pre and post restocking, and differences in Total Length (TL) and weight between wild and restocked populations.

The growth of the captured individuals was assessed through the observation of length-weight relationships. Specimens with available data for weight and total length were used, resulting in 356 restocked and 198 wild individuals. The estimated length-weight relationships were built according the two-parameter power function described by Le Cren (1951):

$$W = aL^b$$

where W is the response variable of total weight, L is the predictor variable of total length, a is the intercept, and b is the slope coefficient. In this case, the slope represents the fish growth coefficient; usually indicating isometric growth when $b = 3$, negative allometric growth when $b < 3$, and positive allometric growth when $b > 3$ (Ricker, 1958). Farmed cobia generally exhibit greater weight-at-length growth in relation to wild cobia, likely due to greater food availability and feeding frequency in the farming environment (Benetti et al., 2010). Based on these premises, variations in the length-weight relationships curves of wild and recaptured restocked fish were analyzed to identify differences between wild and restocked fish.

Generalized linear models (GLMs) (Lindsey, 2000) were used to identify variations in TL and the categorical variable of fish origin (restocked or wild), as well as the interaction of length with fish origin. Furthermore, GLMs were applied to investigate how bottom type and capture depth can influence TL of captured fish, and to predicted possible TL of unreported cobia catch. The GLM with the best fit for TL as a response followed the Gaussian family distribution with an identity link function, with the predictor variables of weight, origin, bottom type, depth, year, and interactions between weight and origin and between substrate type and depth. Fishing gear was kept out of the model due to the heavy dominance of net fishing. The proposed model can be represented by the following:

$$TL = \beta0 + \beta1{:}Origin + \beta2{:}Weight + \beta3{:}Origin{:}Weight + \beta4{:}Bottom + \beta5{:}Depth$$

$$+ \beta6{:}Bottom{:}Depth + \beta7{:}Year + \epsilon$$

where *TL* representes Total Length, $\beta0$ represents the intercept, $\beta1$ to $\beta7$ correspond to the coefficients associated with the predictor variables, and ϵ corresponds to the error representing unexplained variability. GLM fit was assessed considering McFadden's pseudo-R^2 (ρ^2) and Pearsons' adjusted R^2 (R^2). Variable significance was established using $\alpha = 0.05$. Data managing and analysis was conducted in the R environment for statistical computing (version 4.3.1) (R Core Team, 2022). Locally estimated scatter plot smoothing (LOESS) was used to graphically visualize GLM tendencies. The R package *vegan* was applied to perform PERMANOVA (Oksanen et al., 2022), and analysis visualization was conducted using the *ggplot2* R package (Wickham, 2016).

3. Results

3.1 Pre and post-restocking

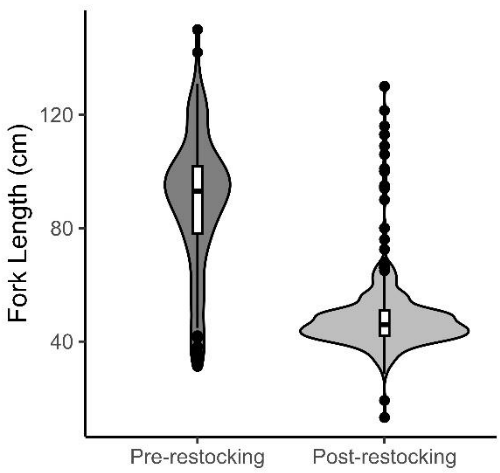

Figure 3. Violin plot of pre (REVIZEE Project) and post-restocking (REPOVOA Project) FL for *R. canadum* in northeastern Brazil.

Captured pre-restocking cobia's Fork Length (FL) ranged from 31.2 cm to150 cm (median: 93 cm, mean: 88.95) (REVIZEE Project), while post-restocking FL ranged from 13 cm to 130 cm(median:46 cm, mean: 48.94 cm) (REPOVOA Project). Post-restocking fish had significantly smaller length than its pre-restocking counterparts (Figure 3).

Considering data from the REPOVOA project the PERMANOVA for the size measurements found no significant difference in total length between restocked and wild fish. Nonetheless, weight did significantly differ. Furthermore, fork length significantly differed between fish pre and post restocking (Table 2). Post-restocking, 356 (~64.25%) of specimens were classified as restocked and 198 (~35.74%) classified as wild. Both restocked and wild generally displayed higher frequency on the smaller sizes present in the capture (median length: 50 cm, median weight: 0.772 cm). Restocked fish displayed Total Length (TL) from 31 cm to 128 cm (mean: 51.82 cm) and weight from 50 g to 13,700 g (mean: 1021.7 g), while wild fish ranged in length from 14.8 cm to 128 cm (mean: 54.13 cm) and in weight from 40 g to 15,500 g (mean: 1458.02 g). Length frequency were more evenly distributed than weight. Wild fish displayed a wider range of both length and weight frenquencies in relation to restocked ones (Figure 4).

