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PRÓ-REITORIA DE PESQUISA E PÓS-GRADUAÇÃO
PROGRAMA DE PÓS-GRADUAÇÃO EM RECURSOS PESQUEIROS E AQUICULTURA

UTILIZAÇÃO DE MODELOS PARA DADOS LIMITADOS NA AVALIAÇÃO DOS ESTOQUES DAS PRINCIPAIS ESPÉCIES DE LUTJANIDAE CAPTURADAS NO NORDESTE

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Tese apresentada ao Programa de Pós-Graduação em Recursos Pesqueiros e Aquicultura da Universidade Federal Rural de Pernambuco como exigência para obtenção do título de Doutor.

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Dedicatória

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Sumário

Resumo

As pescarias artesanais do Nordeste do Brasil caracterizam-se, em sua maioria, por limitações na disponibilidade e na qualidade de dados, o que dificulta a aplicação de métodos tradicionais de avaliação de estoques pesqueiros. Nesse contexto, os modelos para dados limitados (MDL) têm se mostrado alternativas promissoras para subsidiar o manejo, permitindo estimar o estado dos estoques mesmo sob cenários de escassez de informações. Esta tese teve como objetivo geral avaliar a utilidade de modelos para dados limitados, em especial o Stock Assessment Continuum (SAC) Tool, na estimativa do estado dos estoques das principais espécies de Lutjanidae exploradas no Nordeste do Brasil, além de gerar subsídios técnicos para o manejo pesqueiro. No Capítulo I, foi realizada uma avaliação metodológica do desempenho do SAC Tool por meio da reanálise do estoque de *Ocyurus chrysurus*, previamente avaliado no âmbito do programa REVIZEE com métodos tradicionais baseados em idade. Diferentes cenários foram testados, combinando dados de captura, composições de comprimento e informações de história de vida, incluindo configurações integradas e abordagens baseadas exclusivamente em comprimento. Os resultados mostraram que, apesar das diferenças na quantidade e no tipo de dados utilizados, todos os cenários convergiram para a mesma conclusão qualitativa: o estoque encontra-se sobreexplorado e submetido à sobrepesca. Os modelos integrados apresentaram maior precisão, enquanto os cenários baseados apenas em comprimento exibiram maior incerteza, como esperado, mas mantiveram a robustez do sinal de depleção do estoque. Esses resultados indicam que os MDL, quando adequadamente especificados, são capazes de reproduzir padrões consistentes com avaliações tradicionais, mesmo sob forte redução de dados. No Capítulo II, os modelos para dados limitados foram aplicados para atualizar a avaliação dos estoques de quatro espécies-chave de lutjanídeos no Nordeste do Brasil: *Lutjanus analis, Lutjanus jocu, Lutjanus synagris e Ocyurus chrysurus*. Foram utilizados dados históricos de captura, composições de comprimento, índices de abundância e parâmetros de história de vida para estimar o estado dos estoques em termos de biomassa relativa e mortalidade por pesca em relação aos pontos de referência biológicos. De modo geral, os resultados indicaram que a maioria dos estoques apresenta sinais de depleção e níveis de exploração acima do sustentável, reforçando a necessidade de medidas de manejo mais conservadoras e de ações voltadas à recuperação dos estoques. Em conjunto, os resultados desta tese demonstram que os MDL constituem ferramentas robustas e operacionalmente viáveis para a avaliação de estoques em contextos de escassez de informações, como os

observados nas pescarias artesanais do Nordeste do Brasil. Além de validarem a utilidade do SAC Tool, os resultados fornecem evidências de que essas abordagens podem gerar diagnósticos confiáveis sobre o estado dos estoques e apoiar a implementação de estratégias de manejo precaucionárias. Assim, os MDL se apresentam como componentes centrais de um sistema de gestão adaptativo, no qual a incorporação gradual de novos dados tende a aprimorar a precisão das avaliações e a sustentabilidade das pescarias.

Abstract

Small-scale fisheries in Northeast Brazil are largely characterized by limitations in data availability and quality, which restrict the application of traditional stock assessment methods. In this context, data-limited models (DLMs) have emerged as promising alternatives to support fisheries management, allowing the estimation of stock status even under severe data scarcity. The main objective of this thesis was to evaluate the usefulness of data-limited models, particularly the Stock Assessment Continuum (SAC) Tool, for estimating the status of the main Lutjanidae stocks exploited in Northeast Brazil, and to provide technical support for fisheries management. In Chapter I, a methodological evaluation of the performance of the SAC Tool was carried out through the reanalysis of the *Ocyurus chrysurus* stock, previously assessed under the REVIZEE program using traditional age-based approaches. Different scenarios were tested by combining catch data, length compositions, and life-history information, including integrated configurations and length-only approaches. The results showed that, despite differences in the quantity and type of data used, all scenarios converged to the same qualitative conclusion: the stock is overfished and subject to overfishing. Integrated models produced more precise estimates, whereas length-only scenarios displayed higher uncertainty, as expected, but consistently retained the robust signal of stock depletion. These findings indicate that, when properly specified, data-limited models are able to reproduce conclusions consistent with traditional assessments, even under substantial data reduction. In Chapter II, DLMs were applied to update the stock assessments of four key lutjanid species in Northeast Brazil: *Lutjanus analis, Lutjanus jocu, Lutjanus synagris*, and *Ocyurus chrysurus*. Historical catch data, length compositions, abundance indices, and life-history parameters were used to estimate stock status in terms of relative biomass and fishing mortality with respect to biological reference points. Overall, the results indicate that most stocks show clear signs of depletion and fishing pressure above sustainable levels, reinforcing the need for more conservative management measures and actions aimed at stock rebuilding. Taken together, the results of this thesis demonstrate that data-limited models represent robust and operationally feasible tools for stock assessment in data-poor contexts such as the small-scale fisheries of Northeast Brazil. In addition to validating the applicability of the SAC Tool, this study provides evidence that these methods can generate reliable diagnoses of stock status and effectively support precautionary management strategies. Therefore, data-limited models should be viewed as central components of an adaptive management framework, in which the progressive

incorporation of new data is expected to improve assessment accuracy and contribute to the long-term sustainability of fisheries.

Introdução geral

A humanidade vem consumindo recursos naturais de forma consistente ao longo da história. Entretanto, a Revolução Industrial representou um ponto de inflexão nesse processo: a população mundial saltou de pouco mais de 1 bilhão em 1800 para 6 bilhões em 2000 e ultrapassou 8 bilhões em 2021 (UN-DESA, 2022), intensificando de maneira sem precedentes a demanda por alimentos e matérias-primas. Como resultado direto desse crescimento, aliado aos avanços tecnológicos, observou-se a ampliação de alterações ambientais em escala global, incluindo a destruição de habitats e mudanças climáticas, frequentemente sem a consideração de limites de sustentabilidade.

Até o século XIX, a pesca era uma atividade relativamente pequena, restrita à extração limitada de organismos e associada a baixo impacto ambiental. As evoluções tecnológicas observadas no período pós-Segunda Guerra Mundial ampliaram significativamente o poder de captura em escala global e, particularmente, no Brasil (Paes, 2002). A partir da década de 1970, a produção pesqueira marinha passou a apresentar sinais de estabilização, enquanto os desembarques de espécies-chave, como sardinha e camarão, entraram em declínio (Pauly *et al.*, 2002). A extração acima da capacidade de reposição altera a estrutura populacional, reduz recrutamento e capacidade de regeneração dos estoques, podendo levar a colapsos locais (FAO, 1996; Casey e Myers, 1998; Dulvy *et al.*, 2004).

Espécies com crescimento lento, maturação tardia e distribuição restrita, como diversos representantes da família Lutjanidae, são particularmente vulneráveis à sobrepesca. A intensificação da exploração tende a: (i) reduzir o contingente de indivíduos adultos, refletida na diminuição do comprimento médio das capturas; e (ii) antecipar a captura para tamanhos menores, comprometendo o recrutamento e a reposição populacional (Sadovy, 2001; Paes, 2002; Dulvy *et al.*, 2004). Em escala global, a proporção de estoques biologicamente sustentáveis caiu de 90% para 65,8% entre 1974 e 2017 (FAO, 2020).

Apesar da crescente pressão sobre os recursos pesqueiros, a maioria das pescarias é classificada como limitadas em dados, tanto em termos de qualidade quanto de disponibilidade de informações, o que dificulta avaliações de estoques robustas. Diante da escassez de dados típica das pescarias artesanais do Nordeste, modelos para dados limitados (MDL) tornam-se ferramentas essenciais para fornecer diagnósticos minimamente robustos sobre o estado dos estoques. As seções seguintes descrevem: (1)

a evolução da pesca no Brasil, (2) o papel dos lutjanídeos e (3) a relevância dos modelos para dados limitados.

Exploração pesqueira no Brasil

Ao longo do último século, a atividade pesqueira no Brasil passou de uma prática predominantemente artesanal e de subsistência para um setor progressivamente industrualizado e diversificado, assumindo papel relevante na economia nacional. Esse processo de expansão esteve associado a desafios ecológicos, econômicos e sociais, refletindo mudanças tecnológicas, transformações no manejo dos recursos e novas demandas socioeconomicas.

Da pesca artesanal à industrialização (1900-1970)

Até meados do século XX, a pesca no Brasil era essencialmente artesanal, voltada ao consumo local (Prá e D'Agostini, 2023). A organização institucional do setor teve início com a promulgação do Estatuto da Confederação Geral dos Pescadores, em 1950. Ainda na década, o processo de industrialização do país impulsionou a modernização da frota pesqueira com a introdução de embarcações motorizadas, tecnologias de detecção sistemas de conservação, ampliando significativamente a capacidade de captura (Abdallah e Bacha, 1999; Santos *et al.*, 2012).

A criação da Superintendencia do Desenvolvimento da Pesca, em 1962, e o Decreto-Lei 221/1967, que instituiu subsídios fiscais e isenções de combustível, favoreceram a expansão da frota industrial e da capacidade produtiva. Esse período foi marcado por aumento expressivo do esforço pesqueiro e da exploração dos recursos marinhos, sem o desenvolvimento proporcional de mecanismos de monitoramento e controle (Neiva, 1990).

Estabilização e conflitos (1970-1990)

Na década de 1970, tornaram-se evidentes sinais de sobre-exploração com a estagnação da produção marinha e declínio de estoques tradicionais como a sardinha-verdadeira e o camarão. A ausência de delimitação clara de áreas de pesca e o monitoramento deficiente favoreceram práticas predatórias (Paez, 1993; Abdallah e Bacha, 1999). Nesse contexto, os conflitos entre a pesca industrial e artesanal se intensificaram, uma vez que frotas mais capitalizadas passaram a competir diretamente com comunidades costeiras dependentes dos recursos pesqueiros (Diegues, 1995).

Transição para a sustentabilidade (1990-2007)

Na década de 1990, a crescente percepção sobre os limites da exploração pesqueira levou à adoção de políticas voltadas para a sustentabilidade. O Brasil ratificou acordos internacionais, como o Código de Conduta para a Pesca Responsável da FAO (FAO, 1995), e passou a implementar instrumentos de gestão, incluindo períodos de defeso, cotas de captura e áreas protegidas. Entretanto, a efetividade dessas medidas foi limitada pela falta de dados confiáveis e contínuos. Programas de monitoramento, como o ESTATPESCA (IBAMA, 2008a), tiveram papel relevante, mas sua interrupção em 2007 resultou em uma lacuna crítica na gestão dos recursos.

Atualidade (2008-2024)

Nas últimas duas décadas, o setor pesqueiro brasileiro tem enfrentado desafios persistentes relacionados à sobrepesca, à degradação ambiental e às mudanças climáticas. As pescarias artesanais seguem como componente central da economia pesqueira, especialmente no Nordeste e na Amazônia, mas operam sob crescente pressão sobre os estoques (Viana, 2021a, 2021b). Nesse período, a ausência de monitoramento contínuo e de dados sistemáticos limitou a efetividade da gestão. Com o reestabelecimento do Ministério da Pesca e Aquicultura (MPA), houve a retomada da estatística pesqueira nacional, o que resultou na publicação do Boletim Estatístico da Pesca e Aquicultura 2023–2024, e na adoção de políoticas públicas voltadas ao setor, como o Plano Safra da Pesca e Aquicultura (MPA, 2022) e o Plano Nacional da Pesca Artesanal (MPA, 2024).

Lutjanídeos

Os lutjanídeos, comumente chamados de “vermelhos”, compõem parcela relevante das capturas demersais tropicais e possuem alto valor de mercado. Os lutjanídeos são espécies marinhas tropicais e subtropicais encontradas em diversas partes do mundo e possuem um alto valor socioeconômico comercial e recreativo (Grimes 1987, Duarte-Garcia 1999, Freitas et al 2011, Resende et al. 2003). São espécies que desempenham papel ecológico fundamental nos ecossistemas recifais, atuando como predadores de topo que regulam as populações de presas, incluindo peixes menores e invertebrados (Fernandes et al. 2020; Freitas et al. 2011; Monteiro et al. 2009; Moreno-Sanchez et al. 2016; Valle-Lopez et al. 2021). São agrupados com espécies ecologicamente semelhantes, como os meros, compondo o "snapper-grouper complex", caracterizados por baixas taxas de crescimento, maturação tardia e formação de agregações reprodutivas, fatores que aumentam sua vulnerabilidade à pesca intensiva (Chuenpagdee e Pauly, 2005; Schärer-Umpierre *et al.*, 2014; França *et al.*, 2021). Além de seu papel direto como controladores de biomassa, essas espécies participam de fluxos tróficos que conectam habitats costeiros e recifais, transportando energia e nutrientes entre diferentes compartimentos do ecossistema (Derviche et al., 2025). Alterações nas populações dessas espécies, seja por sobrepesca ou perda de habitat, podem gerar efeitos negativos em cascata, comprometendo a resiliência e a capacidade de recuperação dos recifes. Por isso, o manejo sustentável desses predadores é não apenas uma questão de conservação das espécies-alvo, mas também de manutenção das funções ecológicas essenciais dos recifes tropicais.

No Brasil, particularmente na Região Nordeste, os lutjanídeos são historicamente explorados e representam importante fonte de renda para comunidades de pesca artesanal, tanto pelo volume de desembarques quanto pelo elevado valor comercial (Resende, Ferreira e Frédou, 2003). Ao todo, doze espécies de lutjanideos são alvo de pescarias na região, com desembarques que aumentaram de aproximadamente 4.000 toneladas em 1990 para mais de 10.500 toneladas no ano de 2006, gerando receita bruta superior a 58 milhões de reais nesse ano (IBAMA, 2008b; Freire et al, 2021). No início dos anos 2000, o programa REVIZEE avaliou os principais estoques explorados na Zona Econômica Exclusiva (ZEE), incluindo os lutjanídeos do Nordeste, utilizando métodos tradicionais de avaliação baseados em idade, como análise de população virtual e modelos de rendimento por recruta. Essas avaliações indicaram, de forma consistente, estoques sobre-explorados ou próximos do limite máximo de exploração, sem que medidas efetivas de manejo fossem implementadas (Frédou, Ferreira e Letourneur, 2009a, 2009b; Lessa, Bezerra-Júnior e Nóbrega, 2009). A interrupção do programa nacional de estatística pesqueira em 2007 fragmentou as séries históricas de desembarque, especialmente para espécies recifais capturadas pela frota artesanal, agravando a limitação de dados disponível. Entre as espécies avaliadas pelo REVIZEE, quatro respondem pela maior parte dos desembarques regionais e constituem o foco deste estudo: *Lutjanus analis*, *L. jocu*, *L. synagris* e *Ocyurus chrysurus*.

Lutjanus analis

A cioba (*Lutjanus analis*) distribui-se pelo Atlântico Ocidental, do Caribe ao sudeste do Brasil, ocupando ambientes costeiros associados principalmente a recifes e fundos consolidados (Allen, 1985). Os indivíduos atingem comumente 40–50 cm, podendo alcançar cerca de 1 m, com maturidade sexual próxima de 36 cm e longevidade estimada em até 29 anos (Lessa, Bezerra-Júnior e Nóbrega, 2009). Os desembarques foram modestos nas décadas iniciais da série histórica, mas aumentaram progressivamente a partir dos anos 1990, atingindo o pico em 2005, com cerca de 3,3 mil toneladas. Após esse período, observa-se redução nas capturas em relação ao pico histórico, indicando mudança no padrão de desembarques da espécie.

Lutjanus jocu

O dentão (*Lutjanus jocu*) apresenta ampla distribuição no Atlântico Ocidental, ocupando principalmente ambientes recifais e fundos rochosos costeiros, enquanto juvenis ocorrem em áreas litorâneas e estuarinas. A espécie atinge frequentemente 35–45 cm, podendo ultrapassar 1 m, com maturidade próxima de 32 cm e longevidade estimada em até 29 anos (Allen, 1985; Lessa, Bezerra-Júnior e Nóbrega, 2009). Os desembarques aumentaram gradualmente a partir do final dos anos 1990, alcançando máximo em 2003, com cerca de 2,1 mil toneladas. A partir de 2004, observa-se redução nos desembarques em relação ao período de maior captura.

Lutjanus synagris

O ariocó (*Lutjanus synagris*) ocorre ao longo da costa tropical do Atlântico Ocidental, associado a recifes e fundos arenosos vegetados. Os indivíduos medem comumente entre 20 e 30 cm, podendo alcançar 65 cm, atingindo maturidade por volta de 18 cm e vivendo até cerca de 22 anos (Lessa, Nóbrega e Bezerra-Júnior, 2004; Freitas et al., 2011). Os desembarques apresentaram crescimento contínuo ao longo da série histórica, atingindo pico em 2008, com aproximadamente 2,7 mil toneladas, seguido por estabilização das capturas em níveis inferiores ao pico observado.

Ocyurus chrysurus

A guaiúba (*Ocyurus chrysurus*) distribui-se amplamente no Atlântico Ocidental, sendo comum em ambientes recifais costeiros. Os indivíduos apresentam comprimento médio entre 30 e 40 cm, podendo atingir até 90 cm, com maturidade sexual próxima de 20 cm e longevidade estimada em cerca de 19 anos (Lessa, Bezerra-Júnior e Nóbrega, 2009). Essa espécie apresentou os maiores volumes de desembarque entre os lutjanídeos avaliados, alcançando pico em 2004, com cerca de 7,5 mil toneladas. A partir de 2005 observa-se redução contínua nos desembarques em relação ao pico histórico registrado.

Modelos para dados limitados

De modo geral, o manejo pesqueiro busca conciliar a utilização dos recursos em benefício da sociedade com a mitigação dos impactos ambientais associados à atividade pesqueira (Sainsbury, Punt e Smith, 2000; Garcia *et al.*, 2003). Nesse sentido, a avaliação de estoques busca fornecer aos tomadores de decisão informações sobre o equilíbrio entre exploração e manutenção dos recursos ao longo do tempo (Sparre e Venema, 1998).

De forma simplificada, uma avaliação de estoques busca responder a três questões centrais: a escala do estoque, o estado em relação a pontos de referência e a sua produtividade. A escala se refere à quantificação absoluta do estoque, como biomassa total, biomassa desovante. O estado representa a condição atual do estoque em relação a referencias biológicas, por exemplo a razão entre a biomassa atual e a biomassa no rendimento máximo sustentável (B/B_{MSY}) ou a biomassa virgem (B/B_0). Já a produtividade envolve processos que determinam a capacidade de reposição populacional, incluindo parâmetros como a taxa intrínseca de crescimento (r), mortalidade natural (M) e *steepness* (*h*), que refletem a resiliência da espécie à exploração (Cope, 2024b). Entretanto, avaliações robustas dependem da disponibilidade de séries históricas confiáveis de abundancia, idade ou comprimento, informação ausente em grande parte das pescarias mundiais, especialmente em países em desenvolvimento (Dowling et al., 2019; Reis, 1992; Frédou, 2004). Diante desse cenário, modelos para dados limitados (MDLs) vêm sendo desenvolvidos para maximizar a informação disponível e permitir inferências mesmo sob elevada incerteza (Chrysafi e Kuparinen, 2015; Dowling *et al.*, 2019; Cope *et al.*, 2023; Cope, 2024b).

Entre essas abordagens, destacam-se os modelos baseados em comprimento, que utilizam composições de comprimento e parâmetros de história de vida para inferir níveis de exploração e estado do estoque. Métodos baseados em comprimento assumem que a mortalidade por pesca se reflete na estrutura de tamanhos e no comprimento médio das capturas (Pons, Cope e Kell, 2020). Sob essa perspectiva, esses modelos utilizam composições de comprimento para estimar a mortalidade e o estado dos estoques pesqueiros. Como a coleta de dados de comprimento é relativamente simples e de baixo custo, esse costuma ser o principal tipo de informação disponível e, em situações de limitação de dados, pode representar a única fonte de informação para avaliação (Hordyk et al., 2015a; Mildenberger, Taylor e Wolff, 2017). Os principais pressupostos assumidos pelos modelos baseados em comprimento incluem: (1) a representatividade das composições de comprimento amostradas, (2) o estoque se encontra em condição próxima ao equilíbrio, (3) que os parâmetros de história de vida são constantes e representativos da população avaliada e (4) os padrões de seletividade e maturidade podem ser descritos por curvas logísticas. Entre os métodos mais utilizados destacam-se o Length-based Bayesian Biomass (LBB; Froese et al., 2018), que permite estimar o estado do estoque a partir exclusivamente de composições de comprimento, e o Length-Based Spawning Potential Ratio (LBSPR, Hordyk et al., 2015a), amplamente empregado para inferir o potencial reprodutivo remanescente sob diferentes níveis de exploração.

Outra classe de modelos utiliza séries temporais de captura associadas a parâmetros biológicos para estimar níveis sustentáveis de exploração. Métodos baseados em captura permitem inferir produtividade, biomassa relativa e níveis sustentáveis de captura mesmo na ausência de dados independentes de abundância. Para esses modelos, os principais pressupostos são que as séries de captura sejam representativas da biomassa e que o esforço pesqueiro permaneça relativamente estável ao longo do tempo, de modo que variações nas capturas reflitam principalmente mudanças na biomassa do estoque, desconsiderando possíveis alterações na dinâmica e no comportamento da frota. Entre esses métodos, destaca-se o CMSY++ (Froese et al., 2021), amplamente aplicado em pescarias com séries históricas de captura limitadas (MPA, 2022; Chen, 2024; Cardoso et al, 2026).

Além dessas abordagens, modelos integrados combinam diferentes fontes de informação, como capturas, composições de comprimento e parâmetros biológicos dentro de uma estrutura analítica. Ao integrar diferentes fontes de dados e metodologias, modelos integrados tendem a aumentar a confiabilidade das estimativas, especialmente em contextos de alta variabilidade ou limitação de dados. Essa flexibilidade permite construir, dentro de uma mesma estrutura de modelagem, configurações que variam desde abordagens simplificadas até avaliações mais completas, reduzindo a lacuna entre métodos tradicionalmente considerados data-rich e contextos operacionais caracterizados por escassez de informação. Entre essas abordagens destaca-se o Stock Assessment Continuum Tool (Cope, 2024b), empregado neste estudo para integrar diferentes fontes de dados sob cenários de informação limitada.

