UNICA

UNIVERSITÀ
DEGLI STUDI
DI CAGLIARI

Ph.D. DEGREE IN
Life, Environmental and Drug Sciences

Cycle XXXVII

TITLE OF THE Ph.D. THESIS

Study on fisheries resources with particular reference to red coral, spiny lobster and other target demersal species in Sardinian Seas

Scientific Disciplinary Sectors

BIOS-03/A

Ph.D. Student: Isabella Bitetto

Supervisor Maria Cristina Follesa

Final exam. Academic Year 2023/2024
Thesis defense session: July 2025

Summary

Abstract

This PhD thesis contributes to the sustainable management of marine resources in Sardinian waters by addressing critical knowledge gaps in the assessment of key commercial species: red mullet (*Mullus barbatus*), red coral (*Corallium rubrum*) and spiny lobster (*Palinurus elephas*). These resources represent both ecological keystones and economic pillars for regional small-scale fisheries, yet have historically suffered from insufficient scientific evaluation.

The first part of the research presents the inaugural stock assessment of red mullet in Geographical Sub-Area 11 (GSA 11), using data-rich, age-structured models (Extended Survivors Analysis, XSA). The results revealed a sustainably exploited stock, suggesting opportunities for adaptive management and compensation for effort restrictions under the Western Mediterranean Multiannual Management Plan.

The second part focuses on red coral, applying a suite of data-poor models (CMSY, SPiCT and LBSPR) to two distinct populations in northern and north-western Sardinia. This novel application highlighted key biological differences and unsustainable exploitation under current legal size limits. Area-specific management recommendations, including revised minimum conservation reference sizes and effort reductions, were proposed to promote long-term sustainability.

The third part delivers the first stock assessment of spiny lobster in the Asinara Marine Protected Area (MPA), revealing overexploitation driven by a mismatch between capture size and maturity. This assessment establishes a critical baseline for future MPA performance evaluations and highlights the utility of length-based methods in data-limited contexts.

Overall, this thesis integrates modern stock assessment approaches with local monitoring data to deliver actionable insights for management. It reinforces the value of combining biological evidence and adaptive strategies in Mediterranean fisheries. The outcomes support the development of sustainable, resilient fisheries policies in Sardinian waters, aligning ecological conservation with socio-economic viability.

Questa tesi di dottorato contribuisce alla gestione sostenibile delle risorse marine nelle acque sarde affrontando lacune conoscitive critiche nella valutazione di specie commerciali chiave: la triglia di fango (*Mullus barbatus*), il corallo rosso (*Corallium rubrum*) e l'aragosta (*Palinurus elephas*). Queste risorse rappresentano sia elementi ecologici chiave che pilastri economici per la pesca artigianale regionale, ma storicamente hanno sofferto di un'insufficiente valutazione scientifica.

La prima parte della ricerca presenta la prima valutazione in assoluto dello stock di triglia di fango nella Sottoarea Geografica 11 (GSA 11), utilizzando modelli strutturati per età di tipo data-rich (Extended Survivors Analysis, XSA). I risultati hanno rivelato uno stock sfruttato in modo sostenibile, suggerendo opportunità per una gestione adattativa e la compensazione per le restrizioni allo sforzo nell'ambito del Piano di Gestione Pluriennale del Mediterraneo Occidentale.

La seconda parte si concentra sul corallo rosso, applicando una serie di modelli poveri di dati (CMSY, SPiCT e LBSPR) a due distinte popolazioni nella Sardegna settentrionale e nord-occidentale. Questa nuova applicazione ha evidenziato importanti differenze biologiche e uno sfruttamento insostenibile con gli attuali limiti di taglia legale. Sono state proposte raccomandazioni di gestione specifiche per area, tra cui una revisione delle taglie minime dello sbarco e riduzioni dello sforzo, per promuovere la sostenibilità a lungo termine.

La terza parte presenta la prima valutazione dello stock di aragosta nell'Area Marina Protetta (AMP) dell'Asinara, rivelando uno sfruttamento eccessivo guidato da una discrepanza tra la taglia di cattura e la maturità. Questa valutazione stabilisce una linea di base critica per le future valutazioni delle prestazioni dell'AMP ed evidenzia l'utilità dei metodi basati sulla lunghezza in contesti con dati limitati.

Nel complesso, questa tesi integra moderni approcci di valutazione dello stock con dati di monitoraggio locali per fornire informazioni utili per la gestione della pesca in Sardegna, rafforzando il valore della combinazione di evidenze biologiche e strategie adattative nella pesca mediterranea. I risultati supportano lo sviluppo di politiche di pesca sostenibili e resilienti nelle acque sarde, allineando la conservazione ecologica con la sostenibilità socio-economica.

Acronyms

Acronym	Description
ADAPT	ADaptive framework for the Analysis of Pooled Time series Gavaris (1988)
BD	Basal Diameter
BDM	Biomass Dynamic Model
BEMTOOL	Bio-Economic Modelling TOOL (Rossetto et al., 2015; Russo, Bitetto et al., 2017)
B_{MSY}	See Table 1
BSM	Bayesian Schafer Model
CAPAM	Center for the Advancement of Population Assessment Methodology
CFP	Common Fishery Policy
CI	Confidence interval (e.g. 95%)
CL	Carapax length
CMSY	Catch - Maximum Sustainable Yield (Froese et al., 2017)
CPUE	Catch-per-unit of effort
CRAN	Comprehensive R Archive Network
CREA	Consiglio per la Ricerca in Agricoltura e l'Analisi dell'Economia Agraria
CV	Coefficient of Variation
DCAC	Depletion-Corrected Average Catch
DB-SRA	Depletion-Based Stock Reduction Analysis
DCF	Data Collection Framework
DCRF	Data Collection Reference Framework
EU	European Union
FAO	Food and Agriculture Organization
FDI	Fishery Dependent Information (https://stecf.ec.europa.eu/data-dissemination/fdi_en)

Acronym	Description
FLBRP	Fisheries Library Biological Reference Points
FLR	Fisheries Library in R
F_{MAX}	See Table 1
F_{MSY}	See Table 1
GFCM	General Fisheries Commission for the Mediterranean
GSA	Geographical Sub-Area
ICES	International Council for the Exploration of the Sea
IPCC	Intergovernmental Panel on Climate Change
ISTAT	Istituto Nazionale di Statistica
IUCN	International Union for Conservation of Nature
LBB	Length-Based Bayesian Biomass (Froese et al., 2016)
LBSPR	Length-Based Spawning Potential Ratio (Hordyk et al., 2015)
MAP	WestMed Plan
MCRS	Minimum Conservation Reference Size
MEDITS	Mediterranean International Trawl Survey
MPA	Marine Protected Area
MSFD	Marine Strategy Framework Directive
MSY	Maximum Sustainable Yield
OSA	one-step ahead
PPVR	prior/posterior variance ratio
ROV	Remote Operated Vehicle
SAC	Scientific Advisory Committee on Fisheries (GFCM)
SCAA	Statistical Catch at Age
SCAL	Statistical Catch at Length
SPICT	stochastic surplus production model in

Acronym	Description
	continuous time
SPR	Spawning Potential Ratio
SSB	Spawning Stock Biomass
SSCF	Small Scale Coastal Fleet
STECF	Scientific, Technical and Economic Committee for Fisheries
VME	Vulnerable Marine Ecosystem
VPA	Virtual Population Analysis
WFD	Water Framework Directive (Directive 2000/60/EC)
WGREDCORAL	GFCM working Group on red coral
WGSAD	GFCM working Group on demersal species stock assessment
XSA	Extended Survivor Analysis
YPR	Yield per Recruit

Introduction

General context: the global fishery ecosystem

Fisheries play a fundamental role in global food security, economic development and the livelihoods of millions of people. According to the Food and Agriculture Organization (FAO), the world's capture fisheries and aquaculture produced approximately 214 million tonnes of fish in 2020, of which about 179 million tonnes were used for direct human consumption (FAO, 2022). Fish provides over 3.3 billion people with at least 20% of their average per capita intake of animal protein, making it an essential component of global nutrition. In economic terms, fisheries and aquaculture are vital to the livelihoods of more than 58 million people, highlighting the sector's significant contribution to international trade and the economies of coastal nations (FAO, 2020 and 2022).

Nevertheless, fishing can have significant negative impacts on marine ecosystems, especially if the fishing gears do not allow to exploit in a sustainable way the marine populations.

Overfishing is one of the primary threats of fishing, leading to the depletion of target species and compromising their ability to reproduce and recover. This not only reduces biodiversity but can also trigger cascading effects throughout the food web. Moreover, certain fishing methods—such as bottom trawling—cause physical damage to benthic habitats**,** including seagrass beds and coral reefs, which are essential for the survival of many marine species (Books et al., 1999; Dieter et al., 2003). Bycatch, the unintentional capture of non-target species (e.g. juvenile fish), further exacerbates ecological imbalance.

The sustainability of a fishery, meaning the capacity to preserve fish stocks and ecosystems over time while supporting economies and dependent communities, is essential to ensure that marine resources are harvested at a rate that allows populations to replenish naturally, while minimizing environmental harm and preserving the health of ecosystems for future generations (FAO, 2022).

Nowadays, the sustainability of fisheries remains a key concern. The State of World Fisheries and Aquaculture (FAO 2022) report notes that 35.4% of fish stocks are fished at biologically unsustainable levels, a trend that has continued to rise in recent decades. Overfishing, habitat degradation and climate change pose serious challenges to the long-term viability of marine ecosystems and the communities that depend on them (IPCC, 2019; Pauly et al., 2002).

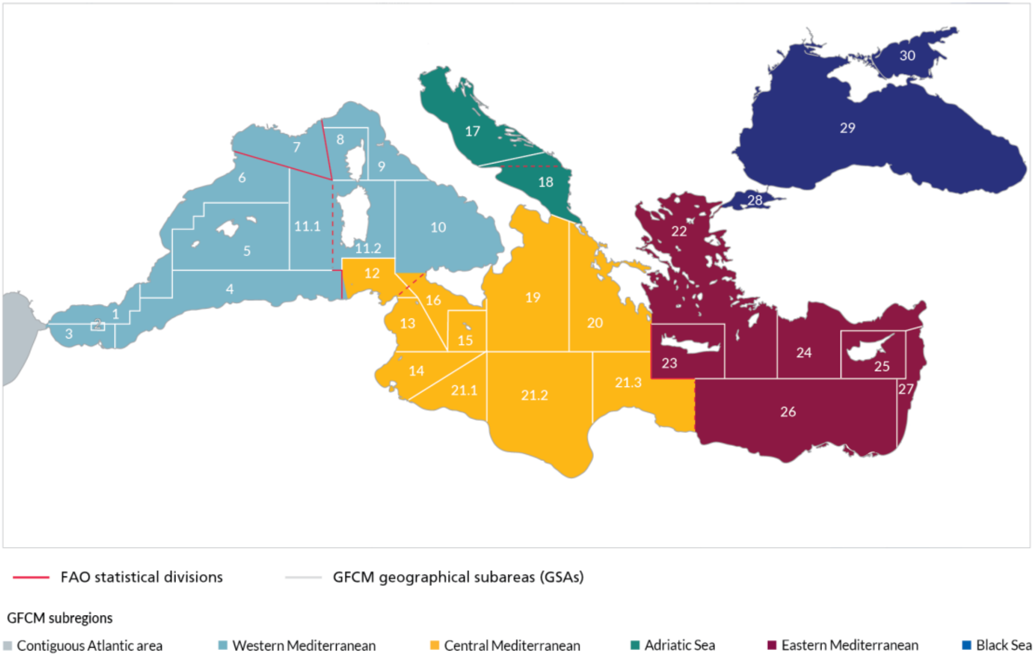
To address these challenges, stock assessment plays a critical role in the sustainable management and conservation of marine fisheries (Hilborn and Walters, 1992). Indeed, the stock assessment is the scientific process of evaluating the status and trends of a fish population respect to reference levels (reference points) of fishing pressure and biomass considered sustainable for the stock. It serves as the scientific foundation for evaluating the status of fish populations and informing the managers about how much can be harvested without compromising the long-term stocks and fisheries viability.

Mediterranean Sea: status of resources and how they are managed

The Mediterranean Sea, though rich in biodiversity and cultural heritage, presents one of the most complex systems in global fisheries. Despite representing only 1% of the world's ocean surface, it is home to nearly 10% of global marine biodiversity and sustains the livelihoods of thousands of coastal communities. However, the status of fisheries in this semi-enclosed and politically diverse region remains critical, with many fish stocks subject to high exploitation rates and the marine ecosystem under growing pressure (Coll et al., 2010; Underwood et al., 2009).

Fishing represents a vital economic and social pillar in the Mediterranean. Over 250,000 people are directly employed in the fisheries sector, particularly in small-scale fisheries, which represent about 80% of the fishing fleet (GFCM, 2020). These fisheries are deeply embedded in the cultural and economic fabric of coastal communities and often represent a valuable historical heritage for the local populations.

The General Fisheries Commission for the Mediterranean (GFCM) is a regional body, established under the FAO, responsible for promoting the sustainable management of fisheries and aquaculture in the Mediterranean and Black Sea. The Mediterranean Sea is divided in management units, named Geographical Sub-Areas (GSA, GFCM *sensu,* Figure 1) through the GFCM Resolutions GFCM/31/2007/2 and GFCM/33/2009/2.



01. Northern Alboran Sea	07. Gulf of Lion	13. Gulf of Hammamet	19. Western Ionian Sea	25. Cyprus
02. Alboran Island	08. Corsica	14. Gulf of Gabès	20. Eastern Ionian Sea	26. Southern Levant Sea
03. Southern Alboran Sea	09. Ligurian Sea and northern Tyrrhenian Sea	15. Malta	21.1. Southwestern Ionian Sea 21.2. South-central Ionian Sea 21.3. Southeastern Ionian Sea	27. Eastern Levant Sea
04. Algeria	10. Southern and central Tyrrhenian Sea	16. Southern Sicily	22. Aegean Sea	28. Marmara Sea
05. Balearic Islands	11.1. Western Sardinia 11.2. Eastern Sardinia	17. Northern Adriatic Sea	23. Crete	29. Black Sea
06. Northern Spain	12. Northern Tunisia	18. Southern Adriatic Sea	24. Northern Levant Sea	30. Azov Sea

Note: At its forty-fifth session in November 2022, the GFCM agreed to divide GSA 21 (Southern Ionian Sea) into three marine subareas. The subdivision of GSA 21 into GSAs 21.1, 21.2 and 21.3 will be applied in 2023.

Figure 1 – Map reporting the Geographical Sub-Areas defined by the GFCM in the Resolutions GFCM/31/2007/2 and GFCM/33/2009/2. Figure downloaded at: https://www.fao.org/gfcm/data/maps/gsas/en/

According to the General Fisheries Commission for the Mediterranean (GFCM) and FAO's assessments, more than 75% of assessed fish stocks in the Mediterranean are fished at unsustainable levels (GFCM, 2022a and b). Key commercial species such as European hake (*Merluccius merluccius*), red mullet (*Mullus barbatus*) and deep-water rose shrimp (*Parapenaeus longirostris*) are subject to overfishing and stock depletion across several GSAs.

Fisheries in the Mediterranean Sea are managed through a combination of regional, sub-regional, and national frameworks aimed at ensuring the sustainable exploitation of marine resources. Over the past two decades, there has been a significant shift towards more structured and science-based fisheries management, particularly under the coordination of the GFCM, playing a central role in designing, recommending and monitoring management strategies to address the growing concerns related to overfishing, habitat degradation and socio-economic vulnerability in the region (GFCM, 2022a and b). The GFCM also plays a key role in supporting small-scale fisheries, improving data collection, and fostering regional cooperation among member countries to ensure the long-term sustainability of marine resources and the livelihoods that depend on them.

Among the most prominent instruments currently in use in Mediterranean are the so-called Multiannual Management Plans (MAPs). These plans are designed as long-term frameworks that aim to rebuild and maintain fish stocks within biologically sustainable levels. They typically rely on the best available scientific advice, incorporating regular stock assessments and indicators of stock productivity, spawning biomass, and fishing mortality (Hilborn & Walters, 1992). MAPs define management objectives and include a set of regulatory tools such as effort and capacity controls, gear restrictions, closed seasons, and minimum conservation reference sizes. Importantly, these plans are adaptable along the years, allowing for revisions based on updated scientific evidence and environmental changes.

Several multiannual plans have been implemented by European Commission and by GFCM in recent years across different parts of the Mediterranean (Figure 2). One of the most notable examples is the Western Mediterranean MAP (WestMed Plan), adopted by the European Union to manage demersal fisheries targeting species such as European hake, red mullet and deep-water rose shrimp. This plan includes annual reductions in fishing effort, technical measures to enhance selectivity, and a regional closure period during peak spawning to protect recruitment (European Commission, 2019). Other examples of management Plans are the one regulating the demersal fisheries in the Strait of Sicily, the MAPs regulating the small pelagic and demersal fisheries operating in the Adriatic Sea.

In addition to plans focused on finfish and crustaceans, the GFCM has also adopted a Multiannual Management Plan for red coral (*Corallium rubrum*, Linneaus, 1758; Gorgonacea, Octocorallia) in all Mediterranean areas (GFCM Recommendation GFCM/36/2012/1**,** Recommendation GFCM/41/2017/5**)**.

In parallel to multiannual plans, spatial conservation tools such as Fisheries Restricted Areas (FRAs) have emerged as critical components of fisheries governance. FRAs are geographically defined zones in which certain fishing activities are prohibited or heavily restricted to protect vulnerable ecosystems and critical habitats. These areas are often designated based on habitat mapping, fishing effort data and stock assessment outcomes. These areas are essential in promoting stock recovery and preserving benthic habitats from destructive gear impacts, such as bottom trawling (GFCM, 2022a and b).

Figure 2 – Infographics of the GFCM management Plan currently in force in Mediterranean and Black Sea. Available at: https://gfcmsitestorage.blob.core.windows.net/website/6.News/SOMFI%202023/Inforgraphics/Infographic_7.jpg

In addition to regionally coordinated management efforts, individual Mediterranean countries—both EU Member States and non-EU coastal nations—implement national fisheries management plans. These plans, often tailored to the specific ecological and socio-economic context of each country, focus particularly on small-scale and local fisheries. While approaches vary across countries, there is increasing convergence toward harmonizing national policies with GFCM recommendations and the principles of the EU's Common Fisheries Policy (CFP) (EU, 2013; GFCM, 2021).

Fishery data collection in the Mediterranean Sea is essential for sustainable management and is coordinated at national, regional and EU levels. National authorities collect data on catches, effort, fleet activity, and socio-economic indicators through port sampling, onboard observers and surveys. For EU countries, the Data Collection Framework (DCF, https://dcf.ec.europa.eu/index_en?prefLang=i) standardizes methods and ensures data quality, supporting scientific analysis and policy-making. Regionally, the GFCM coordinates data collection through its Data Collection Reference Framework (DCRF, https://www.fao.org/gfcm/data/dcrf/fr/**)**, ensuring consistency across EU and non-EU countries.

At the Mediterranean level, ad hoc experts working groups integrate the collected fishery data on specific mathematical models to provide an updated evaluation of the stock status, through the stock assessment process. These working groups, organized under the framework of the GFCM and the STECF (scientific body of European Commission), play a crucial role in providing the scientific basis for sustainable fisheries management (GFCM 2022b; GFCM 2022c; GFCM 2023; GFCM 2024; STECF 2020, STECF 2021a).

In the Mediterranean Sea, the number of stock assessments has increased in recent years, reflecting growing efforts to support science-based fisheries management. According to the General Fisheries Commission for the Mediterranean (GFCM), over 80 stock assessments are currently conducted annually, covering a range of demersal and small pelagic species such as European hake, red mullet, deep-water rose shrimp, anchovy and sardine. However, despite this progress, the overall coverage remains limited. As reported by GFCM (2022b), stock assessments are available for less than 30% of the commercially exploited stocks in the region. Moreover, only about 40% of the Geographical Sub-Areas (GSAs) in the Mediterranean have consistent and up-to-date stock assessments. This uneven coverage, particularly in the eastern and southern Mediterranean, hinders comprehensive management and highlights the need for expanded data collection, regional collaboration and capacity building to improve scientific coverage across the entire basin.

Stock assessment models: tools to inform managers on stock status

A stock assessment is a scientific process used to evaluate the status and trends of a fish population (or "stock") in order to inform sustainable fisheries management (Hilborn and Walters, 1992). It involves the analysis of the collected biological, catch and effort data to estimate key parameters such as: population size or spawning stock biomass (SSB), mortality due to fishing (fishing mortality, F), recruitment (new individuals entering the population).

Stock assessments help determine whether a stock is sustainably exploited, overfished (biomass of the stock has been reduced below a biologically sustainable level), or subject to overfishing (fishing mortality higher than the level considered sustainable) and provide the evidence needed to set appropriate management measures to reduce the risk of stock collapse.

In the stock assessment process reference values for SSB and F are defined to evaluate the status of the stock, namely **reference points** (Sparre & Venema, 1998). The reference points are essential benchmarks used in fisheries management to assess stock status and guide sustainable exploitation according to the fishing pressure and the biomass level, while defining thresholds or targets based on stock productivity and resilience.