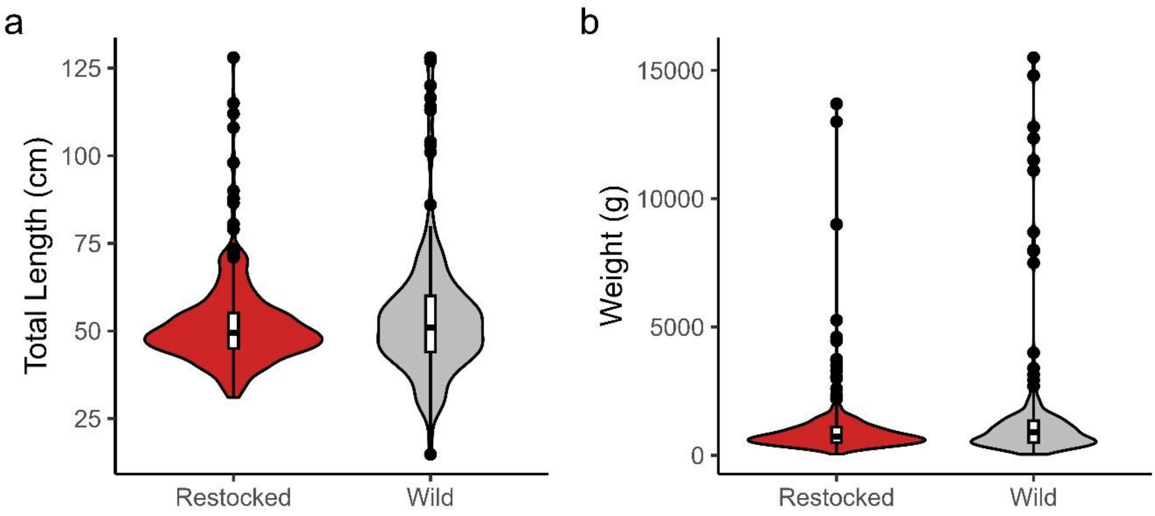

Figure 4. Violin plots of TL (a) and weight (b) distribution of captured *R. canadum*.

Table 2. Summary of PERMANOVA results for *R. canadum* morphometric parameters. * indicates significant values.

Parameters tested	DF	Pseudo-*F*	*p*
Total Length (Restocked and Wild)	1	0.00569	0.063
Weight (Restocked and Wild)	1	5.4546	0.012*
Fork Length (Pre and post restocking)	1	481.78	0.0009*

From August 2017 to July 2018, nearly all captured fish were classified as wild. Catch tended to be higher in the later years (Figure 5a). From January 2015 to August 2017, the vast majority of captured cobia were classified as restocked (Figure 5b).

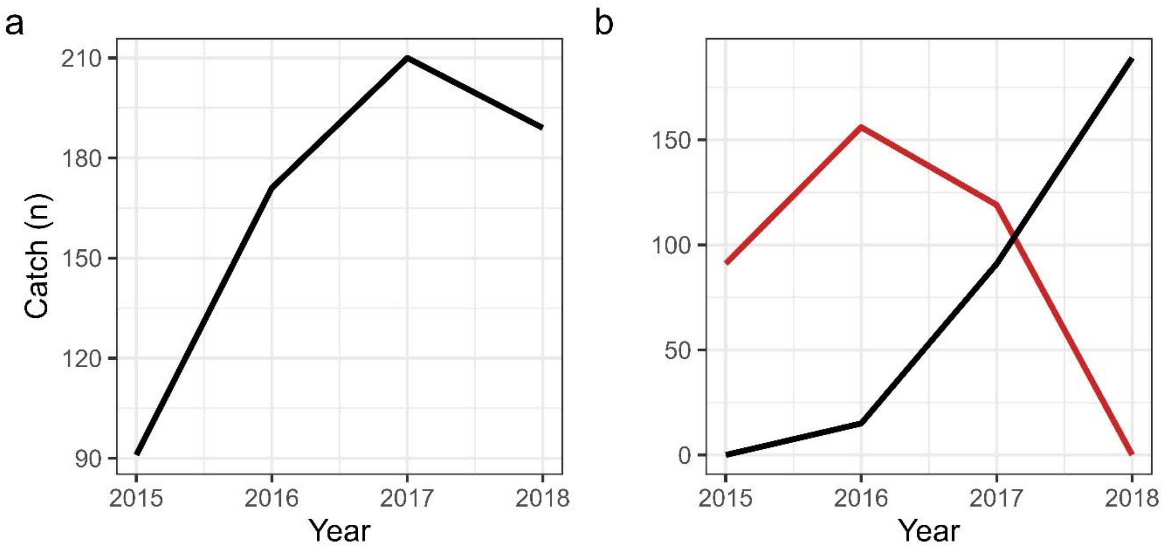

Figure 5. Total reported catch (a) and catch of restocked (■) and wild (■) cobia through the years of monitoring (b).

3.2 Bottom type, fishing gear and catch depth

Out of the total capture, 49 specimens were captured areas with sand bottom (11.6%), 313 in gravel (74.3%), 36 in mud (8.5%) and 26 in rock (6.1%). Catch occuring in sand and gravel bottom had both TL and weight more distributed towards the smaller sizes. Catch ocurring in mud and rock substrates, while still having the majority of individuals concentraded on the smaller sizes, had more presence of bigger fish, both in TL and weight (Table 3). Between restocked and wild fish, catch by bottom type was similar, with a prevalence of gravel catch. However, wild fish were caught more in rock bottoms in relation to restocked, which displayed a higher mud catch (Figure 6).