Embora a gestão pesqueira busque otimizar o uso de recursos e mitigar impactos (Sainsbury, Punt e Smith, 2000), séries históricas completas são raras em pescarias artesanais (Cope et al. 2023). Neste contexto, os MDLs são alternativas pragmáticas aos métodos tradicionais. A maioria dos estoques pesqueiros no Nordeste do Brasil, incluindo os lutjanídeos, possuem dados limitados e, portanto, necessitam de métodos alternativos de avaliação. Além disso, existe a necessidade de atualização do estado dos estoques dessas espécies, que são espécies de grande importância ecológica e socioeconômica no Brasil. Dessa forma, esta tese busca avaliar a eficácia dos MDLs em relação aos métodos tradicionais, validando sua utilidade em pescarias demersais de pequena escala no Nordeste brasileiro e atualizando o estado dos estoques das principais espécies de lutjanídeos da região, fornecendo subsídios para o manejo sustentável e aplicação dessas abordagens a pescarias com características semelhantes.

Objetivos

Geral

Avaliar o desempenho e a robustez de modelos para dados limitados na estimativa do estado dos estoques das principais espécies de lutjanídeos exploradas no Nordeste do Brasil, visando subsidiar o manejo pesqueiro em contextos de escassez de dados.

Específicos

- Avaliar o desempenho de modelos para dados limitados sob diferentes níveis de disponibilidade de informação, comparando suas estimativas com avaliações históricas baseadas em métodos tradicionais, a fim de investigar a robustez dos diagnósticos de estado do estoque.
- Aplicar modelos adequados a dados limitados para estimar o estado atual dos estoques das quatro principais espécies de lutjanídeos exploradas no Nordeste do Brasil, analisando padrões de depleção, mortalidade por pesca e a incerteza associada às estimativas.

- Integrar os resultados metodológicos e aplicados para discutir implicações para o manejo de pescarias demersais tropicais, identificando potencialidades, limitações e diretrizes para adoção desses métodos em sistemas pesqueiros com dados escassos.

Capítulo I

Artigo: "Information content and stock status: comparing traditional and contemporary assessment approaches"

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INFORMATION CONTENT AND STOCK STATUS: COMPARING TRADITIONAL AND CONTEMPORARY ASSESSMENT APPROACHES

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Abstract

Data-limited methods are increasingly used in tropical fisheries where traditional stock assessments are often unfeasible. Here, we evaluate the performance of the Stock Assessment Continuum (SAC) Tool by reassessing the early-2000s evaluation of *Ocyurus chrysurus* carried out under the REVIZEE program. Six scenarios incorporating different combinations of catch and length compositions were compared to the original age-structured Virtual Population Analysis, which served as a benchmark for validation. Across all scenarios evaluated, the SAC Tool indicated that the stock was overfished and experiencing overfishing, with this signal remaining robust despite differences in data availability and model assumptions. Model performance varied with data availability: integrated scenarios produced more precise estimates, whereas length-only approaches exhibited wider uncertainty but retained the same qualitative signal of depletion. These results show that key stock status signals remain robust across modern data-limited approaches, despite major reductions in data inputs and alternative model assumptions, supporting their application in small-scale demersal fisheries. Continued improvement of data collection and refinement of model assumptions will further strengthen the reliability of these approaches.

Keywords: Data-limited stock assessment, length-based methods, integrated models

Introduction

As with all human activities, fishing has an impact on the environment, whether through pollution, habitat disturbance, or intense fishing pressure, which can result in stock depletion. Globally, several fish species of high socio-economic importance have been classified as overfished, with the proportion of assessed fish stocks considered biologically sustainable declining from 90% to 65.8% between 1974 and 2017, while the proportion exceeding sustainability thresholds increased from 10% to 34.2% over the same period (FAO, 2020). However, these global estimates are derived primarily from stocks with formal assessments, whereas a substantial proportion of fisheries worldwide lack sufficient data to support routine stock status evaluation. Indeed, most fisheries are classified as data-limited, indicating that there is a major issue concerning data availability or quality (FAO et al., 2023). This gap highlights the need for assessment approaches suitable for data-limited fisheries.

In the past, assessments of data-limited fish stocks were constrained by the limitations of the data available and were unable to provide reference points such as maximum sustainable yield, total allowable catch, or maximum effort at the sustainable yield (Geromont and Butterworth, 2015; Sagarese et al., 2019). Recently, data-limited models were developed as a subset of stock assessment modelling approaches that attempt to maximize the use of the available data despite its limitations (Chrysafi and Kuparinen, 2015; Cope et al., 2023; Cope, 2024a; Dowling et al., 2019). For instance, when abundance indices and age-composition data are unavailable but length compositions and catch data are available, data-limited methods may provide a more suitable option (Rudd et al. 2021). These models usually have several strong assumptions about the fisheries and the life history or condition of the stocks so the assessment can be performed with limited data. For instance, most catch-based models rely primarily on a time series of removals and assumptions about relative stock depletion, with limited or no explicit incorporation of life-history processes such as growth, mortality, or recruitment. Rather than reducing reliance on assumptions, several catch-based methods have been developed to formalize these assumptions explicitly within a statistical framework. Examples include DB-SRA (Dick and MacCall, 2011) and CMSY++ (Froese et al., 2023, 2021; Martell and Froese, 2013), which rely primarily on time series of removals combined with prior information on stock productivity and relative depletion. When removal data are inadequate or unavailable, methods based on length compositions may prove more appropriate, resulting in an estimate of relative spawning potential or stock status and/or the fishing mortality that led to those values. In general, structured length-based models assume that selectivity and fishing mortality derive the length composition. Examples of length-based methods include the Length-Based Spawning Potential Ratio (LBSPR; Hordyk et al., 2015c, 2015b), which is designed to estimate the remaining spawning potential of a stock following fishing activity, and the Length-based Bayesian Biomass estimator (LBB; Froese et al., 2018), which can operate using only length composition data but internally relies on assumed or informed life-history to assess stock status. Additionally, there are integrated models that can function as catch-only or length-only, as well as integrating these data. For instance, the Stock Assessment Continuum (SAC) Tool (Cope, 2024a, 2024b) was developed to address data-limited scenarios using the age-structure framework of Stock Synthesis (SS3; Cope, 2013; Methot and Wetzel, 2013). As integrated models are more flexible regarding the types of data available, a variety of data-limited methods can be built within the same modelling framework (Cope, 2024a). The SAC Tool represents an advancement over traditional fish stock assessment methods, such as the Thompson and Bell model for example, by providing a more comprehensive approach to data-limited assessments. While the Thompson and Bell model relies on static equilibrium assumptions and primarily focuses on yield-per-recruit calculations, the SAC Tool incorporates dynamic population processes within an age-structured framework. This allows for a more realistic representation of stock dynamics, including recruitment, variability and time-varying fishing pressure. Additionally, the SAC Tool's ability to integrate diverse data types within a single framework enhances its applicability across a broader range of fisheries scenarios, improving assessment robustness and management decisions.

In Brazil, especially on the northeast coast, most fisheries are considered data-limited as they are mostly characterized by its artisanal and small-scale features (IBAMA, 2007). Small-scale fishing fleets from the Northeast Brazil are mainly composed of small/medium size, which can vary from subsistence to commercial fishing, and can present a high diversity of fishing gears and exploited species (ICMBio, 2021). In the 1990s, the Brazilian government funded the REVIZEE project to explore the potential biological resources of the country’s Exclusive Economic Zone (Lessa et al., 2009). In the scope of the REVIZEE project several studies were performed, including stock assessment for a variety of fish species (Lessa et al., 2009; MMA, 2006). Currently, data on these stocks, especially associated with small-scale and artisanal fisheries, are limited due to interruptions in national data collection programs over recent decades and the discontinuation of the Brazilian national fisheries monitoring system. As a result, many stocks are considered data-limited, motivating the development of alternative sources of information such as reconstructions of catch time series, which have become a crucial input for stock assessment in data-limited contexts (Freire et al. 2021).

Here, a methodological case study is presented in which a stock previously assessed under the REVIZEE project is used as benchmark to evaluate the behavior of a data-limited assessment framework. Using the same dataset, alternative stock assessment configurations using different data types within the same modelling framework were applied to examine how outputs respond to reduced information and different model assumptions. The *Ocyurus chrysurus* stock was selected as a case of study due to its socioeconomic importance and because it has been the subject of robust assessment conducted during the REVIZEE project. From this perspective, this study proposes an evaluation of the performance of an integrated assessment framework under data-limited conditions to assess stocks of demersal fish species from the northeastern coast of Brazil.

Methods

Data collection

The stock area corresponds to the Northeast Brazil Marine Ecoregion, as defined by Spalding et al. (2007) that was also used in the original REVIZEE assessment (Figure 1). Historical landings of *Ocyurus chrysurus* were compiled from two primary sources: (1) the comprehensive reconstruction of commercial landings from 1950–2015 for artisanal and industrial fleets by Freire et al. (2021), and (2) the Sea Around Us catch database (https://www.seaaroundus.org/). Both datasets were filtered to include only landings within the Northeast Brazil Marine Ecoregion (ME; Spalding et al., 2007). To match the temporal scope of the original REVIZEE assessment, the landings time series used here was restricted to 1950–2000 (Figure 2). Length composition data originated from the REVIZEE Program (MMA, 2006; Lessa et al., 2009). Samples were collected between 1996 and 2000 from industrial longline fleets operating off Northeast Brazil, responsible for over 95% of landings for *O. chrysurus* during the period (IBAMA, 2008). Monthly length samples were obtained from landing points within the stock area (Figure 3). These data represent the primary source of empirical information used in the SAC Tool assessment. Life-history parameters matched those used in the original assessment (Frédou et al., 2009a) and are summarized in Table 1. These parameters describe key biological processes, including growth, natural mortality, maturation, and reproduction, and are used to parametrize the population model within the SAC Tool. Due to the lack of quantitative fecundity information, individual egg production is assumed proportion to weight, thus the weight-fecundity parameters were assumed equal to the weight–length relationship.

Base model assessment

The benchmark for comparison was the original O. chrysurus assessment conducted in the early 2000s under the REVIZEE Project (Lessa et al., 2009). This assessment applied the Thompson & Bell yield-per-recruit framework (Thompson and Bell, 1934) in combination with an age-based Virtual Population Analysis (Gulland, 1965), using catch-at-age data, natural mortality estimated from the Ault et al. (1998) survivorship model, and life-history parameters consistent with an unexploited equilibrium assumption. Reference points derived from the analysis were F0.1, Emax, and Ecurrent, the latter exceeding the conservative exploitation threshold (E > 0.5), indicating overexploitation. This original assessment was treated as the base case, and its published results were used directly as a base-case benchmark for the SAC Tool scenarios.

SAC Tool framework

All data-limited scenarios were fitted using the Stock Assessment Continuum Tool (Cope 2024a,b), which operates within the age-structured Stock Synthesis (SS3) modelling framework (Methot and Wetzel, 2013). Required biological and fishery inputs included: natural mortality (M), von Bertalanffy growth parameters (L_∞, K, t_0), maturity and selectivity ogives, weight–length parameters, Beverton-Holt stock-recruit parameters (steepness $h = 0.7$; $\ln R_0$ estimated by the model), landings (when applicable), and length compositions. Initial selectivity parameters were derived from a catch-curve analysis (TropFishR; Mildenberger et al., 2017) and subsequently estimated by the model. Reference points were stock spawning biomass at maximum sustainable yield (SSB_{msy}) and fishing mortality at MSY (F_{msy}). The overall workflow of the SAC Tool, including data inputs, model structure, and outputs, is summarized in Figure 4.

Model benchmarking strategy

Before applying data-limited methods to new fisheries, model performance is often evaluated through simulation testing (e.g., pseudo-data fits; Chong et al., 2020; Pons et al., 2020; Punt et al., 2016; Wetzel & Punt, 2015) or by re-fitting alternative models to data from a well-established assessment (Rudd et al. 2021). Here, we adopted the latter approach: the data from the REVIZEE assessment were re-analyzed under six data-limited configurations to evaluate whether the SAC Tool could reproduce the qualitative and quantitative outcomes of the traditional, data-rich assessment. This benchmarking approach enables validation of model behavior under realistic data conditions.

Scenario design

The scenarios were designed to represent realistic assessment configurations commonly encountered in data-limited fisheries. Rather than exploring arbitrary model variants, the selected scenarios reflect standard uses of the SAC Tool, allowing evaluation on how assessment outputs respond to progressively reduced information. Each scenario corresponds to a plausible combination of data availability and modeling assumptions routinely applied when landing histories, recruitment information, or complete length time series are unavailable.

1. SC1 – Integrated (catch + lengths): Includes landings (1950–2000), length compositions (1996–2000), life-history parameters, and freely estimated annual recruitment.
2. SC2 – Integrated without recruitment estimation: Same as SC1, but recruitment deviations constrained to zero, assuming a deterministic stock-recruit relationship.
3. SC3 – Integrated with truncated length data: Only the final three years of length compositions included; landings and recruitment estimation retained.
4. SC4 – Length-only (constant catch formulation): Landings excluded; lengths drive estimation of an average F over time based on an internally generated constant-catch assumption.
5. SC5 – Length-only without recruitment estimation: Same as SC4 but without recruitment deviations.
6. SC6 – Length-only (direct F estimation): Landings excluded; F estimated directly from length compositions and M, analogous to the Length-based Integrated Mixed Effects (LIME) approach of Rudd & Thorson (2018).

All scenarios used identical life-history inputs to isolate the influence of data availability on model behavior.

Performance metrics

Performance was evaluated by analyzing consistency in the assessment outputs across scenarios. Only a limited set of metrics can be meaningfully compared due to fundamental differences between the Thompson & Bell framework and the SAC Tool. Fishing mortality (F) was therefore selected as the primary quantitative metric, as is estimated in both approaches. Stock status was compared qualitatively using relative biomass indicators. Although depletion metrics such as SSB/SSB_{msy} can, in principle, be derived under both frameworks, the historical Thompson & Bell assessment did not report SSB_{msy} explicitly, and stable SSB_{msy} estimates were not available across all data-limited SAC Tool scenarios. As a result, direct numerical comparisons of biomass-based status metrics were not possible. Instead, SAC Tool outputs were interpreted using its internal limit reference point (0.25 x SSB_0) as a screening threshold for qualitative stock status classification.

Results

Variability among scenarios was evaluated descriptively based on the magnitude and spread of model outputs. Across all configurations, scenarios converged qualitatively to the same stock-status conclusion. As expected for data-limited assessments, reductions in available information were associated with wider uncertainty intervals, whereas scenarios incorporating more data exhibited narrower confidence intervals, indicating greater apparent precision. The reference scenario presented a total initial biomass (B_0) of 11,944 T, an F of 0.274, relative fishing mortality of 4.98, indicating fishing pressure was far above the sustainable limit, and the exploitation rate of 0.617 indicated the stock was overexploited (Frédou et al., 2009a; Lessa et al., 2009).

Across all scenarios, results consistently indicated an overfished stock and highlighted elevated fishing mortality (Table 2). The SAC Tool also reproduced the main features of the observed length compositions, with differences in fit reflecting expected reductions in information content among length-only configurations (Figure 5).

Integrated model scenarios

The three first scenarios were set as integrated models, as it considered landings and length compositions as inputs. In these cases, scale and status of the stock were estimable as the models have the minimum data required to do so.

Scenario 1 estimated total spawning biomass (B_0) of 18,032 tons, with the current spawning biomass (SSB) at only around 13% of B_0 (Figure 6a) well below the SAC Tool internal limit reference point (0.25 x SSB_0). In addition to the biomass being well below desired levels, the exploitation ratio F/F_{msy} of 2.52 shows that contemporary fishing mortality ($F = 0.35$) had been considerably higher than the level associated with MSY (Figure 7a). Overall, SC1 depicts a stock still well below historical productivity and likely experiencing continued overexploitation.

Scenario 2 reported B_0 of 18,767 tons and gave the most relatively optimistic outcome among the integrated models, with SSB representing 22% of B_0 (Figure 6b). Fishing mortality remains above optimal levels ($F = 0.22$; $F/F_{msy} = 1.60$), but much lower than in SC1 and SC3 (Figure 7b). The absence of recruitment estimates in SC2 resulted in slightly lower apparent fishing pressure and higher relative biomass, as the model compensated for constant recruitment by increasing the estimated population scale ($\ln R_0$), thus accommodating the same landings time series with a lower estimated F, highlighting the role of recruitment dynamics in perceived stock depletion in integrated models.

The third scenario presented B_0 of 18,022 tons and showed a more depleted condition, with SSB at 12% of B_0 and only 48% of SSB_{msy} (Figure 6c). These values suggest that current biomass is substantially below both historical and MSY-based reference points. Fishing pressure remains high ($F = 0.36$; $F/F_{msy} = 3.32$), consistent with ongoing overfishing (Figure 7c). Although limiting the length data to the last three years, SC3 still detects high exploitation and low relative biomass, showing that recent length information can capture the current overfished state when recruitment estimates are included.

All integrated scenarios (SC1–SC3) produced relative biomass estimates ($SSB/SSB_0 = 0.12 – 0.22$) that consistently indicated an overexploited stock, in agreement with the status inferred from the base assessment. Although the point estimates differed slightly, all values remained well below unfished levels, confirming substantial depletion. Fishing mortality estimates were also consistent across integrated scenarios (1.6 – 2.58 x F_{msy}), indicating that exploitation remains above the maximum sustainable level. When compared to the base model $F_{current} = 0.274$, the integrated scenarios suggest similar or higher fishing pressure, with SC2 producing the lowest estimate, possibly due to the removal of recruitment effects. Overall, the integrated models behaved coherently with the base assessment, reinforcing that the stock remains overexploited.

Length-only scenarios

The last three scenarios were composed of length-only models, where the time series of landings were removed from the analysis. In these scenarios stock scale is not estimated, only stock status and fishing pressure.

Using a length-only, constant-catch approach, SC4 presented $F = 0.51$ (Figure 7d) and $SSB/SSB_0 = 0.15$ (Figure 6d). This scenario tends to overestimate fishing mortality compared to integrated models, reflecting the model's emphasis on fitting length composition patterns under the assumption of relatively constant catch.

Excluding recruitment in SC5 led to $F = 0.39$ (Figure 7e) and $SSB/SSB_0 = 0.21$ (Figure 6e). Relative to SC4, this reduces the apparent fishing pressure and increases relative biomass, mirroring the effect of recruitment removal observed in integrated models. This reflects the same pattern observed in the integrated scenarios, where removing recruitment variability leads to higher biomass estimates and lower apparent fishing pressure.

SC6, which estimates F directly from length data, presented $F = 0.43$ (Figure 7f) and $SSB/SSB_0 = 0.17$ (Figure 6f). While the point estimate of F is closer to integrated model values, the uncertainty around it is extremely large. This indicates that length-only estimate-F approaches may produce plausible point estimates but large uncertainty intervals, highlighting the sensitivity of these models to data limitations and assumptions, though realistic in the expectations that less data should generally lead to more uncertainty.

Despite differences in magnitude and precision, all length-only scenarios consistently indicated overexploitation ($SSB/SSB_0 < 0.25$) and fishing mortality above MSY levels ($F/F_{msy} > 1$). However, their uncertainty patterns varied notably: SC4 produced the highest F and lowest biomass, SC5 moderated these values when recruitment was fixed, and SC6 presented plausible point estimates but large uncertainty intervals driven by parametrization.

Scenario Synthesis

The ensemble of model scenarios and the historical base assessment converge on a single management-relevant conclusion: *Ocyurus chrysurus* in the study area is currently overfished and subject to overfishing (Figure 8). Integrated assessments (SC1 – SC3) produced F medians of 0.22 - 0.36 (F/F_{msy} = 1.6 - 2.6) with SSB/SSB_0 = 0.12 - 0.22. Length-only approaches (SC4 – SC6) were more sensitive to modeling assumptions, SC4 returned the highest F (0.51; F/F_{msy} = 3.8), SC5 decreased F when recruitment was removed, and SC6 yielded a point estimate comparable to integrated models but produced unrealistic uncertainty that precludes confident management inference from its intervals. These patterns are consistent with the conclusions of the original Thompson-Bell assessment conducted under the REVIZEE Project, which indicated exploitation rates above sustainable levels. Despite methodological and reference points differences between models, both indicated that exploitation was exceeding sustainable levels and rebuilding measures were required.

Discussion

It is expected that assessment methods will respond differently to reductions in data availability, leading to contrasts in uncertainty and inferred stock status. In general, when fewer data are available, uncertainty increases, a desirable property for data-limited approaches (Cope, 2024a). The comparative performance of the models revealed clear contrasts in biomass and fishing mortality estimates, offering insight into the suitability of different assessment frameworks for demersal fisheries in Northeast Brazil. The assessment conducted for *O. chrysurus* in the early 2000s, one of the first for this and other lutjanids (Frédou et al., 2009a; MMA, 2006), benefited from relatively rich datasets, including age- and length-composition information and life-history parameters. This assessment served as the base model and benchmark for evaluating all other scenarios. Although some differences across scenarios are expected due to varying data inputs, qualitative consistency among outputs is generally anticipated.

Assessing performance

The comparative assessment across the six data-limited scenarios and the base model revealed consistent signals of stock depletion for *O. chrysurus*, despite differences in data richness, modelling assumptions, and analytical frameworks. Several scenarios excluded landing data, others constrained recruitment variability, and the relative weighting of biological or fishery information. Nevertheless, all scenarios consistently classified the stock as overfished, mirroring the results of the early 2000's assessment. Although these approaches rely on fundamentally different modelling philosophy, the convergence of outcomes suggest that the available data, even when simplified, can carry a strong and non-conflicting signal of unsustainable exploitation. This consistency across methods may indicate that the overexploited status is robust to violations of some biological assumptions and to alternative ways of weighting data sources within the assessment.

The scenarios were categorized into two main groups: the integrated models (SC1 – SC3) and length-only models (SC4 – SC6). Integrated scenarios, which incorporated landings, lengths, and life-history parameters, produced the most coherent and stable estimates of F relative to the base case. These models rely on removals to approximate stock scale and use lengths to inform relative stock status and selectivity, leading to more balanced trade-offs between information richness and model assumptions (Cope 2024a; Rudd et al. 2021). Among these, SC2 produced the most precise stock-status estimates, driven by the effect of constraining recruitment deviations. When recruitment is deterministic, variability in length structure cannot be transmitted into biomass dynamics, reducing uncertainty intervals and biased relative biomass estimates (Rudd and Thorson, 2018, Thorson et al, 2019). This pattern matches expectations: constraining recruitment variability increases statistical precision but may underrepresent the true uncertainty associated with stock dynamics, particularly for a moderately long-lived tropical demersal species, such as *O. chrysurus*. Length-only scenarios provide estimates with larger variance, as expected and desirable for models relying solely on size composition data. Without historical landings, these models cannot resolve absolute scale and instead interpret size information through assumptions about mortality, growth, and selectivity. Uncertainty increased substantially in scenarios where F is estimated directly from length data, a byproduct of using asymptotic variability; Bayesian variance estimation could get around this issue (Punt and Hilborn, 1997).