Table 1 reports the main reference points utilized in the STECF and GFCM working groups on stock assessment, including the definition and the bibliographic reference.

Table 1 – Summary of the main reference points used in the stock assessment process, including definitions and references.

Reference Point	Definition	Reference
B_{MSY}	Biomass that produces the Maximum Sustainable Yield (MSY); used as a target for stock biomass.	Hilborn & Walters (1992); Cadrin et al. (2015)
B/B_{MSY}	Ratio of current biomass to BMSY; indicates stock status relative to the MSY benchmark.	Cadrin et al. (2015)
B_{lim}	Biomass limit reference point; below this level, the stock is at high risk of reproductive impairment.	Cadrin et al. (2015)
B_{pa}	Biomass precautionary threshold; set above B_{lim} to account for uncertainty and avoid critical depletion.	Cadrin et al. (2015)
F_{MSY}	Fishing mortality rate that leads to MSY; used as a limit or target to ensure sustainable fishing pressure.	Hilborn & Walters (1992); Cadrin et al. (2015)
F/F_{MSY}	Ratio of current fishing mortality to FMSY; indicates whether fishing pressure is sustainable.	Cadrin et al. (2015)
SPR / SBR	Spawning Potential Ratio or Spawning Biomass per Recruit; proportion of unfished reproductive capacity remaining under current fishing pressure.	Hordyk et al. (2015); Froese et al. (2016)
MSY	Maximum average catch that can be sustainably harvested over the long term.	Hilborn & Walters (1992)

Reference Point	Definition	Reference
F_{max}	Fishing mortality rate that maximizes yield per recruit; often used as an upper reference point in management.	Beverton & Holt (1957); Quinn & Deriso (1999)
$F_{0.1}$	Fishing mortality rate at which the slope of the yield-per-recruit curve is 10% of the slope at the origin; considered a conservative proxy for FMSY.	Beverton & Holt (1957); Cadrin et al. (2015)

Stock assessments use two main types of data: **fishery-dependent** and **fishery-independent**. Fishery-dependent data come directly from monitoring activities of commercial and recreational fishing, including catch records, effort and size or age of fish caught. This data reflects the impact of fishing on the population. In contrast, fishery-independent data are collected through scientific surveys that do not rely on commercial fishing, such as trawl or acoustic surveys. These provide unbiased information about fish abundance, distribution and biological characteristics, helping scientists to estimate stock health more accurately. Both types of data are essential for reliable stock assessments and sustainable fisheries management.

Stock assessment models can be broadly classified into **data-rich** and **data-limited** approaches, depending on the amount and quality of data available for the stock being assessed.

In the next session a general overview, including the main stock assessment models reviewed in the context of this thesis, is provided, with a final synthesis. A more detailed description is provided for the models applied in chapters 1, 2 and 3.

Data-rich stock assessment models

In data-rich fisheries, where long-term series of commercial catch data, survey data, effort and biological data are available, analytical models are widely used.

These include models such as:

- Virtual Population Analysis (VPA) and Cohort Analysis;

- Statistical Catch-at-Age (SCAA) and Statistical Catch-at-Length (SCAL) models;
- Biomass Dynamic Models (intermediate complexity).

Virtual Population Analysis (VPA)

Virtual Population Analysis (VPA)**,** also known as Cohort Analysis, is a widely used analytical deterministic method in fisheries science for reconstructing the historical population dynamics of exploited fish stocks (Gulland, 1983). VPA estimates the abundance and mortality rates of age-structured populations by working backward from catch-at-age data, assuming that all individuals are removed from the population through natural mortality or fishing. One of the core assumptions is that natural mortality (M) is known and that catch data are accurate and representative (Gulland, 1983). These models are typically applied to species with well-defined age structures and long lifespans, such as European hake**,** which are landed in large volumes and subject to systematic age reading (GFCM, 2022b, GFCM 2023; GFCM 2024).

One of the main advantages of VPA is its relatively simple model structure, that allows to apply quite easily, utilizing existing freely available tools; the integration of fishery dependent and fishery independent information allows to take advantage of the information provided by the survey data on the age structure population, not only relying on the fraction exploited by the fishery. Finally, this tool is compatible with many stock assessment frameworks, providing information on the fishing mortality reference points.

One of its limitations includes the algorithm nature, working backward (from the most recent years to the past ones); indeed, this element makes the final stock assessment results more susceptible to last year of data than the whole time series. Another critic aspect is the assumption that the catch data are exact, without observation errors; for this reason the tool cannot provide confidence intervals around the status of the stock. These limitations make this tools less suitable for short-lived or poorly monitored species (Pope, 1972; Gulland, 1983). Despite these limitations, VPA remains a foundational tool in fisheries science and continues to inform key management decisions worldwide (ICES, 2005).

The Extended Survivor Analysis (XSA) is a widely used age-structured stock assessment method within the family of Virtual Population Analysis (VPA) models. It was developed to improve traditional VPA by incorporating statistical tuning procedures that adjust population estimates using external data sources, such as scientific surveys or catch-per-unit-effort (CPUE) indices. Unlike classical VPA, which relies solely on catch-at-age data and assumes perfect knowledge of fishing mortality, XSA applies a statistical shrinkage technique to stabilize estimates of fishing mortality in the oldest age groups, where data are often sparse or uncertain (Shepherd, 1999). This makes it particularly useful for long-lived demersal species, such as European hake, where accurate assessment of older age classes is critical. Its application has become standard practice in European fisheries assessments, especially under the GFCM framework (GFCM, 2022b, GFCM 2023, GFCM 2024).

Statistical Catch-at-Age (SCAA) and Statistical Catch-at-Length (SCAL) models

Statistical Catch-at-Age (SCAA) and Statistical Catch-at-Length (SCAL) models are advanced analytical frameworks used in fisheries stock assessments to estimate population dynamics using both fishery-dependent and fishery-independent data. Unlike traditional Virtual Population Analysis, which is deterministic and retrospective, SCAA and SCAL are forward-projection, likelihood-based models that incorporate uncertainty and variability in observations and processes (Methot & Wetzel, 2013). These models integrate multiple data sources, including catch-at-age or catch-at-length compositions, indices of abundance (e.g. trawl surveys) and biological parameters such as growth, natural mortality and selectivity. The main hypotheses include known or estimable selectivity patterns and observation errors and they assume the availability of reliable and structured data over time. SCAA is especially suitable for species where age data are available and regularly sampled (e.g. hake, cod, or sea bream), while SCAL is preferred in cases where length composition is easier to obtain or more representative—often the case for tropical or small-scale fisheries where ageing is difficult or expensive (Maunder & Punt, 2013).

The advantages of SCAA and SCAL include their statistical rigor, ability to estimate parameters simultaneously and capacity to account for uncertainty and missing data. However, their disadvantages are related to increased computational complexity, sensitivity to model structure and priors and the need for extensive, high-quality datasets. These models form the basis of integrated stock assessment frameworks such as Stock Synthesis (SS3), widely used in global fisheries science and endorsed by regional fisheries management organizations (Methot & Wetzel, 2013; GFCM, 2022b; GFCM 2023; GFCM 2024).

Biomass Dynamic Models

Biomass Dynamic Models (BDMs) are among the simplest and most widely used tools in fisheries stock assessment, being in the group of data-rich models, the ones requiring the catch and survey information aggregated and not by age class. Indeed, they are less data-intensive than age-structured models but still require time series of catch and effort. For this reason they are considered as intermediate-complexity models.

These models describe the overall changes in biomass over time in relation to fishing effort or catch, using population-level parameters such as intrinsic growth rate (r) and carrying capacity (K) (Hilborn & Walters, 1992). The most well-known BDM is the Schaefer model, a logistic surplus production model that assumes a compensatory growth response in the stock to reductions in biomass due to fishing. Key assumptions include that the population follows a predictable growth curve, that catches are accurately reported and that recruitment and mortality are implicitly captured in the biomass trend. BDMs are typically applied to long-lived, aggregated stocks for which detailed biological data (e.g., age or length composition) are not available, such as small pelagics, tuna or mixed-species tropical fisheries (Prager, 1994).

The advantages of BDMs lie in their simplicity, minimal data requirements and ease of use, especially in the early stages of management. However, they are limited by their oversimplified nature, inability to model age or size structure and their sensitivity to assumptions about equilibrium conditions and the accuracy of historical catch and effort data. They are best used as exploratory or interim models and often serve as a foundation for more complex assessments or management strategy evaluations (Froese et al., 2017; GFCM, 2022b; GFCM 2023; GFCM 2024).

The Stochastic Production model in Continuous Time (SPiCT) is a biomass dynamic model designed for fisheries stock assessment, particularly in data-limited and data-moderate contexts and widely used in ICES and GFCM context. SPiCT builds upon classical surplus production models by introducing a Bayesian framework and modeling biomass and fishing mortality as stochastic processes in continuous time, rather than using discrete time steps (Pedersen & Berg, 2017). This formulation allows SPiCT to account for both process error (natural variability in population dynamics) and observation error (in data such as catches and abundance indices), providing more realistic uncertainty estimates around key parameters such as biomass, fishing mortality, and MSY-based reference points. The model typically requires time series of total catch and at least one abundance index, such as a CPUE or survey-derived index.

SPiCT assumes that population dynamics follow a Pella-Tomlinson surplus production model, which generalizes the logistic growth function to allow for different shapes of the production curve. Its main advantages include the ability to quantify uncertainty rigorously, flexibility in model fitting and the generation of probabilistic outputs useful for risk-based management. Moreover, it provides diagnostics for stock status relative to reference points like B/B_{MSY} and F/F_{MSY}. However, limitations include sensitivity to short or highly uncertain data series, computational intensity and the need for prior information on key parameters, which may be challenging in poorly studied fisheries. The model is widely used in ICES, GFCM and STECF working groups (STECF 2021a; STECF 2020; GFCM 2022b; GFCM 2022c; GFCM 2023; GFCM 2024), with a series of dedicated meetings at ICES level to provide advice based on this model (ICES, 2024).

Data-poor stock assessment models

Data-poor assessment models are analytical approaches designed to evaluate the status of fish stocks when traditional, data-rich methods are not applicable due to a lack of detailed biological, fishery or survey data. Unlike full analytical stock assessments—which typically rely on long time-series of catch-at-age, abundance indices, and life-history parameters—data-poor methods operate with minimal information, often using only catch time series, basic life-history traits (e.g., growth rate, longevity), or expert judgment (Carruthers et al., 2014).

These models include:

- **Yield per Recruit;**
- **Catch-MSY** and **CMSY;**
- **Length-based models**, such as **Length-Based Spawning Potential Ratio (LB-SPR)**;
- **Depletion-based methods.**

Yield per recruit

Yield per recruit (Y/R) models are a fundamental tool in fisheries science used to evaluate how fishing mortality and age at first capture affect the expected yield from a single recruit over its lifetime (Beverton and Holt, 1957; Quinn and Deriso, 1999). These models are particularly useful for understanding the trade-offs between harvesting fish at younger versus older ages. By incorporating growth (usually via the von Bertalanffy growth function), natural mortality, and fishing mortality, Y/R models estimate the yield produced by an average recruit under various fishing scenarios. A key strength of this approach is its ability to inform decisions about optimal exploitation strategies, such as identifying the fishing mortality rate that maximizes yield per recruit and assessing the effects of size or age limits on catches. Although they do not account for population dynamics like recruitment variability or stock-recruitment relationships, Y/R models are still valuable for data-limited fisheries or as a component of more complex assessments. They are especially relevant for long-lived demersal species, where delaying capture to older ages can significantly increase yield and reproductive output.

Catch-MSY and CMSY

Catch-MSY and its Bayesian extension CMSY (Catch-MSY with Monte Carlo simulation) are widely used data-poor stock assessment methods developed to estimate Maximum Sustainable Yield (MSY) and other reference points using only catch data and basic information on species productivity. These models operate by simulating thousands of possible population trajectories based on surplus production models, while filtering those consistent with observed catches and known biological resilience (Froese et al., 2017). The key assumptions include that the population follows a logistic growth curve (i.e., Schaefer model), that catch data reflect true removals, and that reasonable estimates of intrinsic growth rate (r) and carrying capacity (K) can be inferred from life-history traits or expert input.

Catch-MSY and CMSY are typically applied to data-limited stocks, including small pelagic species, tropical multi-species fisheries and coastal demersal stocks where traditional stock assessments are infeasible. These models are especially valuable for developing-country fisheries or artisanal sectors, where systematic biological sampling is limited.

Their advantages include low data requirements, intuitive implementation and transparent assumptions, which make them accessible and useful for rapid assessments and management advice.

Limitations include sensitivity to input assumptions (especially priors for r and biomass depletion levels), inability to account for age or size structure and reduced accuracy for short time series or heavily misreported catches (Martell & Froese, 2013; Rosenberg et al., 2014). Despite these caveats, CMSY has been adopted in several international frameworks, including GFCM, as a pragmatic tool for precautionary management in data-poor fisheries (GFCM 2022b; GFCM 2022c; GFCM 2023; GFCM 2024).

Recent advancements in this family of models have led to the development of CMSY++ (Froese et al., 2023), which incorporates important methodological enhancements. These include improved treatment of catch uncertainty, refined priors for resilience, and expanded diagnostic tools, all of which contribute to more robust and transparent stock assessments. This thesis applies the original CMSY approach and the new developments CMSY++ in the assessment of the red coral stock (Chapter 2), acknowledging the developments introduced with CMSY++ offers a more complete picture of current methodologies available for data-limited fisheries.

Length-Based Spawning Potential Ratio (LB-SPR) and the Length-Based Bayesian (LBB) models

Length-based assessment models, such as the Length-Based Spawning Potential Ratio (LB-SPR) and the Length-Based Bayesian (LBB) model, are increasingly used in data-poor fisheries to estimate stock status from simple length-frequency data. These models bypass the need for age data, making them highly suitable for species where age determination is often limited due to logistical or economic constraints (Hordyk et al., 2015; Froese et al., 2016). LB-SPR estimates the Spawning Potential Ratio (SPR)—a proxy for reproductive capacity—by modeling the equilibrium distribution of lengths in the catch, assuming known growth parameters (von Bertalanffy growth function), natural mortality (M) and size at maturity. It compares the current SPR with reference values (e.g., 40%) to infer whether the stock is overfished. LBB, on the other hand, is a Bayesian length-based model that fits observed length frequencies to estimate parameters such as F/M (fishing to natural mortality ratio), $L\infty$ (asymptotic length) and relative biomass (B/BMSY), while incorporating uncertainty and priors (Froese et al., 2016).

These models are particularly well-suited for slow-growing species or those with limited age data, such as groupers, snappers, or invertebrates like lobsters.

Their advantages include minimal data requirements, cost-effectiveness and rapid diagnostics for management, especially when integrated with precautionary frameworks.

Limitations include sensitivity to incorrect growth and mortality estimates, assumption of steady-state conditions and potential biases when size-selective fishing or recruitment variation is high (Hordyk et al., 2015). Despite these constraints, both LB-SPR and LBB are commonly applied in GFCM working groups, as part of a toolbox for data-limited fisheries (GFCM 2022b; GFCM 2022c; GFCM 2023; GFCM 2024).

Depletion-based methods

Depletion-based methods, such as the Depletion-Corrected Average Catch (DCAC) and Depletion-Based Stock Reduction Analysis (DB-SRA), are tools developed for use in data-limited fisheries where traditional stock assessments are not feasible due to the absence of detailed time series on abundance or age structure. These models aim to provide sustainable catch advice by incorporating historical catch data, estimates of natural mortality (M), productivity and assumptions about stock depletion levels (MacCall, 2009; Dick & MacCall, 2011). DCAC calculates an allowable catch level that balances long-term yield with conservation, by adjusting the average historical catch for estimated depletion and productivity parameters. DB-SRA, a more sophisticated extension, uses a stochastic approach to simulate thousands of biomass trajectories consistent with catch history and biological parameters and selects those that do not result in implausible population collapse.

These methods are particularly applicable to moderately to highly exploited stocks where the only reliable data are long-term catch records and expert knowledge on stock status. They are commonly applied to coastal demersal species, elasmobranchs or invertebrates such as lobsters and crabs, especially in small-scale fisheries lacking systematic monitoring. The advantages of DCAC and DB-SRA include their adaptability to limited data conditions, ease of implementation, and ability to incorporate uncertainty in a precautionary way. However, their limitations include high sensitivity to assumptions about depletion levels and natural mortality, limited capacity to detect recent trends, and inability to provide detailed insights into population structure or dynamics (Carruthers et al., 2014).

In this group of models, the Leslie-Lewis method (Hilborn and Walters, 1992) by length approach is used to estimate the size structure and potential abundance of a stock using length-frequency data. This adaptation applies the same principles as the original method—typically used with CPUE and cumulative catch—but uses average length or length class frequencies over cumulative removals to estimate stock size and exploitation patterns. It is particularly useful in data-limited fisheries where aging is difficult or not available, such as in tropical or artisanal contexts. The data required are catch length-frequency distributions over time, along with estimates of effort and, ideally, length-specific selectivity.

Advantages include its simplicity, low data requirements and ability to provide initial estimates of stock status without detailed biological or age data. However, the method has several limitations: it assumes constant selectivity, no growth or recruitment during the sampling period and a linear relationship between cumulative removals and average size, which may not hold in dynamic systems. It is also sensitive to sampling bias and variability in gear selectivity.

Synthesis of stock assessment methods

A synthesis of the stock assessment models described in the previous section has been made in Table 2, summarizing the type of model, the data needed, the advantages and disadvantages, the species on which the model was generally applied and the bibliographic reference.

Table 2 – Synthetic table reporting the main models applied in the stock assessment process; the models indicated with light green background are the data-rich and intermediate models, the ones with white background are data-limited.

Model	Type	Data needed	Advantages	Disadvantages	Applicable on	Reference
VPA	Age-structured (deterministic)	Catch-at-age, natural mortality, selectivity	Simple to apply, widely used, provides reference points	Sensitive to M, assumes reliable catch-at-age data	demersal species with age data	Pope (1972); Gulland (1983); ICES (2022)
XSA	Age-structured (VPA with statistical tuning)	Catch-at-age, survey tuning indices, natural mortality	Simple to apply, widely used; improves VPA with external indices, provides reference points	Sensitive to M, assumes reliable catch-at-age data	long-lived demersal stocks	Shepherd (1999); ICES (2022)
SCAA and SCAL	Statistical age/length-structured (likelihood-based)	Catch-at-age or length, indices, biological parameters	Flexible, incorporates uncertainty, integrates various data sources, deal with data gaps, provides reference points	Computationally intensive, requires multiple data sources	species with age/length sampling	Methot & Wetzel (2013); Maunder & Punt (2013); FAO (2022)
SPiCT	Biomass dynamic (Bayesian, continuous time)	Catch time series, abundance index, life-history priors	Stochastic, handles uncertainty well, provides reference points	Requires tuning, sensitive to short/uncertain time series	Small pelagics, demersal species	Pedersen & Berg (2017);
YpR	Age-structured (deterministic, analytical)	Growth parameters, natural mortality, maturity, selectivity	Simple, useful for reference points like F_{MAX} and $F_{0.1}$	No recruitment or biomass dynamics, assumes equilibrium	Demersal species, reef fishes, data-limited species	Beverton & Holt (1957); Quinn & Deriso (1999)
LB-SPR	Length-based (equilibrium, empirical)	Length-frequency data, life-history parameters (natural mortality, L_∞, $L_{m50\%}$)	Requires only length data, Simple to apply	Assumes equilibrium, sensitive to natural mortality and growth assumptions	Groupers, snappers, lobsters, reef species	Hordyk et al. (2015); Froese et al. (2016)
CMSY	Biomass dynamic (Bayesian, catch-only)	Catch time series, species resilience, depletion assumptions	Very low data requirements, good for initial assessments	Depends heavily on priors, no age or size structure	Small pelagics, tropical multispecies, artisanal stocks	Froese et al. (2017); Martell & Froese (2013); Rosenberg et al. (2014)
Depletion-based methods	Biomass dynamic (catch-only)	Catch time series, natural mortality, depletion levels, prior knowledge	Practical in data-limited contexts, simple, precautionary	Sensitive to assumptions, not suited for short-term trends	Demersal species, elasmobranchs, lobsters, coastal species	MacCall (2009); Dick & MacCall (2011); Carruthers et al. (2014)
Leslie-Lewis (by length)	Depletion-based (length, empirical)	Length-frequency over time, effort, basic selectivity	Very simple, needs minimal data, useful for early-stage assessments	Assumes no growth/recruitment, sensitive to sampling bias	Demersal species, reef fish	Hilborn and Walters (1992)

Sardinian fishery and key marine resources

The seas surrounding Sardinia, coded as the Geographical Sub-Area 11 (Figure 3) in the GFCM context, have long played a central role in the island’s economy, culture and identity. With a rich maritime tradition dating back to ancient times, fishing has been a cornerstone of coastal livelihoods and local traditions. Sardinia, with nearly 1,900 kilometers of coastline, offers an exceptionally favorable environment for both fishing and aquaculture activities. According to the 2021 report by CREA (2021), in 2019 the region accounted for 8,160 tons of fishery landings—representing 4.7% of the national total—and generated revenues of €63.2 million, corresponding to 7.1% of Italy’s overall fisheries income.