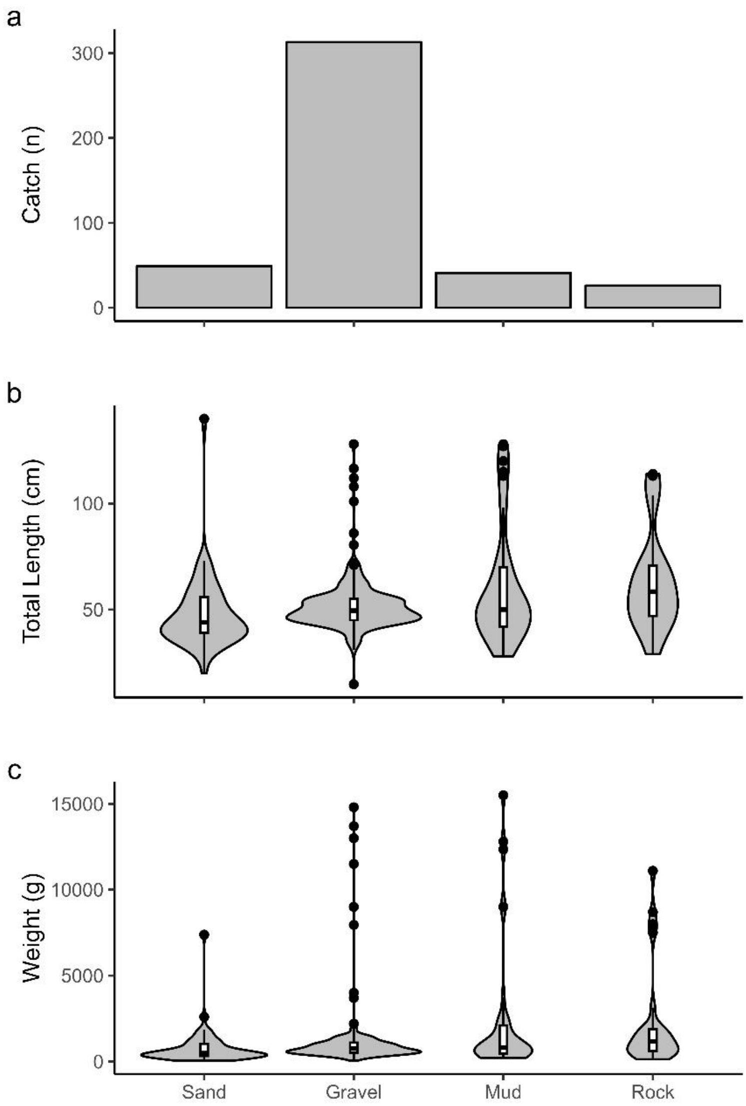

Figure 6. Total (a) restocked (b) and wild (c) catch by bottom type, and size distribution (d, e) by bottom type.

Table 3. Mean and median TL and weight by bottom type of *R. canadum* catch.

Substrate type	MeanTL	Mean weight	Median TL	Median weight
Sand	47.97 cm	810.51 g	44 cm	480 g
Gravel	51.87 cm	1037.85 g	49.5 cm	750 g
Mud	60.58 cm	2396.62 g	50 cm	750 g
Rock	64.78 cm	2461.3 g	60 cm	1200 g

For fishing gear, 414 individuals were captured utilizing net fishing (98.3%), 5 individuals were captured utilizing line fishing (1.2%), and 2 were captured utilizing spearfishing (0.5%) (Figure 7a). The few individuals caught using spearfishing (mean TL: 113.5 cm, mean weight: 9550 g) and line fishing (mean TL: 95.56 cm, mean weight: 9140 g) were notably larger than the ones caught on nets (mean TL: 52.05, mean weight: 1069 g). The vast majority of fish were captured in a depth of 0 m to 25 m. Net fishing assessed a wider range of depth than other fishing gears, but with most individuals caught in < 20 m (mean: 17.41). Line fishing generally assessed deeper areas (mean: 26.18 m), and spearfishing generally assessed shallower area (mean: 11.05 m) (Figure 7b). The only individual caught in more than 40 m was captured with line fishing.

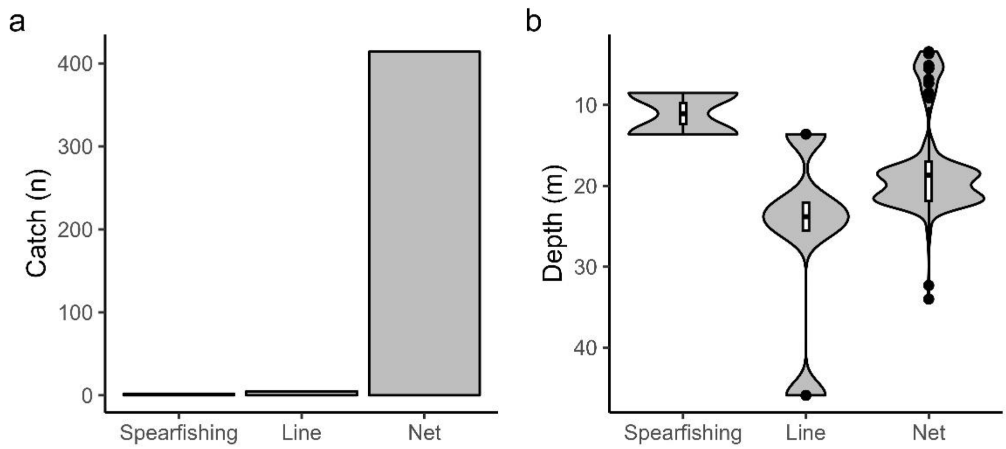

Figure 7. Catch (a) and violin plots of catch depth by fishing gear (b).