Nonetheless, all length-only scenarios identified the stock as depleted relative to sustainable levels, matching the F estimates of those reported in the historical base assessment. Direct quantitative comparison between the historical Thompson-Bell assessment and the SAC Tool outputs is inherently limited by the distinct conceptual frameworks of each approach. The earlier assessment relied on yield-per-recruit and exploitation-per-recruit reference points (e.g., $F_{0.1}$, E_{max}, $E_{current}$), whereas the SAC Tool produces MSY-based estimates, such as F_{MSY} and relative spawning biomass. Because these metrics are not directly compatible, fishing mortality (F) represents the only parameter that can be meaningfully compared across frameworks. Even so, F alone does not fully define stock status, which ultimately depends on the resulting spawning stock biomass and recruitment dynamics. The close alignment of F estimates, despite differences in data richness, model structure, and uncertainty, demonstrates that the SAC Tool and the historical Thompson-Bell assessment can infer terminal-year fishing pressure from population structure interpreted through species-specific life-history constraints, supporting the argument that data-limited frameworks, when properly specified, can produce management-relevant indicators that agree with established assessments even in data-poor contexts.

Overall, despite differences in model structure and precision, every scenario agreed with the base scenario on the fundamental stock-status classification: *O. chrysurus* is overfished and undergoing overfishing. This consistency across disparate modelling approaches strengthens confidence in the qualitative conclusion, even when quantitative outputs differ or carry substantial uncertainty. The more flexible modelling framework of SS3 allows more options for future data inclusion and model specification.

Recruitment estimates in the SAC Tool and implications

Recruitment estimation in the SAC Tool is grounded in the Stock Synthesis framework, which uses deviations from the Beverton and Holt stock-recruit relationship (Cope 2013; Methot and Wetzel, 2013). In data-limited configurations, recruitment deviations are informed indirectly through the interaction of length composition, growth, natural mortality, and selectivity patterns (Cope 2024a). Lengths act as proxies for age structure, enabling the model to infer periods of stronger or weaker recruitment based on shifts in size frequency, though with substantial sensitivity to the assumed or estimated selectivity curve (Rudd and Thorson, 2018). This approach provides a valuable advantage: it avoids imposing the strict assumption of constant recruitment, which often underlies simpler length-based methods, such as LBSPR (Hordyk et al. 2015a). By allowing empirical deviations, the SAC Tool incorporates biologically plausible variability and can better resolve the separation between fishing mortality and recruitment dynamics, two processes that otherwise become confounded in purely length-based perspectives (Cope, 2024a). However, this flexibility comes with trade-offs. When recruitment is allowed to vary (e.g. SC1 and SC3), uncertainty naturally increases, and this effect persists even in data-rich scenarios. Patterns in length data are not always strong enough to uniquely identify recruitment pulses, particularly in tropical multispecies fisheries where selectivity is broad and growth rates are rapid (Chong et al., 2020). This uncertainty should not be interpreted as a flaw but rather as a desirable reflection of data-limited assessments, preventing the artificial precision that emerges when structural variability is suppressed (Cope 2024a; Rudd et al. 2021). Conversely, when recruitment is fixed (e.g. SC2 and SC5), the model produces narrower confidence intervals and smoother biomass trajectories but at the cost of biological realism. These scenarios tend to overestimate relative biomass and underestimate fishing mortality because they cannot attribute observed size-structure compression to poor recruitment. In practical stock-assessment contexts, this reinforces the need for caution when disabling recruitment estimation: it may stabilize outputs but risks bias toward optimistic status classifications.

"Constant-catch" vs "F-estimate" in length-only models

The two length-only configurations in the SAC Tool, constant catch (SC4, SC5) and direct F estimation (SC6) represent distinct conceptual approaches to interpreting size compositions in the absence of removals. The "constant catch" approach uses an assumed or approximate average catch to anchor the scale of fishing pressure. In this formulation, F is derived similarly to LBSPR and related length-based mortality estimators (Hordyk et al. 2015c; Cope 2024a): the model fits a catch-curve like mortality signal to the observed size distribution, with the assumed catch level constraining the scale of depletion. When there are multiple years of length compositions, it fits them as a proper time series without the need to assume an equilibrium fishing mortality. This method generally produces more stable estimates because fishing mortality is translated through the assumed constant catch (Cope, 2024a). Thus, uncertainty is typically lower than in direct F-estimation models. By contrast, the F-estimate approach (SC6) attempts to infer fishing mortality directly from length data and natural mortality alone, closely resembling the conceptual logic of LIME (Rudd & Thorson 2018). Without any catch information, the model must rely exclusively on the changes in length-frequency assuming a constant, but estimated, selectivity, and the assumed growth parameters. This results in far greater uncertainty and instability, especially when length samples are sparse in some years or recruitment variability is high (Hordyk et al, 2015b; Rudd and Thorson, 2018). The wide and occasionally unrealistic confidence intervals in SC6 are consistent with expectations for models that attempt to solve simultaneously for selectivity, recruitment, and fishing mortality from a single dataset with limited samples.

From a methodological perspective, the constant catch formulation stabilizes fishing mortality estimation by imposing an artificial, fixed catch to guide the model, reducing confounding between F, recruitment, and selectivity, but assumes a fixed catch history. This approach generally produces more precise estimates and narrower confidence intervals, but its reliance on an assumed constant catch means that absolute F values may be biased if the true fishing pattern differs from the assumption, and temporal variability in fishing effort cannot be captured. In contrast, the direct F-estimation formulation infers fishing mortality solely from length data and natural mortality, without assuming any catch. While this allows the model to operate in a real context of "length-only", it results in far greater uncertainty, and higher sensitivity to sparse length data, recruitment variability, and mis-specified selectivity. Both approaches are reliable within their respective contexts, and the SAC Tool's flexibility allows analysts to select the formulation most suitable for the available data while acknowledging the inherent trade-offs (i.e., each method has its pros and cons).

Management implications

The consistent conclusion across all SAC Tool scenarios that *O. chrysurus* is overfished and undergoing overfishing closely matches the base scenario, which represents the original assessment from the early 2000s and serves as the reference model. Importantly, this alignment occurs despite the testing of different assumptions that were implicit in the earlier Thompson–Bell and VPA framework. Scenarios assuming constant recruitment, variable recruitment, or constant catch represent alternative representations of population dynamics and data availability that were not explored in the historical assessment. Even under these simplified configurations, all scenarios detected depletion, indicating that the signal of overexploitation is robust to different structural assumptions about population dynamics and data inputs. This demonstrates that contemporary data-limited methods not only reproduce key outcomes of a historically data-rich assessment but also provide a flexible framework to explicitly evaluate how these assumptions influence the inference of stock status. For multispecies demersal fisheries in Northeast Brazil, where historical landing series are incomplete and monitoring programs remain resource-limited (Frédou et al 2017; Silva et al 2021; Silva et al 2025), length-based and integrated data-limited approaches provide feasible and informative alternatives. Length samples are generally cheaper to collect, less susceptible to systemic reporting biases, and more easily validated than catch statistics (Thorson et al. 2019), making them practical first-line tools for routine monitoring in small-scale fisheries where institutional capacity is constrained (Chong et al. 2020; Medeiros-Leal et al. 2023). Nonetheless, data-limited assessments should be interpreted as components of an adaptive management system rather than definitive endpoints. As emphasized by Dowling et al. (2019, 2023), indiscriminate or uncritical application of data-limited methods can lead to misinterpretation. Transparent communication of uncertainty, continued data collection, and progressive integration of new information are therefore essential. Within this context, the SAC Tool's flexible age-structured framework allows assessments to evolve as additional data become available, progressively strengthening inference and improving comparability with data-rich benchmarks such as the original assessment, while also clarifying how different data inputs influence model outputs and whether conflicting signals are present (Cope, 2024a).

Taken together, these findings indicate that data-limited assessments may reliably replicate qualitative stock status trends observed in historical, data-rich assessments, and executed within a common framework. The consistent pattern of overfishing across all model scenarios, and their agreement with the base scenario underscores the usefulness of these methods and supports their application in contemporary management. This demonstrates that data-limited approaches are not only practical but also are also of defensible consideration for informing precautionary management, including effort reductions, harvest controls, and spatial protections, in tropical demersal fisheries where comprehensive historical data are lacking, while providing a framework that can be added to in the future as more data and life history information becomes available.

Conclusion

This study reassessed the early-2000s stock evaluation of *Ocyurus chrysurus* using contemporary data-limited approaches implemented through the SAC Tool. By benchmarking six alternative scenarios against the original data-rich assessment, we demonstrated that modern data-limited methods can consistently reproduce the same qualitative conclusion: the stock is overfished and experiencing overfishing. This alignment is notable given the substantial reduction in data inputs relative to the original assessment, and it provides strong evidence that simplified, length-based and integrated data-limited approaches are scientifically defensible for tropical demersal fisheries. The integrated scenarios, even under limited data availability, produced estimates of fishing mortality and stock depletion that closely matched the base scenario. Length-only scenarios also converged on the same qualitative stock status, despite exhibiting greater uncertainty. Collectively, these results validate the use of SAC Tool configurations across a wide data-availability gradient and highlight their utility for fisheries where long-term monitoring is incomplete or inconsistent. The successful replication of the original assessment's conclusions underscores the robustness of both the historical evaluation and the contemporary methods used here. As Brazilian fisheries face persistent gaps in data collection, these findings demonstrate that credible management advice can be generated without the extensive datasets historically required. Data-limited approaches should be viewed as an entry point into an adaptive management framework, with assessments gaining precision as new data, such as improved catch reporting, length samples, age structures, or abundance indices, are incorporated into the modeling framework. Overall, this reassessment shows that data-limited methods, when applied carefully and transparently, can play a central role in the sustainable management of tropical demersal resources. Their demonstrated ability to replicate the key conclusions of a traditional data-rich assessment provides a solid foundation for their broader adoption in Brazilian fisheries science and management.

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Tables

Table 1: Input parameters and their treatments in the Stock Synthesis – DL reference model for the mutton snapper *Lutjanus analis* from the Northeast Brazil. Sources: 1 – Lessa, Bezerra Júnior and Nóbrega 2004; 2 – Araújo, Martins and Costa 2002.

Parameter	**Estimates**	**Treatment**	**Source**
Mean age at 50% maturity A_{50}	2.60	Fixed	1
VBGF Asymptotic length L_{∞}	56.71	Fixed	2
VBGF growth coefficient ${k_{yr}}^{-1}$	0.130	Fixed	2
VBGF Age at length 0 t_0	-0.773	Fixed	2
Mean length at 50% maturity L_{50}	20.15	Fixed	1
Mean length at 95% maturity L_{95}	26.03	Fixed	1
Natural Mortality M	0.17	Fixed	1
WL relationship - α	0.035	Fixed	1
WL relationship - β	2.74	Fixed	1
Weigh - based fecundity coefficient	0.035	Fixed	-
Weigh - based fecundity exponent	2.74	Fixed	-
Steepness *h*	0.70	Fixed	-

Table 2: Summarized results of the Stock Assessment Continuum Tool analysis for six assessment scenarios of Ocyurus chrysurus from Northeast Brazil. Scenarios represent different levels of data availability and modeling assumptions, ranging from integrated catch–length configurations to length-only approaches. The historical Thompson-Bell assessment (REVIZEE) is included as a benchmark for fishing mortality. Biomass-based depletion metrics are not available for the base model

Scenario	**Initial biomass (B_0)**	**Relative biomass (SSB/SSB_0)**	**Fishing mortality (F)**	**Relative F (F/F_{msy})**	**Stock status**
Base model (REVIZEE)	-	-	0.274	-	Overexploited
Scenario 1	18,032 tons	0.127	0.347	2.53	Overexploited
Scenario 2	18,767 tons	0.220	0.220	1.58	Overexploited
Scenario 3	18,022 tons	0.119	0.360	3.32	Overexploited
Scenario 4	-	0.151	0.514	3.83	Overexploited
Scenario 5	-	0.210	0.389	2.87	Overexploited
Scenario 6	-	0.172	0.435	1.44	Overexploited

Figures

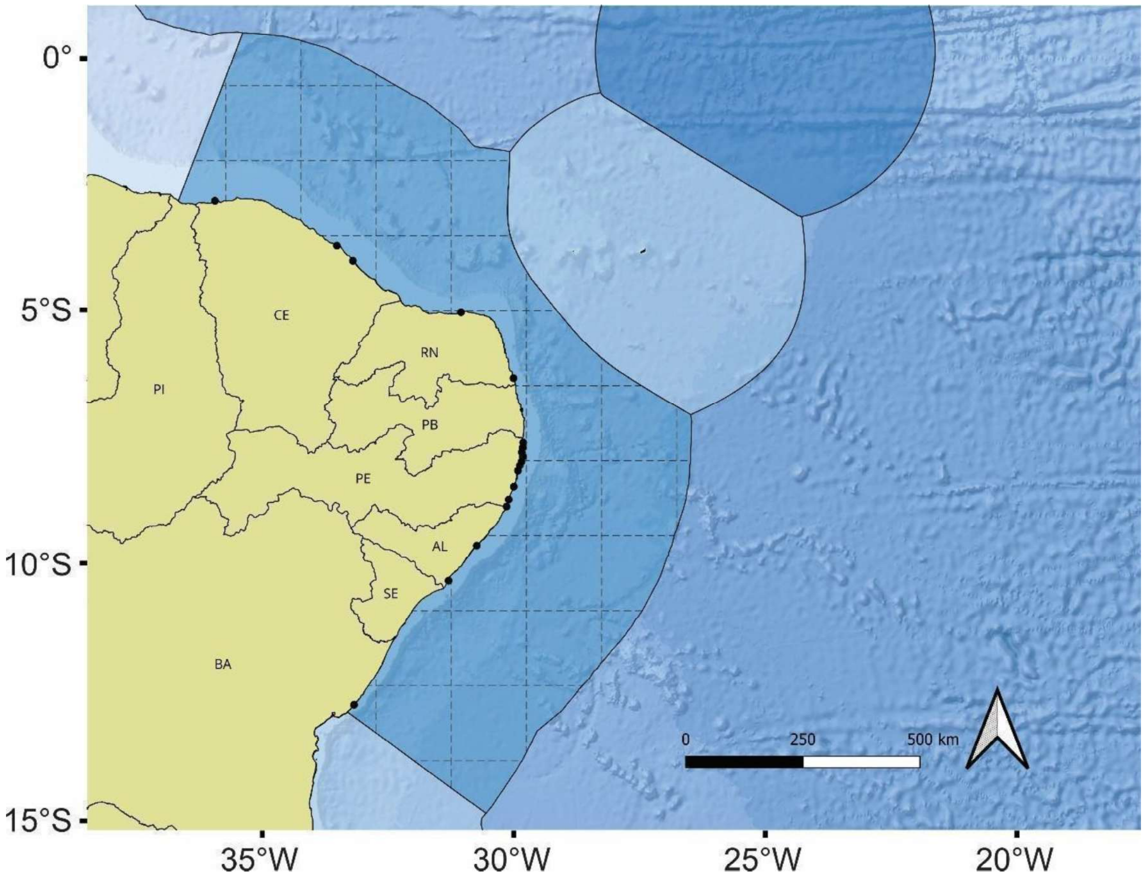

Figure 1: Map showing the spatial domain of the Ocyurus chrysurus stock evaluated in this study. Black points indicate sampling or landing sites for length data. The shaded region corresponds to the Northeast Brazil Marine Ecoregion as defined by Spalding et al.

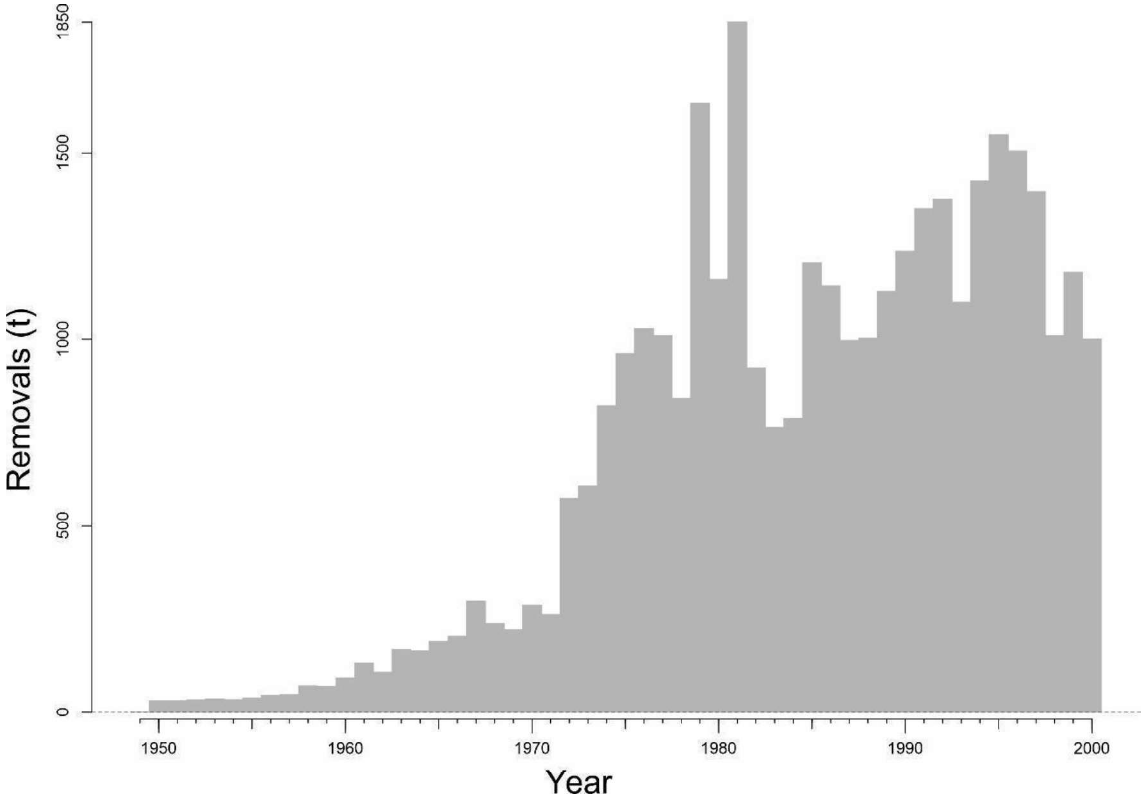

Figure 2: Time series of annual landings used as input for the integrated SAC Tool scenarios (SC1–SC3). These landings provide the stock-scale information required by the model and represent the historical exploitation of *Ocyurus chrysurus*.

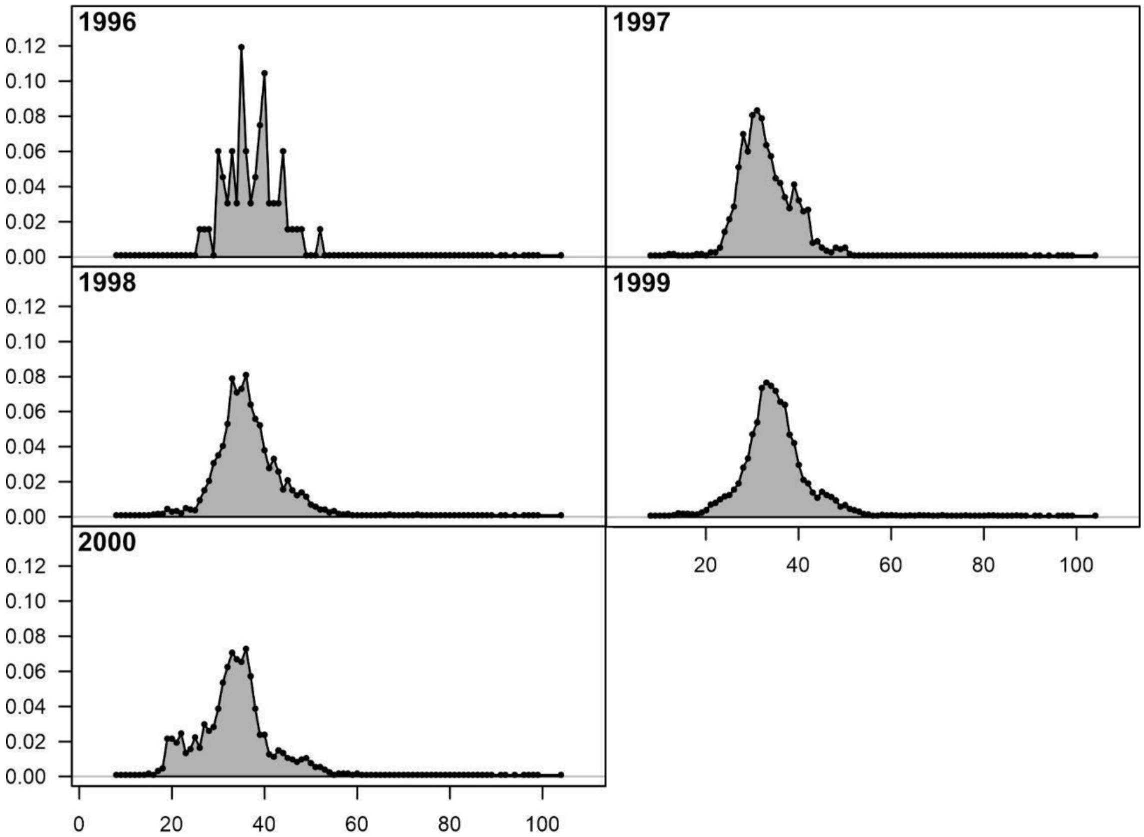

Figure 3: Normalized length compositions used as population structure inputs for both integrated and length-only scenarios. Each panel represents one year of observations.