As of the latest data available from the European Commission's Fleet Register (consulted in March 2025), Sardinia's fishing fleet comprises 1,326 vessels, representing approximately 11% of Italy's national fleet. The total gross tonnage (GT) of the Sardinian fleet stands at 14,914, with a combined engine power of 53,748 kilowatts (kW). Notably, 452 of these vessels are registered in ports located in Northern Sardinia, accounting for a gross tonnage of 4,768 GT and an engine power of 22,652 kW. Despite a declining trend over the years, Sardinia maintains one of the largest regional fishing fleets in Italy, underscoring its enduring significance in the national maritime sector.

The island's marine ecosystem supports a wide range of commercially valuable species, with the fishing fleet mainly targeting demersal resources. In addition to the demersal target species included in the Western Mediterranean MAP, highly prized resources like the red coral and the Mediterranean spiny lobster (*Palinurus elephas,* Fabricius, 1787) hold significant economic and ecological importance, particularly in the western and southern sectors of the island.

Figure 3 – Location of Sardinian waters, corresponding to GSA 11 of the GFCM Geographical Sub-Areas.

Demersal stocks

Demersal species typically have limited mobility compared to pelagic species, often remaining within relatively confined areas or specific habitats such as rocky substrates, sandy bottoms, or seagrass beds. These species represents the bulk (over 50 %, ISTAT, https://www.istat.it/en/) of the landing of the commercial demersal fishery in Sardinian waters, targeting mainly European hake, red mullet, deep-water rose shrimp, giant red shrimp (*Aristaemorpha foliacea*), blue and red shrimp (*Aristaeus antennatus*) and Norway lobster (*Nephrops norvegicus*).

For this reason an appropriate evaluation of the stock status of these resources is of paramount importance to ensure the viability of the fleets depending on them, in strict combination with biological sustainability criteria.

Age-structured stock assessment models are particularly well-suited for assessing the status of demersal stocks due to their ability to capture the biological and ecological complexity of these species, typically exhibiting age-specific differences in growth, maturity, natural mortality and susceptibility to fishing.

A wide range of fishery dependent and fishery independent data, including robust biological information, is currently available for the main demersal stocks exploited by Sardinian demersal fleets, due to the presence of the these stock in the European Data Collection Program since more than 20 years.

This data are routinely utilized during the annual STECF and GFCM expert working groups on stock assessment to evaluate the status of the stocks applying data-rich stock assessment models and provide scientific advice. The information on the stocks status is routinely used to adapt the Multiannual Management Plan (MAP) for demersal stocks in the Western Mediterranean Sea, adopted by the European Union under Regulation (EU) 2019/1022. This plan, which came into force in July 2019 and covering waters off the coasts of Italy (including Sardinia), France, and Spain, was developed in response to persistent overfishing of key demersal stocks. Sardinia, being part of the Geographical Sub-Area 11 as defined by the GFCM, is directly impacted by this plan.

Although the red mullet is one of the main target of demersal fishery and one of the species covered by the MAP, the species was never assessed in Sardinian waters, being only assessed in the Tyrrhenian Sea, where it was evaluated applying data-rich methodologies and specifically statistical catch at age and biomass dynamic models (STECF, 2021a).

Red coral

Ecological features

Unlike the demersal resources, red coral is a longevous sciaphilous benthonic sessile octocoral, endemic of the Mediterranean basin, that forms arborescent colonies over rocky habitats (Bramanti, L., Iannelli, M., & Santangelo, G., 2009; Garrabou, J., Harmelin, J.G., 2002).

Red coral shows peculiar biological and ecological characteristics that distinguish this species markedly for the demersal species. Being a sedentary organisms and characterized by patchy distribution in banks and not evenly across the seafloor, the fishing target known coral-rich spots, often repeatedly, leading to localized depletion. Due to its peculiar life history traits, red coral is susceptible to anthropogenic pressures, with fishing ahead, followed by climate change related stressors (Torrents et al., 2005, Bavestrello et al., 2015; Toma et al., 2022). Indeed, the species shows slow growth rate, late sexual maturity, a lifespan that can potentially overcome a century (Garrabou and Harmelin, 2002; Marschal et al., 2004). Thus, restoring the areas heavily impacted from fishing activities could potentially take decades.

From an ecological perspective, *C. rubrum* shows a wide bathymetric distribution, and acts as structuring organism in deep-sea rocky habitats, particularly over coralligenous biocoenosis, which are regarded both as major biodiversity hotspots of the Mediterranean, and as Vulnerable Marine Ecosystem (VME) (FAO, 2009).

The extensive studies undertaken with the ROV (Remote Operated Vehicle) conducted along the Sardinian coasts (Follesa et al., 2013; Cau et al., 2015a) at depths >80 metres, documented a great variability in coral population structure, showing different sizes patterns characterized by a high occurrence of large colonies on the northern western coasts and small-medium sized colonies in the northern populations.

The fishery and the economic importance

Its red carbonatic skeleton has been widely appreciated in the global jewellery market for centuries and, at present days, it can be considered the precious coral par excellence (Tsounis et al., 2010; Cattaneo-Vietti et al., 2016). FAO statistics documented a dramatic decline (~80%) of red coral catches within the Mediterranean, from 98 tons in 1978 to the minimum of 18.9 tons recorded in 1998; after that, values remained always below 40 tons (FAO global capture database, https://www.fao.org/fishery/en/knowledgebase/106). Along Italian coasts, red coral banks have been exploited for centuries through non-selective and highly destructive towed gear such as St. Andrews cross and “Italian bar” (Cattaneo-Vietti, 2017), until their official ban in Europe, occurred in 1994.

In the Mediterranean context, the island of Sardinia (Italy) is an historical hotspot for red coral fishery; e.g., in 1991 Sardinia was the most productive site in the western Mediterranean Sea (3 tons per year) (Santangelo et al., 1993; Cannas et al., 2010).

Protection and management

C. rubrum is included since 2014 in the International Union for Conservation of Nature (IUCN) red list, that is a global inventory that assesses the conservation status of plant and animal species, being a key indicator for monitoring the ecological status of coastal waters (European Water Framework Directive, WFD, 60/2000/CE) and a taxa of special interest within the Marine Strategy Framework Directive (MSFD) to achieve the sea resources sustainability (“Good Environmental Status”, European Parliament, Council of the European Union 2008; European Commission 2010).

Within GFCM Competence Area, several actions for monitoring and protecting this important resource have been put in place, including harmonised data collection for red coral fishery, since 2013 (Res. GFCM/35/2011/2; GFCM/41/2017/5; GFCM/45/2022/2) and the establishment of stricter management measures, including minimum legal basal diameter of 7 mm, harvesting only by authorized SCUBA divers, (without the use of ROV), limited number of licenses, catch limits, minimum fishing depth of 50 m (Rec. GFCM/43/2019/4). For management purposes, red coral populations are divided into shallow- and deep-dwelling populations (<50m of depth), with the latter being the target of fishing pressure since those dwelling above 50m of depth are currently under protection (Rec. GFCM/43/2019/4).

An alternative management scheme has been proposed in Caddy (1995), specifically useful for sedentary species: rotating harvest regime. Currently, only few areas of Morocco and Greece are applying this type of measures.

In the last 30 years, Sardinian Administration has established some restrictive regulations to allow responsible exploitation of discovered red coral banks within its waters: technical measures (SCUBA divers with hammer, depth limit (below 80 m), season of harvesting (May-November)); controls (minimum legal basal diameter of 10 mm (+-20% tolerance on undersized), limited number of licenses (max 25 authorized divers), weight limit (2.5 kg/day/diver)); annual logbooks.

Sardinia has been selected at GFCM level as a model that, differently from other Italian Regions and other Mediterranean areas, applied a strict regulation for the harvest of red coral (Follesa et al. 2013) since 1998 and because, over the last 15 years, has launched several monitoring programs to collect demographic data on colonies harvested by authorized SCUBA divers, through both landing and through Onboard Scientific Observers (Carugati et al., 2020).

Stock assessment of red coral: status of the art

Despite the urgent need to manage this precious resource, stock assessment for red coral is quite rare, both in scientific literature and in official GFCM reports. The more applied model in literature is Yield per recruit models, utilised by Tsounis et al. (2007), and the Leslie-Lewis tables by length (Hughes, 1984; Santangelo et al., 2007, Bramanti et al., 2009).

Nevertheless, for the evaluation of this peculiar resource, the age structured stock assessment models (e.g. Yield per recruit) are not considered as appropriate due to several reasons. Firstly, the sedentary nature of the red coral does not allow to meet the dynamic pool assumption of Caddy, due to the not uniform distribution of the resource and of the fishing effort across the fishing area. Moreover, the red coral population cannot be considered, as made in the case of demersal species, as a single connected pool, where individuals mix freely and are equally available to fishing.

Considering the Leslie-Lewis tables by length, the application to this species can be importantly limited by the length-structure availability, not easily covering the whole length distribution and the whole lifespan.

It should be noticed that the available information for red coral populations across Geographical Sub-Areas (GSA, GFCM sensu) within the Mediterranean Sea suffers from low spatial and temporal coverage, often coupled with inconsistent data collection and sampling protocols. This makes in general quite difficult to assess red corals stocks across Mediterranean areas at GFCM level.

Another aspect to be considered for the stock assessment of this species is the availability of biological information on growth, maturity and mortality. Knowledge on growth, mortality, and sexual maturity of red coral has increased over the last decades, for both shallow and deep populations dwelling in Western Mediterranean (Marschal et al., 2004; Gallmetzer et al., 2010; Bramanti et al., 2005, 2014; Priori et al., 2013; Espinosa et al., 2019; Garrabou and Harmelin 2002; Torrents et al., 2005; Torrents and Garrabou 2011; Tsounis et al., 2006; Santangelo et al., 2003; Porcu et al., 2017). However, the morphological plasticity of red coral colonies, that seem to adapt to local environmental conditions, and discrepancies in protocols used to investigate such parameters highlighted considerable uncertainty for several life-history traits, e.g., growth, size at first maturity.

Sardinia has collected through logbook and ad hoc monitoring program since many years an big amount of information on the landing and size structure on the catches of red corals, including unique information on growth, through the ageing of more than 50 colonies. Respect to other Mediterranean areas, is actually the unique GSA having available data for the application of stock assessment models to this species, including landings time series, number of licenses to derive catch per unit of effort and biological information.

The availability of this data made possible the application of a range of the stock assessment models described in chapter 2.

Spiny lobster

Another important commercial marine resource characterizing the Sardinian fishery is the European spiny lobster. Commonly referred to as “aragosta rossa” (red lobster), spiny lobster is a benthic (nectobenthic) crustacean species, typically found on rocky or detrital substrates in coastal and continental shelf areas of the northeastern Atlantic and the Mediterranean Sea. Unlike sessile benthic organisms such as red coral, which are permanently attached to the substrate, and unlike demersal species like European hake, which actively swim just above the seabed, *P. elephas* is a motile benthic species that moves along the seafloor, particularly during its nocturnal foraging activities. It inhabits depths ranging from 20 to over 150 meters, with a strong preference for complex rocky environments that provide shelter during daylight hours. The species is characterized by slow growth, late sexual maturity and low reproductive rates, making it particularly susceptible to overexploitation (Goñi et al., 2003; Gharsalli et al. 2022).

In Sardinian waters, *P. elephas* has historically been a highly valued target for artisanal fisheries, though its stocks have shown signs of decline due to intensive harvesting. Conservation measures such as seasonal closures and size limits have been implemented in various Mediterranean regions to aid in population recovery (Goñi et al., 2003; Follesa et al., 2009).

Currently the spiny lobster fishery involve the 25% of artisanal fishing vessels, although a relevant amount of individuals are harvested by trawlers and recreational fishery (Follesa M. C., 2012). Sardinia was, with Western Sicily, the Italian region with the highest production of spiny lobster. Nevertheless, at the end of 80ties this resources showed, as in the whole Mediterranean Sea, a gradual decrease in the landing and in the mean sizes landed, as a consequence of the increase in fishing pressure.

Autonomous Sardinia Region established, in agreement with scientists, 14 fishery restricted areas aimed at facilitating the recovery of the stock, in combination with the other technical measures already in place (Decreto N. 2102/DecA/87 of 11.08.2010, Regulation (CE) N. 1967/2006). The Asinara Marine Protected Area (MPA), established in 2002, encompasses approximately 10,732 hectares of coastal waters surrounding Asinara Island in northwestern Sardinia. Managed by the Asinara National Park Authority, the MPA is divided into three zones with varying levels of protection: Zone A (integral reserve), Zone B (general reserve), and Zone C (partial reserve). Zone A, covering about 5% of the area, is strictly off-limits to all human activities, including fishing and access. Zone B, comprising 65% of the MPA, allows for regulated activities, while Zone C, making up the remaining 30%, permits certain sustainable uses under specific regulations (Gazale et al., 2022). Fishing within the MPA is highly regulated to preserve marine biodiversity. A general ban on fishing activities is enforced, with exceptions granted to small-scale fishers from Porto Torres and Stintino. These fishers may operate beyond 150 meters from the coast, excluding fully protected areas, and must adhere to strict guidelines. Additionally, trawling is prohibited within three nautical miles along the west coast and within the 50-meter bathymetric contour on the eastern and southern coasts. Among the species under strict protection within the MPA is the European spiny lobster, which benefits from habitat conservation and fishing restrictions aimed at promoting the recovery of its overexploited populations.

The institution of no-take zones showed encouraging results in terms of increase in biomass with a consequent improvement of the stock status due to the spill-over of juveniles (Follesa et al., 2007a, 2007b, 2011).

To evaluate resources of the same genus (*Palinurus argus*) but not present in Mediterranean Sea, in literature have been applied cohort analysis models and surplus yield models (Puga et al., 1991). Afterwards, Fadragas & Stefánsson (2005) utilized ADAPT VPA, a stock assessment method based on catch at age numbers combined with tuning indices from fishery independent data (e.g. scientific survey) (Stefánsson 1992). In literature are not many reported examples for Mediterranean Sea of stock assessment of this species, except in Tunisia (Gharsalli,et al., 2022; Rjeibi, 2012) and in Portugal (Santos et al., 2002).

For the stock of spiny lobster in Sardinian waters, the application of age structured methods is not possible, due to limited catch time series and limited biological information. Nevertheless, in Sardinia, an evaluation of the reproductive parameters of *P. elephas* populations in two different fully protected areas (Su Pallosu and Bugghergu), including their surrounding commercial zones was made by Porcu et al. (2022).

In the context of Asinara MPA monitoring program, data on some length structures of the catches were collected. This data provided a basis to make a first attempt of stock assessment of spiny lobster in Asinara MPA (Figure 4) to evaluate the impact of the MPA on the stock recovery.

Figure 4 – Asinara Island Marine Protected Area.

Objectives

The principal objective of my PhD work was to **improve the knowledge regarding the exploitation status of the main species characterizing the fishery in Sardinian Seas**, consulting the available relevant reports on Mediterranean stock assessment working groups and identifying the species not yet evaluated in the relevant *fora*.

In this context, the status of the red mullet stock in GSA 11 was never evaluated and represented a gap to be filled for the demersal fisheries operating in Sardinian waters, annually evaluated by the STECF for the Western Mediterranean Management Plan, although the data-richness available for this species that is part of the EU Data Collection Framework since 2002. The first objective of my PhD is **to carry out a stock assessment to evaluate the status of red mullet in Sardinian waters** to fill this gap and provide insights for management objectives.

In **chapter 1** the type of data (fishery dependent and fishery independent) collated to be integrated in the stock assessment are presented; the chapter includes a detailed description of the data-rich methods used and describes the results achieved in terms of fishing mortality, SSB, recruitment and reference points.

More importantly, other two marine resources, characterising the Sardinian commercial fishery, have never been evaluated through stock assessment models: red coral and spiny lobster.

The red coral showed an alarming decline, both at Mediterranean and Sardinia level; although a GFCM Management Plan is en force for red coral in the whole GFCM competence area and Sardinia Region applies since more than 30 years a very strict regulation to safeguard this resource, the exploitation status of red coral have never been evaluated neither in Sardinian waters. This resource, declared by IUCN at risk of extinction, represents a very sensitive organism characterised by extremely slow growth, patchy distribution, high susceptibility to climate change and sea bottom trawling disturbance. The consequence of this, is that many years are needed for stock recovery and restoration of the areas exploited by the scuba divers, making urgent to evaluate the status of this stock, especially in Sardinia that is the main producer of red coral in the whole Mediterranean Sea.

Although some attempts are present in literature to evaluate this resource in other areas of Mediterranean (e.g. Corsica), the model applied were characterised by important limitations that prevented to use this information for management purposes.

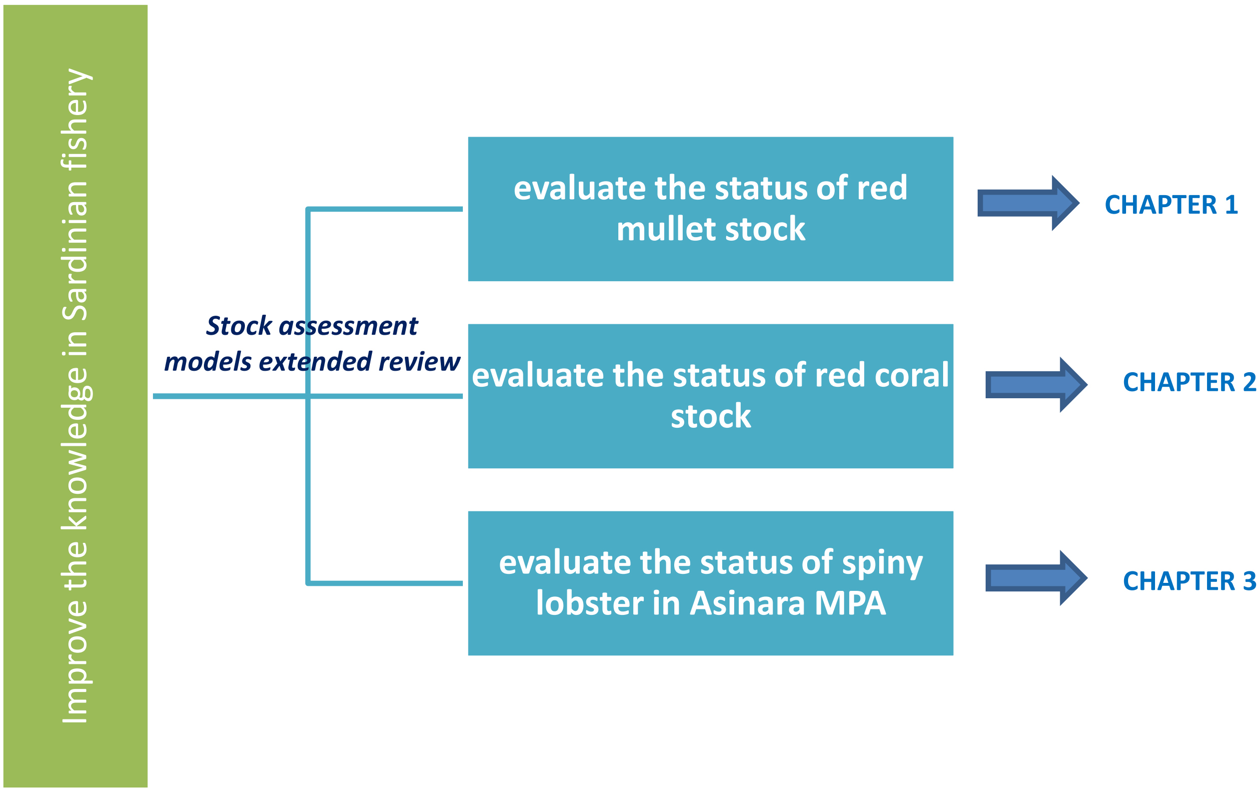
The second objective of my PhD is to **evaluate the status of red coral stock in Sardinian waters**, focusing separately on the Northern and the Northwestern red coral stocks. This objective needed to be addressed in 4 steps:

- *examining in depth the wide spectrum of the stock assessment models* present in literature and utilized in the ad hoc stock working groups at the Mediterranean for the selection of the more appropriate stock assessment model based on data availability (temporal coverage, type of data, biological information), ecological characteristics of the species and knowledge on stock dynamics.
- *selecting the more appropriate models* for the evaluation of the red coral stock status in Sardinian waters;
- *applying the models* to the Northern and North-western Sardinian waters red coral stocks separately;
- *integrating the results* of the different models to provide useful insights *for management purposes,* including socio-economic considerations.

In **chapter 2** the commercial data used to evaluate the red coral stock status in Northern waters and North-western waters are presented in detail, with a specific focus on the age data and model used to estimate the growth parameters for the two considered populations. In the same chapter are described the three models selected to evaluate the status of the two red coral stocks; the results of the three models are compared, integrated and synthesized to provide a consolidated advice that can be used to inform ad hoc management actions.

The third objective of my PhD was to **improve the knowledge about the stock status of spiny lobster**, with a particular focus on the Asinara MPA to evaluate the impact of this spatial management measure on the stock recovery.

Chapter 3 of my PhD thesis describes the data collected under the monitoring program in the Asinara MPA on spiny lobster and how they have been integrated with the biological available information to preliminary assess the status of the local population, using a data-poor stock assessment methodology.