3.3 Length-weight relationships

Different inclinations in the length-weight regressions can be observed between wild and restocked populations. The allometric paremeter values were b = 2.9123 for the restocked population and b = 2.6365 for its wild counterpart (Figure 8). This indicates that restocked fish tend to have higher weight-at-length growth in relation to wild fish. Thus, restocked fish seem to have a more pronounced increase in weight in relation to their length compared to the wild fish population. Both parameters dislayed b < 3, indicating negative allometric growth as per the classification of Ricker (1958). Accordingly, both populations tended towards growth more in length than in weight.

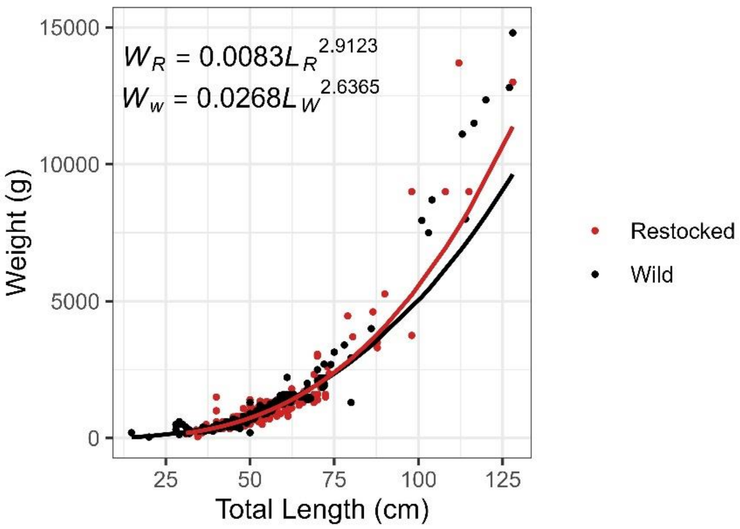

Figure 8. Length-weight relationships for restocked (R^2 = 0.9714) and wild (R^2 = 0.9042) cobia. W_R: Restocked fish weight, W_W: Wild fish weight, L_R: Restocked fish length, L_W: Wild fish length.

3.4 Generalized Linear Models

All variables in the GLM model were significant as predictors of TL, except for Bottom (Mud) (Table 4). The model displayed ρ^2 = 0.2335 and R^2 = 0.8579, indicating a reasonable fit (figure S2). Overrall, expected TL were below the length of first maturity (L50) for both males and females in all years, with a downward trend throughout the years. Captured fish had TLmostly below the L50 for both sexes. However, around 10 and 30 m, TL is expected to be above the L50 for males, and below the L50 for females (Figure 9).

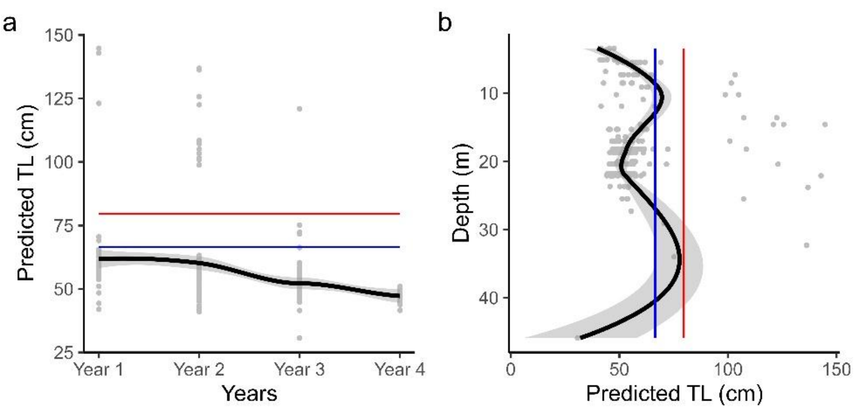

Figure 9. Locally Estimated Scatterplot Smoothing (LOESS) representation of GLM predicted TL for cobia through the years after restocking (a) and for depth of capture (b). The red line represents the estimated L50 for females, and the blue line for males.

Expected TL for all bottom types and origins displayed a downward trend through the years. Both wild and restocked fish's TL was expected to be below the reported L50 for females in all years. Wild cobia TL was expected to be slightly above the L50 for males in the first year, and below it in the later years. Cobia captured in sand, gravel and mud bottoms were expected to have TL below the L50 for both male and females. Cobia captured in rock bottom were expected to have TL between the L50 for males and females in the first year, above both in the second year, and below both in the third and fourth year (Figure 10). In sand bottom, expected TL was only above the L50 for males below 6.5 m. In gravel, expected TL was above the L50 for males and females aroud 35 m, and below females but above males around 25-30 m and 40 m. In rock bottom, TL was expected to be above the L50 for males and females, from around 12 m to around 27 m, and above L50 for males around 10 m and from 30 m to 35 m. In mud bottom, expected TL was only above the L50 for males from 13 m to 15 m, and below the L50 for both sexes in all other depths (Figure 11).