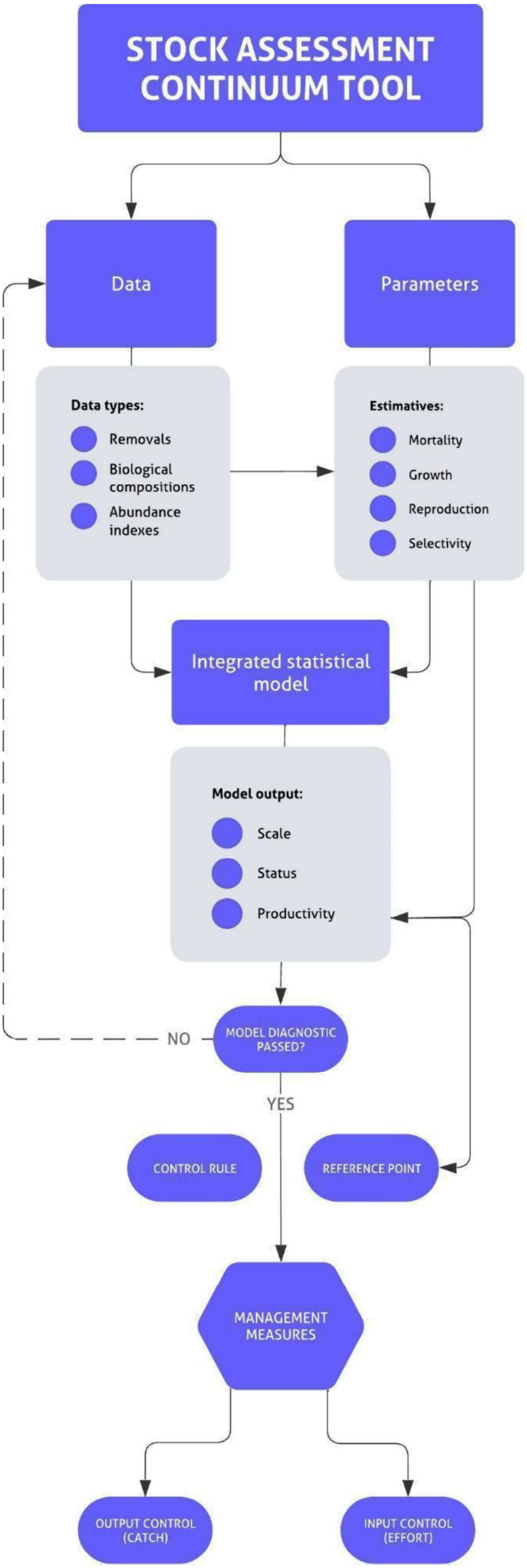
STOCK ASSESSMENT CONTINUUM TOOL
Data
Parameters
Data types:
Removals
Biological compositions
Abundance indexes
Estimatives:
Mortality
Growth
Reproduction
Selectivity
Integrated statistical model
Model output:
Scale
Status
Productivity
MODEL DIAGNOSTIC PASSED?
NO
YES
CONTROL RULE
REFERENCE POINT
MANAGEMENT MEASURES
OUTPUT CONTROL (CATCH)
INPUT CONTROL (EFFORT)

Figure 4: Diagram summarizing the SAC Tool structure, including data inputs (landings, biological compositions, abundance indices), parameter specifications (growth, mortality, selectivity, recruitment), the integrated statistical modeling framework, and derived outputs on stock scale, status, and productivity.

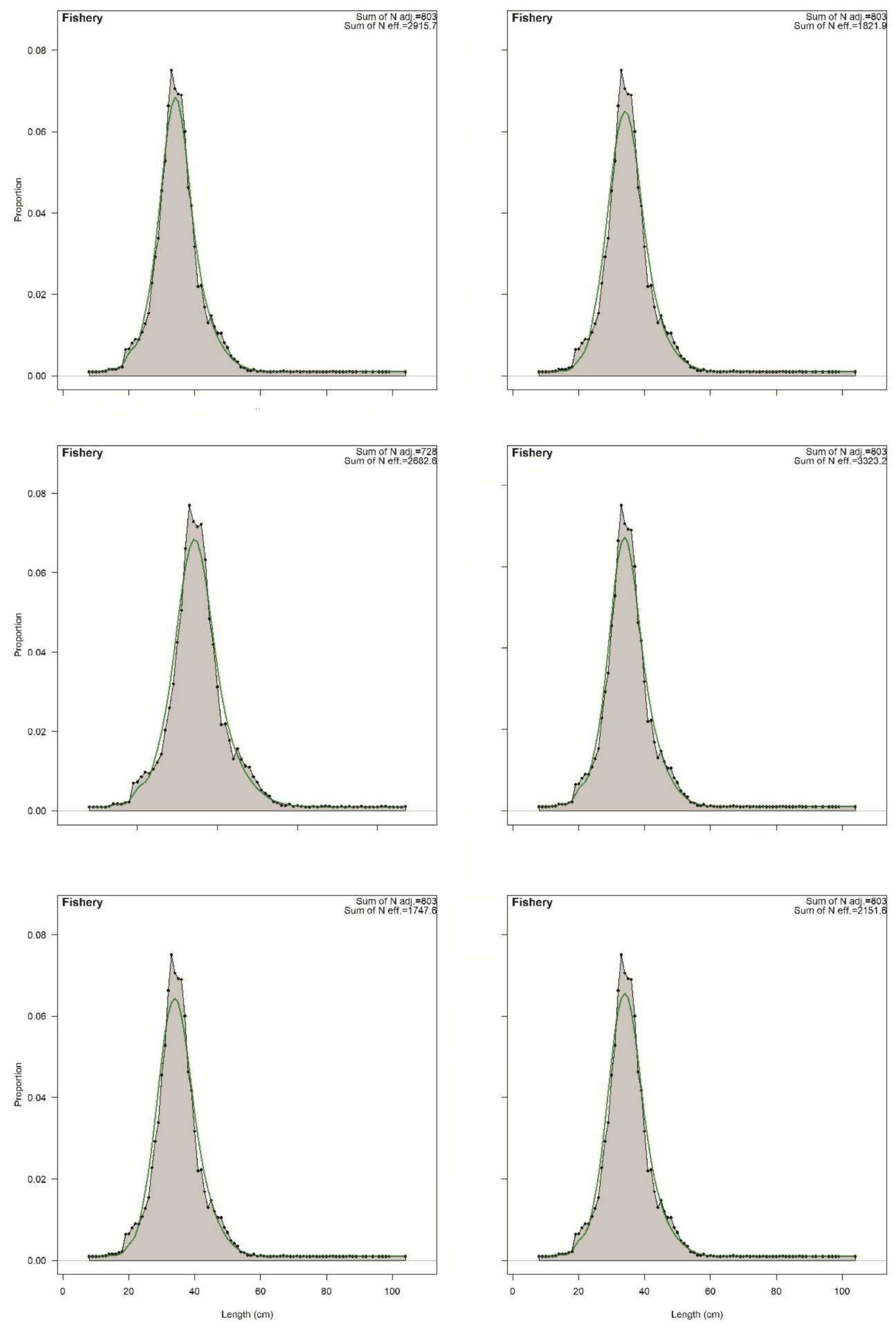

Figure 5: Composite fits to observed length compositions for each SAC Tool scenario. Panels (a–f) correspond to scenarios SC1–SC6, respectively. Black points represent observed proportions, and green lines represent model-predicted length compositions. Panels are ordered according to scenario number.

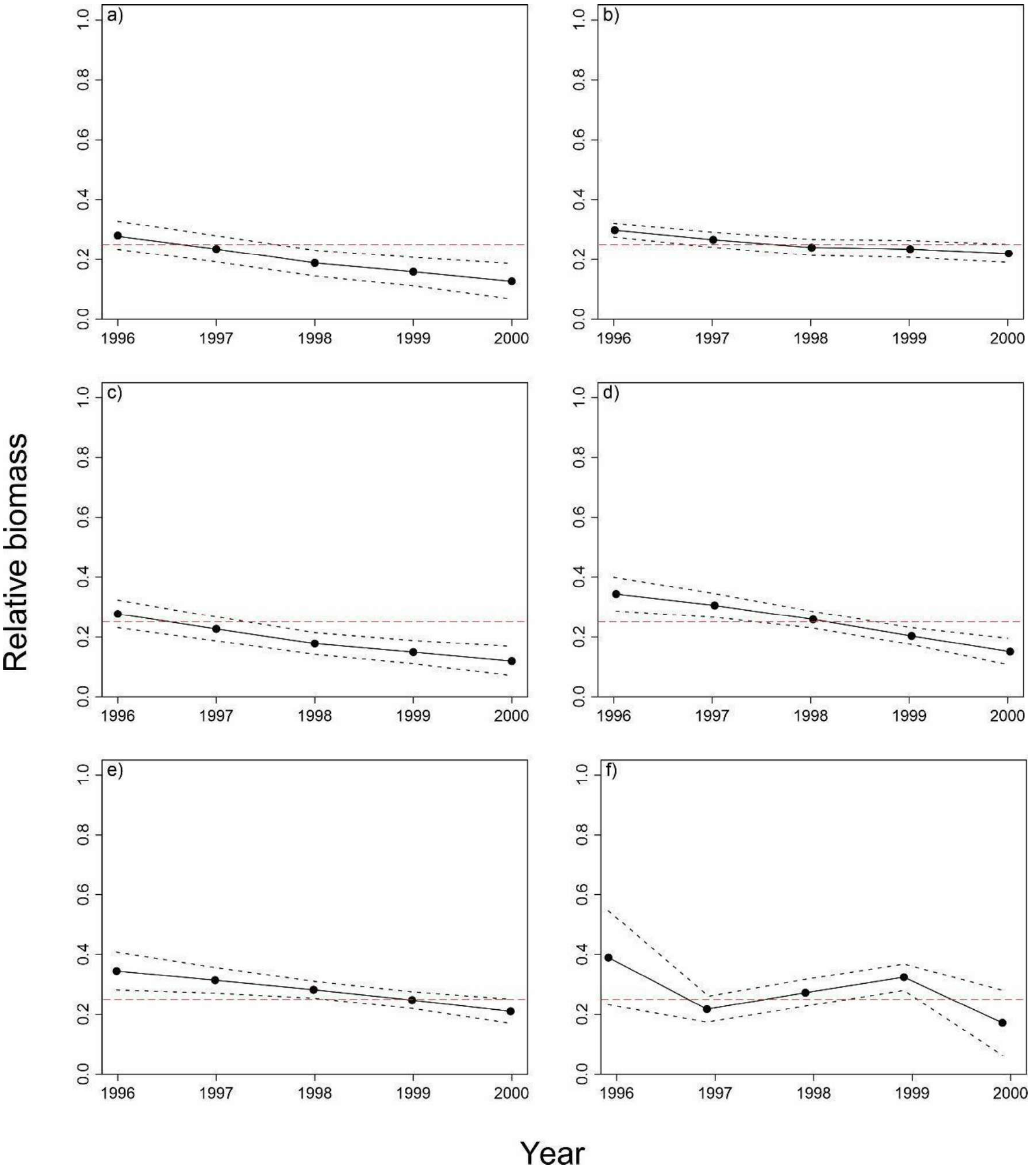

Figure 6: Estimated relative spawning biomass (SSB/SSB$_0$) from 1996 to 2000 for each SAC Tool scenario. Panels (a–f) correspond to scenarios SC1–SC6, respectively. Solid black lines and dots represent the model estimate and dashed black lines represent uncertainty intervals. Dashed red line represents the SAC Tool limit reference point of 0.25 x SSB$_0$, used for qualitatively stock status classification.

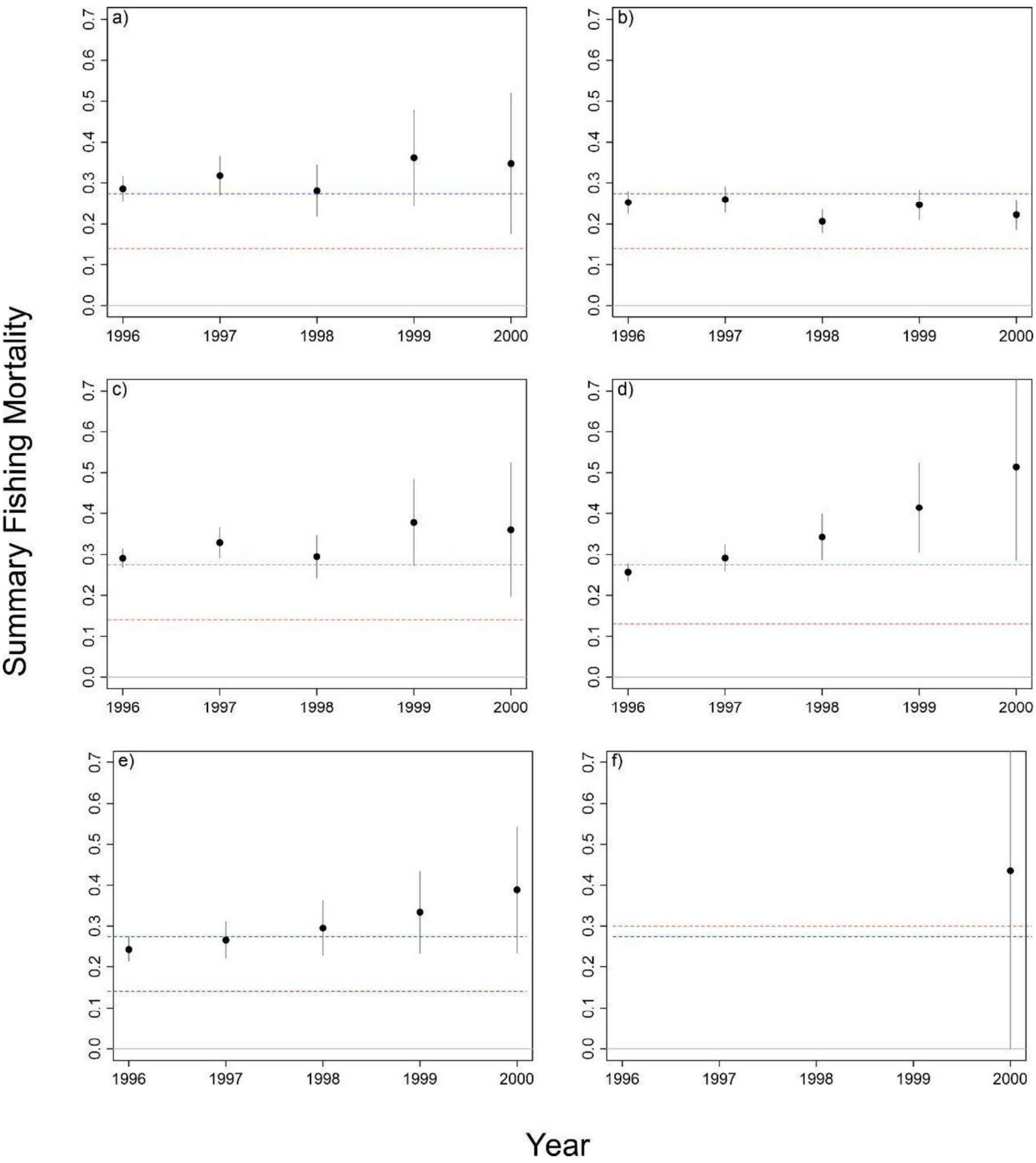

Figure 7: Estimated fishing mortality for each SAC Tool scenario. Panels (a–f) correspond to scenarios SC1–SC6, respectively. Points represent median estimates and vertical bars indicate uncertainty intervals. The red dashed line marks the MSY-based reference point ($F/F_{msy} = 1$). The blue dotted line represents the fishing mortality estimated in the historical Thompson & Bell assessment (REVIZEE), shown for reference.

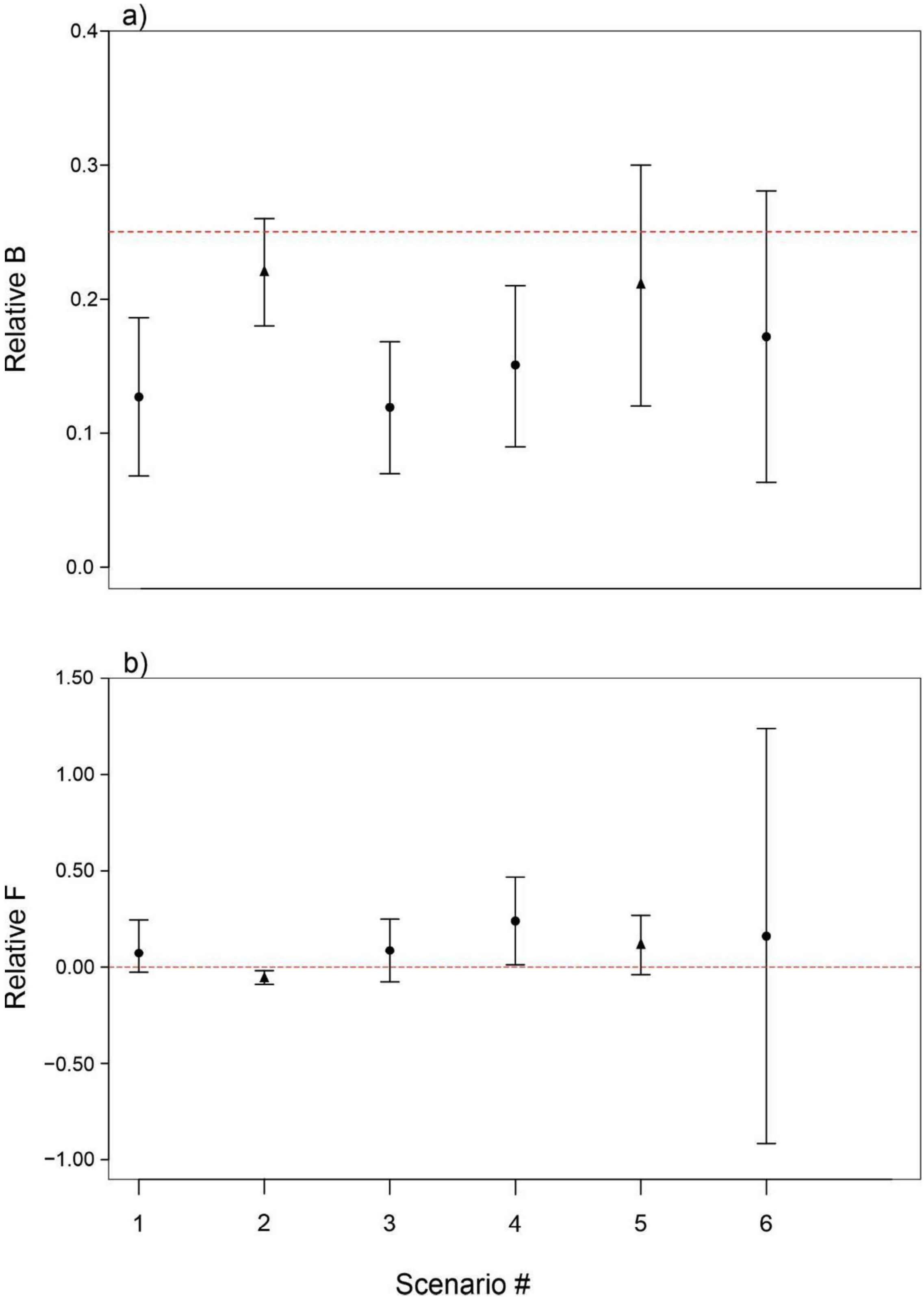

Figure 8: Terminal-year stock status across SAC Tool scenarios: (a) relative biomass (SSB/SSB$_0$) for each scenario (SC1–SC6). Points show median estimates with uncertainty bars. The red dashed line marks the SAC Tool limit reference point (0.25 B/B$_0$), below which the stock is considered overfished and (b) relative fishing mortality expressed as the difference between each scenario's F estimate and the F obtained in the historical REVIZEE assessment. Values above zero indicate higher fishing mortality than the base model; values below zero indicate lower estimates. The red

dashed line at zero represents equality with the base-model F. Circles indicate scenarios with estimated recruitment, whereas triangles indicate scenarios with fixed recruitment.

Capítulo II

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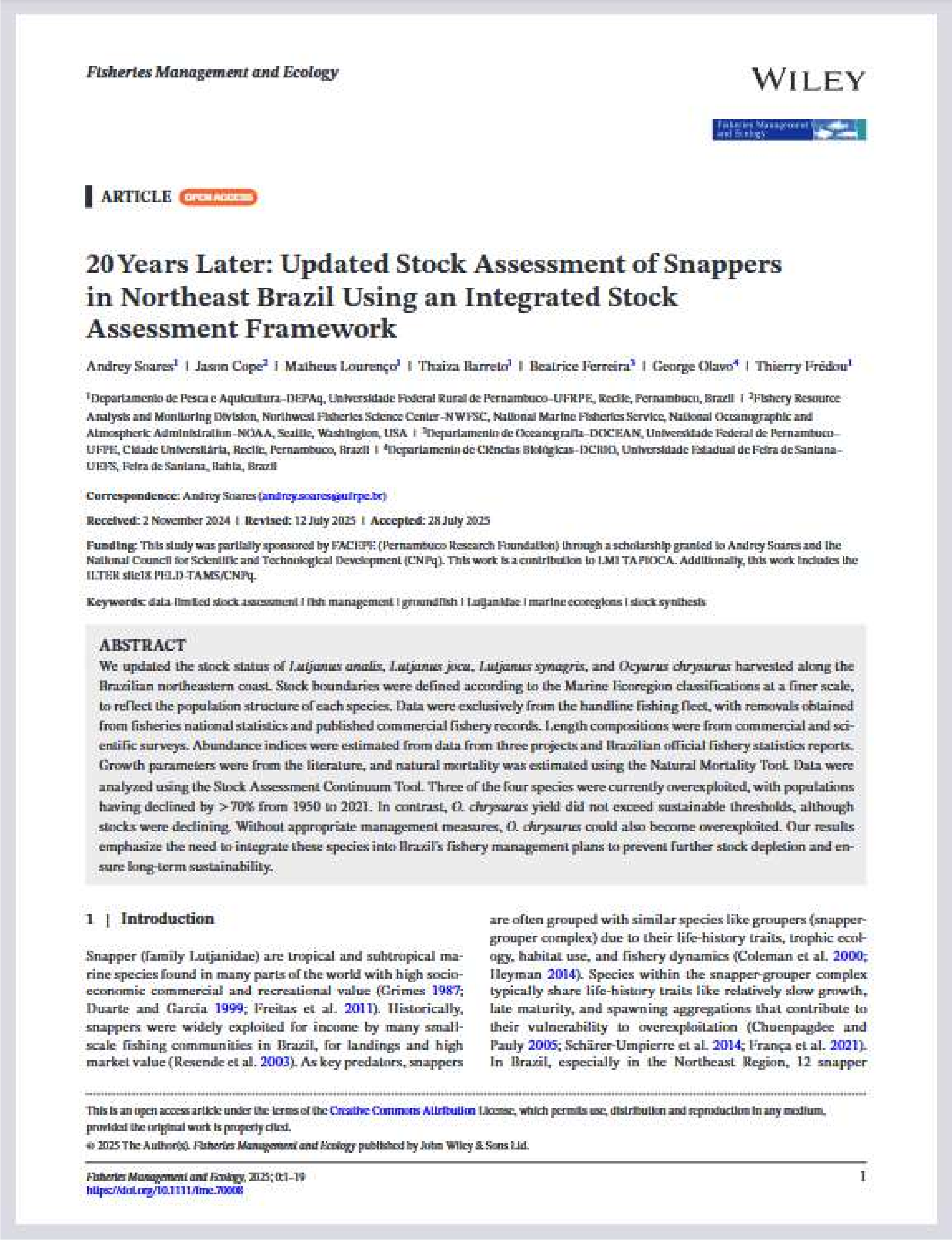

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20 Years Later: Updated Stock Assessment of Snappers in Northeast Brazil Using an Integrated Stock Assessment Framework

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Keywords: data-limited stock assessment | fish management | groundfish | Lutjanidae | marine ecoregions | stock synthesis

ABSTRACT

We updated the stock status of *Lutjanus analis*, *Lutjanus jocu*, *Lutjanus synagris*, and *Ocyurus chrysurus* harvested along the Brazilian northeastern coast. Stock boundaries were defined according to the Marine Ecoregion classifications at a finer scale, to reflect the population structure of each species. Data were exclusively from the handline fishing fleet, with removals obtained from fisheries national statistics and published commercial fishery records. Length compositions were from commercial and scientific surveys. Abundance indices were estimated from data from three projects and Brazilian official fishery statistics reports. Growth parameters were from the literature, and natural mortality was estimated using the Natural Mortality Tool. Data were analyzed using the Stock Assessment Continuum Tool. Three of the four species were currently overexploited, with populations having declined by >70% from 1950 to 2021. In contrast, *O. chrysurus* yield did not exceed sustainable thresholds, although stocks were declining. Without appropriate management measures, *O. chrysurus* could also become overexploited. Our results emphasize the need to integrate these species into Brazil's fishery management plans to prevent further stock depletion and ensure long-term sustainability.