Chapter 1: Exploitation status of red mullet (Linnaeus, 1758) in Sardinian waters

1.1 Introduction

Figure 1.1 photo of a red mullet (*M. barbatus* Linnaeus, 1758).

The red mullet (Figure 1.1) is a demersal species widely distributed throughout the Mediterranean Sea, including Sardinian waters (Figure 1.2), where it is an important target of small-scale and trawl fisheries. Biologically, it is a fast-growing, short-lived species, with individuals typically reaching maturity within their first year of life. Red mullet inhabits sandy and muddy bottoms, usually at depths between 10 and 300 meters, and feeds primarily on benthic invertebrates. In Mediterranean Sea its spawning season occurs mainly in late spring and summer, with reproduction and recruitment strongly influenced by environmental factors such as temperature and substrate type (Carbonara et al. 2015).

Spawning areas of red mullet are found around all coasts of Sardinia at depths between 50 – 100 m with a general low temporal persistence (Figure 1.3, extracted from Giannoulaki et al. 2013).

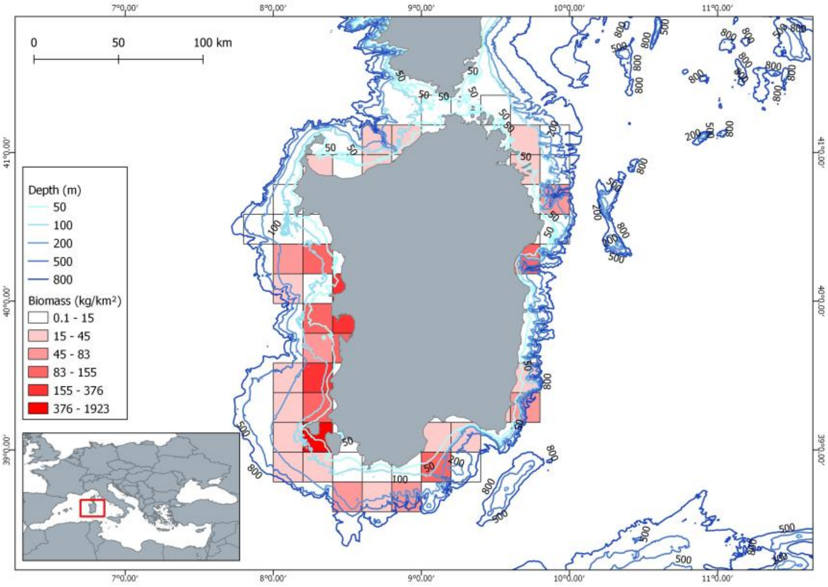


Figure 1.2 – Spatial distribution of red mullet in Sardinian waters (MEDITS data, average 2018-2021). Data download from https://data.jrc.ec.europa.eu/dataset/f25092c4-3f0f-449f-ba60-5fbfe385defc (resolution 0.2 degrees)

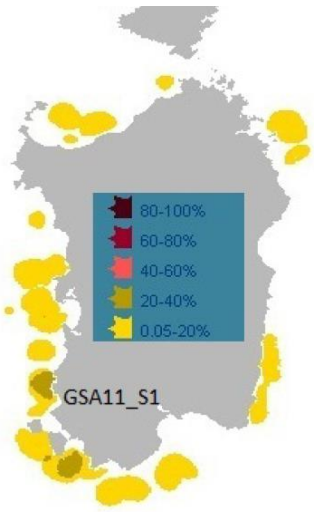


Figure 1.3 – Location of sensitive habitats of red mullet in Sardinian waters. Figure extracted from Giannoulaki et al., 2013.

Although the red mullet is one of the main target of demersal fishery and one of the species covered by the Western Mediterranean MAP, the species was never assessed in Sardinian waters, being only assessed in the Tyrrhenian Sea (GSA 9 and 10), where it was evaluated applying data-rich methodologies and specifically statistical catch at age and biomass dynamic models (STECF, 2021a) and is evaluated as sustainably exploited.

The aim of this chapter is fill this gap on the stock status evaluation of this important resource of the Sardinian demersal fishery.

1.2 Materials and Methods

1.2.1 Data

In Sardinian waters, the average annual landing of *M. barbatus* was approximately 131 tons over the period 2019–2021, according to FDI data. This species accounted for about 14% of the total landings from the main demersal gears—bottom trawls (OTB), gillnets (GNS), and trammel nets (GTR)—as reported under the EU Data Collection Framework (DCF).

Red mullet is primarily exploited by trawl fisheries (OTB), which contributed around 86% of the total landings during the same period. However, the species is also a relevant target for small-scale fisheries using gillnets and trammel nets, which together accounted for an additional 17 tons per year, on average, between 2019 and 2021 (Figure 1.4).

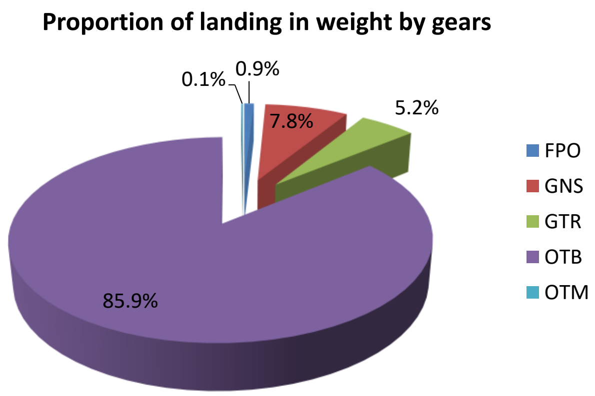


Figure 1.4 – Proportion of red mullet landings split by gear. FPO: pots, GNS: gill-nets, GTR: trammel nets, OTB: trawlers, midwater otter trawl. Data from: https://stecf.ec.europa.eu/data-dissemination/fdi_en

<u>*Commercial data (fishery dependent)*</u>

The commercial data for the red mullet in Sardinian waters can be differentiated into two main types: aggregated and from biological sampling. The aggregated data corresponds to the landing and the discard amount fished by the fleet by year, quarter, gear and vessels length. This data are freely available and can be downloaded from the website of the STECF, in the section Fishery Dependent Information (FDI): https://stecf.ec.europa.eu/data-dissemination/fdi_en. From the FDI this information is available from 2013.

Another aggregated source of information is provided by the length-frequency distribution of the individuals landed by year, gear, quarter and vessel length (when available). This information is not freely available and it is submitted by the Italian Ministry of Agriculture, Food Sovereignty and Forestry to the European Commissions through an annual data call (https://dcf.ec.europa.eu/data-calls/medbs_en).

The University of Cagliari (Department of Life and Environmental Sciences) is in charge to carry out the biological sampling in Sardinian waters (GSA 11, GFCM *sensu*), in collaboration with the Consorzio Nazionale Interuniversitario per le Scienze del Mare (CoNISMa) under the EU Data Collection Framework Programme (https://dcf.ec.europa.eu/index_en?prefLang=it).

Under this sampling program, the sampling frame is represented by the total number of fishing trips carried out by the fleet operating in the area (Figure 1.4). A selection of fishing trips is firstly made (sampling units), following a temporal (e.g. quarterly) and technical (e.g. gear, métier[1]) stratification, to be monitored by the observers (blue arrows in Figure 1.5). From the catch of each fishing trip, a representative sample for each species caught is registered (sampling unit 2) and for a sub-sample length measurements are collected in order to detect seasonal differences in the demographic structure and composition of landings and discards for different métiers. Several sub-samples are collected to record the data on the length-frequency distributions and biological parameters, namely the sex, the maturity stage, the individual weight and age. The catch of selected fishing trips is sampled directly at landing site or, alternatively, through monitoring on

[1] A specific combination of gear type, target species, fishing area and season used by a fleet segment. https://dcf.ec.europa.eu/data-calls/definitions-and-terminology/f/fishing-activity-metier_en?prefLang=mt

board by the scientists involved in the sampling program. The monitoring on board allows the observation of the fraction of the catch discarded by the fishers (e.g. because below the minimum conservation reference size).

The length-frequency distributions of the total Sardinian landing by quarter, gear, métier and year is derived through a raising procedure (Figure 1.5, red arrows) that expands backward the length-frequency distributions observed in the sub-samples to the total weight caught in the fishing trip, to the total landing of all the sampling frame.   The discard amount is derived applying the discard ratio approach (Cochran, 1953). The length-frequency distribution observed during the sampling on-board were raised to the estimated discard amount.

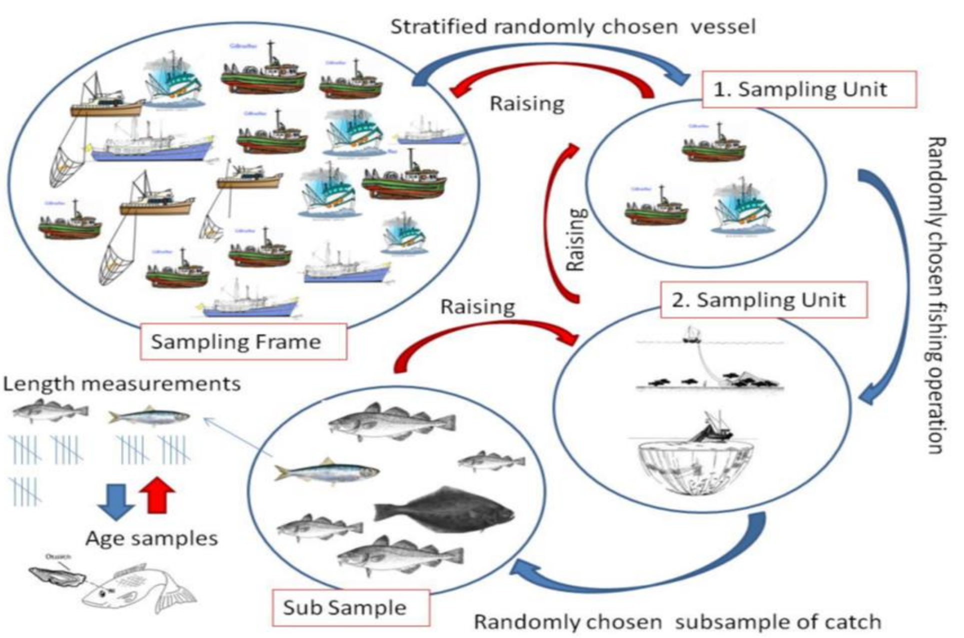


Figure 1.5 – Scheme of the different sampling stages (blue arrows) and raising procedure (red arrows) in the system of data collection of catches. Image extracted from Vølstad FAO 2014.

These raised length-frequency distributions are not publicly available and have been made available by the Department of Life and Environmental Sciences for the purposes of this PhD thesis. The mean length of the individuals in the trawlers landing is between 10 cm and 20 cm of total length, while the discarded fraction is generally characterized by individuals below 12 cm (Figure 1.6).

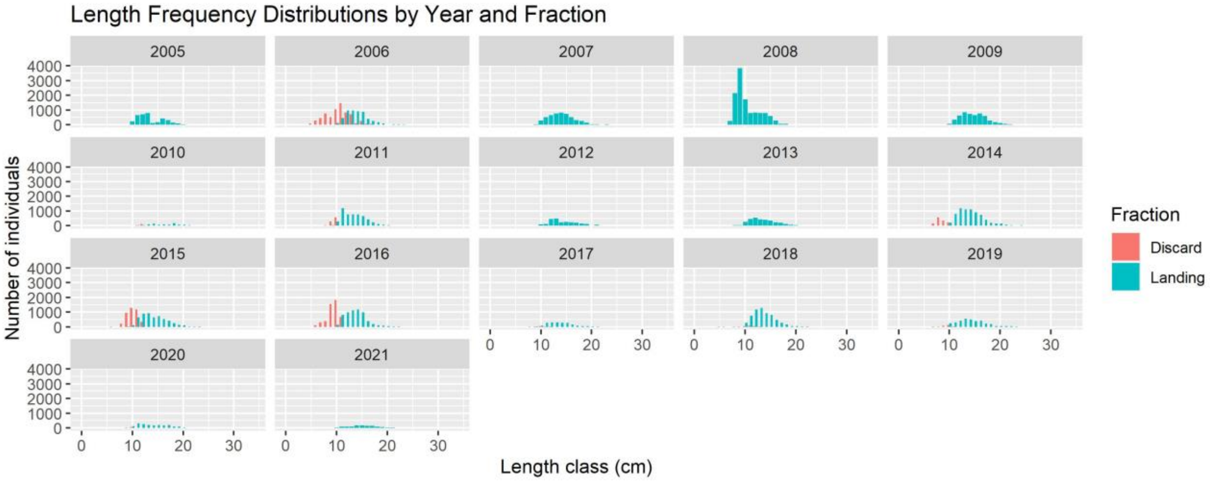


Figure 1.6 – Length-frequency distributions (number in thousands) of commercial landing (blue) and discard (pink) of red mullet in Sardinian waters for trawlers from 2005 to 2021. Distributions raised to the total landing and discard.

The discard amount and corresponding length-frequency distributions are available in the years since 2009; for this reason firstly the discard amount was reconstructed from 2005 to 2008, applying the ratio between discard and landing (D/L) of the years 2009-2011 to the landing of the 2005-2008 years (Table 1.1). Then, the corresponding length-frequency distributions were derived raising them to the reconstructed discard volume.

Table 1.1 – Discard (only trawlers) and landing (total) amount in tons by year, used in the assessment. The discard value in bold and underlined are estimated.

year	discards	landings
2005	**<u>5.6</u>**	116
2006	**<u>8.6</u>**	178
2007	**<u>8.9</u>**	185
2008	**<u>9.3</u>**	193
2009	0	222
2010	4	47
2011	10	170
2012	0	102
2013	0	129
2014	10	264
2015	30	266
2016	51	232
2017	2	96
2018	4	289
2019	3	200
2020	1	114
2021	0	78

Scientific survey data (fishery independent)

The MEDITS (Mediterranean International Trawl Survey) data (Spedicato et al., 2019) represents the main fishery independent source of information for demersal species in Mediterranean Sea (Figure 1.7). The MEDITS survey is an international coordinated bottom-trawl surveys in the Mediterranean started in 1994 and is aimed at providing data useful for describing species spatial distribution and occupation, quantifying changes in the fish populations, through indices of demography (e.g., size structure and biological traits), thus contributing to the routine stock assessments and the development of management advice tools. The MEDITS survey aims at providing also data useful for describing species diversity at community level. MEDITS is carried out every year, during spring and beginning of summer. MEDITS covers the Sardinian waters since 1994 (Figure 1.8) and red mullet is one of the key target species of the program.

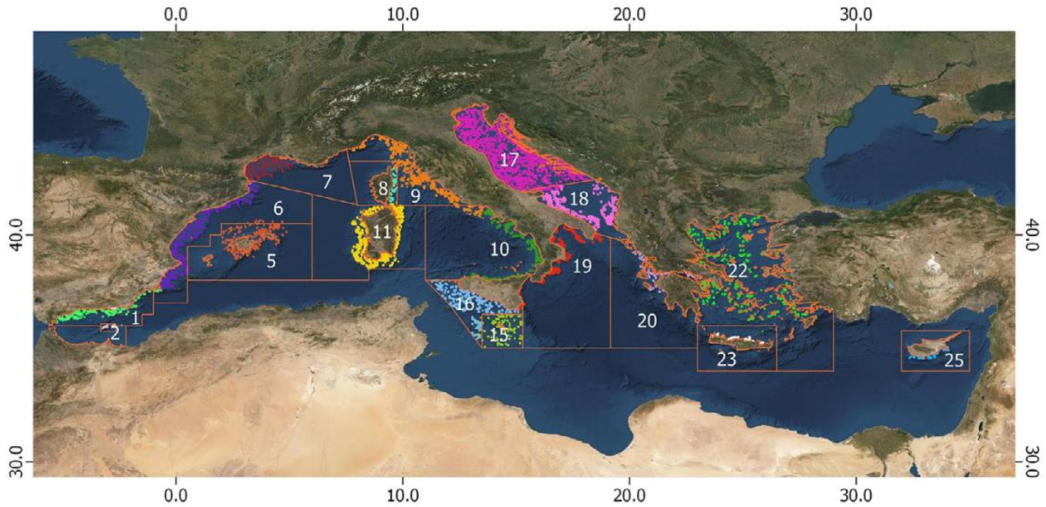


Figure 1.7 - Study area of the MEDITS bottom trawl surveys, showing the hauls allocated to the geographical sub-areas established by the General Fisheries Commission for the Mediterranean. Figure from Spedicato et al. (2019).

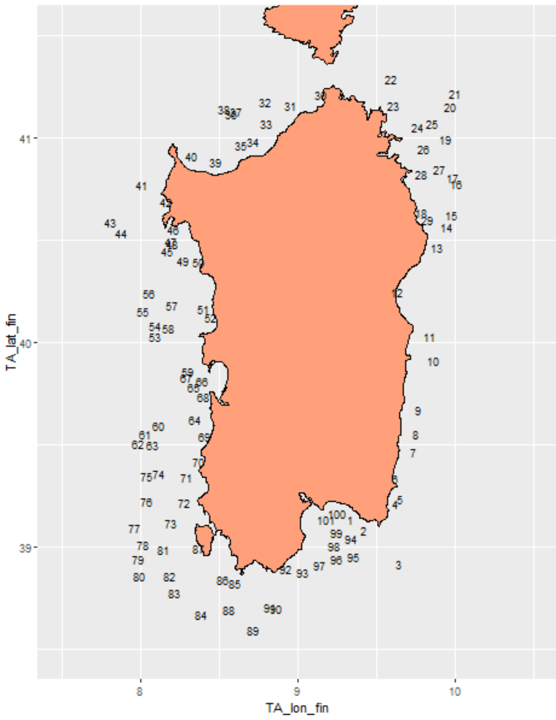


Figure 1.8 – Location of the hauls carried out during the MEDITS bottom trawl survey in Sardinian waters.

The sampling design is random stratified with the number of planned hauls distributed in each depth stratum (10-50 m, 50-100 m, 100-200 m, 200-500 m and 500-800 m) proportionally to the stratum surface in the area (GSA). For each haul: hauls information (position, shooting and hauling depth, duration of haul, distance covered, etc…), all the species caught (weight and number of individuals in the haul) are recorded. For the target species (e.g. European hake, red mullet, etc…) the data on the lengths, sex, maturity stage are also collected.

The data collected are, then, used to estimate relative indices of abundance (number of individuals and kg per square km) to be integrated as tuning in the stock assessment models.

The abundance and biomass indices by GSA were calculated through stratified means (Cochran, 1953). This implies weighting of the average values of the individual standardized catches and the variation of each stratum by the respective stratum areas in each GSA:

$$Y_{st} = \sum \frac{Y_i A_i}{A} \qquad \textbf{(Eq. 1)}$$

$$Var(Y_{st}) = \frac{\sum \frac{A_i{}^2 s_i{}^2}{n_i}}{A^2} \qquad \textbf{(Eq. 2)}$$

where:

A is the toal survey area,

A_i is the area of the i-th stratum,

s_i is the standard deviation of the i-th stratum,

n_i is the number of valid hauls of the i-th stratum,

Y_i is the mean of the i-th stratum,

Y_{st} is the stratified mean abundance,

$Var(Y_{st})$ is the variance of the stratified mean.

The variation of the stratified mean is then expressed as the 95 % (α=0.05) confidence interval:

$$CI = Y_{st} + t_{\frac{\alpha}{2},n-1}\sqrt{\frac{Var(Y_{st})}{n}} \qquad \textbf{(Eq. 3)}$$

where $t_{\frac{\alpha}{2},n-1}$ is the critical value of the Student's t-distribution with n−1 degrees of freedom, at the desired confidence level (e.g., 95%).

In Table 1.2 the number of hauls carried out in each depth stratum for GSA 11 and the surface of each stratum is reported.

Table 1.2 – MEDITS stratification scheme in GSA 11 (Sardinian waters): depth stratum, surface and number of planned hauls.

Depth stratum	Total surface (km^2)	Number of hauls
10 - 50 m	5374	20
50-100 m	5094	19
100-200 m	6628	24
200-500 m	5417	21
500-800 m	4462	17
Total	26975	101

In Figure 1.9 are reported the MEDITS red mullet abundance indices, showing an overall increasing trend in the recent years and a sharp decrease in 2021.

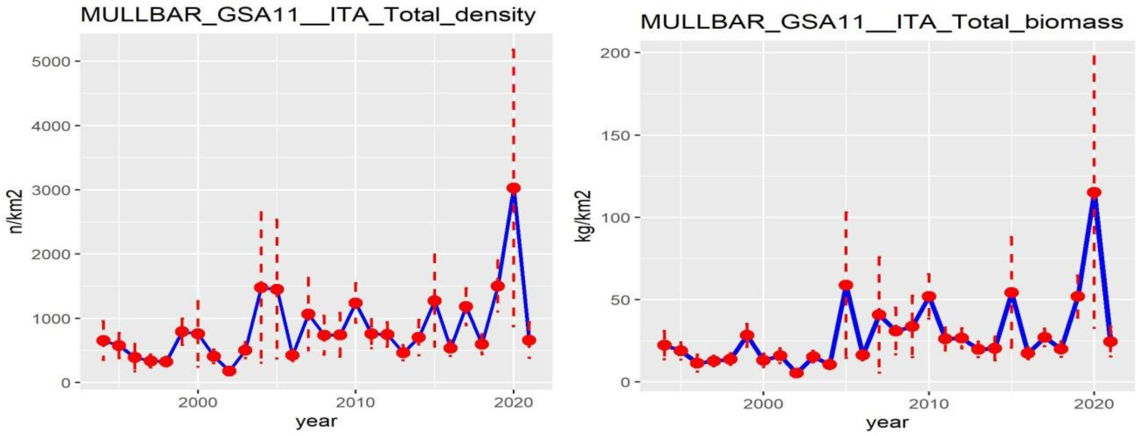


Figure 1.9 – Abundance indices (left N/km2, right kg/km2) for red mullet in GSA 11 from MEDITS survey (1994-2021).