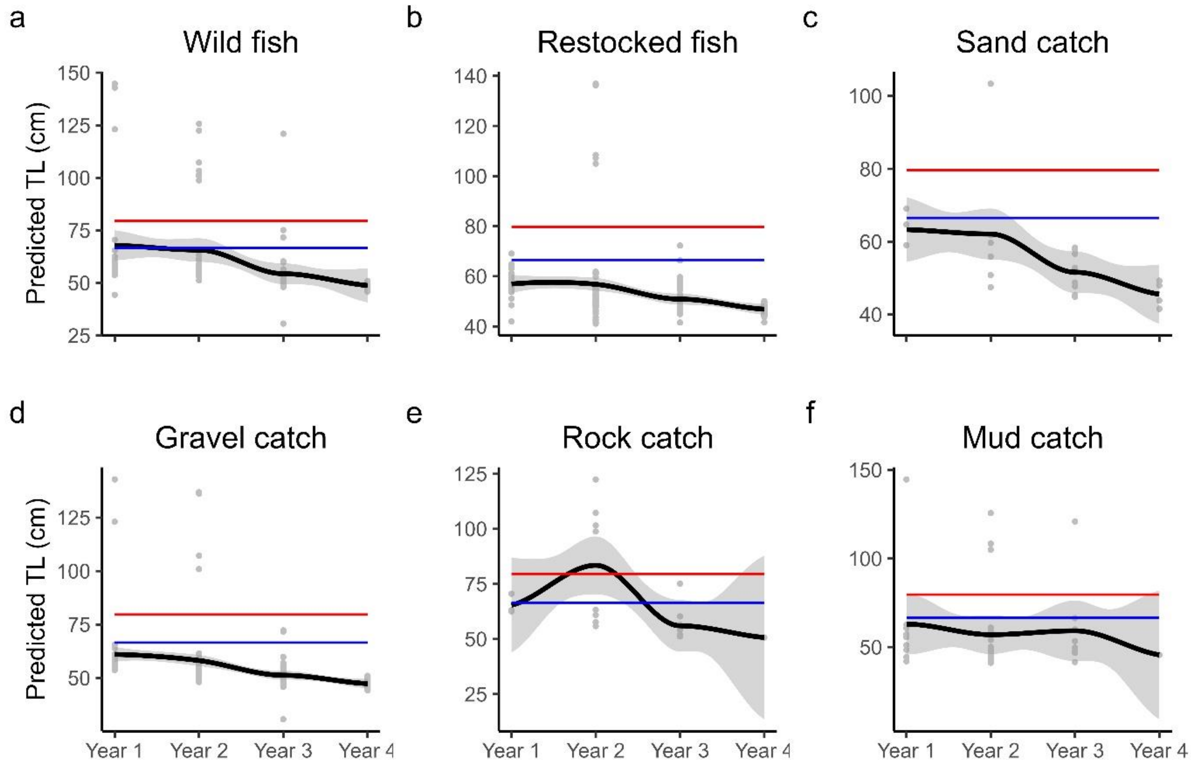

Figure 10. LOESS representation of GLM predicted TL through the years for the different fish origins (a, b) and bottom types (c, d, e, f). The red line represents the estimated L50 for females, and the blue line for males.

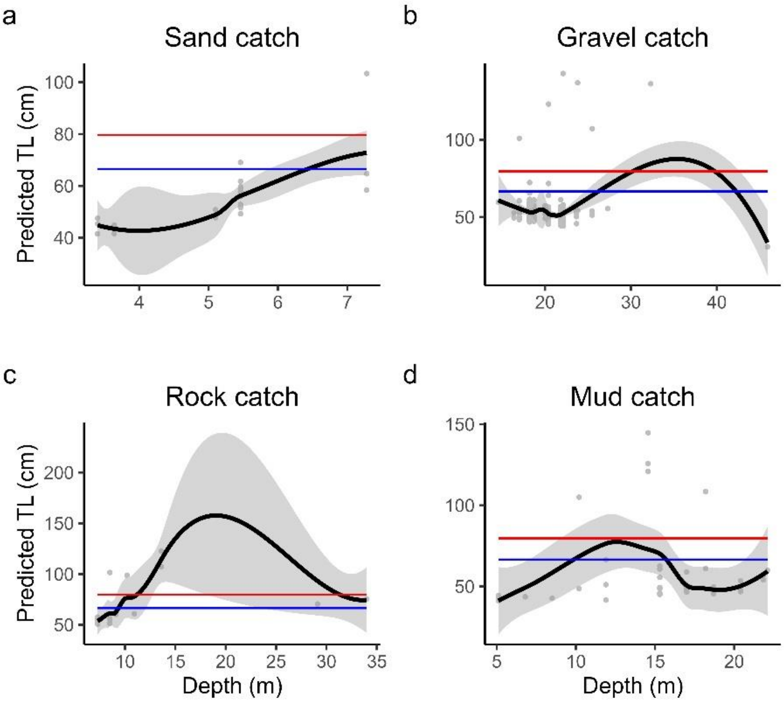

Figure 11. LOESS representation of predicted TL for depth of capture for sand (a), gravel (b), rock (c) amd mud (d) catch. The red line represents the estimated L50 for females, and the blue line for males.