1 | Introduction

Snapper (family Lutjanidae) are tropical and subtropical marine species found in many parts of the world with high socio-economic commercial and recreational value (Grimes 1987; Duarte and Garcia 1999; Freitas et al. 2011). Historically, snappers were widely exploited for income by many small-scale fishing communities in Brazil, for landings and high market value (Resende et al. 2003). As key predators, snappers are often grouped with similar species like groupers (snapper-grouper complex) due to their life-history traits, trophic ecology, habitat use, and fishery dynamics (Coleman et al. 2000; Heyman 2014). Species within the snapper-grouper complex typically share life-history traits like relatively slow growth, late maturity, and spawning aggregations that contribute to their vulnerability to overexploitation (Chuenpagdee and Pauly 2005; Schärer-Umpierre et al. 2014; França et al. 2021). In Brazil, especially in the Northeast Region, 12 snapper

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20 YEARS LATER: UPDATED STOCK ASSESSMENT OF SNAPPERS IN NORTHEAST BRAZIL USING AN INTEGRATED STOCK ASSESSMENT FRAMEWORK

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Abstract

We updated stock status of *Lutjanus analis*, *Lutjanus jocu*, *Lutjanus synagris*, and *Ocyurus chrysurus* harvested along the Brazilian northeastern coast. Stock boundaries were defined according to the Marine Ecoregion classifications at a finer scale, to reflect population structure of each species. Data were exclusively from the handline fishing fleet, with removals obtained from fisheries national statistics and published commercial fishery records. Length compositions were from commercial and scientific surveys. Abundance indices were estimated from data from three projects and Brazilian official fishery statistics reports. Growth parameters were from literature and natural mortality was estimated using the Natural Mortality Tool. Data were analyzed using the Stock Assessment Continuum Tool. Three of the four species were currently overexploited, with populations having declined by > 70% from 1950 to 2021. In contrast, *O. chrysurus* yield did not exceed sustainable thresholds, although stocks were declining. Without appropriate management measures, *O. chrysurus* could also become overexploited. Our results emphasize the need to integrate these species into Brazil's fishery management plans to prevent further stock depletion and ensure long-term sustainability.

Keywords: quantitative fisheries, fish management, data-limited, groundfish, fishery modelling.

Introduction

Snapper (family Lutjanidae) are tropical and subtropical marine species found in many parts of the world with high socioeconomic commercial and recreational value (Grimes 1987, Duarte and Garcia 1999, Freitas et al. 2011). Historically, snappers were widely exploited for income by many small-scale fishing communities in Brazil, for landings and high market value (Resende, Ferreira and Frédou 2003). As key predators, snappers are often grouped with similar species like groupers (snapper-grouper complex) due to their life history traits, trophic ecology, habitat use, and fishery dynamics (Coleman et al. 2000; Heyman 2014). Species within the snapper-grouper complex typically share life-history traits like relatively slow growth, late maturity, and spawning aggregations that contribute to their vulnerability to overexploitation (Chuenpagdee and Pauly 2005;

Schärer-Umpierre et al. 2014; França et al. 2021). In Brazil, especially in the Northeast Region, 12 snapper species are targeted by fishing fleets, with *Lutjanus analis* (mutton snapper), *L. jocu* (dog snapper), *L synagris* (lane snapper) and *Ocyurus chrysurus* (yellowtail snapper) supporting the largest landings (Resende, Ferreira and Frédou 2003). Adults of these species inhabit rocky bottoms or coral reefs, while juveniles are more commonly found in coastal waters associated with coastal reefs, seagrass meadows or estuarine zones and share trophic ecology characteristics, with a diet based mainly on fish and crustaceans, and to a lesser extent, molluscs and annelids (Lessa, Bezerra Júnior and Nóbrega 2004; Monteiro, Giarrizzo and Isaac 2009).

In the 1950s, Portuguese fishers introduced vertical longlines, known as *Pargueiras*, to Brazilian fleets as an alternative to tuna fisheries that were already starting to decline (Resende, Ferreira and Frédou 2003). Since then, snappers were target species of several fishing fleets that peaked in the 1980s before declining thereafter (Ivo and Sousa 1988; Ximenes and Fonteles-Filho 1988). The decline was usually attributed to depletion of stocks of southern red snapper (*Lutjanus purpureus*), which was the most fished snapper that was later supplanted by other snapper species. Since the 1990s, snappers accounted for ~40% of total landings by demersal fisheries in Brazil due to increased production of other snapper species, including *L. analis*, *L. jocu*, *L. synagris* and *O. chrysurus*, which were mainly fished in Northeast Brazil (Resende, Ferreira and Frédou 2003; Olavo 2004; Klippel et al. 2005; Frédou, Ferreira and Letourneur 2009a; Begossi, Lopes and Silvano 2012). In the early 2000s, the Brazilian government's REVIZEE project (Lessa, Bezerra Júnior and Nóbrega 2004) conducted stock assessments of several fish species, including snappers, using age-structured Virtual Population Analysis (VPA) and the Thompson and Bell Yield-Per-Recruit model (Lessa, Bezerra Júnior and Nóbrega 2004; Frédou, Ferreira and Letourneur 2009b, 2009a). Despite identifying overfishing and overexploitation, management plans were never implemented for these fisheries. To make matters worse, the official Brazilian fisheries statistical program – ESTATPESCA (IBAMA 2008) ceased to exist in 2007, thereby stopping the collection and processing of fishery data, especially for coral reef fishes (Frédou et al 2017; Silva et al 2021; Silva et al 2025).

Some stock assessment approaches use data-limited models that attempt to maximize use of available limited data (Chrysafi and Kuparinen 2015; Dowling et al. 2019; Cope et al. 2023; Cope 2024a). For example, when data on abundance indices and age and growth are unavailable or of low quality, data-limited methods can provide ways to move forward by outlining assumptions and exploring uncertainty (Cope 2024a). Catch-based models use catch time series that can be combined with species life history data (e.g., growth equation parameters, maximum length, and age) and assumptions of stock status to estimate sustainable catches (Cope 2013). Other methods are based on length frequency distributions (LFD) and life history to estimate sustainable fishing rates and current relative stock status, such as mortality estimators based on average length that assume fishing mortality directly influences average length of catches (Gedamke and Hoenig 2006; Pons, Cope and Kell 2020; Then et al 2018). LFD data is easy and cheap to collect, so is usually the primary (or only) type of data collected in data-limited fisheries (Hordyk et al. 2015; Mildenberger, Taylor and Wolff 2017). Because integrated models can be flexible to available data types, data-limited methods can be built in the same modelling framework (Cope 2024a). Fisheries management often aims to optimize yield, while balancing environmental impacts and socioeconomic impacts (Sainsbury, Punt and Smith 2000; Garcia et al. 2003), so is highly variable and influenced by multiple factors that can change over time. Additionally, lack of comprehensive data in developing countries and small-scale fisheries often hinders development of effective management plans (Cope et al. 2023).

Most fish stocks and associated fisheries in Northeast Brazil, including snappers, are data-limited, which necessitates alternative assessment methods. We updated stock assessments for four economically important lutjanid species in Northeast Brazil: *L. analis*, *L. jocu*, *L. synagris*, and *O. chrysurus* using the Stock Assessment Continuum Tool (SACT) (Cope 2024a, 2024b) an integrative stock assessment model with historical catch data, length compositions, available abundance indices, and life history. We sought to determine if stocks of *L. analis*, *L. jocu*, *L. synagris*, and *O. chrysurus* were being overexploited, and if so, to estimate reference points for fishery harvest management.

Methods

Stock definition

Stock assessments were defined within boundaries for snapper stocks of the Brazilian northeastern coast according to defined marine ecoregions (MEs) definitions (Spalding et al. 2007; Figure 1). This definition was selected based on regional homogeneity of species composition, habitats, oceanographic characteristics, and fishery dynamics within the ME of the northeastern Brazilian coast, which has high levels of biodiversity and is considered a priority for management and conservation (CBD 2014; Eduardo et al. 2018). The region includes several Marine Protected Areas (e.g. "APA Costa dos Corais", "APA Guadalupe", "APA Barra de Mamanguape"; Ferreira and Maida 2007). Using MEs as the boundary for stock definition provided an appropriate proxy for inferring stock boundaries in the Southwest Atlantic and offered more accurate and finer results than broader systems like Large Marine Ecosystems (LMEs). This was especially relevant for species like snappers, which may have population structures that align with finer ecological scales, such as those defined by MEs. Recent research on otolith shape and chemical composition of *Lutjanus synagris* identified dissimilarities among populations across different MEs (Dos Santos et al. 2022). However, individuals did not differ significantly within the Northeast Brazil ME, which reinforced the idea of a single stock in this area. In contrast, otolith characteristics differed significantly between Eastern and Northeast Brazil MEs, which suggested these areas should be treated as distinct management units. Although this evidence suggests separation of stocks between different MEs, further large-scale studies comparing age composition, growth, mortality, and reproduction along a latitudinal gradient are required to substantiate a hypothesis of distinct stocks across these regions.

Data

Data were from the commercial handline fishing fleet, which composed more than 95% (IBAMA 2008) of the catches of these species. Fisheries data for snapper assessments consisted of catch, length-frequency data, and abundance index (Figure 2). Historical catch data were obtained from official reports on commercial fisheries from 1950 to 2007 (IBAMA 2008), a reconstruction from 2008 to 2015 separated by state (Freire et al. 2021), and a compilation of catch time series from the Sea Around Us Project (Sea Around Us 2024), revised and extended by the REPENSAPESCA Project until 2021 (Ferreira, Olavo and França 2022) by geographical units (Northeastern Brazilian states) and taxonomic units (species) of interest for stock assessment purposes (Figure 3).

Length compositions were from REVIZEE, PRO-ARRIBADA, and REPENSAPESCA projects. The REVIZEE project during the 1990s collected large amounts of data from the Brazilian EEZ from industrial fishing fleet based in Natal-BR, landings from small-scale artisanal fishing fleets from various fishing communities in the

Northeast states, and data from scientific surveys (MMA 2006). Data were collected monthly from five northeastern Brazilian states: Ceará, Rio Grande do Norte, Pernambuco, Alagoas, and Bahia (Frédou 2004). The PRO-ARRIBADA project, implemented in 2008, provided basic information about feeding and reproductive aggregations of socioeconomically important fish species. The project covered four broad areas, two of which were within the range of the Northeast Brazil ME and provided length data from 2009 to 2014. The REPENSAPESCA project, which aimed to assess trends in the fisheries and the population structure of commercially important reef fish, provided length composition from 2019 to 2021. Although official commercial fishery records ceased in 2007, post-2007 sampling continued at the same landing sites using the same protocols established during the earlier monitoring programs. While this ensured methodological consistency, representativeness of post-2008 data relative to the broader commercial fishery cannot be conclusively verified. This limitation was explicitly recognized in our analysis and interpretation.

Abundance was indexed as catch-per-unit-of-effort (CPUE = kg/day, catch in kg per day at sea for each vessel). CPUE was estimated using data from the REPENSAPESCA project (from the state of Rio Grande do Norte), the PRO-ARRIBADA project (from the state of Pernambuco), and the ESTATPESCA program, Brazil's official fishery statistics until 2007 (states of Rio Grande do Norte, Paraíba, Pernambuco, and Bahia). Raw CPUE was used because standardization was not possible due to lack of factors that can influence catch and effort, such as depth, vessel type, and spatiotemporal distribution. Diversity of sources and heterogeneity of data, such as differences in fleet type or fishing area, also hindered standardization CPUE, so abundance was indexed solely as raw CPUE.

Life history

Growth parameters for most species were sourced directly from peer-reviewed studies within the stock area. However, for *L. analis*, no peer-reviewed literature was available within the stock area, so growth parameters were estimated using the FishLife package (Thorson et al. 2017), which provides standardized life-history estimates based on phylogenetic and ecological covariates. The instantaneous natural mortality coefficient (*M)* was estimated for all species using the Natural Mortality Tool (NMT) (Cope and Hamel 2022) based on the arithmetic mean of four estimators that rely on maximum observed age: $M = 4.889 * {T_{max}}^{-0.916}$, $M = \exp(1.717 - 1.01 * \ln(T_{max}))$ (Then et al 2015), $M = 5.4/T_{max}$ (Hamel and Cope 2022), and $M = 3k/(\exp\left(k * \left((0.302 * T_{max}) - T_0\right)\right) - 1)$ (Alverson and Carney 1975).

Population dynamics

Biomass and stock status indicators were estimated using the SACT framework (Cope 2024b) that uses the Stock Synthesis age-structured modelling framework (Methot and Wetzel 2013) as a flexible integrated analysis to model variable data availability to estimate population dynamics (Cope 2013). This approach requires input parameters for natural mortality (M), von Bertalanffy growth parameters (L_{inf}, K, and t_0), sizes at 50% and 95% maturity and selectivity, coefficients of the weight-length and fecundity-weight relationships, parameters of the stock-recruit relationship (steepness and initial recruitment at the carrying capacity $lnR0$), and catch, length, and (if available) relative abundance (Figure 4). Due to a lack of data on fecundity at weight, fecundity-weight coefficients were set to be the same as the weight-length relationship. Steepness (h) was set to 0.7, the estimated mean value for Perciformes based on the *FishLife* package (Thorson et al. 2017; Thorson 2020). Initial selectivity inputs were estimated using the catch-curve method in the *TropFishR* package (Mildenberger, Taylor, and Wolff, 2017), as preliminary estimates of the size at full selectivity based on observed length-frequency data. These values were then used to set the initial parameters for the prior distributions in SACT as part of our modeling approach. The model can estimate selectivity but relies heavily on these priors in data-limited contexts due to absence of detailed gear-specific or age-structured data. In our assessment, selectivity was semi-informed and initialized using empirical estimates that subsequently allowed adjustment within bounds defined by priors during model fitting. This intermediate approach balanced the need for model flexibility with limitations of sparse data, to reduce parameter uncertainty while maintaining biological plausibility. Reference points for spawning stock biomass (SSB) included spawning biomass at maximum sustainable yield ($\mathrm{SSB}_{\mathrm{MSY}}$) as a minimum stock size threshold (MSST) and 125% of $\mathrm{SSB}_{\mathrm{MSY}}$ as a management target (SSB_{target}). The instantaneous fishing mortality (F) reference point was the fishing mortality at maximum sustainable yield ($\mathrm{F}_{\mathrm{MSY}}$). Reference points were estimated by SACT based on life-history parameters provided as model inputs, including growth, natural mortality, maturity, and length-at-capture, under assumptions of constant selectivity and no explicit stock-recruitment relationship.

Assessing uncertainty

Catch time series were composed of three linked sources: (1) for 1970–2007, catches were from the official Brazilian program of data collection, ESTATPESCA (IBAMA, 2008), which compiles all national fishery statistics as the most reliable catch information; (2) for 1950–1969 and 2008–2015, Freire et al. (2021) reconstructed marine commercial landings data by systematically addressing gaps and inconsistencies in Brazil's official fisheries statistics from national statistics, scientific literature, and expert consultations to estimate unreported catches, discards, and other components absent from official records; and (3) for 2016–2021, Ferreira et al. (2022) used a similar approach to extrapolate reconstructions for selected species. Given the lack of official catch statistics during the last decade, we evaluated sensitivity of stock status estimates to uncertainty in post-2015 catch data. Specifically, we tested 18 alternative catch scenarios for each species species during 2016–2021, by adjusting removals by ±10% to ±50%, in 5% increments, from a baseline scenario derived by Freire et al. (2021) and Ferreira et al. (2022), while maintaining the same trend trajectory (Figure 5). These catch trajectories were used to evaluate robustness of stock status estimates to uncertainty in recent removals by systematically testing how sensitive model outputs are to reasonable variations in catch levels. Each scenario was subject to full model fitting and sensitivity analysis. To integrate results across all scenarios, we applied an ensemble modeling framework in which each scenario was weighed equally. Stock Synthesis outputs were processed to extract key management metrics (e.g., fishing mortality, biomass ratios, and recruitment), constructed probability distributions from their estimates and uncertainties, and combined them into weighted ensemble trajectories. The equal weighting scheme reflects our assumption that all scenarios were equally plausible representations of the system, avoiding subjective prioritization. The ensemble outputs, including mean trajectories, uncertainty bounds, and Kobe plot quadrant probabilities, provide a more robust synthesis than individual scenario assessments by accounting for variability across model structures and assumptions. This approach ensures that management inferences are derived from a balanced integration of all available evidence. A bootstrap routine was then used to quantify the probability that each species fell into one of four risk categories, defined by relative fishing mortality and spawning stock biomass within the Kobe plot framework. In the green quadrant (lower right), the stock is not overfished and no overfishing is occurring, which is considered low risk, indicating a sustainable and healthy stock status. The orange quadrant (upper right) reflects a stock that is not overfished, but overfishing is occurring, representing moderate risk and signaling potential need for management action. In the yellow quadrant (lower left), the stock is overfished, but overfishing is not occurring, also indicating moderate risk. Finally, the red quadrant (upper left) represents stocks that are both overfished and experiencing overfishing, a high-risk scenario typically requiring urgent intervention.For the final model, convergence was tested using the Carvalho et al. (2021) method, which provides a diagnostic flow chart for model outputs. The first test included checking if the Hessian matrix was positive and definite, to ensure the function converged to a unique maximum likelihood estimate. The second test was a jitter analysis of initial values to ensure global convergence. The third test was for random distribution of residuals that indicated model assumptions were acceptable. The fourth test was a sensitivity analysis of productivity parameters to verify consistency of results. The last test was a 5-year retrospective analysis to verify consistency of results over time.

Results

Diagnostic analysis

The input parameters used in the Stock Assessment Continuum Tool reference model for four snapper species (*Lutjanus analis, Lutjanus jocu, Lutjanus synagris, and Ocyurus chrysurus*) sampled along the northeastern Brazilian coast between 1950 and 2021 are shown in Table 1. These parameters include life history traits such as maximum age, age and length at maturity, growth parameters from the von Bertalanffy Growth Function (VBGF), natural mortality rates, weight–length relationships, fecundity estimates, and the steepness parameter (h) of the stock–recruitment relationship. Data sources include peer-reviewed studies and the FishLife database, as indicated. Where confidence intervals (CIs) are available, they are reported alongside the parameter estimates.

Key stock status indicators for the four snapper species, based on the Stock Assessment Continuum Tool results, are depicted in Table 2. The unfished spawning stock biomass (SSB) estimates represent the total reproductive biomass if no fishing had occurred. The catch at maximum sustainable yield (MSY) is the estimated highest average annual catch that can be maintained without depleting the stock. The spawning stock biomass at MSY (SSB_{MSY}) indicates the reproductive biomass level that supports MSY. Ratios comparing the 2021 spawning stock biomass to SSB_{MSY} (SSB_{2021}/SSB_{MSY}) indicates whether the stock is above or below sustainable levels. Fishing mortality at MSY (F_{MSY}) is the rate of fishing that achieves MSY, while the ratio of fishing mortality in 2021 to F_{MSY} (F_{2021}/F_{MSY}) indicates current fishing pressure relative to sustainable limits. Finally, the stock biomass status categorizes each stock as overexploited or underexploited and whether overfishing is occurring. These metrics provide a comprehensive view of stock health and fishing pressure to guide management decisions.

The SACT estimation fitted size composition data well (Figure 6 ; Table 2). For all four species, diagnostics were within the acceptable range. Final gradients of model outputs were small (< 0.001), and Hessian matrices for parameters were positive and definite. Residuals for length compositions and abundance indices were randomly distributed, except for the length composition of *O. chrysurus* (Figure S1**Error! Reference source not found.**). All 50 jitter runs for each species were stable despite variation in initial values, with most runs converging to the same solution as the base model for each species (Figure S2). For all species, final model outputs for biomass and fishing mortality were not sensitive to variation in natural mortality or steepness (Figure

S3). Retrospective analyses indicated low bias for most species, except *L. analis*, due to an imbalance in the sample size among final years (Figure S4).

Lutjanus analis

Removals increased until the mid-1970s, and reached a historical peak in 1977, before declining sharply in the 1980s (Figure 3a). Thereafter, removals increased between 1988 and 1996 and stabilized thereafter. Length composition data for 1996–2000, 2009–2014 and 2019–2021 were well fit by the model (Figure 6a). The abundance index did not deviate significantly from the fitted trend but decreased abruptly at the end of the period (Figure 7a).

Total stock biomass (B) estimates fluctuated from 15,000 t in 1950 to 2,900 t in 2021 (Figure 8a). A steady equilibrium in stock spawning biomass (SSB) between the early 1980s and 2010 was below B_{MSY}. Relative spawning biomass ranged from 99.6% at the beginning of the period to 14% in 2021, near B_{target}since the late 1970s, with low signs of recovery before a sharper decline in the last decade (Figure 8b). Current spawning biomass was below the limit ($SSB_{2021}/SSB_{MSY} \approx 0.44$). Recruitment fluctuated greatly in the last two decades (Figure 8c), with peaks in 1999 (>2,200 recruits) and 2014 (~1,900 recruits). Fishing mortality after 1974 surpassed $F/F_{MSY} = 1$, and was lower only briefly between 1980 and 1994, before rising again until the end of the period ($F_{2021}/F_{MSY} \approx$ 2.38; Figure 8d).

Lutjanus jocu

Removals increased until the late 1990s, then declined sharply, before plateauing in 2007 (Figure 3b). Length composition data for 1996–2000, 2009–2014 and 2019–2021 were well fit by the model (Figure 6b). Most length composition data was from the REVIZEE project in the 1990s, but the last decade was well represented. The abundance index was only available from 1995 through 2014 and missing for the end of the period (Figure 7b).