In Sardinian waters (GSA11) the MEDITS took place in different seasons of the year, with consequent detection (e.g. 2004 and 2007, Figure 1.10) or not detection of recruitment. This was considered during interpretation of available survey indices in the assessment, excluding the age 0 from the tuning indices.

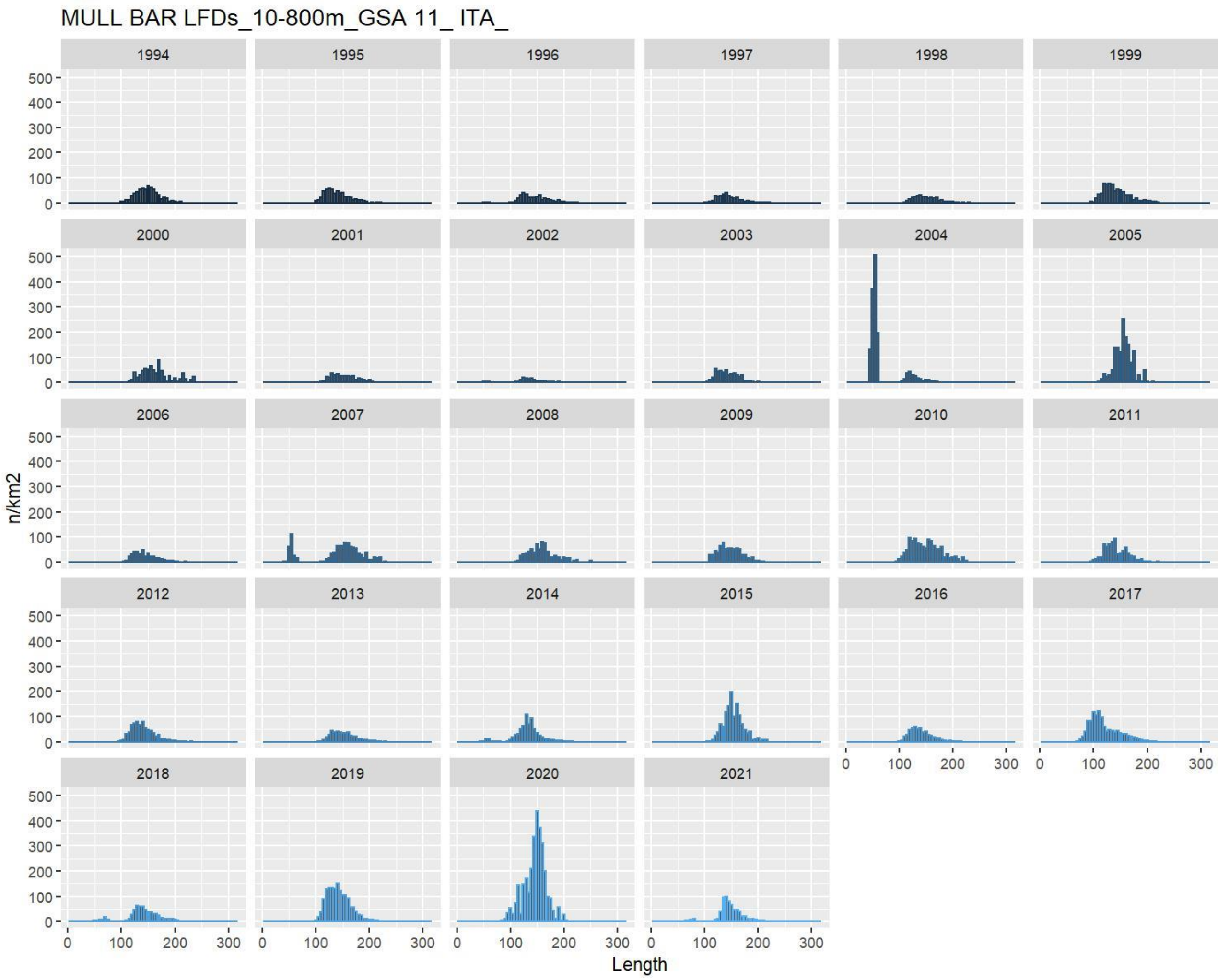


Figure 1.10 – Abundance indices (N/km2) by length class (length-frequency distribuions) for red mullet in GSA 11 from MEDITS survey (1994-2021).

Growth, maturity and natural mortality

Following a stratification scheme by sex and length class, a fixed number of otoliths are extracted from a sub-sample of individuals; subsequently, the otoliths are processed and the age is assigned to each individual by an trained reader, following the through the ageing protocol described by Carbonara and Follesa (2019). Specifically, 2438 females and 2077 males were collected for the age.

The nls (Nonlinear Least Squares) R CRAN function is used to fit the von Bertalanffy nonlinear model (Eq. 4) to age-length data by minimizing the residual sum of squares between observed and predicted values applying an iterative optimization algorithm. The equation of the von Bertalanffy growth model is detailed by Eq. 4 and shown in Figure 1.11.

$$L(t) = L_\infty(1 - e^{-K(t - t_0)}) \qquad \textbf{(Eq. 4)}$$

where:

L(t) is the length at age t,

L_∞ is the asymptotic length (the maximum theoretical length the organism can reach);

K is Growth coefficient (the rate at which the organism approaches L_∞);

t_0 is the theoretical age at which the length would be zero.

The data on the individual weights at length (7420 females and 6592 males collected) are then used to derive the coefficients (a and b) of the length-weight relationship (Eq. 5).

$$W(L) = aL^b \qquad \textbf{(Eq. 5)}$$

where:

W is the weight of the individual (in gram);

L is the length of the individual (in cm).

The estimated von Bertalanffy parameters and length-weight relationship coefficients are reported in Table 1.3 and are consistent with what found in Adriatic by Carbonara et al. (2018).

Table 1.3 Parameters of the von Bertalanffy parameters and length-weight relationship for red mullet in Sardinian waters. Length in cm and weight in grams.

Sex	L_∞	**K**	t_0	**a**	**b**
Females	29.41	0.237	-0.752	0.011	3
Males	23.225	0.31	-0.792	0.009	3

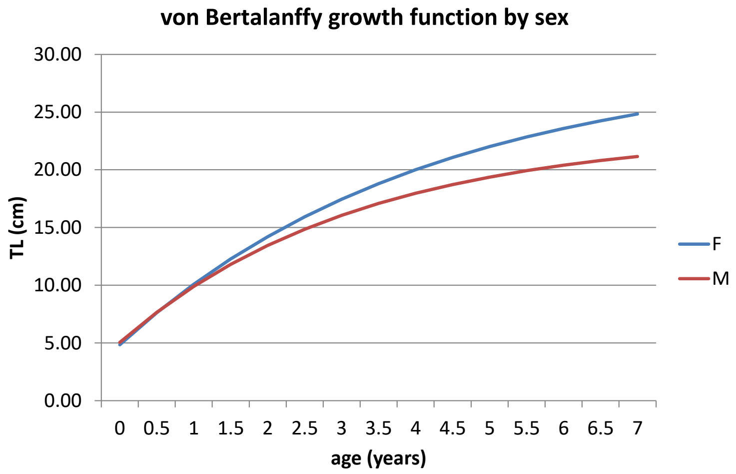


Figure 1.11 – von Bertalanffy growth curve by sex for the red mullet in Sardinian waters.

The red mullet spawning season in Sardinian waters lasts from April to June (DCF data). The size at first maturity is estimated on the basis of a procedure assigning a maturity stage to each sampled individuals following the FAO Atlas of the maturity stages of Mediterranean fishery resources (Follesa and Carbonara, 2019). A logistic curve is, then, estimated, through which the proportion of matures is associated to a length class; the size at first maturity ($L_{m50\%}$, corresponding to the length at which the 50% of individuals are mature) is finally derived as around 12 cm for females and 10 cm for males, in agreement with Carbonara et *al.* (2015).

This information, integrated with the growth rate from the von Bertalanffy growth function, bring to the assumption that in the 0-age class (recruits, new individuals entering in the population) the individuals are all immature, while from age 1 onward they are all matures.

The growth parameters have been finally used to estimate the natural mortality (M); there are different methodology to estimate M vector by age. For consistency with the assessments on red mullet carried out in the closer areas (GSA 9 and 10, Tyrrhenian Sea), it was decided to apply the Chen and Watanabe (1989) method, a widely used approach based on age and life-history parameters. It is a non-constant, age-dependent model that refines earlier empirical models by accounting for the natural decline in mortality as fish age, up to a point where senescence may increase mortality again.

In Table 1.4 are reported the natural mortality and maturity at age vectors used in the assessment.

Table 1.4 - M and proportion of mature individuals by age for red mullet in Sardinian waters.

Age (years)	**0**	**1**	**2**	**3**	**4+**
Proportion of mature individuals	0	1	1	1	1
Natural mortality	1.38	0.79	0.58	0.5	0.44

1.2.2 Stock assessment model

Selection of the stock assessment model

The available data for the stock of red mullet in Sardinian waters include a substantial dataset collected under the EU Data Collection Framework (DCF) since 2005 (EU, 2008; EU, 2017).

Firstly, the monitoring program gathered length-frequency distributions from both commercial catches and scientific bottom trawl surveys (MEDITS program) for the years 2005–2021 (Spedicato et al., 2019). The commercial data include discard estimates, providing critical information on age-0 individuals caught by trawlers.

In addition to discard sampling, the monitoring program enabled the estimation of von Bertalanffy growth parameters, which were subsequently used to derive catch-at-age matrices for both commercial landings and survey indices through a deterministic age slicing procedure (Sparre & Venema, 1998). Furthermore, these growth parameters were used to estimate the natural mortality vector based on life-history models such as Chen & Watanabe (1989), and to calculate individual weight-at-age from the established length–weight relationships.

This biological dataset was complemented by the construction of a maturity-at-age vector, using empirical observations on gonadal development stages collected during routine sampling under the national monitoring program.

The availability of this comprehensive and high-resolution dataset supports the application of data-rich, age-structured stock assessment models, enabling the tracking of cohorts through time.

The primary model typically used in the GFCM context for data-rich stocks is the Extended Survivors Analysis (XSA), whose application is described in detail in the following section.

Extended Survivor Analysis (XSA) stock assessment model

Extended Survivors Analysis (XSA) is a widely used age-structured stock assessment model, particularly in fisheries management. It is a type of Virtual Population Analysis (VPA) that uses auxiliary data, typically from research surveys, to estimate population abundance and fishing mortality. XSA was developed to address some of the limitations of traditional VPA, such as its sensitivity to the accuracy of terminal fishing mortality rates. The method was applied using the age data obtained by the slicing of the length frequency distributions of the landing and survey data.

The *age slicing procedure* is a method used in fisheries science to estimate the age composition of a fish population based on length-frequency. This approach involves assigning an age to each individual or length class using a known growth model (e.g. von Bertalanffy growth function) derived from a subsample of aged individuals. In its deterministic form, age slicing assigns a single, fixed age to each length class, usually by inverting the growth equation to estimate the corresponding age.

The length-frequency distributions of commercial catches and of the survey indices were transformed in catch-at-age matrices to be used in the XSA (Figure 1.12 and 1.13)), using the growth parameters in section 1.3. The age slicing was carried out in R environment, applying the a4aGr function of the FLR platform (https://flr-project.org/doc/Modelling_growth_and_its_uncertainty_in_FLa4a.html).

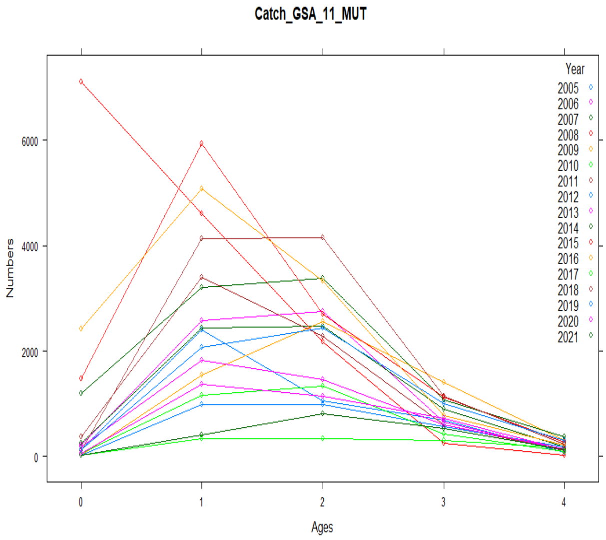


Figure 1.12 - Commercial catch age structure derived applying the age slicing procedure.

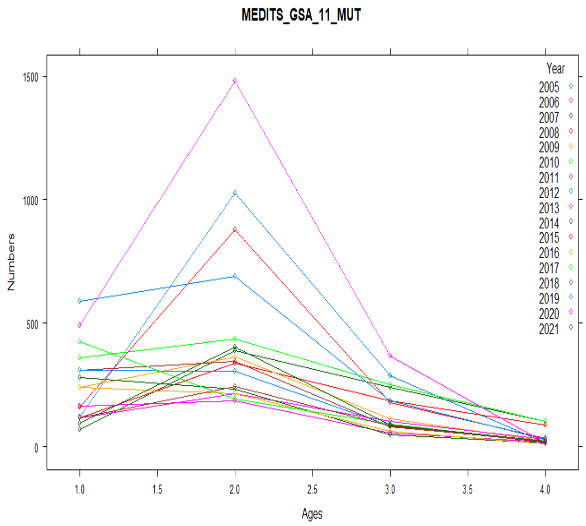


Figure 1.13 – Indices (N/km^2) by age derived applying the age slicing procedure.

XSA is based on the principle of reconstructing past population sizes from catch data. The fundamental equation of VPA, which XSA builds upon, is:

$$N_{a,y} = C_{a,y} + N_{a+1,y+1}e^{M_a} \qquad \textbf{(Eq. 6)}$$

where:

$N_{a,y}$ is the number of fish of age *a* in year *y,*

$C_{a,y}$ is the catch of fish of age *a* in year *y,*

M_a is the natural mortality rate of fish of age *a.*

XSA enhances this basic VPA framework by incorporating survey data to "tune" the estimates of population size and fishing mortality. This tuning process helps to reduce the uncertainty in the assessment.

The main steps of the XSA are 3:

1. **Cohort analysis**: XSA performs a cohort analysis, working backwards through time for each group of fish born in the same year (cohort). This process estimates the number of fish that were alive at each age in each year, based on the catches and natural mortality.
2. **Survey calibration**: XSA uses survey indices of abundance to calibrate the VPA. This is achieved by regressing the survey indices against estimates of population abundance derived from the VPA. Survey catchability[2] (the proportion of the population caught by the survey gear) is assumed as separable into age-specific and year-specific components. This assumption simplifies the model and reduces the number of parameters to be estimated.

   In this step the parameter *qage* has to be established. It is the maximum age (or "tuning age"**)** at which survey indices (like trawl or acoustic surveys) are considered reliable and thus used to tune the stock assessment model.

   The *rage* is another key parameter in the survey calibration. It is the age at which fish first enter the population considered in the analysis — typically the age when they **r**ecruit to the fishery or become catchable in surveys. It determines where the cohort tracking begins, especially in calculating abundance and mortality from catch-at-age data.

   Combined with *qage* (maximum tuning age), it defines the range of ages used for survey tuning and assessment.

---

[2] In relation to survey indices, catchability is the proportionality constant that relates an index of abundance (e.g., catch-per-unit-effort in a survey) to the true population size. Catchability represents how much of the fish population is "catchable" by a specific survey method.

3. **Shrinkage**: This technique involves shrinking the estimates of fishing mortality in the most recent years towards an average fishing mortality rate over a specified period. This helps to mitigate the influence of noisy or unreliable catch data in the terminal year.

   An age range (*shrinkage.ages*) has to be indicated that specifies the age classes for which fishing mortality estimates are *shrunk* (i.e., adjusted) toward a common mean value across years. For ages included in *shrinkage.ages*, the model applies a penalty that pulls the F estimates toward the mean F over time, because the oldest age classes often have low catches and are under-sampled in surveys (due to selectivity, low abundance).

   An year range, *shrinkage.years*, needs to be set, to specify the terminal years of the assessment in which F estimates are shrunk toward the mean across ages.

   The *shrinkage* parameter in XSA controls the strength of the penalty applied during the tuning process to stabilize F estimates over specified ages and years. Shrinkage works by minimizing a penalized likelihood function. A higher shrinkage value means stronger smoothing (more regularization). A lower value allows F to vary more freely (less constraint). When shrinkage is high, the model trusts the tuning data less (survey indices), smoothing the F estimates more heavily, pulling them toward the mean over time or age.

The **step 1** is based on the Baranov (1918) catch equation:

$$C_{a,y} = N_{a,y} \frac{F_{a,y}}{F_{a,y}+M_a} (1 - e^{-F_{a,y}+M_a)}) \qquad \textbf{(Eq. 7)}$$

where: $F_{a,y}$is the fishing mortality rate of fish of age *a* in year *y.*

Step 2 assumes the separability of survey catchability, following the equation:

$$q_{a,y} = q_a \, q_y \qquad \textbf{(Eq. 8)}$$

where:

$q_{a,y}$ is the catchability at age a in year y,

q_a is the age-specific catchability,

$q_y$is the year-specific catchability.

Moreover, the survey index $I_{a,y}$is related to population abundance $N_{a,y}$ (estimated by Eq.6) through a linear regression:

$$I_{a,y} = q_{a,y} N_{a,y} \qquad \textbf{(Eq. 9)}$$

XSA estimates the catchability parameters (q) by fitting a regression model to the survey data.

In the **step 3** the shrunken fishing mortality $F'_{a,y}$ is calculated as:

$$F'_{a,y} = w\, F_{a,y} + (1 - w)\, F_{a,mean} \qquad \textbf{(Eq. 10)}$$

where:

w is the shrinkage weight (between 0 and 1),

$F_{a,mean}$*is the mean fishing mortality rate of age a over a specified period (a common approach is to use the average F over the most recent years).*

The major **assumption** of the method is the flat selectivity for the oldest ages (selectivity as classical ogive).

The XSA software, implemented in the FLR (Fisheries Library in R) framework, https://flr-project.org/) was applied to the red mullet stock, combining the two sexes. The survey indices from MEDITS data from 2005 to 2021 have been used for the tuning not including age 0, because the recruitment was not detected every year and could bias the XSA recruitment reconstruction.

The following settings for the XSA were explored to identify the best combination.

qage: 1,2,3

rage[3] *:* -1,0,1

shrinkage: 0.5,1,1.5,2

nb of years for shrinkage: last 3,4,5 years of the time series

nb of ages for shrinkage: last 2,3 ages.

[3] *rage* = -1 means that the recruitment age is undefined or not used for tuning.

Selection of the best settings combination

In stock assessment models like XSA, *residuals* represent the differences between observed survey indices and model-predicted values, typically on the log scale. They are calculated for each age and year where tuning data are available. Analyzing these residuals is essential to evaluate the goodness of fit and diagnose model performance. A common qualitative tool for the evaluation of residuals is the bubble plot, where residuals are visualized as circles: the size of each bubble reflects the magnitude of the residual; the color or fill (positive vs. negative) indicates whether the model over- or under-predicts abundance.

Patterns in bubble plots—like consistent underestimation at certain ages or over time—may suggest model misspecification, problems with tuning indices or unaccounted variability. A well-fitting model should show residuals randomly distributed without clear trends.

Retrospective analysis is a diagnostic tool used in stock assessment to evaluate the stability and consistency of model estimates over time. It involves re-running the assessment multiple times, each time removing the most recent year of data (one by one), and comparing the resulting trends in key parameters like biomass, fishing mortality, and recruitment. By examining how estimates change as recent data are excluded, it is possible to detect systematic biases or model misspecifications. If estimates for past years shift substantially with the removal of new data, the model may be overfitting recent observations or underestimating uncertainty. These patterns are often visualized in "retro plots", where trends from successive peels are overlaid. A consistent model should show overlapping trajectories, while diverging trends suggest the need for model refinement or alternative assumptions.

The reference points to evaluate the status of the stock were estimated using FLBRP package (https://github.com/flr/FLBRP) with an Yield-per-Recruit (YPR) analysis. The YPR curve is a quantitative tool in fisheries science that describes the relationship between fishing mortality (F) and the expected lifetime yield obtained from a single recruit, incorporating growth, natural mortality and selectivity parameters, and is used to identify reference points that optimize harvest while avoiding overexploitation. This analysis is applied when a relationship between parental stock and number of recruits is not defined yet and can estimate a proxy of the F_{MSY}, namely $F_{0.1}$.

$F_{0.1}$ is the fishing mortality at which the slope of the YPR curve (Figure 1.16) is 10% of the slope at the origin (i.e., when F is close to 0 0).