Table 4. Summary of GLM results. * indicates signficative values

Variable	Estimate	Std. Error	*t* value	*P*
Intercept	3,88E+06	6,75E+05	5.756	1.79e-08*
Origin	1,93E+03	8,02E+02	2.405	0.016644*
Weight	7,14E+00	2,66E-01	26.797	< 2e-16*
Bottom(Gravel)	2,92E+04	6,22E+03	4.700	3.67e-06*
Bottom(Mud)	5,69E+03	6,32E+03	0.901	0.368080
Bottom(Rock)	1,62E+04	6,05E+03	2.672	0.007860*
Depth	3,29E+03	1,03E+03	3.209	0.001446*
Year	1,91E+03	3,34E+02	-5.719	2.20e-08*
Origin:Weight	-7,98E-01	3,24E-01	-2.461	0.014294*
Bottom(Gravel):Depth	3,95E+03	1,03E+03	-3.828	0.000151*
Bottom(Mud):Depth	2,86E+03	1,04E+03	-2.738	0.006484*
Bottom(Rock):Depth	3,04E+03	1,04E+03	-2.922	0.003685*

4. Discussion

4.1 Restocking effectivness and sustainability

Recapture rates for cobia were similar to a meager (*Argyrosomus regius*) restocking assessment with similar tagging in the Islas Baleares (3.3%). *A. regius* is another coastal, large, oportunistic predator, and this recapture rate could be common for fish in this ecological niche. The growth in catch during the first years after restocking indicates that restocking efforts could have proven succeful in strenghthening the cobia stock in Rio Grande do Norte (RN). However, the post-restocking monitoring focused on obtaining catch data on a timely basis from small-scale artisinal fisheries, and no fishing effort data was collected. Without fishing effort data, it could be possible that the effort was higher in the years after restocking, due to the restocking being made known to the fishermen in information campaigns. Nonetheless, this case is unlikely, as artisanal net fisheries in the regiontend to target multiple species (Vasconcellos et al., 2011). Furthermore, fishermen did report and increase in cobia catch. Thus, assuming constant fishing effort, restocking did have a positive effect on the artisinal fishery. Additionaly, two years is the standard time of sexual maturity for cobiain regions with similar L50 to northeastern Brazil (Hamilton et al., 2021; Richards, 1967), making the observed growth in cacth in later years a possible result of restocked fish reproduction. This could also explain the classification of most of the catch in the later years as wild, as opposed as the majority being classified as restocked in the earlier years. Cobia born in the wild probably did not develop the higher weight-at-length ratios of farmed individuals, likely as a result of the lower resource availability in the wild environment.

During the discussions regarding the appropriate tag choice for identifying *R. canadum* fry, considerations were made to minimize damage to the specimen's tissue and would not compromise the fry's swimming ability. Furthermore, potential additional effects of the tag, such as increased predation rates due to the marker colors, and the possibility of the marks being absorbed by the fish’s tissue as they grow into adulthood were considered. Finally, plastic tags were the most cost-effective way of tagging the whole restocked population. Cobia is a migratory species (Shaffer & Nakamura, 1989), and restocked fish could have moved to locations outside the monitoring range. The plastic tags could also have broken off as the specimens grew. Nonetheless, wild and restocked fish differed in weight but not in length, and different length-weight allometric patterns were found between both populations. In fact, a higher allometric coefficient was already reported for farmed cobia (Benetti et al., 2010) in relation to wild (Bohnsack & Harper, 1988) in the Caribbean. This, coupled with the smaller size composition of post-restocking catch and the sexual maturity time being concurrent with fish being classified as wild in the later years, is an indicator of the accuracy of the LEK-based fishermen observations in the absence of tags.

In the years following the restocking, mean TL was expected to be below the size of first maturity (L50) for this species, and expected to be decreasing through the years. This evidentiates an unsustainable trend for this post-restocking fishery, affected by some factors, such as gear type and timing of catch. However, the majority of fish utilized in the reproductive study conducted by Hamilton et al. (2021) were caught utilizing handline and spearfishing, which tends to select bigger individuals, and thus presenting a possibility of oversetimating the L50 for cobia, according to the authors. Line and spearfishing are more selective types of fishing gear, and consequently, mor sustainable. This is refletected in the mean TL for these gears' catch being above the L50 for *R. canadum*. Net fishing, conversely, is less selective, with smaller mesh sizes targeting multiple species. Thus, it presents a higher risk of catching immature fish (Herron et al., 2020). The majority of monitored catch resulted from net fishing, and the restocking could have provided an great influx of young cobia, resulting in a higher catch in the following years and a predominance of smaller sizes in the catch. Even considering possible overestimation for the L50, the size composition of the post-restocking cobia catch in RN demands more attention for cobia stocks, as overfishing could possibliy be a problem.

While catch was different between years, no difference was noted between months or seasons. Cobia migration is mainly temperature-driven (Jensen & Graves, 2020), and the temperature difference between seasons in this tropical region might not be enough to cause noticeable migration at this scale.

4.3 Habitat use

The bottom types with fish size expected to be above L50 were rock and gravel, indicating that post-restocking adult cobia caught off RN tend to have a preference for those bottom types. This could also be a reflection of more fishing effort being directed to those areas, but again, this is unlikely as the monitoring followed multispecific artisinal fisheries utilizing mostly net fishing, and cobia would not be the only target species. Cobia is found in a variety of bottom types (Carpenter & Niem, 1999), but records of a preference for specific bottom types were not found in the literature.

However, the species is known for displaying following behavior with other large animals (Félix & Hackradt, 2008; Shaffer & Nakamura, 1989) and being associated with structures, avoiding open water: a behavioral pattern already present in young fish (Joseph et al., 1964). Cobia is a target species for sportfishing (Estrada et al., 2016; Scheld et al., 2020) as a consequence of this behavior.