Total biomass was relatively steady, before declining sharply in 1988 and again in 1996, when it declined ~66%, with a recovery between 1997 and 2002, and a decline thereafter, when it declined 43% until the end of the period (Figure 9a). Spawning stock biomass declined to below 30% of initial values, and by the beginning of the last decade, the stock was below the limit ($SSB_{2021}/SSB_{MSY} \approx 0.82$; Figure 9b). Recruitment was dynamic throughout the period, with large recruitments in 1994, 1995, and 1996 (Figure 9c). Fishing mortality increased steadily until the last decade, to surpass MSY (Figure 9d), but was at sustainable levels by the end of the period ($F_{2021}/F_{MSY} \approx 1$).

Lutjanus synagris

Removals were below 500 tons in early decades, before rising above 1500 tons between 1992 and 2008, where it stayed thereafter (Figure 3c). Length compositions were based on low sample sizes (Figure 6c) and the abundance index was only available before 2010 (Figure 7c).

Total biomass declined steadily since the beginning of the period, increasingly after the 1970s (Figure 10a), with a partial recovery between 1998 and 2003, and a decline thereafter. Spawning stock biomass first dropped below MSY at the end of the 1990s, recovered until 2015, and declined sharply to low levels thereafter (Figure 10b) ($\mathrm{SSB}_{2021}/\mathrm{SSB}_{\mathrm{MSY}} \approx 0.78$). Recruitment was relatively steady, with peaks in 1997, 2007, and 2016 (Figure 10c). Fishing mortality was constant until 1990, but increased regularly thereafter, to surpass $\mathrm{F}_{\mathrm{MSY}}$ after 2000, and was dangerously high by the end of the period (Figure 10d) ($\mathrm{F}_{2021}/\mathrm{F}_{\mathrm{MSY}} \approx 2.59$).

Ocyurus chrysurus

Removals increased since the start of the period, especially after 1972, and surpassed 2000 tons in 2003 and remained stable since then (Figure 3d). Length compositions were from 1996 to 2000 and 2009 to 2014, and lacking thereafter, except in 2020 (Figure 6d). The abundance index was available from 1995 to 2011 and missing thereafter (Figure 7d).

Total biomass decreased steadily between the start of the period and 1996, with a peak between 1997 and 2001, after which the stock sharply declined until 2014, when it stabilised until the end of the period (Figure 11a). Spawning stock biomass was never below MSY but crossed the B_{target} into the precautionary zone ($\mathrm{SSB}_{2021}/\mathrm{SSB}_{\mathrm{MSY}} \approx 1.42$) in the last decade (Figure 11b). Recruitment increased steadily, with peaks in 1993, 1998, and 2004 (Figure 11c). Fishing mortality was below the reference point of $F/F_{MSY} = 1$ in the entire period but increased in the last decade ($F_{2021}/F_{MSY} \approx 0.86$; Figure 11d).

Uncertainty

For each species, different landings scenarios converged to the same final status. *L. analis* had an 88.9% probability of being overfished and experiencing overfishing, and an 11.1% probability of being overfished but not experiencing overfishing (Figure 12a). *L. synagris* had a 96.6% probability of being overfished and experiencing overfishing, and a 3.1% probability of experiencing overfishing but not overfished (Figure 12b). *L. jocu* had a 49.6% probability of being overfished and experiencing overfishing, a 43.3% probability of being overfished but not subject to overfishing, and a 7.1% probability of being neither overfished nor undergoing overfishing (Figure 12c). *O. chrysurus* had a 57.0% probability of being neither overfished nor subject to overfishing, and a 39.0% probability of experiencing overfishing but not overfished (Figure 12d). Stock status estimates were generally robust to uncertainty in catch data. Consistency among scenarios, particularly for *L. analis* and *L. synagris*, indicated stability in assessment outcomes despite uncertainty in catch assumptions.

Discussion

Ours is the first formal and comprehensive stock assessment of all four snapper species on the northeast coast of Brazil in the past 20 years. Our primary objective was to highlight the critical need for science-based management of demersal fisheries in the region. Our results revealed clear evidence of prolonged overexploitation of some of the assessed stocks, which has yet to be addressed by any formal management framework in the region but highlights an urgent need for a regulatory framework to prevent further depletion of these stocks. By updating the status of these key fisheries, we aimed to facilitate the integration of scientific assessment into regional management planning to stimulate adoption of sustainable harvest strategies. Our study, therefore, is pivotal for bridging the gap between scientific assessment and development of active management policies in the region. Although assessments of other fisheries resources have been completed, such as shrimp (Barros et al. 2021; Peixoto et al. 2021; Aragão et al. 2022), recent assessments of demersal fish in the North and Northeast regions are rare (Ferreira, Olavo and França 2022). While the REPENSAPESCA project preliminarily assessed the status of these species, it relied on the Large Marine Ecosystem (LME16) approach, which may have led to mixed signals due to the potential presence of distinct stocks in different regions. In contrast, we used marine ecoregions (MEs), which are considered a more appropriate boundary for stock definition, for finer-scale and more accurate assessments. Using historical catch and length data and abundance indices, we evaluated the status of the four main socioeconomically important snapper species caught along the northeastern coast of Brazil. Our results indicated that three of the four stocks have been overexploited for at least a decade, with estimated fishing mortality still much higher than sustainable levels. This suggests that these stocks are currently being overexploited.

An advantage of Stock Assessment Continuum Tool is flexibility in handling multiple types of data, including catch data, length compositions, abundance indices and life-history (LH) information, which is particularly valuable for data-limited fisheries, such as ours (Methot and Wetzel 2013), to allow for a more refined and data-informed assessment of stock status (Rudd et al. 2021). This flexibility allows the evaluation of how different data types contribute to model outputs and where key assumptions, such as selectivity or mortality, drive uncertainty (Cope et al 2023; Cope 2024a; Rudd et al 2021). This allows practitioners to identify which inputs are most informative and where improved data collection would reduce model uncertainty. However, depending on inputs provided and assumptions made, the model output was still data-limited, even when using a complex modelling framework (Cope 2024a). One particular limitation of SACT for data-limited fisheries was selectivity (Cope 2024a; Cope 2024b). For data-limited fisheries like ours, the lack of data on gear- and size-specific selectivity necessitates the use of simplified or assumed selectivity curves, which may introduce bias in model outputs if the true selectivity differs significantly from these assumptions (Hovgard and Lassen 2000; Cope 2024a). As a result, model estimates of fishery mortality, biomass, and stock status be sensitive to assumptions, thereby underscoring the need for caution when interpreting results and for future efforts to improve empirical data on gear performance and size-at-capture (Chen, Chen and Stergiou 2003; Hoshino et al 2014). Thus, while SACT offers a comprehensive approach, the quality of output is influenced by quality and breadth of available data (Cope 2024a). Our study also demonstrated the importance of incorporating sensitivity analyses to more accurately characterize uncertainty in model specifications (Tagliarolo, Cope and Blanchard 2021).

Results of our assessment using the Stock Assessment Continuum Tool confirmed stock assessments of *L. analis*, *L. jocu*, and *L. synagris* as overfished and experiencing overfishing more than 20 years ago (Frédou, Ferreira and Letourneur 2009a, 2009b). Previous assessments used traditional age-structured methods, Virtual Population Analysis (VPA) and Yield-Per-Recruit models, indicated that *L. analis*, *L. jocu*, and *L. synagris* were overfished and subject to overfishing, whereas *O. chrysurus* was under significant exploitation pressure (Frédou et al. 2009a). Consistency among modeling approaches and assessment periods suggests a persistent pattern of overexploitation for these species that reinforces the need for management intervention. In contrast, our assessment of *O. chrysurus* stock status (not overfished and not undergoing overfishing) differed from the earlier assessment (overexploited), perhaps because more recent data used in our assessment, despite gaps and limitations, captured changes in fishing effort or stock recovery since the earlier assessment. Alternatively, methodological differences between the earlier assessment (Frédou et al. 2009a) and ours may have influenced how exploitation status was interpreted, particularly in the absence of fishery-independent data. Finally, shifts in fleet behavior, species targeting, or market dynamics may have altered fishing pressure on *O. chrysurus* relative to other species. This historical comparison supports the credibility of the current assessment, while emphasizing the chronic nature of overfishing for most snapper stocks and also highlights the value of regular stock assessments using updated methods and data to track changes in exploitation status over time, to guide the development of effective, adaptive management strategies.

Table 2 highlights important contrasts in the exploitation status and fishing pressure across the four snapper species studied along the northeastern Brazilian coast.

Notably, Lutjanus analis and Lutjanus synagris exhibited clear signs of overexploitation, characterized by spawning biomass levels below sustainable targets and fishing mortality rates substantially exceeding biological reference points. For L. synagris, these results closely align with findings from García-Caudillo et al. (2024) for the southern Gulf of Mexico, where the species was also found to be overfished, highlighting similar pressures across different parts of the species' range and reinforcing concerns about stocks' depletion. This combination indicates that these stocks are under significant stress from current fishing activities, and without effective management interventions, their recovery may be compromised. The situation calls for management measures such as closed seasons or closed fishing areas to alleviate fishing pressure and allow rebuilding of reproductive capacity (Shertzer et al. 2024). Lutjanus jocu, meanwhile, presents a relatively more moderate picture. Although its spawning biomass is somewhat depleted, fishing mortality is only slightly above sustainable levels. This suggests that while the stock is vulnerable, it may respond positively to management aimed at reducing fishing effort to avoid further depletion, as seen in other cases (SEDAR 2021; Bacheler et al. 2025), and continued monitoring will be critical to detect trends and ensure that exploitation remains within safe biological limits. In contrast, Ocyurus chrysurus stands out as currently underexploited, with spawning biomass above sustainable reference points and fishing mortality below the threshold associated with maximum sustainable yield. These patterns mirror those observed in García-Caudillo et al. (2024), where the species was also found to be in relatively healthy condition under a precautionary assessment framework. This relatively favorable status offers an opportunity to implement precautionary management practices that maintain stock productivity and prevent overfishing before it becomes a concern (FAO 1995; Fisheries and Oceans Canada 2009). In conclusion, managing snapper fisheries in the Northeast of Brazil requires a multifaceted approach that integrates ecosystem considerations, climate change adaptation, precautionary principles, and strong stakeholder involvement. The present assessment underscores the critical role of improved data collection to enhance the accuracy and reliability of stock assessments to support evidence-based management. Our assessment highlights the limitations imposed by inconsistent or missing data, particularly in later years of the assessed period, which limits detecting recent changes in fishing pressure, recruitment, and biomass. Establishing a systematic and continuous data collection program, including standardized catch records, biological sampling of length, age, and maturity, and fishery-independent surveys, is critical for reducing uncertainty in model estimates and strengthening the scientific basis of future assessments and the development of more responsive and precautionary management strategies (FAO 2005). Lack of a management response is a significant challenge in fisheries management in Northeast Brazil. Effective fisheries management requires integration of peer-reviewed science into decision-making processes, moving beyond academic stock assessments toward actionable management advice (Hilborn 2011). This highlights a need for more responsive and dynamic management that uses scientific data to foster collaboration among researchers, policymakers, and stakeholders. Strengthening the link between stock assessments and management actions through comprehensive and adaptive strategies will be crucial for ensuring the long-term sustainability of fish stocks and the communities that depend on them (Alcock 2004). Based on model results for L. analis, L. jocu, and L. synagris, these three fisheries are at risk if current fishing effort continues. This serves as an example of small-scale fisheries struggling due to neglect, with no consistent data collection or stock assessments. For O. chrysurus, although the fishery is currently at safe levels, increasing fishing pressure could lead to a precarious situation without proper management measures. Therefore, catch accounting, data collection, and accurate life history estimates are needed to reduce uncertainty in results of stock assessments for these species, so we recommend these four species be prioritized for inclusion in future Brazilian fisheries management plans, including continuous on-site monitoring (i.e., recording landings and discards), control, and surveillance of the fisheries, along with continuous collection of biological samples, as well as for other species that share similar life history traits or are associated with similar demersal fisheries on the Northeast coast. The protocol followed in this work, including life-history parameters estimation, stock assessment, and sensitivity analysis, can be replicated for other species of the Brazilian Northeast coast and elsewhere.

Broader Management Implications

Management of snapper stocks in Northeast Brazil cannot be considered in isolation because fisheries are multispecies and of low selectivity (Lessa 2006; Lucena-Frédou et al. 2021). Gear used by these fisheries often captures multiple species, so management must be part of an interconnected system, rather than focusing on single-species stock assessments (Frédou 2009b). This multi-species perspective aligns with the principles of Ecosystem-Based Fishery Management (EBFM), which advocates for a holistic approach that incorporates ecological relationships, such as predator-prey dynamics, habitat dependencies, and species interactions, into management plans (Garcia 2003). The four assessments presented here enhance understanding of the status of snapper stocks in Northeast Brazil, where stock assessments and data-driven management are limited. Our results are intended to inform ongoing discussions within local fisheries co-management councils and governmental bodies, such as the Brazilian Ministry of Fisheries (MPA) and the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA), particularly as Brazil advances toward more structured and adaptive fishery management. Given the multispecies nature of these fisheries and data gaps in the region (MMA 2006; Lessa, Bezerra Júnior and Nóbrega 2004), this information can aid in prioritizing management actions, particularly when addressing data-poor fisheries. Currently, no harvest control rules, or species-specific management plans exist for these stocks, so stock status information is essential for prioritizing management actions (Frédou et al 2017; Silva et al 2021; Silva et al 2025). In the absence of data-rich assessments, our results can support the implementation of precautionary measures, including spatial or seasonal closures and participatory monitoring strategies. In addition to ecosystem complexities, climate change must be integrated into management strategies to ensure long-term sustainability of snapper fisheries. Effects of climate change, such as ocean warming, changes in current patterns, and acidification are likely to alter fish distributions, reproductive cycles, and habitat suitability (Cheung et al. 2009; Petitgas et al. 2013; Sydeman et al. 2015). Such changes could exacerbate challenges already faced by multispecies fisheries, highlighting the need to incorporate climate-related variables into stock assessments and management plans (Vinther et al 2004; Dolan et al 2016). For instance, future management strategies could include adaptive measures that allow for flexible response to shifting species distributions or altered ecosystem productivity, to ensure management is still relevant under changing environmental conditions.

Our findings are relevant for future applications, such as Marine Spatial Planning (MSP) or Management Strategy Evaluation (MSE) frameworks tailored for the region. Adopting a precautionary approach within an adaptive management framework is crucial for addressing ecological and environmental uncertainties by promoting conservative catch limits and allowing for adjustments as new data become available to ensure management remains responsive to real-time ecosystem changes (Rodriguez-Perez et al

2023). MSE can be valuable for enabling testing of management strategies and, by simulating possible outcomes, it can identify the most effective strategies under conditions of uncertainty, as a key component of adaptive fisheries management in dynamic, data-poor fisheries (Butterworth 2007, 2008), like those in the Northeast of Brazil. However, effective fisheries management is not solely about ecological and environmental considerations but must also account for socioeconomic realities of communities that depend on these resources (Garcia 2003; Rodriguez-Perez 2023). Snapper fisheries are vital to the livelihoods of many local fishers (Ivo and Sousa 1988; Resende, Ferreira and Frédou 2003; Frédou, Ferreira and Letourneur 2009a), so management strategies need to balance ecological sustainability with socioeconomic well-being. Co-management practices that involve collaboration among government agencies, fishers, and local communities offer a pathway to achieving this balance. By involving stakeholders directly in decision-making, co-management can foster local stewardship, improve compliance with regulations, and ensure management is grounded in local knowledge and experience, while support for alternative livelihoods during closed seasons or stock recovery periods can help alleviate economic pressures on fishers to ensure short-term sacrifices lead to long-term benefits (Berkes 2009; Motta et al 2022).

To integrate these considerations effectively, MSP and other management options like the Precautionary Approach (Dowling et al. 2019; Ono, Langangen and Stenseth 2019; Mildenberger et al. 2022) are valuable tools that can be employed. MSP facilitates the organization of ocean space to minimize conflicts and promote sustainable resource use by identifying and protecting critical habitats. A spatially explicit approach is particularly relevant for multispecies fisheries, such as snapper fisheries, by helping to safeguard essential fish habitats and optimize the allocation of ocean resources (Frédou 2009b). By combining MSP with precautionary and adaptive management strategies, fisheries management in the Northeast of Brazil can become more resilient to environmental and socioeconomic changes, by ultimately supporting sustainability of fish stocks and reliant communities.

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Figures

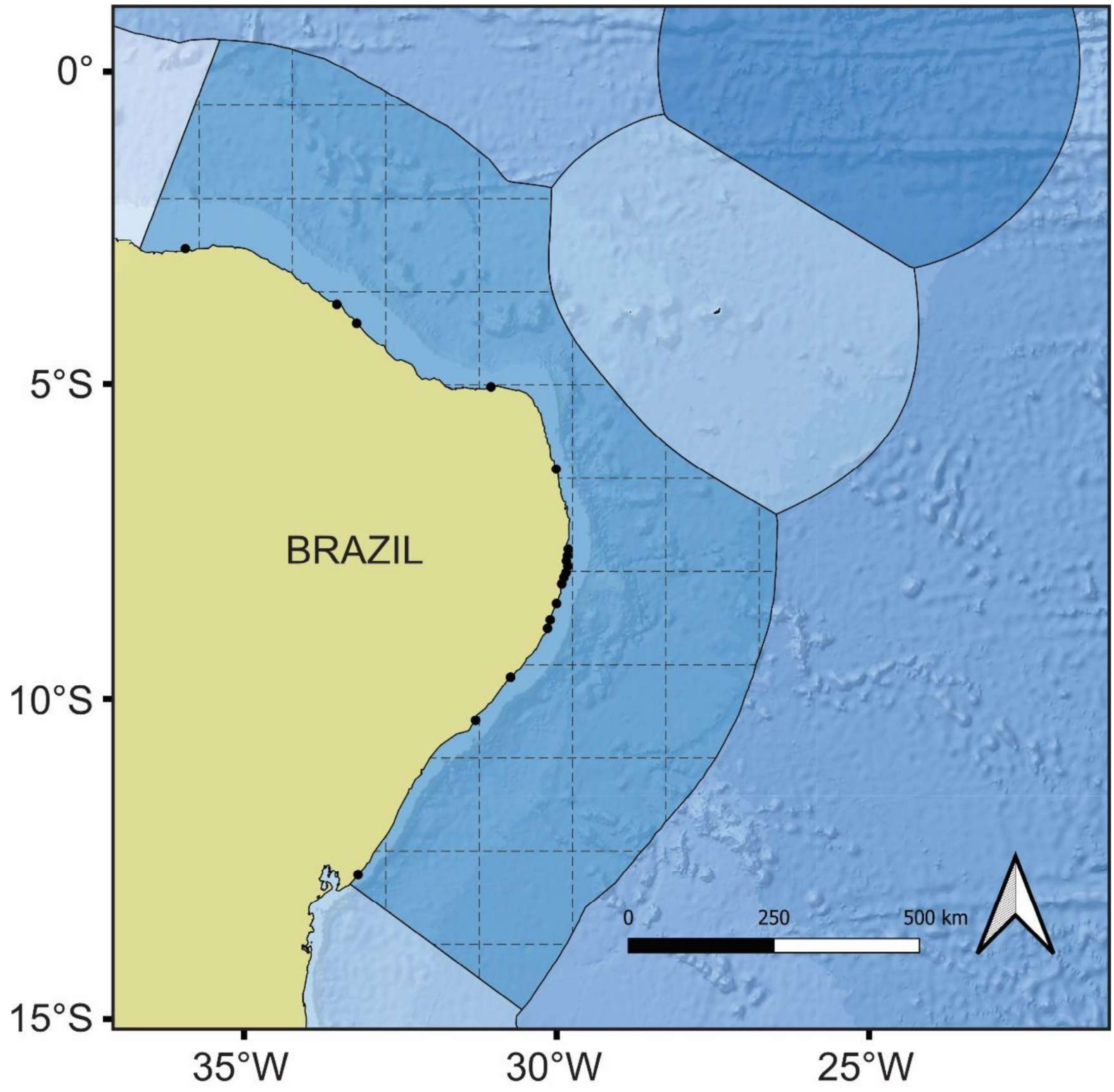

Figure 1: Study area with delimitations of Marine Ecoregions on the Northeastern coast of Brazil. The cross-hatched area represents the snapper stock area in the Northeast Brazil ME. Black dots along the coast represent landing ports.

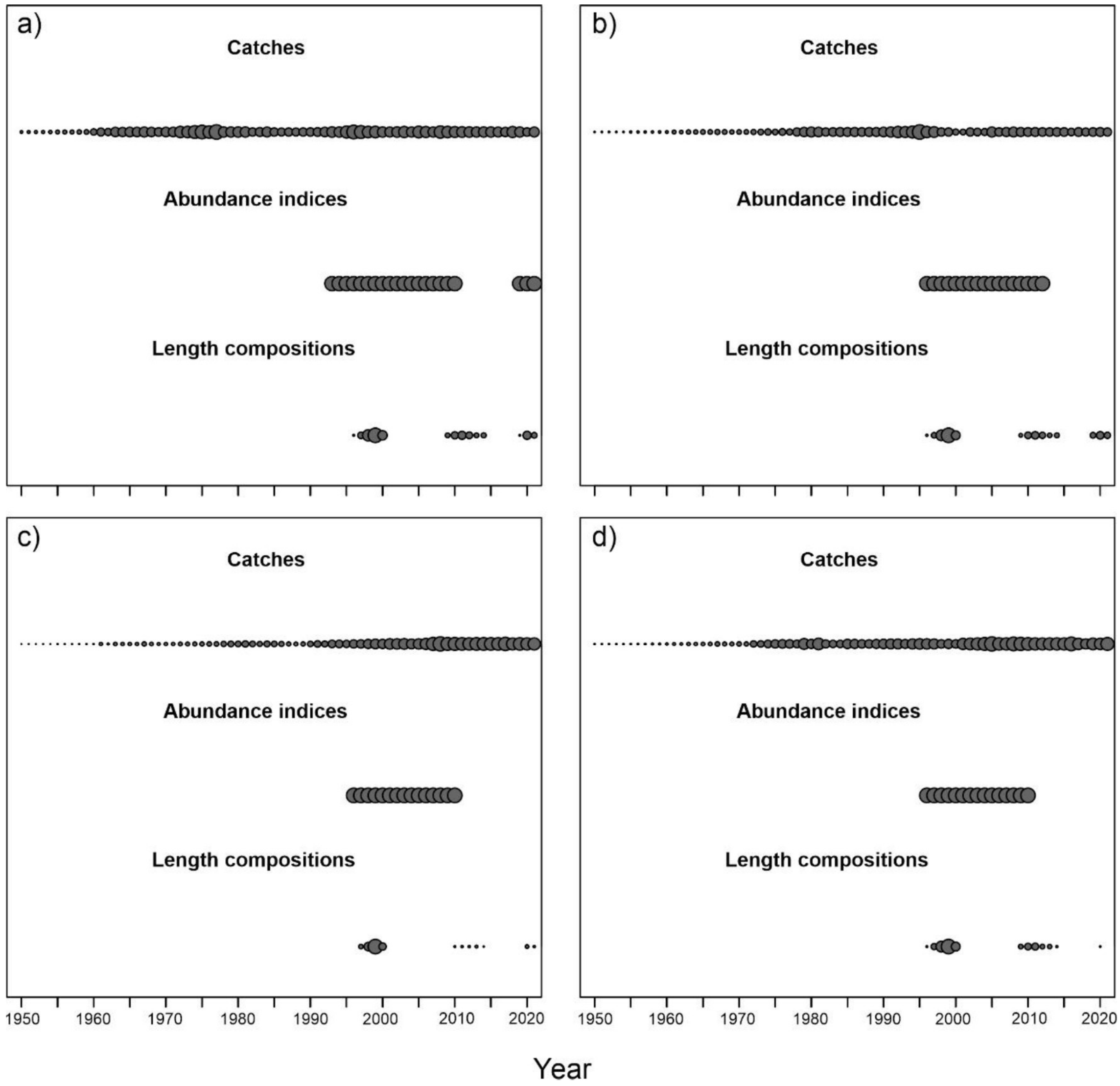

Figure 2: Catches, abundance indices, and length compositions used in stock assessments of (a) *Lutjanus analis*, (b) *Lutjanus jocu*, (c) *Lutjanus synagris*, and (d) *Ocyurus chrysurus* along the northeastern Brazilian coast during 1950–2021. Bubble sizes are scaled top represent the absolute values of catches, abundance indices, and the number of individuals measured for length compositions.