Another reference point that the YPR analysis allows to estimate is the F_{MAX}, corresponding to the maximum of the YPR curve (Table 1.5). However, this level is never used as reference to evaluate the status of the stock, because is considered risky and not precautionary. Thus, the advice is provided on the basis of the average fishing mortality in the last three years respect to $F_{0.1}$.

1.3 Results

The settings combination corresponding the best run in terms of diagnostic (retrospective and residuals) is:

qage=3; *rage*=-1; *shrinkage*=0.5; *shrinkage.years*=4; *shrinkage.ages*=2.

The results show oscillating SSB and F along the years with a decrease in catches and F in recent years. This is consistent with the decrease in the effort established by the Western Mediterranean MAP (Figure 1.14).

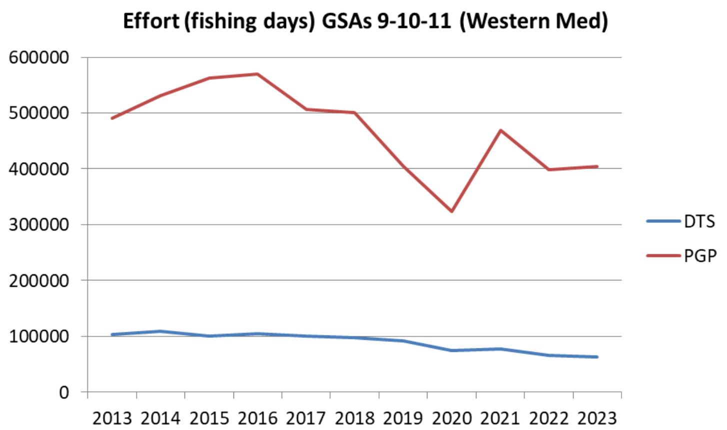


Figure 1.14 Effort (fishing days) time series (FDI data, https://stecf.ec.europa.eu/data-dissemination/fdi_en) for Italian trawlers (DTS) and polyvalents (PGP) operating in GSAs 9-10-11.

The level of SSB is higher in the recent year, reaching the levels of the beginning of the time series (Figure 1.15).

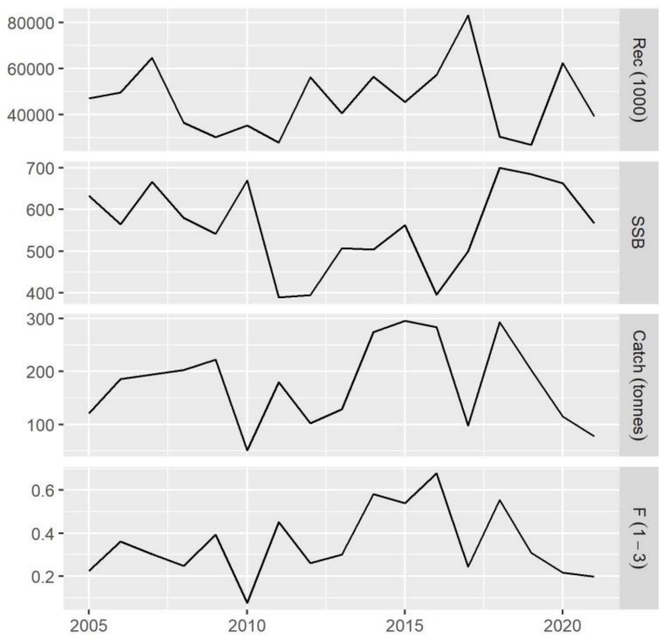


Figure 1.15 - Summary of the stock assessment results for red mullet in GSA 11. Recruitment in thousands, spawning stock biomass (SSB) in tons, observed catch in tons, average F in the age range 1-3 years.

The residuals bubble plot shows residuals in the indices not so pronounced and it does not show any trend.

The retrospective analysis seemed quite stable, especially for recruitment and F (Figure 1.16).

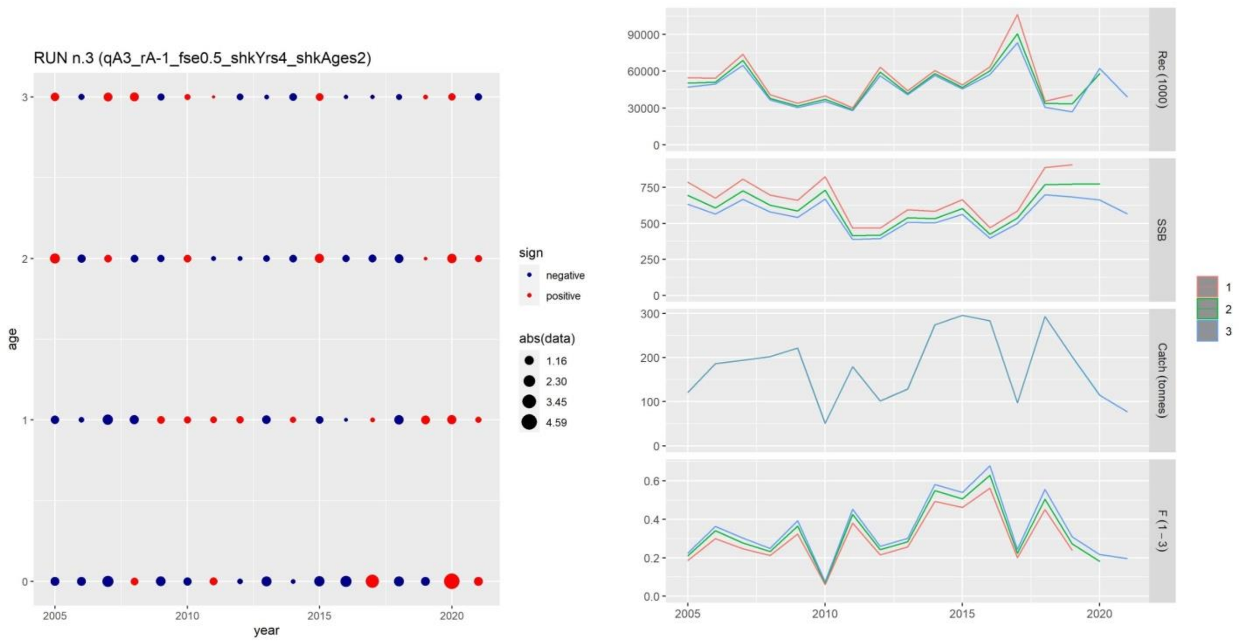


Figure 1.16 - Diagnostic and retrospective analysis of the best XSA model for red mullet in GSA 11.

The results show an F current (average of the last 3 years) equal to 0.22 and, thus below the $F_{0.1}$ (=0.3)(Figure 1.17 and Table 1.5). Thus, the stock is considered sustainably exploited.

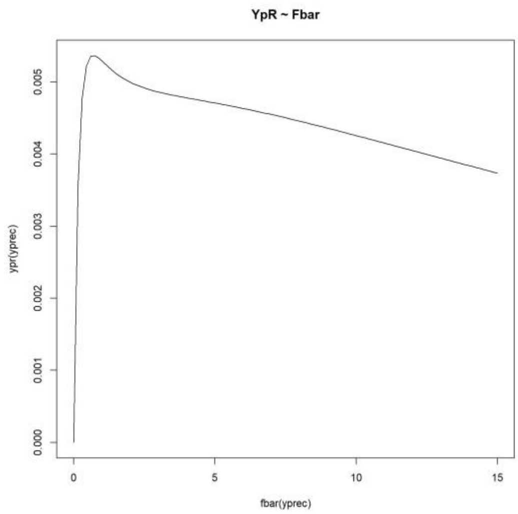


Figure 1.17 – yield-per-recruit curve for the estimation of $F_{0.1}$. On the x-axis are the different fishing mortality levels and on the y-axis the corresponding yield-per-recruit.

Table 1.5 – Reference point estimated in the YpR analysis for red mullet in Sardinian waters.

Reference points	F	Total Yield	Recruitment	SSB	Biomass
$F_{0.1}$	0.328201	207.8276	42387.13	642.7968	851.3141
F_{MAX}	0.690836	227.6626	42387.13	334.8744	542.1369

1.4 Conclusions

This chapter furnishes a comprehensive account of the data sources and the analytical model employed to evaluate the status of the red mullet stock inhabiting Sardinian waters. The application of the Extended Survivors Analysis (XSA) model was meticulously informed by the availability of a robust and complete understanding of the species' biology, the characteristics of the at-sea population and the size structure of commercial catches. The assessment's findings indicated that the red mullet stock in Sardinian waters is currently being exploited sustainably, a conclusion that aligns with the assessments conducted in adjacent geographical areas, specifically the Tyrrhenian Sea (GSA 9) and the Southern Tyrrhenian Sea and Strait of Sicily (GSA 10)(https://www.fao.org/gfcm/data/safs/fr/).

This detailed stock assessment was presented to and scrutinized by the GFCM Stock Assessment Working Group on Demersal Species (WGSAD) in 2022 (GFCM 2022b; GFCM 2022c). Following a thorough review, the assessment was validated and officially endorsed by the working group. This endorsement signifies its scientific credibility and its suitability for providing quantitative advice to the GFCM. The complete assessment report has been made publicly accessible on the GFCM website at the following link: https://gfcmsitestorage.blob.core.windows.net/website/5.Data/SAFs/DemersalSpecies/2021/SAF_MUT_11_RefY2021.pdf.

This assessment makes a significant contribution to building a complete overview of the status of demersal resources within Sardinian waters and within the broader context of the Western Mediterranean Multiannual Plan. Notably, it highlights the potential for existing fishing opportunities on sustainably exploited stocks like red mullet, which could serve to partially offset economic losses experienced by the fishing sector due to the implementation of fishing effort regimes and catch limits imposed on overexploited species such as giant red shrimp and blue and red shrimp, as mandated by European Union regulations under the MAP (European Union, 2019).

The dissemination of this kind of scientifically robust information is of paramount importance for several reasons. Firstly, it serves to enhance the awareness and understanding of fishers regarding the state of different fish stocks. Secondly, it promotes the adoption of more sustainable fishing strategies that prioritize the exploitation of stocks assessed as sustainably exploited or underexploited. Thirdly, it has the potential to increase the trust of fishers in fisheries management processes and the scientific advice underpinning them, ultimately leading to improved compliance with and accomplishment of management measures.

In the specific context of Sardinia, where the small-scale coastal fleet plays a crucial role in the regional fisheries sector, contributing significantly to both the local economy and cultural heritage, the results of this assessment provide particularly useful insights. They suggest a potential opportunity for this fleet to strategically target red mullet to a greater extent than European hake, a species that continues to be classified as overexploited in the region. This shift in targeting could contribute to the economic viability of the small-scale fleet while promoting the sustainable utilization of marine resources.

Chapter 2: Exploitation status of two *C. rubrum* sub-populations in Sardinian waters (Western Mediterranean)

2.1 Introduction

Figure 2.1 – Red coral colony.

C. rubrum, commonly known as red coral (Figure2.1), is a benthic, colonial octocoral endemic to the Mediterranean Sea, characterized by peculiar biological and ecological traits that render this species particularly vulnerable to overexploitation and slow to recover, posing significant challenges to sustainable management and to the selection of appropriate stock assessment models (Garrabou & Harmelin, 2002; Tsounis et al., 2006; Santangelo & Bramanti, 2007; Bramanti et al., 2014).

Red coral is sessile and sedentary, inhabiting rocky substrates at depths ranging from 10 to over 300 meters, though commercial harvesting is most common between 50 and 130 meters. It forms dense aggregations, often referred to as "coralligenous assemblages," which are critical components of Mediterranean biodiversity hotspots.

A comprehensive analysis of the distribution and occurrence of *C. rubrum* across mesophotic and upper bathyal zones along the Italian coasts of the Mediterranean Sea, was made by Toma et al. (2022a) based on remotely operated vehicles (ROVs) and other underwater survey methods, importantly contributing to map red coral forests (Figure 2.2) at depths ranging from 50 to over 200 meters, revealing that these deep-water populations are more widespread and ecologically significant than previously understood. The findings highlight the presence of dense aggregations in several regions, including Sardinia, Liguria, and the Tyrrhenian and Ionian Seas, often associated with rocky substrates and steep slopes.

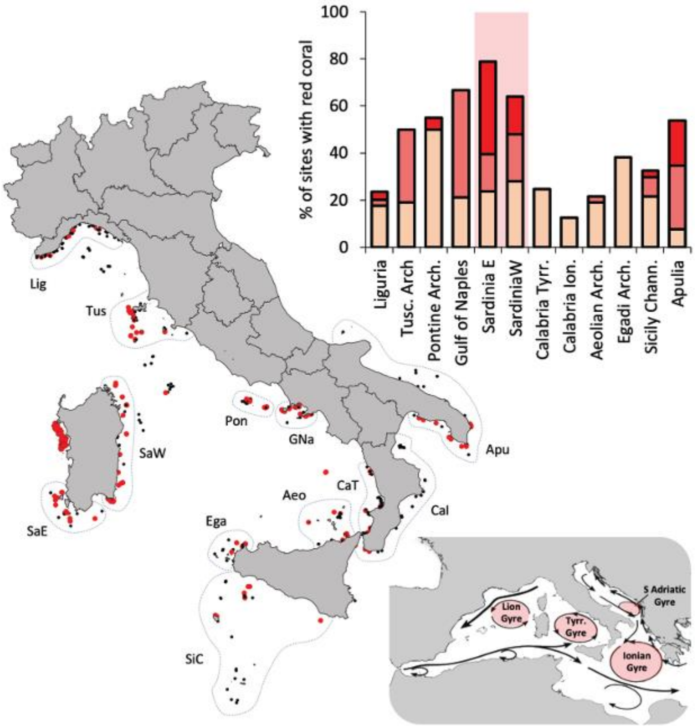


Figure 2.2 - Geographic distribution of the investigated sites showing the presence (red dots) or absence (black dots) of red coral. The histograms (upper inset) represent the percentage of sites with red coral in each considered macro-area (identified in the map by the dashed lines). The colours of the stacked bars indicate the percentage number of sites with scattered (light pink), aggregated (dark pink), and dense (red) populations. The pink box indicates the macro-areas encompassed in the red coral hotspot. The figure in the lower inset shows the shallow-water Mediterranean circulation with the gyres putatively involved in the evidenced red coral distribution. Lig: Liguria, Tus: Tuscan Archipelago, SaE: eastern Sardinia; SaW: western Sardinia, Pontin Archipelago, GNa: Gulf of Naples, CaT: Tyrrhenian Calabria, Aeo: Aeolian Archpelago, Ega: Egadi Archipelago, SiC: Sicily Channel, Cal: Ionian Calabria, Apu: Apulia. Figure extracted by Toma et al. 2022a.

Red coral growth rate is exceptionally slow, with axial extension typically ranging from 0.2 to 0.6 mm per year, and the formation of commercially valuable colonies (e.g., >7 mm diameter) can take 20 to 50 years (Tsounis et al., 2006; Garrabou & Harmelin, 2002).

Reproductive traits further constrain its resilience. Red coral is a gonochoric species (separate sexes), with internal fertilization and a brooding strategy, meaning that larvae are retained and released in a developed state. Larval dispersal is highly limited, often restricted to a few meters, leading to high levels of local population structure and low recolonization capacity following disturbance (Santangelo et al., 2007). This spatial and reproductive isolation makes local populations particularly susceptible to depletion and renders recovery times extremely long.

In addition, red coral displays a low natural mortality rate, and most observed population declines are directly attributed to harvesting. Traditional extraction methods, such as dredging (now mostly banned), and modern scuba harvesting target large, mature colonies, further skewing the size structure of populations toward younger, non-reproductive individuals. Field studies have shown that in heavily exploited areas, average colony height and density are significantly reduced, and signs of demographic bottlenecks are evident (Bramanti et al., 2014).

Despite the low naturality rate, Toma et al. 2022b also highlighted a massive occurrence of recent deep mortality events, mainly along the eastern and southern coast of Sardinia and in the Campanian Archipelago. Thirty sites with extensive patches of dead colonies still in place were reported from 70 m to around 200 m, but their formation remains unclear.

2.2 Materials and Methods

2.2.1 Data

The available data for the red coral in Sardinian waters are quite complete and represent a unique case in Mediterranean Sea of data availability for this species.

Commercial basal diameter frequencies

In northern Sardinia, colonies are typically collected at depths of 80–90 meters, whereas in the north-western coast, harvesting occurs at greater depths, around 100–120 meters.

Red coral colonies, harvested by the "*corallari*" operating in the north-western Sardinian waters, were collected under the Sardinian sampling program in the years 2007, 2008, 2009, 2012, 2013, 2014, 2015 and 2023. In the years 2007, 2008, 2009 and 2023 the data were collected at landing place, while the remaining years were collected with monitoring on board (Carugati et al., 2020). The landing places considered are Fertilia, Alghero and Bosa (Figure 2.3), representing about the 80% of the red coral production of the north-west Sardinian coast (logbook data provided by Sardinia Region).

In the northern part of the Island, the Golfo dell'Asinara, Castelsardo, Isola rossa and Santa Teresa di Gallura (Figure 2.3) were sampled in 2012 with monitoring on board (Carugati et al., 2020).

In both sites, for each colony the basal diameter and height were collected. As prescribed in regional regulations (Regional Decree N.1204/DecA/83 of the 08.08.2012), the basal diameter was measured in the stem, in the mid between the base and the first branch. The number of colonies and the corresponding basal diameter length-frequency distributions by year and area, for which the basal diameter and height were collected, are reported by year and area in Table 2.1. Figure 2.4 shows the basal diameter frequency distributions by year and area.

Table 2.1 – Number of sampled colonies by area and by year.

Year	**2007**	**2008**	**2009**	**2012**	**2013**	**2014**	**2015**	**2023**
North-Western waters	1770	513	1372	3562	11319	379	553	76
Northern waters				1173				

Figure 2.3 – Location of the sampled ports. North-western waters: Golfo dell'Asinara, Fertilia, Alghero and Bosa. Northern waters: Castelsardo, Isola rossa, Santa Teresa di Gallura.

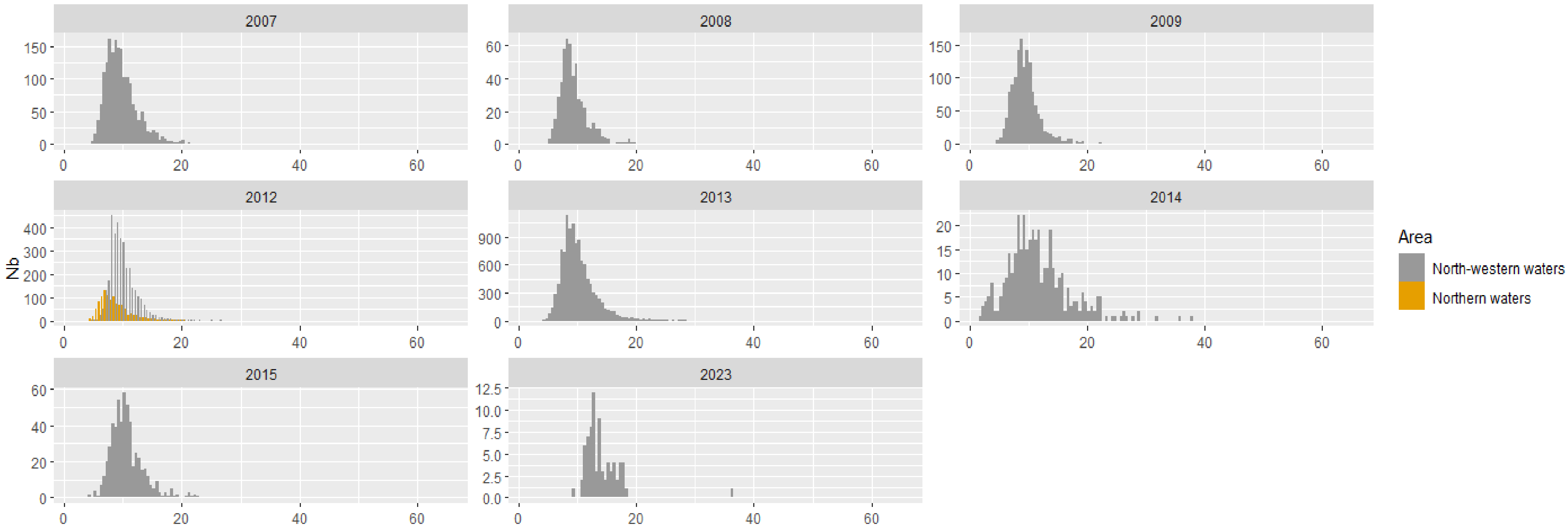


Figure 2.4 – Basal diameter (mm) frequency distributions. On the x-axis are the basal diameters. In the years 2007, 2008, 2009 and 2023 the data were collected at landing place, while the remaining years were collected with monitoring on board. In yellow the distribution collected in Northern waters, in grey the ones collected in North-western waters.