Rock and gravel bottoms display more structural complexity than mud and sand, representing an habitat preference for cobia. Besides graveil, wild cobia tended towards more rock bottoms, while restocked tendend towards mud. This is likeky a result of catch composition, as bigger individuals are expected to prefer rock bottom, and fish considered wild were generally bigger. Farmed cobia could also possibly develop different behavioral patterns as a result of the growth in captivity. This could be a factor influencing the higher catch rate of cobia using net fishing, as opposed to line and spearfishing. Fish associated with structures and other large animals would not be very suceptible to net fishing. Moreover, structural complexity has been an important aspect in the assessment and conservation of similar species, such as the yellowtail kingfish (*Seriola lalandi*) (Rees et al., 2018). Indicator of fish behavior, such as habitat preference, are essential to the asessement of interactions between wild and farmed fish in restocking contexts (Salvanes & Braithwaite, 2006).

4.4 Implications for management and conservation

Cobia is a species with very high potential for restocking, as a favorable species for aquaculture, ocurring in most coastal areas and being present in fisheries worldwide (Benetti et al., 2021; Shaffer & Nakamura, 1989). Thus, cobia restocking could mitigate possible overfishing while causing minimal ecosystemic imbalances. However, most post-restocking cobia catch in RN was small and expected to be caught before sexual maturity. This could diminish the growth in population number providaded by the restocking, making the fishery activitiy itself a possible setback for the very conservation efforts of restocking. Thus, fishery management measures should be taken to address post-restocking fishery effects. Even though net fishing seems to catch mostly immature cobia in this restocking context, prohibiting net fishing for subsequent years for fisheries such as the ones present in this study could be socio-economically devastating (Diegues, 2008). Management actions should take into acount artisanal fishermen input.

For multispecific artisanal fisheries, the preference for releasing small cobia catch in the first two years post-restocking should be included in the pre-restocking awereness campaigns. This would alleviate immature fish catch, ensuring restocked individuals reach maturity before being caught and enhancing fishery sustenainability. Just restocking cobia in contexts such as this is not enough; close attention to fisheries pre and post-restocking should be considered in order to realize a technically robust restocking with a sustainable subsequent fishery. Furthermore, bottom type information can be useful to infer habitat use of target species, and assess possible differences between restocked and wild individuals.

5. Conclusion

Restocking of cobia in the coast of RN most likely did have a positive effect on catch, and fishermen noticed an increase in cobia stocks. In fact, fishermen proved essencial to the restocking assessment, as they were able to distinguish between restocked and wild based on morphological aspects and catch composition, in the absence of tags. We emphasize the role of Local Ecological Knowledge in the REPOVOA restocking project assessment. Further, we propose that restocking alone is not enough to responsibly strengthen cobia stocks in this context, where artisanal net fishery is predominant. Cobia seemed to occur more over gravel bottoms in RN, but more studies are needed to assess the habitat use of the species and its relation to fisheries. We propose the challenge to other researchers to view LEK as an essential tool to integrate, when possible, into artisanal fishery science. Cobia restocking is still an overlooked subject when it comes to the research of this species, which displays great aquaculture potential and a presence in fisheries around the World.

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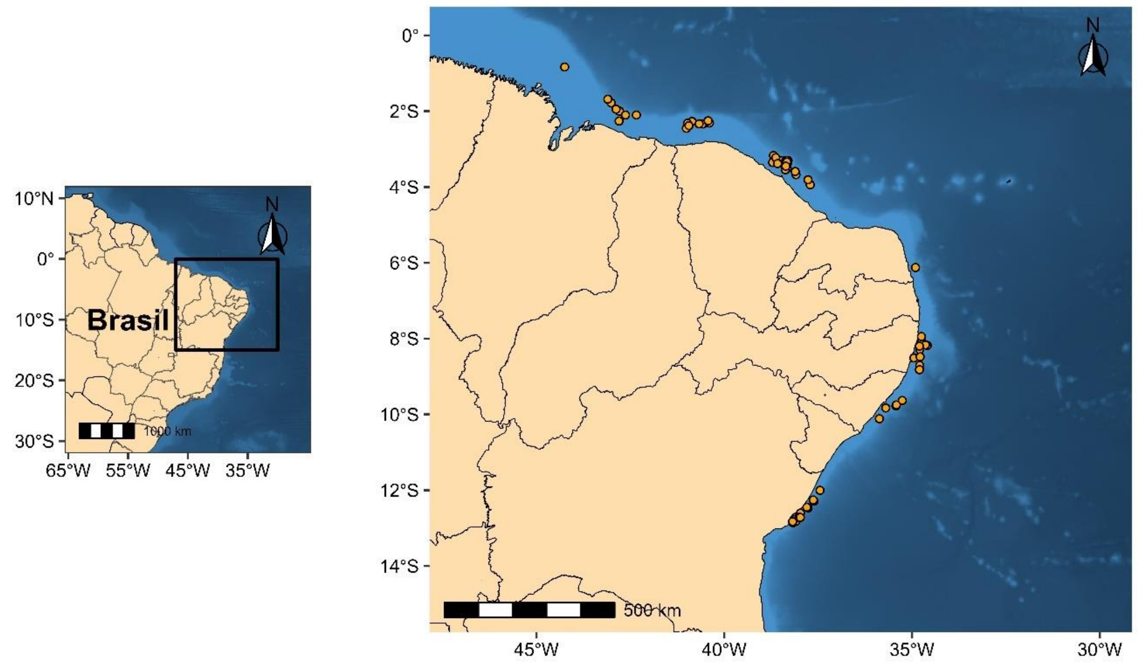
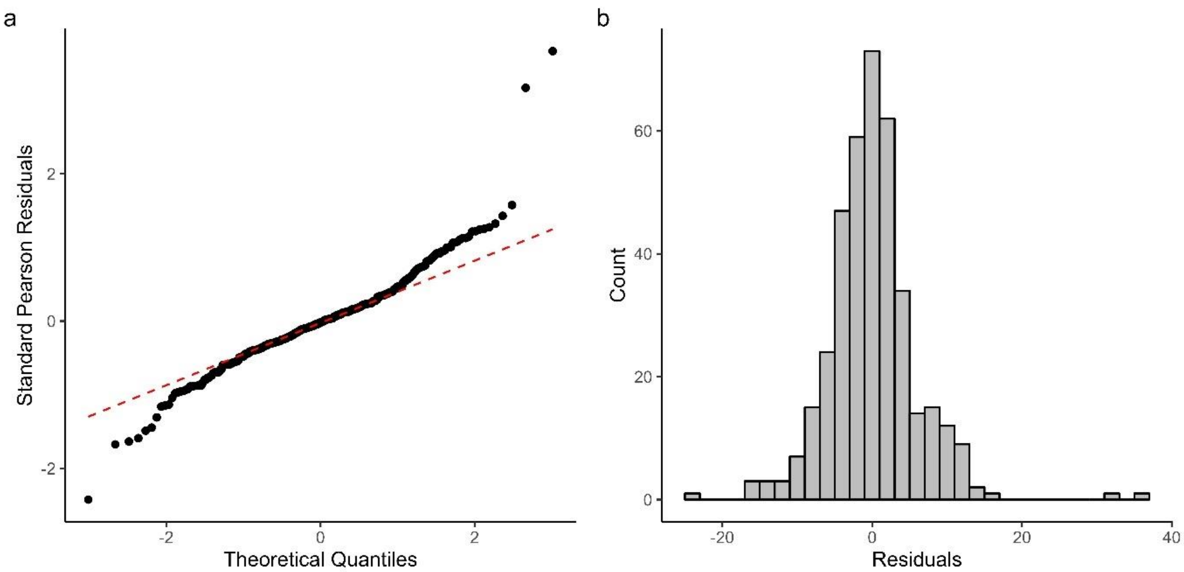
Supplementary Material