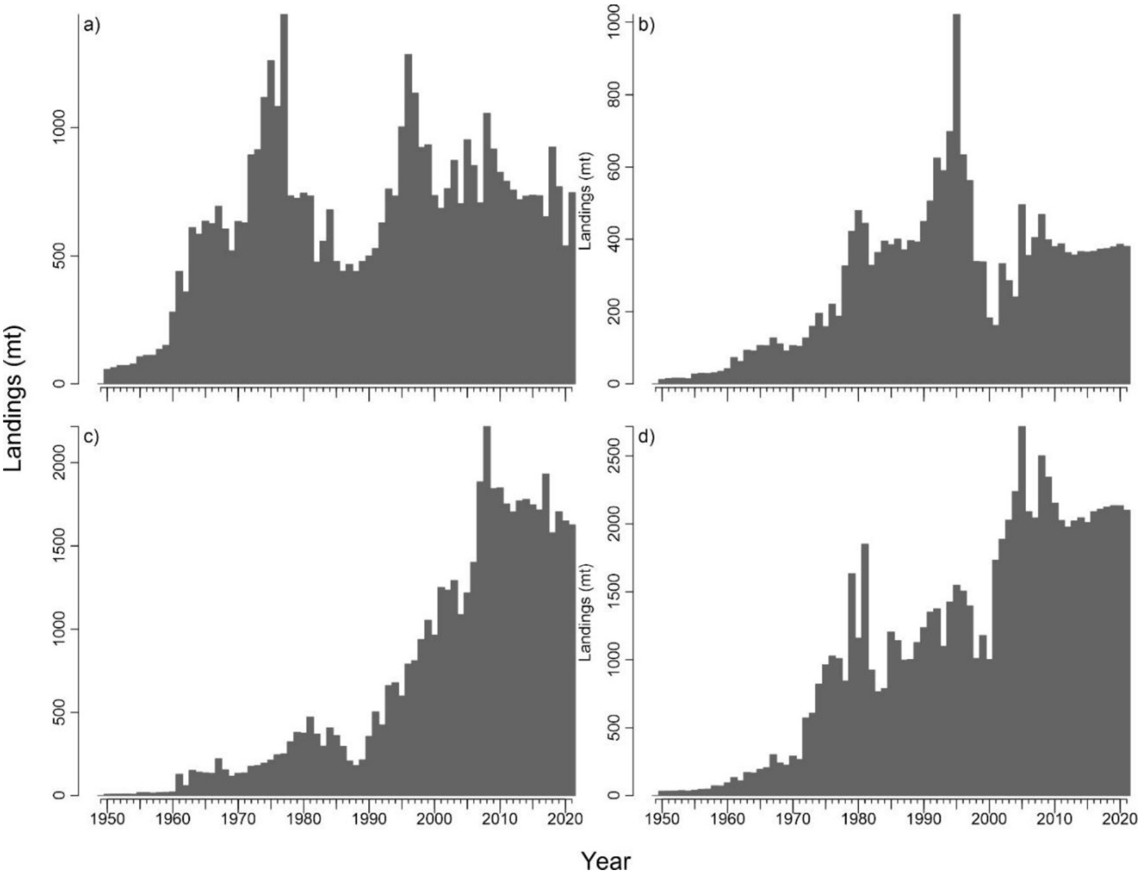

Figure 3: Landings of (a) *Lutjanus analis*, (b) *Lutjanus jocu*, (c) *Lutjanus synagris*, and (d) *Ocyurus chrysurus* along the northeastern Brazilian coast during 1950–2021.

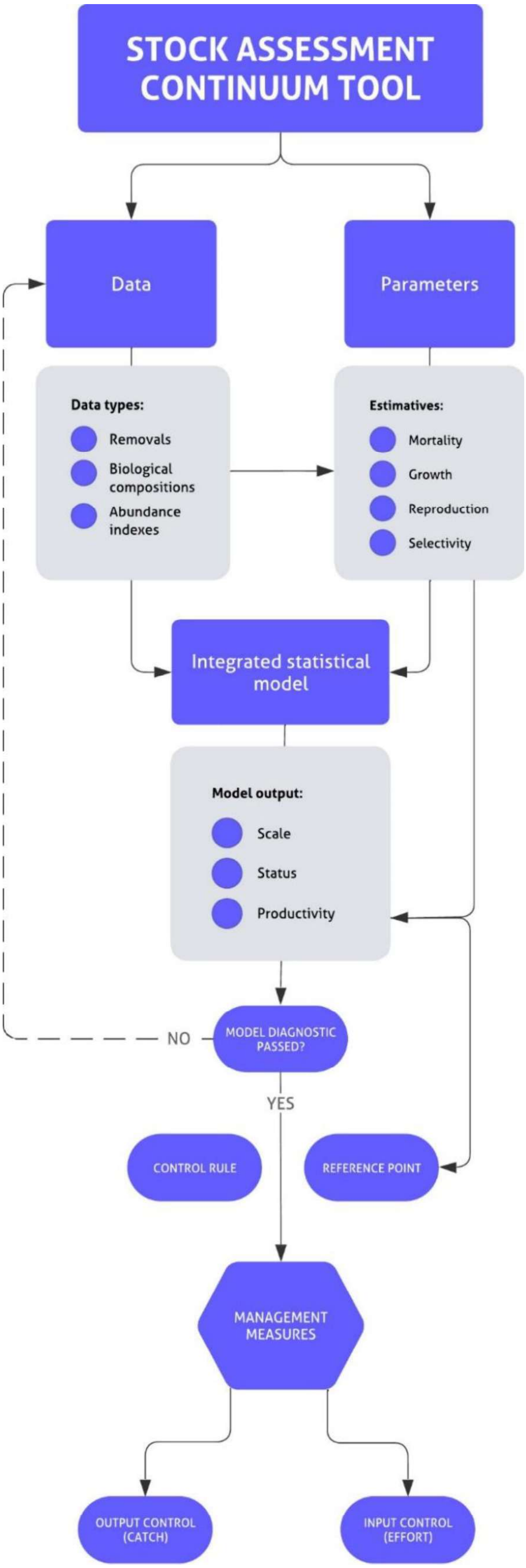

Figure 4: Flow chart illustrating the Stock Assessment Continuum Tool work path used to assess status of stocks of (a) *Lutjanus analis*, (b) *Lutjanus jocu*, (c) *Lutjanus synagris*, and (d) *Ocyurus chrysurus* along the northeastern Brazilian coast during 1950–2021. solid arrows

indicate guidance regarding flow of the process from the top to the bottom. The dotted line indicates a detour path if diagnostic tests fail.

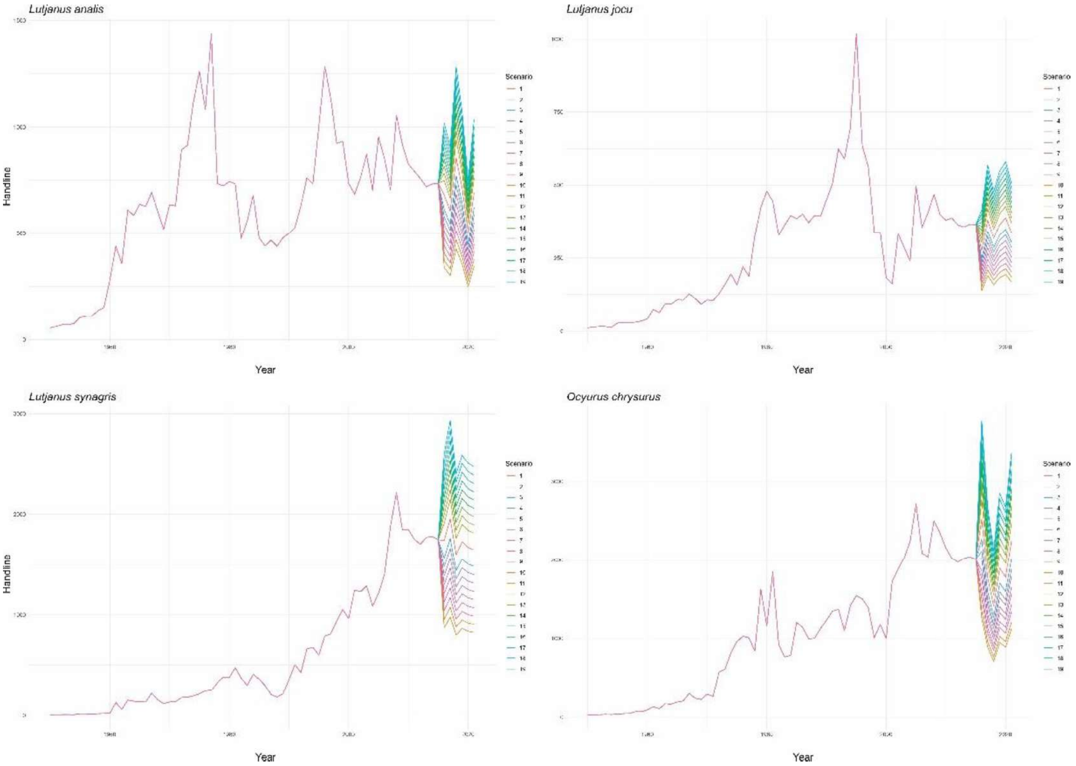

Figure 5: Alternative catch scenarios for 2016–2021 used in sensitivity analyses of stock status estimates of (a) *Lutjanus analis*, (b) *Lutjanus jocu*, (c) *Lutjanus synagris*, and (d) *Ocyurus chrysurus* along the northeastern Brazilian coast during 1950–2021. Each line represents a hypothetical catch trajectory, scaled by ±10% to ±50% (in 5% increments) relative to the base scenario while preserving the original scale.

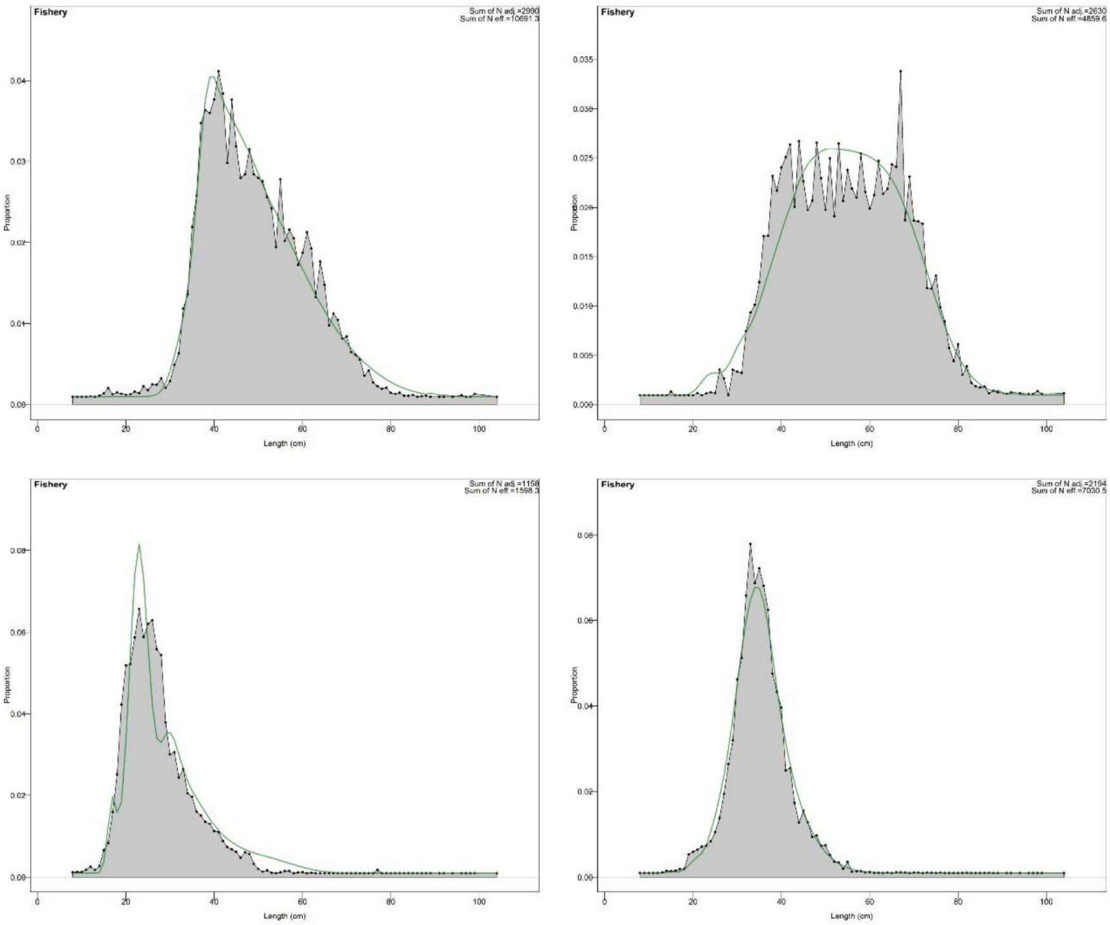

Figure 6: Length distributions of (a) *Lutjanus analis*, b) *Lutjanus jocu*, c) *Lutjanus synagris*, and d) *Ocyurus chrysurus* sampled along the northeastern Brazilian coast during 1950–2021. Dots indicate observed values, and green lines indicate model estimates.

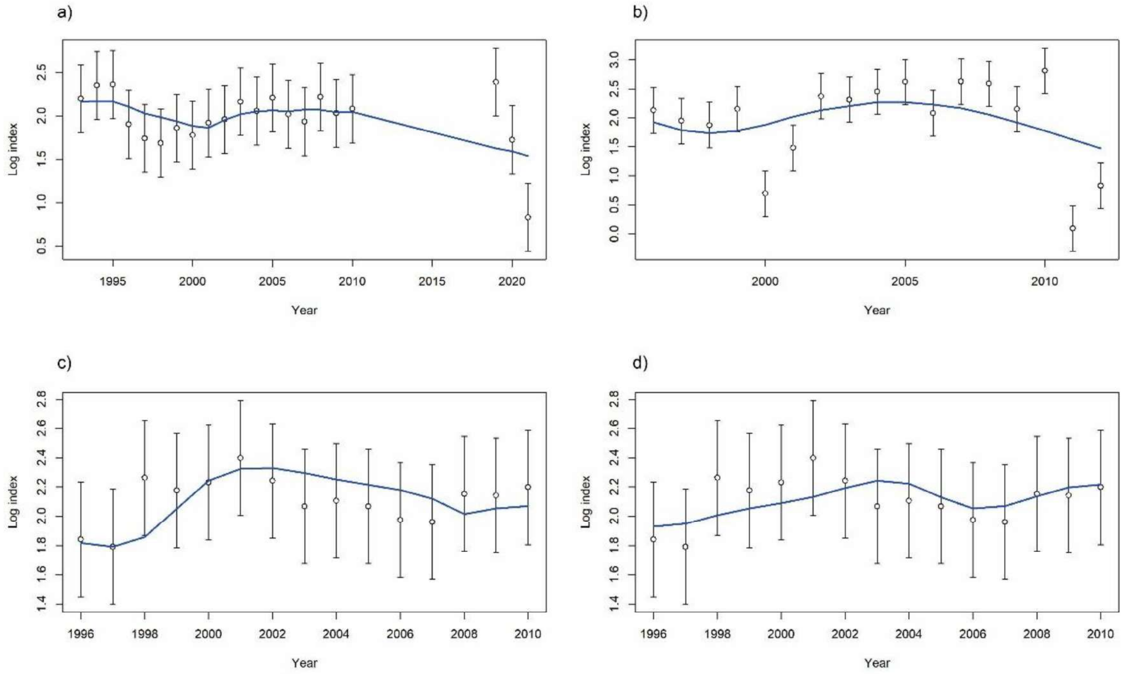

Figure 77: Index of abundance of a) *Lutjanus analis*, b) *Lutjanus jocu*, c) *Lutjanus synagris*, and d) *Ocyurus chrysurus* sampled along the northeastern Brazilian coast during 1950–2021. Dots represent observed values, blue lines indicate model estimates, and vertical lines indicate coefficient of variation.

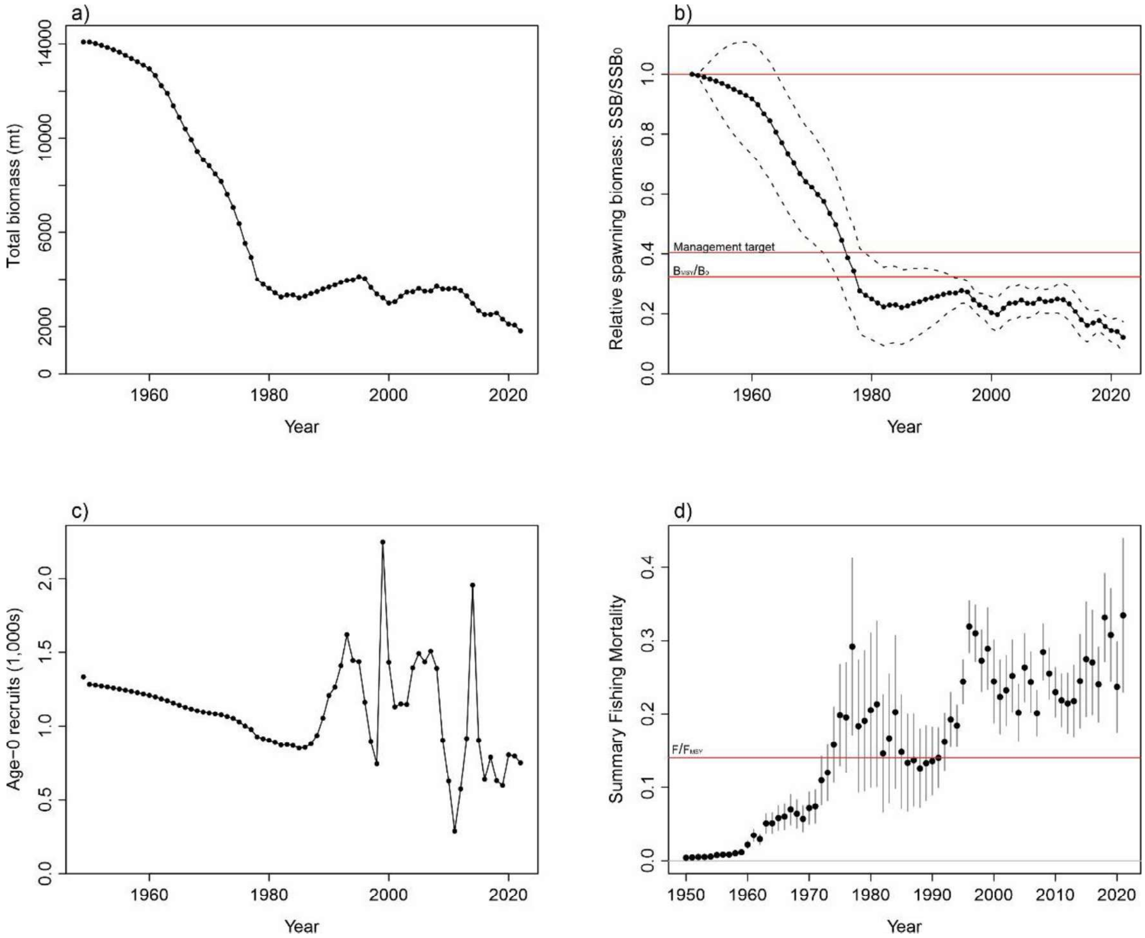

Figure 88: Spawning stock biomass (SSB) (a), relative spawning biomass SSB⁄SSB0 (red horizontal lines represent relative SSB at MSY and the management goal of 25% above MSY) (b), age-0 recruitment (c), and fishing mortality (red horizontal line represents fishing mortality at MSY) (d) estimated by the Stock Assessment Continuum Tool for *Lutjanus analis* along the northeastern Brazilian coast during 1950–2021.