Catch time series and number of licenses

Catch data on red coral (coinciding with landing, being the discard null for this precious coral), including the associated number of authorized operators, are available from 1996 to 2022 by area from the logbook information. In some years the landing was available by port, thus it has been possible to derive a time series of landing for the Northern-western waters and a separated for the Norther waters (Figure 2.5). Comparing the landing observed onboard and the weight declared in the logbook in 5 monitored fishing days in 2014 and 2015 in Bosa and Alghero a correction factor of 1.54 was estimated and used to correct the logbook information. In a precautionary manner, the correction factor was applied to the catch of the years without monitoring on board. In 2007 the harvest of red coral was forbidden. In 2014 the fishing season was reduced at only one month and half. The catch-per-unit of effort has been estimated for each year from 1996 as the landing divided by the number of active licenses in the year.

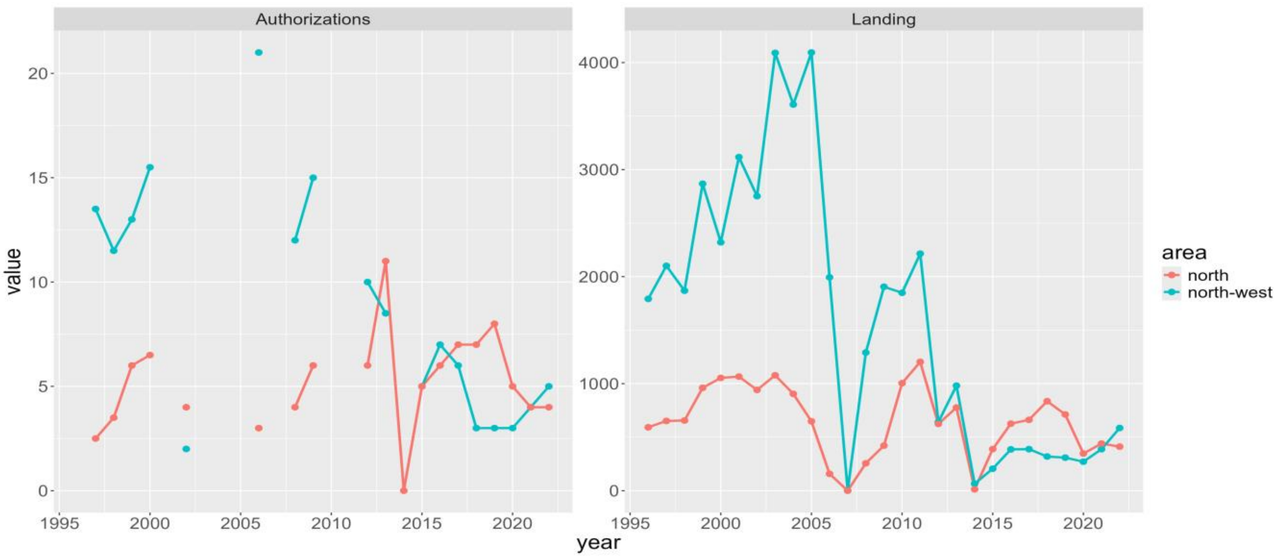


Figure 2.5 – Landing (kg) and number of authorized operators (active licenses) by area and year area (North-western in turquoise, North in pink).

Growth, maturity and natural mortality

A total of 62 colonies collected through the monitoring on board in the years 2011-2012, in Alghero (n=25, basal diameter range 5.8 -12.7 mm) and Castelsardo (n=37, 5.8 -12.7 mm) were processed and aged following the methodology described in Marschal et al. (2004). The 62 colonies were deliberately acquired from the "*corallari*" for this purpose, aiming to balance the need for comprehensive coverage of the basal diameter classes while maintaining cost efficiency in the purchase of samples. A linear regression model was fit on the age-basal diameter data (Figure 4), following the growth models fitted for other coral genera in different areas (e.g. Prouty et al., 2011; Hitt et al., 2020; Marriott et al., 2020). The linear fitting, BD ~ age, was firstly assessed separately by area, followed by an evaluation of the significance of the area's effect. To test the significant difference between the two linear models, including their interaction, a third linear model was evaluated on the whole dataset, including the area as categorical variable:

$$BD \sim 0+Age + Area + Age*Area + \varepsilon \quad \textbf{(Eq. 11)}$$

where BD is the basal diameter, Age the assigned age, Area the harvest area and ε is the error term.

The slopes of the linear models by area (corresponding to the growth rate, gr thereafter) was then used to estimate K for each area, defined as the measures of the exponential rate of approach to the asymptotic basal diameter (BDinf). This step, although not necessary for the estimation of SPiCT model, served as a prerequisite for estimating natural mortality to apply LBSPR.

The slope of the linear model (growth rate, gr thereafter) by area was then used to estimate K, defined as the measures of the exponential rate of approach to the asymptotic basal diameter (BD_{inf}), where a proxy of BD_{inf} was derived as the maximum observed basal diameter multiplied by 0.95 (=43.42 mm), following the formula: $K = -\frac{\ln(\frac{BD_{inf}-E(BD)}{BD_{inf}})}{t}$, where E(BD) is the expected basal diameter at age, derived as E(BD)=gr*age.

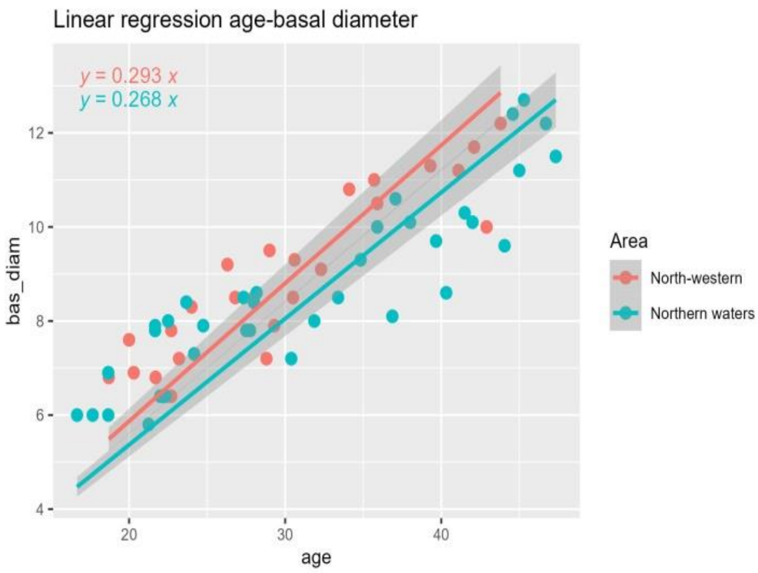


Figure 2.6 - Age readings versus basal diameter and linear growth curve by area (North-western in pink, North in turquoise). Points indicate observed values, while lines the fitted linear model

Table 2.2 – von Bertalanffy growth parameters for North-western and Northern red coral stock.

vBG parameter	North-western stock	Northern stock
BD_{inf} (mm)	43.42	43.42
K	0.00755	0.00687
t_0	0	0

The aged colonies range between 5.8 and 12.7 mm of basal diameter, corresponding to an age range of 16-47 years (Figure 2.6). The fitting of linear growth model on the basal diameter and age data collected in North-western and Northern Sardinian waters highlighted a different growth rate *gr* in the two areas (Northern waters 0.268 mm/year, North-western waters: 0.293 mm/year; Figure 2.6), corresponding to a higher K (as exponential rate of approach to the asymptotic basal diameter, BD_{inf}) in North-western waters, equal to 0.00755, and a value of 0.00687 in Northern waters.

The linear model including the area as categorical variable showed a pvalue < 0.05 on the area and on the age, while no significance for the interaction between age and area (Table 2.3).

Table 2.3- Summary of the linear growth model with the *area* as categorical variable. Equation: BD ~ 0+Age + Area+Age*Area

```
Residuals:
     Min       1Q   Median       3Q      Max
-1.65172 -0.46631  0.01108  0.53470  1.55647
Coefficients:
                        Estimate Std. Error t value Pr(>|t|)
Age                      0.20468    0.02093   9.780 7.05e-14 ***
AreaNorth-western        2.82912    0.64715   4.372 5.18e-05 ***
AreaNorthern waters      3.03667    0.44645   6.802 6.30e-09 ***
Age:AreaNorthern waters -0.02572    0.02503  -1.028    0.308
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1
Residual standard error: 0.7868 on 58 degrees of freedom
Multiple R-squared:  0.9927,	Adjusted R-squared:  0.9922
F-statistic:  1985 on 4 and 58 DF,  p-value: < 2.2e-16
```

The analysis of the height of the analysed colonies revealed distinct morphological differences between the two sub-populations. The colonies in the Northern waters were characterized by smaller heights (min=32, median=68 mm, max= 129 mm) than North-western waters (min=15, mean=155.35 mm, max= 368.8 mm); the wider basal diameters are quite similar in the two areas (Northern waters: min=4.4, median=7.9 mm, max= 20.4 mm; North-western min=2.6, median=9.4 mm, max= 24.1 mm) (Figure 2.7).

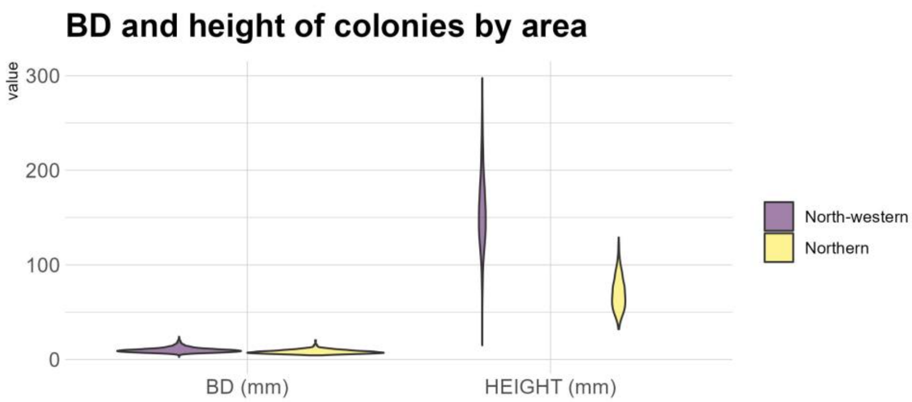


Figure 2.7 - Violin plots of basal diameter (left panel) and height (right panel) of the sampled colonies in North-western and northern waters. North-western is purple-coloured, North yellow-coloured.

Although the interaction term between area and age was not significant, based on the morphological differences between the two populations and to take into account the local fishery characteristics, the stock assessments were conducted separately for the two areas, and the results are presented accordingly.

The size at first maturity was collected by Santangelo et al. (2003): BDm50% 1.4-2.3 mm (in this study set as the middle value, 1.85 mm).

A scalar value for natural mortality was derived through the Barefoot ecologist app (http://barefootecologist.com.au/shiny_m) using the BD_{inf}, K (by area) and a longevity of 150 years (our samples corresponding to about 141 years). The obtained values by area are reported in Table 2.4, indicating the methods included in the average.

Table 2.4 – Scalar values for M estimated with barefootecologist.com.au/shiny_m for the two areas. M/K ratios are also reported by area.

Method	**Reference**	**M**	
		North-western	**Northern**
Then_nls	Then et al., 2015	0.050	0.050
Then_lm	Then et al., 2015	0.035	0.035
Hamel_Amax	Hamel, 2015	0.036	0.036
Then_VBGF	Then et al., 2015	0.033	0.031
Hamel_k	Hamel, 2015	0.013	0.012
Jensen_k 1	Jensen, 1996	0.011	0.010
Jensen_k 2	Jensen, 1996	0.012	0.011
Average M		**0.0273**	**0.0265**
K		0.008	0.007
M/K		**3.615**	**3.858**

2.2.2 Stock assessment models

Selection of the stock assessment models

Given these characteristics—low growth rate, delayed maturity, limited dispersal, sedentary behavior, and high site fidelity—red coral does not conform to the assumptions of traditional stock assessment models used for mobile, fast-growing fish species. Models that rely on rapid recruitment and large-scale population mixing, such as age-structured or biomass dynamic models (e.g., VPA, Schaefer), are likely unsuitable or overly optimistic in this context.

Instead, the selection of stock assessment models for red coral must be conservative and spatially explicit, ideally incorporating colony size structure, density per unit area, and habitat-specific population trends. Length- or structure-based models, such as Length-Based Spawning Potential Ratio (LB-SPR) or spatial depletion models that consider fine-scale population units, may be more appropriate.

Considered the availability of a quite long landing time series (1996-2023), a catch-per-unit of effort time series, two global production models were applied, one data-poor, CMSY (Froese et al., 2021), and one data-intermediate, SPiCT (Pedersen and Berg, 2017).

Taking advantage of the monitoring of landing basal diameter structures for several years, the data-poor Length –Based Spawning Potential Ratio (Hordyk et al., 2015 and 2016) was also applied. The description of the general assumptions of each of the three models, the settings applied to the specific rec coral case studies and the extended results are described in the Results section.

<u>CMSY: Catch time series as the basis for fish stock assessments</u>

CMSY is based on a modified Schaefer surplus production model (Eq.12). The model provides the option to use the Bayesian Schafer Model (BSM), including catch per unit of effort (CPUE) time series. The main advantage of BSM, compared to other implementations of surplus production models, is the focus on informative priors and the acceptance of short and incomplete (i.e., fragmented, with missing years) abundance data. CMSY allows to estimate fisheries reference points (MSY, F_{MSY}, B_{MSY}), the status or relative stock size (B/Bmsy) and the fishing pressure or exploitation (F/F_{MSY}).

$$B_t + 1 = B_t + r * B_t * (1 - B_t / K) - C_t \qquad \textbf{(Eq. 12)}$$

where:

B_t is the stock biomass at time t,

r is the intrinsic rate of population increase,

K is the carrying capacity[4],

C_t is the catch at time t.

From the Schaefer model, the MSY and associated reference points are defined as:

$$MSY = (r * K) / 4 \qquad \textbf{(Eq. 13)}$$

$$B_{MSY} = K / 2, \; F_{MSY} = r / 2 \qquad \textbf{(Eq. 14)}$$

The CMSY model and Bayesian stock assessment utilizes prior to provide a representation of our initial knowledge or beliefs about a parameter before observing current data. In the context the priors are essential because they help inform the model when data are scarce or uncertain and allow the inclusion of expert knowledge, previous studies, or literature-based estimates.

The CMSY model uses priors for:

- Intrinsic growth rate *r* (based on species resilience),
- *Relative biomass* ranges for start, intermediate, and final years (e.g., B_{start}/K, B_{int}/K, B_{end}/K).

The main steps implemented by the CMSY model are three:

1. Sample pairs of r and K across plausible ranges.
2. Simulate biomass trajectories using the catch time series.
3. Filter combinations of r and K that produce biomass within the assumed prior ranges and never collapse (<10% of K).

Four scenarios were considered based on two different hypotheses on resilience and on depletion state:

1. Resilience very low, depletion medium-strong-strong;
2. Resilience very low, depletion medium-strong-medium;
3. Resilience low, depletion medium-strong-strong;

[4] The maximum biomass or population size that an environment can sustain indefinitely, given the available resources (e.g., food, habitat, oxygen) and environmental conditions.

4. Resilience low, depletion medium-strong- medium.

SPiCT: stochastic surplus production model in continuous time

The stochastic surplus production model in continuous time, SPiCT, represents a state-space implementation of the Pella-Tomlinson surplus production model in continuous time. The model has a general state-space form that can contain process and observation-error as well as state-space models that assume error-free catches. This method has been widely applied to the ICES stocks (ICES, 2024).

In the settings, the classical Schaefer (1954) model was assumed (Eq. 12). Moreover, priors were defined to inform the model about the inter-annual variability of the catch, the process error, the observation error and the error on the F. Medium depletion was assumed at the beginning of the time series, in line with CMSY runs. The extended SPiCT settings are reported in Table 2.7. The same data used in CMSY were utilized. The "Checklist for the acceptance of a SPiCT assessment" was applied to evaluate the quality of the SpiCT runs (available at: https://github.com/DTUAqua/spict/tree/master).

Table 2.7 - Input data, settings and priors used for the SPiCT models.

Data/parameters	Setting
Catch data period	whole time series available (1996-2022)
Catch data periodicity	Annual
Biomass index	CPUE (=landing/number of authorizations)
Biomass index lag	No
Catch uncertainty scaling	No
Index uncertainty scaling	No
Initial stock depletion (B/K)	logbkfrac=N(log(0.4),0.1^2)
Shape of the production curve	Fixed to Schaefer (n=2)
Intrinsic growth rate	logr=N(log(0.06),0.02^2), reference:
	https://www.sealifebase.se/summary/Corallium-rubrum.html
Interannual variability in catch	logsdc=N(log(0.5),0.3^2)
Process error	logsdb=N(log(0.1),0.3^2)
Error on fishing mortality	logsdf=N(log(4),0.5^2)

Data/parameters	Setting
Observation error	logsdi=N(log(0.2),0.5^2)
Carrying capacity	logK=N(log(50,0.5^2))

Length-Based Spawning Potential Ratio

LBSPR method (Length Based Spawning Potential Ratio, Hordyk et al, 2015 c and 2016) is an equilibrium based data-poor method, assuming that the length composition data is representative of the exploited population at steady state. The model was developed for data-limited fisheries. This method uses sampled length structures, some information on the growth potential of the species, namely M/K ratio and a proxy of L_{inf}, and the proportion of mature individuals by length. It is based on the spawning potential of the stock in terms of spawning potential ratio (SPR) (estimated as SSB fished population/SSB unfished population). It does not require knowledge of the natural mortality rate (M), but only the ratio (M/K), which varies less across stocks and species than M (Prince et al. 2015). The size at first maturity nd the growth parameters used to derive the natural mortality at age are the ones described in chapter 2.3.

For Northern-western waters, where more than one year of data were available, LBSPR was run including uncertainty on BD_{inf}, $L_{m50\%}$, $BD_{m95\%}$, M/K ratio, CV on BD_{inf}. 250 random runs were carried out assuming a constant $BD_{m50\%}/BD_{inf}$ ratio and a constant $BD_{m95\%}$ - $BD_{m50\%}$ range. The extended set of parameters is reported in Table 2.10.

Table 2.10 – Setting for including uncertainty on LBSPR results: M/K is the ratio by area (Table 3), BDinf=43.42 mm, BDm50% and BDm95% are set as 1.85 and 8 mm respectively, according to Santangelo et al. 2003.

parameter	low	middle	up
CV	0.075	0.15	0.3
M/K	M/K*0.75	M/K	M/K*1.25
Bdinf perturbed	BDinf*0.75	BDinf	BDinf*1.25
BDm50% perturbed		BDinf*BDm50%/Bdinf	
BD95% perturbed		BDm50% + (BDm95%-BDm50%)	

The projected SPR was estimated on 2023 basal diameter frequency distributions for North-western waters and for 2012 (only year available) for Northern waters varying the size at first capture from 7 (current minimum conservation reference size, MCRS, according to GFCM Recommendation GFCM/43/2019/4) to 15 mm of basal diameter.

2.3 Results

CMSY: Catch time series as the basis for fish stock assessments

North-western Sardinian waters stock

CMSY results, based only on catch time series, show in all runs that the North-western waters stock biomass is below the safe biological limits, while the exploitation rate is below F_{MSY}. This is shown utilizing the kobe plot representation (Figure 2.8.a). The kobe plot is a widely used visual tool in fisheries management to assess and communicate the status of fish stocks in relation to biological reference points. It provides a two-dimensional view of the trade-off between stock biomass and fishing pressure, helping managers make informed decisions. On the x-axis there is the relative biomass to the B_{MSY}, while on the y-axis the current fishing pressure compared to the level that would achieve MSY. The green box corresponds to a healthy stock, sustainably fished, the orange box to healthy biomass, but overfishing occurring, the yellow-box to a stock overfished, but no overfishing currently and, finally the red box to the critical condition of a stock overfished and in overfishing. The BSM results, that integrate also the CPUE information, provide the same information with less uncertainty (Figure 2.8.b).