FigureS1. Capture locations for cobia during the REVIZEE project (1998-2000).



FigureS2. GLM Q-Q Plot (a) and residual distribution (b).

4. CONSIDERAÇÕES FINAIS

De maneira geral, o beijupirá é alvo de estudos extensivos, sobretudo no contexto da piscicultura marinha. Embora as discussões científicas sobre seu potencial na piscicultura sejam amplas globalmente, com ênfase em tecnologia de produção, a atenção às populações selvagens e aos estoques pesqueiros frequentemente é restrita a determinadas regiões. Apesar da presença de pescarias do beijupirá em vários países, há uma escassez de conhecimento científico em regiões onde a pesca ocorre. A ênfase e grande importância no potencial da piscicultura marinha para a espécie acarretou um menor interesse e carência de estudos da dinâmica de populações e relações com as variáveis ambientais oceanográficas no ambiente marinho, assim como as análises do estado de exploração da pesca comercial para a espécie. Mesmo com o grande potencial da espécie para cultivo e a abundância de publicações, nenhuma publicação foi encontrada sobre repovoamento do beijupirá, demonstrando um potencial inexplorado dessa prática.

O repovoamento do beijupirá na costa do Rio Grande do Norte apresentou impacto positivo no aumento na captura, conforme relatado pelos pescadores e pelo aumento da frequência de exemplares capturados após o repovoamento. O Conhecimento Ecológico Local (CEL) mostrou-se essencial para distinguir entre peixes repovoados e selvagens, destacando a importância da integração do CEL na ciência pesqueira. O estudo permitiu ainda identificar e descrever informações importantes relacionadas a estrutura de tamanhos e pesos, as relações da estrutura populacional da espécie com as variáveis oceanográficas, principalmente com a profundidade e geomorfologia do substrato, demonstrando preferências claras da espécie por substratos consolidados e deslocamentos para áreas mais distantes da costa e de maiores profundidades com o aumento de tamanhos e, consequentemente, idade. Exemplares repovoados apresentaram também maior ganho de peso em relação ao comprimento, em relação aos espécimes selvagens, demonstrando a vantagem de inserir na natureza exemplares com uma maior probabilidade de sobrevivência e desempenho de seu crescimento, para fins de melhoramento dos estoques pesqueiros.

Contudo, o estudo sugere que o repovoamento isolado não é suficiente para fortalecer os estoques do beijupirá em regiões onde a pesca artesanal com redes predomina, podendo ser impactado pelo volume de exemplares imaturos que essa arte de pesca explora. Mais estudos mostram-se necessários para compreender o uso do habitat do beijupirá, especialmente em relação à pesca, incorporando o CEL como ferramenta no estudo de pescarias artesanais. Apesar do potencial na piscicultura marinha e da presença global nas pescarias, projetos de repovoamento do beijupirá e de outras espécies marinhas são raros e em certos casos apresentam um grande potencial, com técnicas viáveis para recompor e manter a biomassa dos estoques dos recursos pesqueiros marinhos. Os resultados obtidos no presente estudo apresentam contribuições valiosas nas relações da dinâmica populacional do beijupirá, sua pescaria e o ambiente marinho, constituindo um referencial para futuros projetos de repovoamento na região nordeste do Brasil.

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