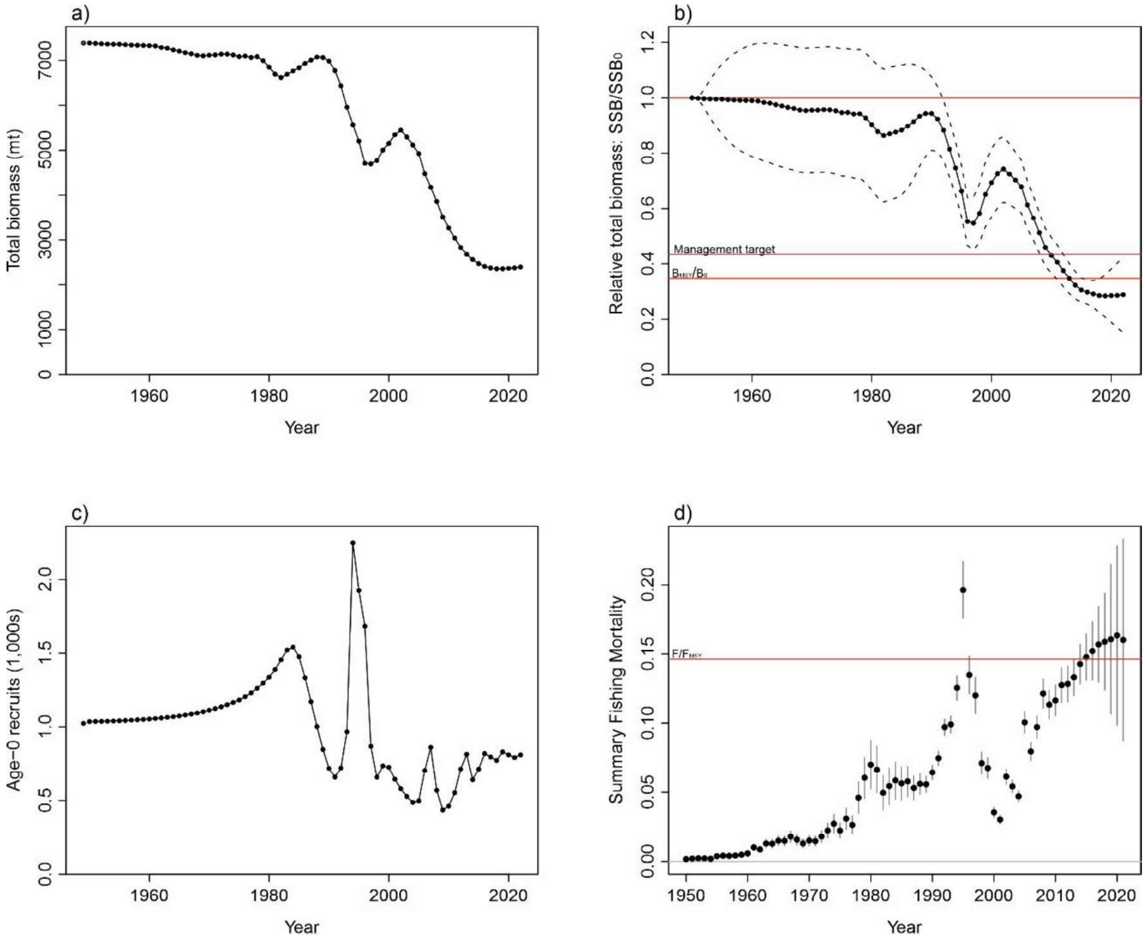

Figure 99: Spawning stock biomass (SSB) (a), relative spawning biomass SSB⁄SSB0 (red horizontal line represents relative SSB at MSY and the management goal of 25% above MSY) (b), age-0 recruitment (c), and fishing mortality (red horizontal line represents fishing mortality at MSY) (d) estimated by the Stock Assessment Continuum Tool for *Lutjanus jocu* along the northeastern Brazilian coast during 1950–2021.

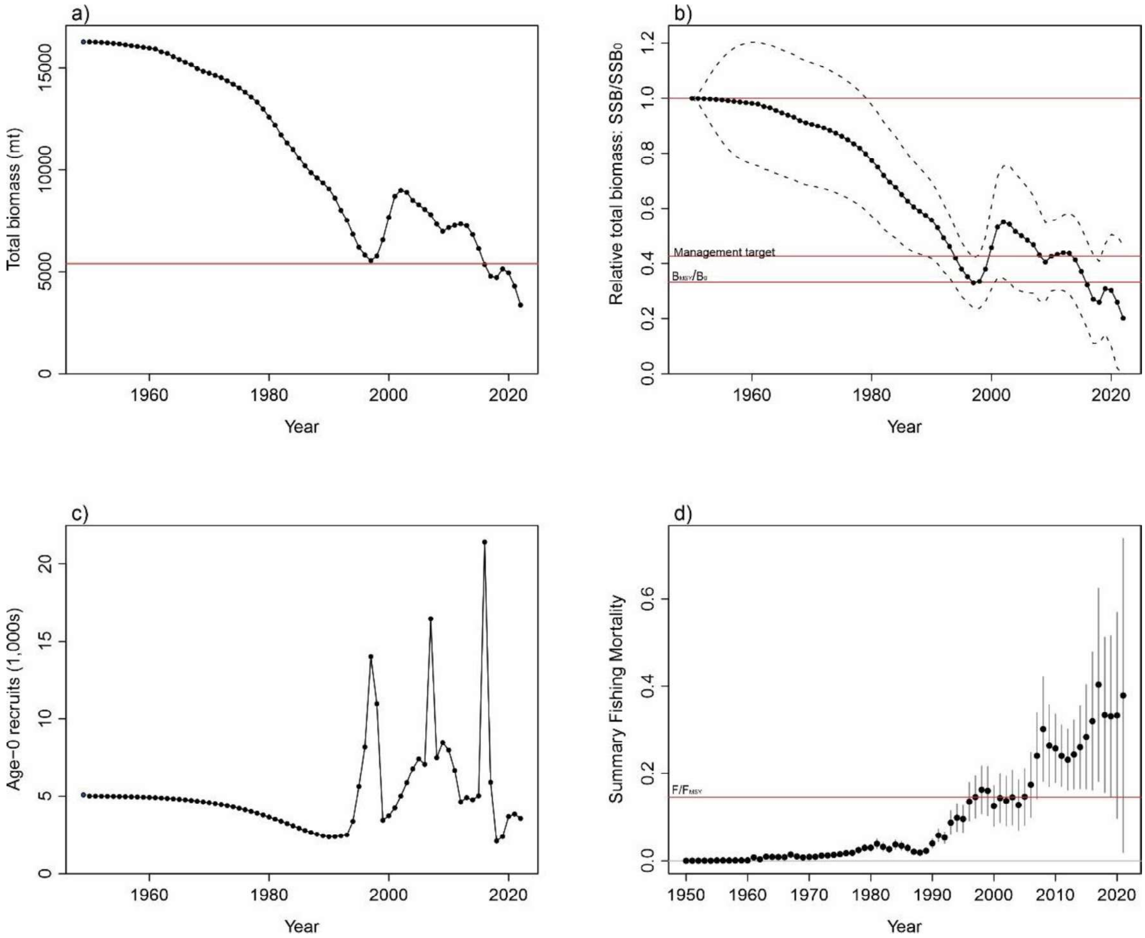

Figure 1010: Trajectory of stock spawning biomass (SSB) (a), relative spawning biomass SSB⁄SSB0 (red horizontal line representing the relative SSB at the MSY and the management goal of 25% above MSY) (b), age-0 recruitment (c), and fishing mortality (red horizontal line representing the fishing mortality at the MSY) (d) estimated by the Stock Assessment Continuum Tool for *Lutjanus synagris* in the Northeast Brazil between 1950 and 2021.

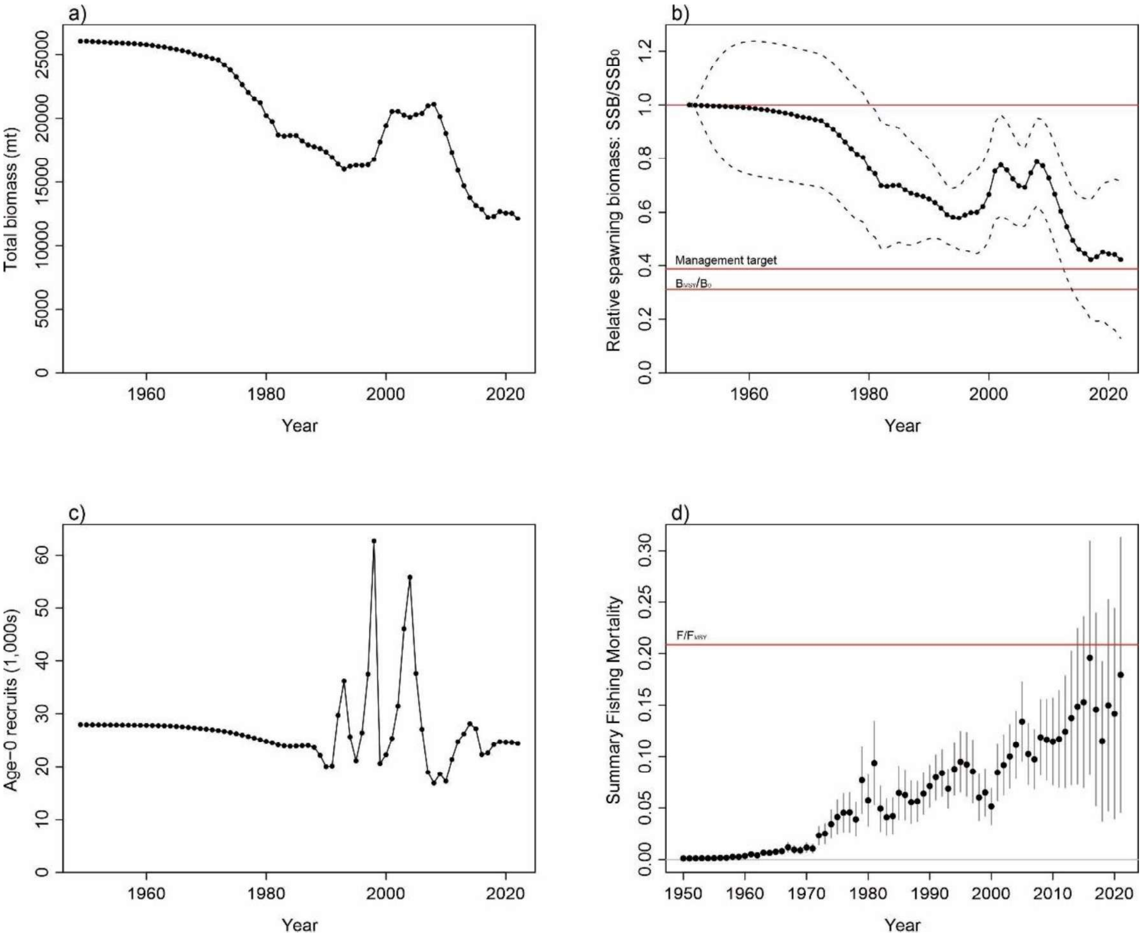

Figure 1111: Trajectory of stock spawning biomass (SSB) (a), relative spawning biomass SSB/SSB0 (red horizontal line representing the relative SSB at the MSY and the management goal of 25% above MSY) (b), age-0 recruitment (c), and fishing mortality (red horizontal line representing the fishing mortality at the MSY) (d) estimated by the Stock Assessment Continuum Tool for *Ocyurus chrysurus* in the Northeast Brazil between 1950 and 2021.

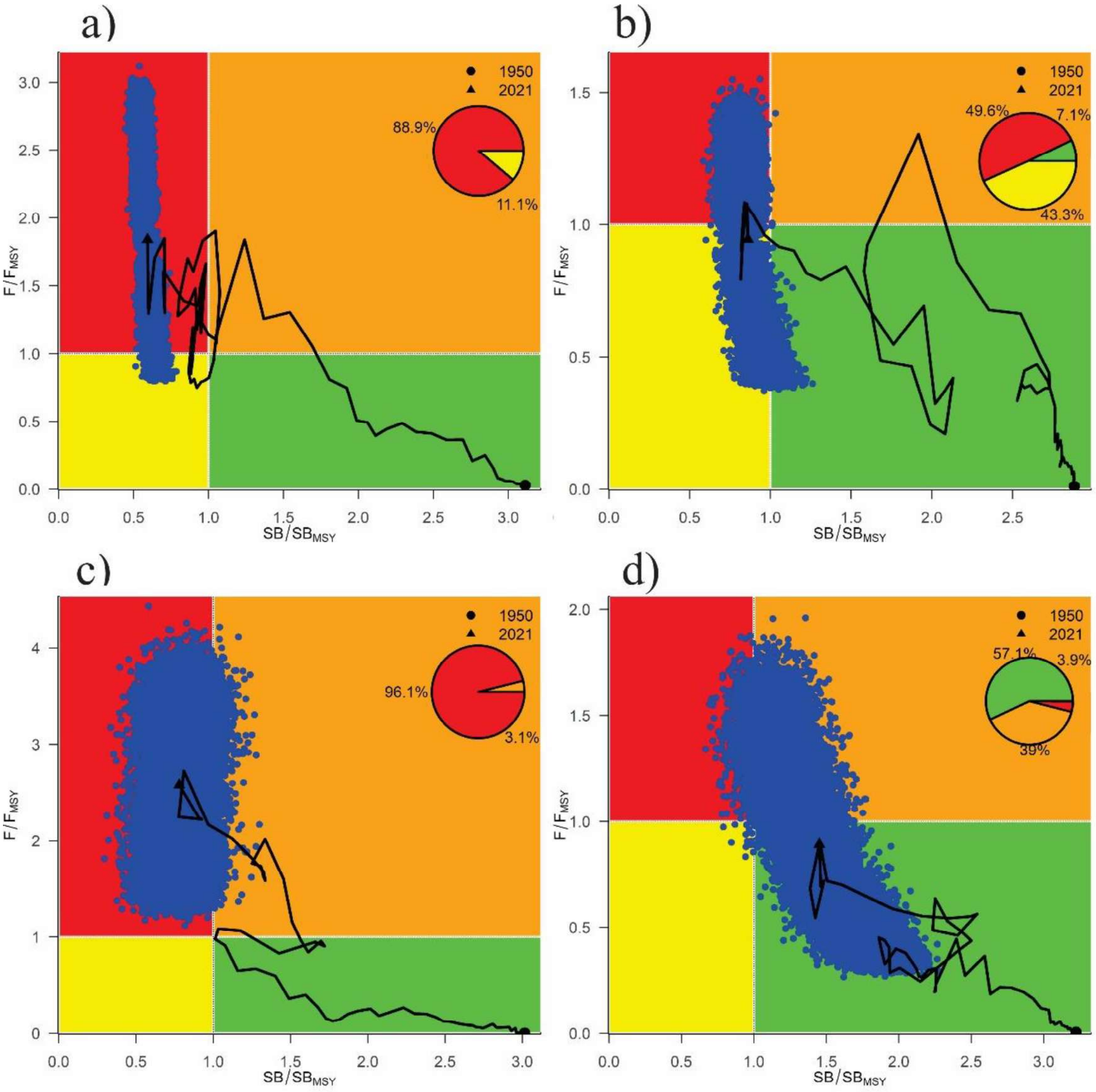

Figure 12: Relative fishing mortality (F) in relation to relative spawning stock biomass (SSB) of a) *Lutjanus analis*, b) *Lutjanus jocu*, c) *Lutjanus synagris*, and d) *Ocyurus chrysurus* sampled along the northeastern Brazilian coast during 1950–2021. Red (top left) corresponds to "overfished and under overfishing"; green panel (bottom right) corresponds to "under no risk"; yellow (lower left) corresponds to "overfished"; and orange (upper right) corresponds to "under overfishing". Blue dots represent individual bootstrap runs for each combination of randomly sampled F and SSB . Pie charts indicate the probability of each species falling within each risk category.

Tables

Table 1: Input parameters used in the Stock Assessment Continuum Tool reference model for a) *Lutjanus analis*, b) *Lutjanus jocu*, c) *Lutjanus synagris*, and d) *Ocyurus chrysurus* sampled along the northeastern Brazilian coast during 1950–2021 (sources: 1 – Lessa, Bezerra Júnior and Nóbrega 2004; 2 – Previero et al. 2011; 3 – Schwamborn et al. 2023, 4 – Araújo, Martins and Costa 2002).

Parameter	*Lutjanus analis*			*Lutjanus jocu*			*Lutjanus synagris*			*Ocyurus chrysurus*		
	Value	CI	Source	Value	CI	Source	Value	CI	Source	Value	CI	Source
Maximum age A_{max}	29	-	1	29	-	1	22	-	1	19	-	1
Mean age at 50% maturity A_{50}	2.27	-	1	2.89	-	1	1.81	-	1	2.24	-	1
VBGF Asymptotic length L_{∞}	92.3	-	Fishlife	87.8	-	2	59.7	-	3	56.7	-	4
VBGF growth coefficient ${k_{yr}}^{-1}$	0.16	-	Fishlife	0.10	-	2	0.20	-	3	0.13	-	4
VBGF Age at length 0 t_0	NA	-	Fishlife	-1.49	-	2	NA	-	3	-0.77	-	4
Mean length at 50% maturity L_{50}	28.00	-	1	32.4	-	1	18.1	-	1	20.1	-	1
Mean length at 95% maturity L_{95}	34.00	-	1	36.4	-	1	23.3	-	1	26.0	-	1
Natural Mortality M	0.21	0.17 – 0.25	-	0.22	0.19 – 0.25	-	0.24	0.20 – 0.28	-	0.29	0.25 – 0.34	-
WL relationship - α	0.02	-	1	0.02	-	1	0.01	-	1	0.03	-	1
WL relationship - β	2.96	-	1	2.97	-	1	3.08	-	1	2.74	-	1
Weight-based fecundity coefficient	0.02	-	-	0.02	-	-	0.01	-	-	0.03	-	-
Weight-based fecundity exponent	2.96	-	-	2.97	-	-	3.08	-	-	2.74	-	-
Steepness h	0.70	-	-	0.70	-	-	0.70	-	-	0.70	-	-

Table 2: Spawning stock biomass (SSB), catch at maximum sustainable yield (MSY), stock biomass at MSY, SSB in 2021 in relation to SSB at MSY, fishing mortality at MSY, fishing mortality in 2021 in relation to fishing mortality at MSY, and stock biomass status estimated with the Stock Assessment Continuum Tool for *Lutjanus analis*, *Lutjanus jocu*, *Lutjanus synagris*, and *Ocyurus chrysurus* sampled along the northeastern Brazilian coast during 1950–2021.

Parameter	*Lutjanus analis*		*Lutjanus jocu*		*Lutjanus synagris*		*Ocyurus chrysurus*		Dimension
	Estimates	SD	Estimates	SD	Estimates	SD	Estimates	SD	
Spawning stock biomass unfished	7,500	236	3,348	209	8,090	631	11,793	1,412	Tons
Catch at maximum sustainable yield (MSY)	638	20	403	25	807	63	1,941	228	Tons
Stock Spawning Biomass at MSY (SSB_{MSY})	2,409	76	1,162	72	2,683	210	3,659	433	Tons
SSB_{2021}/SSB_{MSY}	0.586	-	0.814	-	0.779	-	1.422	-	-
Fishing mortality at MSY (F_{MSY})	0.126	0.001	0.146	0.001	0.146	0.001	0.208	0.002	$Year^{-1}$
F_{2021}/F_{MSY}	1.831	-	1.002	-	2.629	-	0.859	-	-
Stock biomass status	Overexploited and under overexploitation		Overexploited and under slight overexploitation		Overexploited and under heavy overexploitation		Underexploited and not under overexploitation		-

Considerações finais

A exploração pesqueira no Brasil em geral é historicamente marcada pela limtação robustos, dificultando tanto a avaliação dos estoques quanto a implementação de políticas adequadas de manejo. Nesse contexto, as questões centrais deste estudo foram: (a) a viabilidade de modelos para dados limitados como alternativa métodos tradicionais e (b) a necessidade de atualização do estado dos estoques das principais espécies de lutjanídeos exploradas comercialmente. A partir de uma abordagem metodológica atual, esta tese buscou responder a essas questões e contribuir para o fortalecimento da gestão sustentável da pesca no Brasil, sendo seus resultados apresentados em dois artigos científicos que compõem o núcleo do trabalho.

O primeiro artigo avaliou o desempenho de modelos para dados limitados em comparação com abordagens tradicionais considerando pescarias tropicais de pequena escala. Diferentes configurações foram testadas utilizando o Stock Assessment Continuum Tool, escolhido por permitir a execução de avaliações sob diferentes níveis de disponibilidade de dados dentro de uma mesma estrutura de modelagem. Os resultados indicaram que, embora dependam de pressupostos mais restritivos e apresentem maior incerteza, esses modelos são capazes de fornecer diagnósticos úteis sobre o estado dos estoques em contextos onde os dados são escassos ou fragmentados. Entre as abordagens disponíveis, modelos baseados em comprimento mostram-se particularmente adequados para pescarias artesanais, uma vez que se utilizam de dados relativamente simples e baratos de coletar e permitem inferências objetivas sobre o estado do estoque (Medeiros-Leal et al., 2023). Em contraste, modelos baseados apenas em captura podem ser úteis para estimativas de produtividade e limites de captura, mas dependem de pressupostos fortes sobre a relação entre captura e biomassa, frequentemente difíceis de sustentar em pescarias multiespecíficas e pouco monitoradas. Assim, a escolha do método deve sempre considerar a disponibilidade e qualidade das informações, bem como a biologia das espécies avaliadas.

O segundo artigo apresentou uma atualização do estado dos estoques das quatro principais espécies de lutjanídeos exploradas no Nordeste do Brasil, representando a primeira avaliação abrangente dessas espécies em aproximadamente duas décadas. Utilizando dados de captura, composições de comprimento, índices de abundancia e parâmetros de produtividade dentro da estrutura do SAC Tool, foi possível estimar biomassa e mortalidade relativas mesmo em um contexto de dados limitados. Os resultados indicam que três das quatro espécies avaliadas apresentam elevada probabilidade de se encontrarem simultâneamente sobrepescadas e sob sobrepesca, enquanto *Ocyurus chrysurus* apresenta situação relativamente mais confortável, embora ainda sujeita a risco caso o esforço de pesca siga aumentando. Esses resultados evidenciam a necessidade de medidas de manejo capazes de reduzir a pressão pesqueira e favorecer a recuperação dos estoques.

A discussão integrada dos dois estudos reforça o papel estratégico dos modelos para dados limitados em regiões como o Nordeste do Brasil, onde limitações logísticas e financeiras dificultam a coleta contínua de informações pesqueiras. Mesmo sob condições adversas, é possível gerar estimativas consistentes que subsidiem decisões de manejo, embora a qualidade das avaliações dependa diretamente da melhoria contínua dos sistemas de monitoramento.

Os resultados obtidos possuem implicaões diretas para a gestão pesqueira nacional. A condição crítica observada para parte das espécies indica a urgência de ações voltadas à redução da mortalidade por pesca, incluindo medidas como restrições sazonais, áreas de proteção marinha e instrumentos de planejamento espacial marinho. Igualmmente importante é a integração da comunidade pesqueira no processo de tomada de decisão, uma vez que o sucesso de qualquer política de manejo depende do envolvimento e da aceitação dos principais atores. A abordagem adotada nesta tese, baseada na utilização de uma estrutura integrada capaz de acomodar diferentes tipos e níveis de dados, oferece ainda um caminho replicável para avaliação de outras espécies com características ecológicas semelhantes, contribuindo para a paronização e ampliação de avaliações em regiões com limitação de informações.

Conclui-se, portanto, que esta tese não apenas respondeu às questões científicas inicialmente propostas, como também demonstrou a aplicabilidade prátioca de modelos para dados limitados na avaliação e gestão de pescarias tropicais. Ao combinar avanços metodológicos com diagnósticos atualizados do estado dos estoques, o estudo contribui para o desenvolvimento de estratégias mais sustentáveis de exploração dos recursos marinhos. Mais do que isso, evidencia a necessidade de um compromisso contínuo com a coleta de dados, o aprimoramento das políticas de manejo e a integração entre ciência, gestão e sociedade, elementos essenciais para garantir a sustentabilidade ecológica e socioeconômica das pescarias e das comunidades que elas dependem.

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