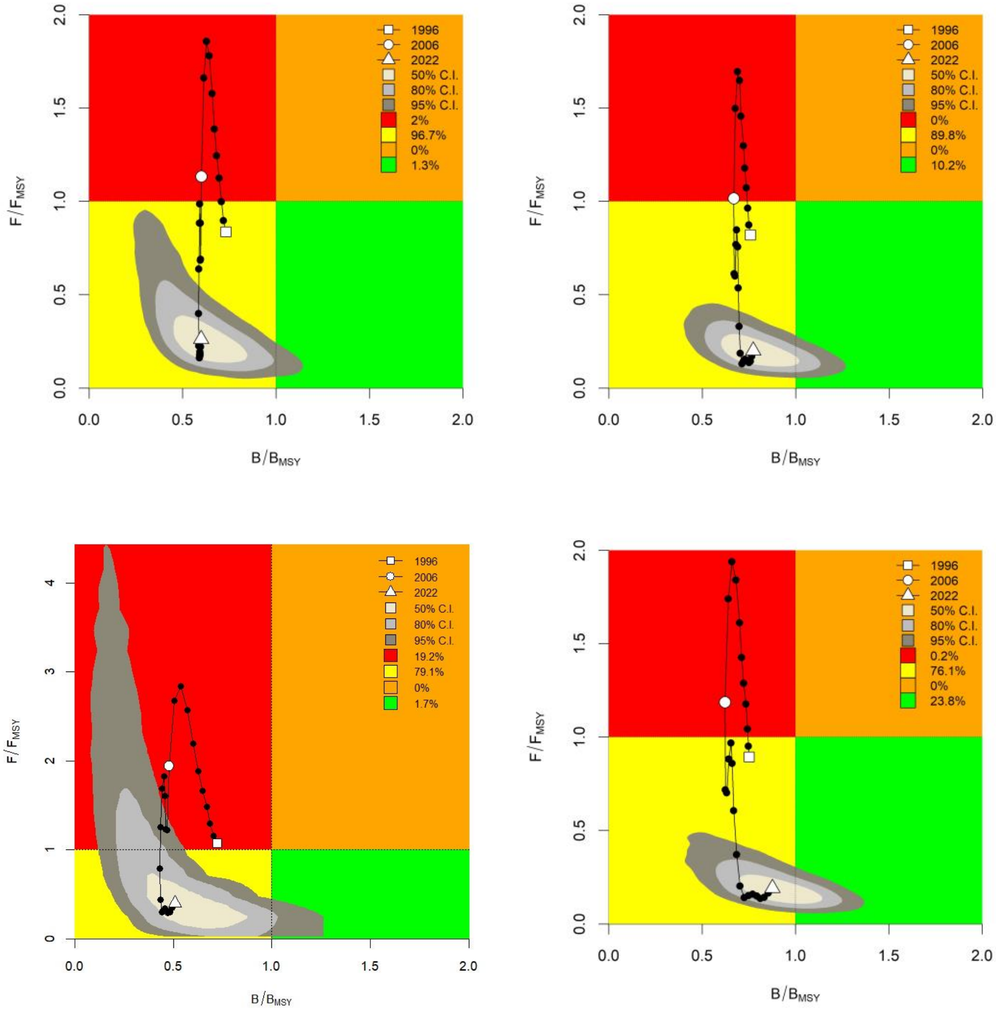


Figure 2.8.a - Kobe plots (CMSY) across the different scenarios in North-western waters. First row: run1 and run2; second row: run 3 and run 4. Run 1: Resilience very low, depletion medium-strong-strong. Run2: Resilience very low, depletion medium-strong-medium. Run3: Resilience low, depletion medium-strong-strong. Run4: Resilience low, depletion medium-strong- medium.

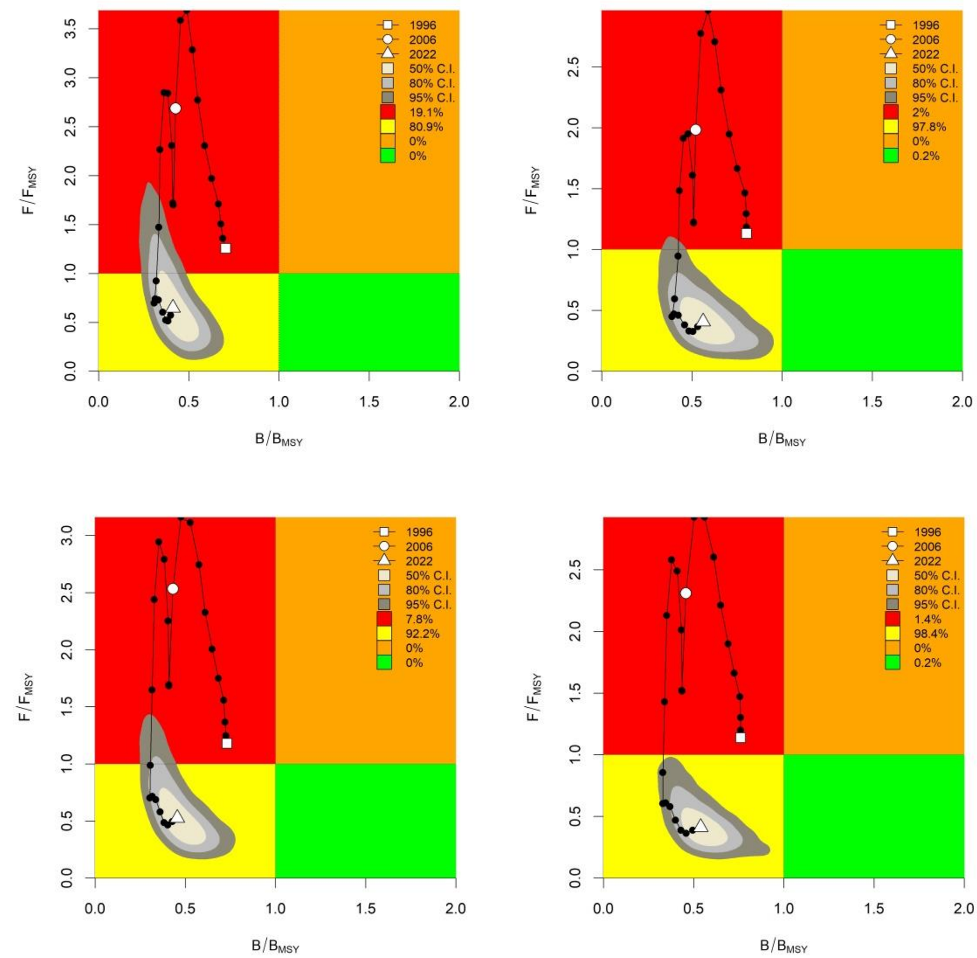


Figure 2.8.b - Kobe plots (CMSY-BSM) across the different scenarios in North-western waters. First row: run1 and run2; second row: run 3 and run 4. Run 1: Resilience very low, depletion medium-strong-strong. Run2: Resilience very low, depletion medium-strong-medium. Run3: Resilience low, depletion medium-strong-strong. Run4: Resilience low, depletion medium-strong- medium.

The fitting of the stock size time series improves importantly in the BSM output, supporting the integration of the CPUE as complementary information (Figures 2.9,2.10,2.11, 2.12, first panels of the second row). The results of the CMSY-BSM model showed that the fitting of the r and K, independently if using or not the CPUE, is more stable when assuming low resilience (Figures 2.9,2.10,2.11, 2.12, second panels of the first row).

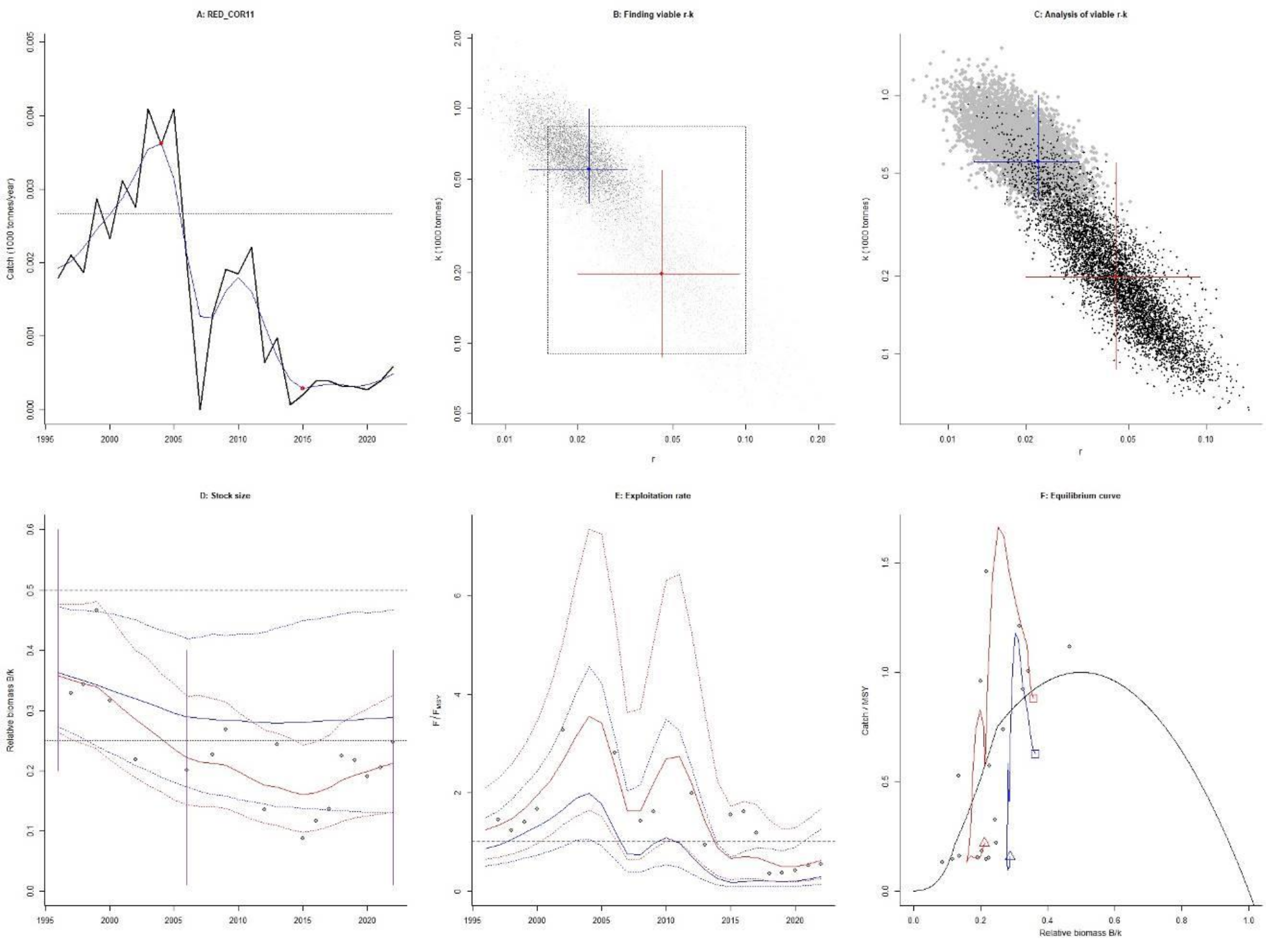


Figure 2.9 – North-western waters: CMSY-BSM fitting run 1. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

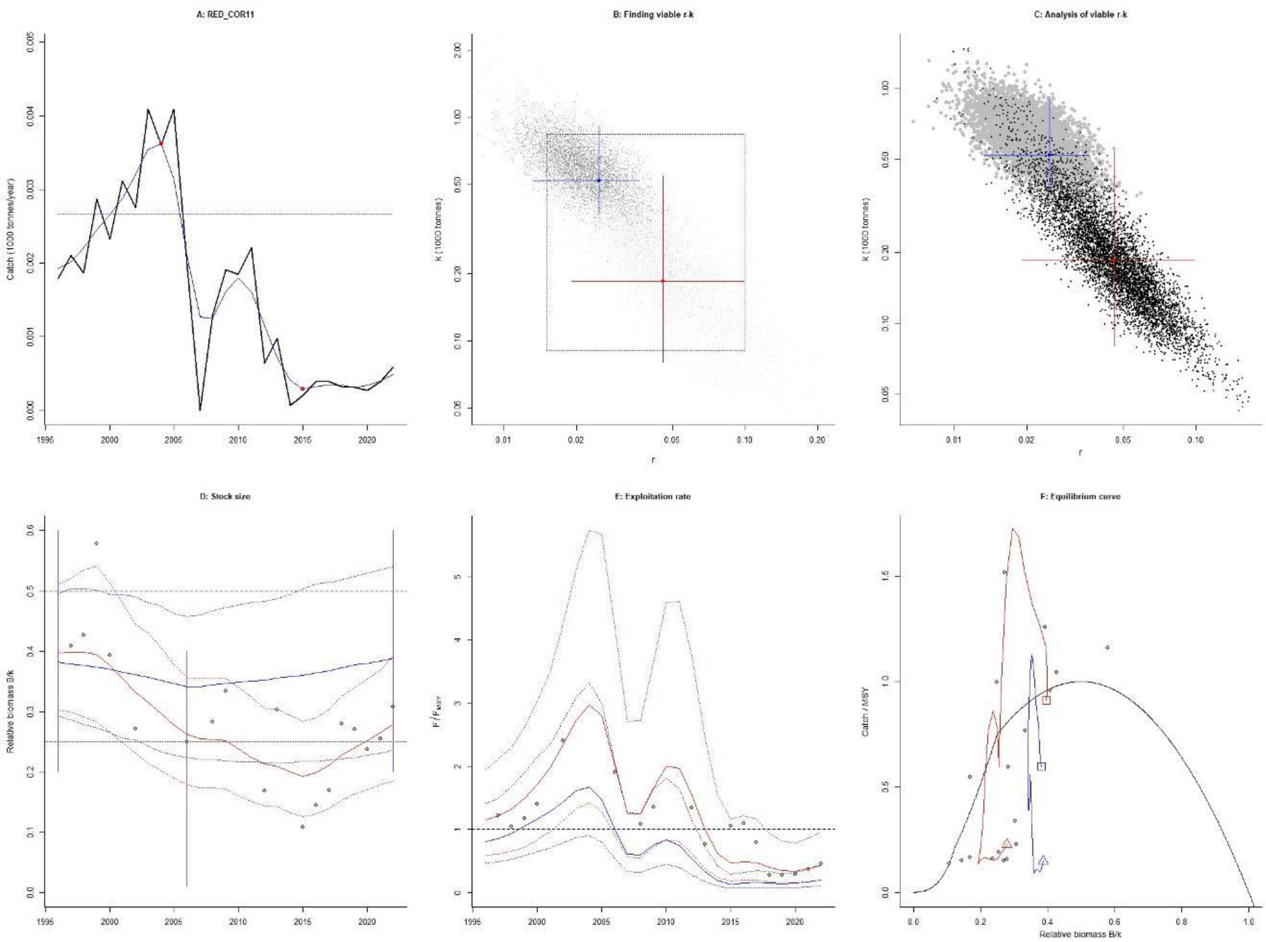


Figure 2.10 – North-western waters: CMSY-BSM fitting run 2. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

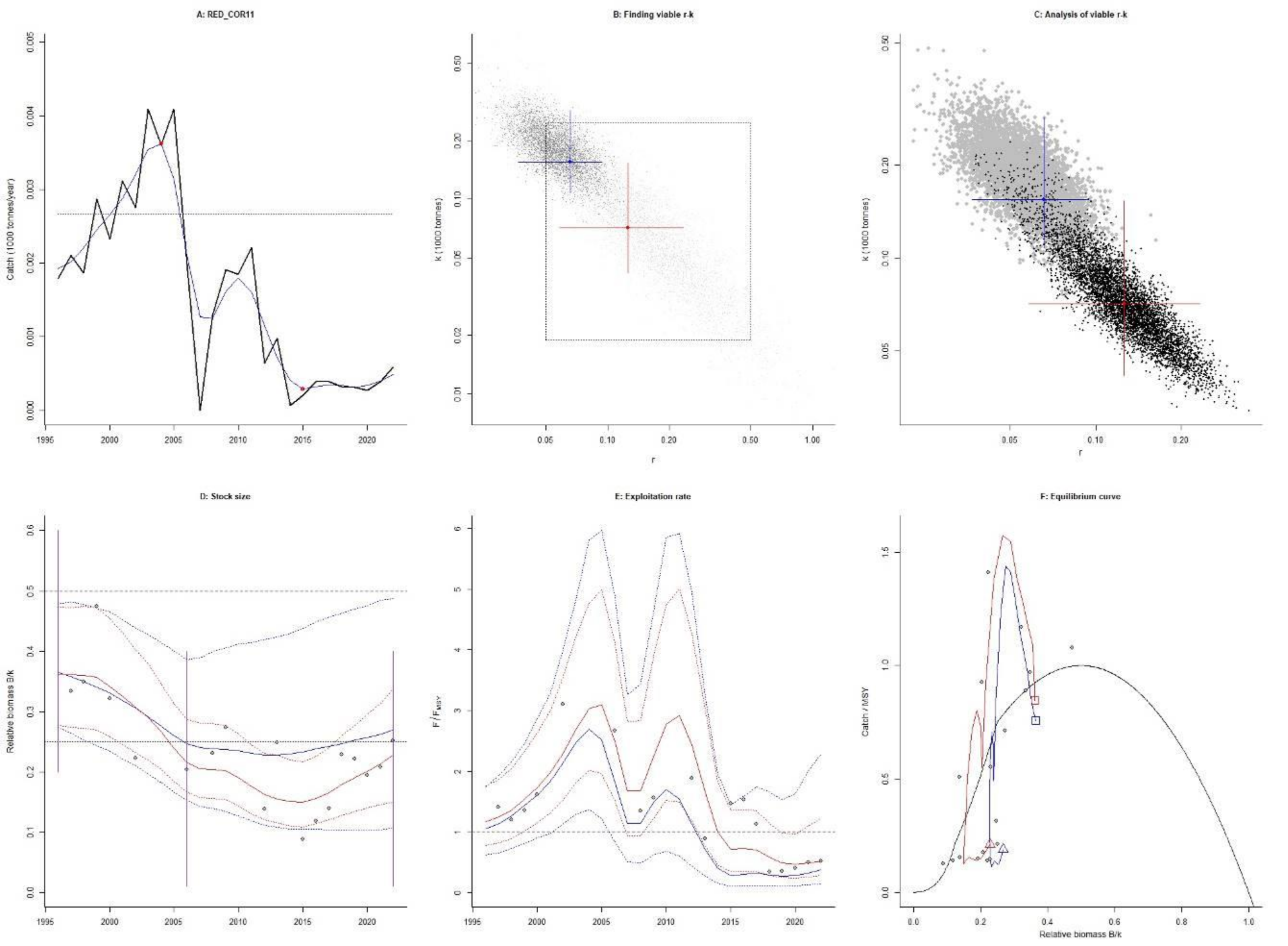


Figure 2.11 – North-western waters: CMSY-BSM fitting run 3. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

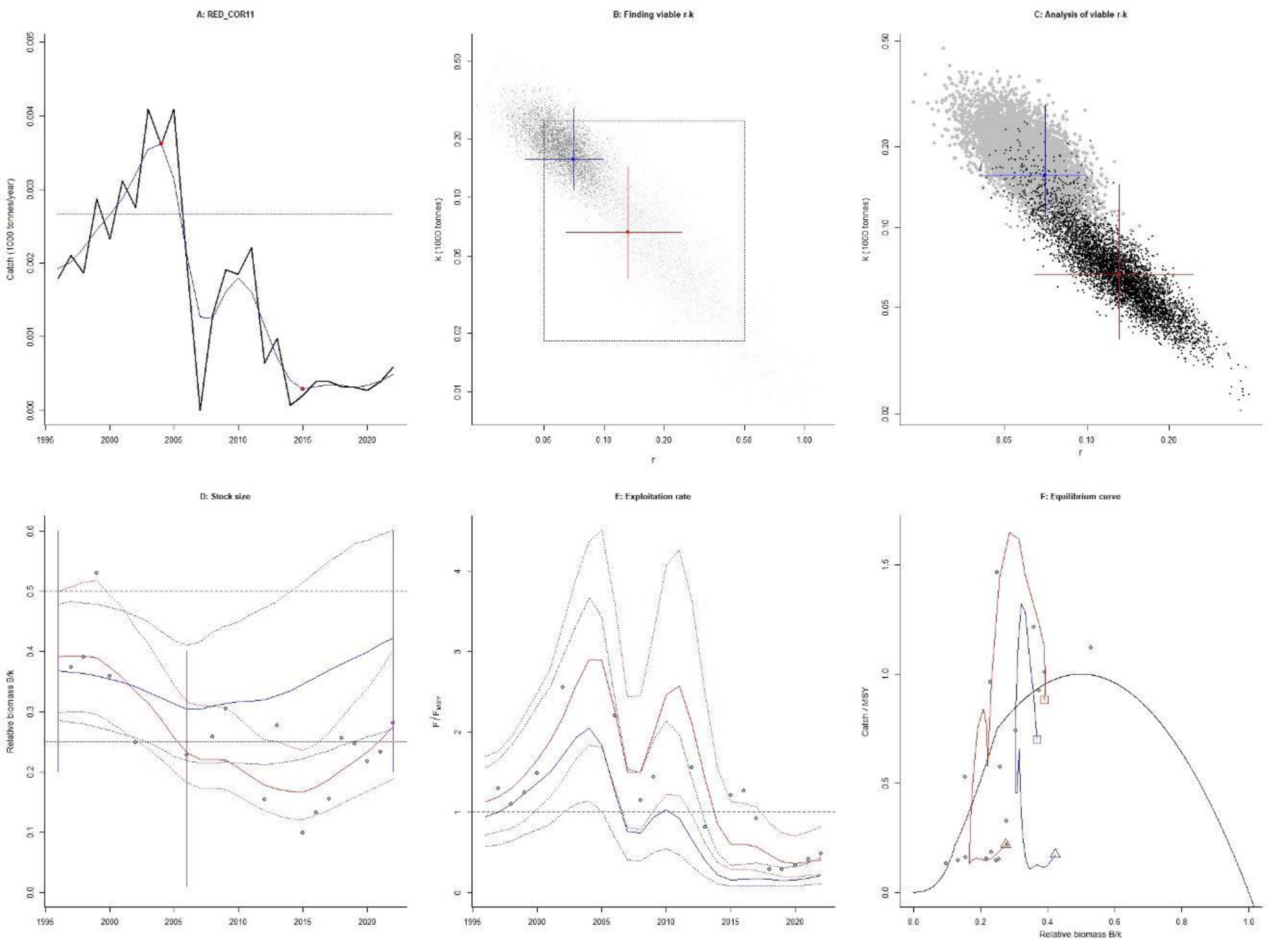


Figure 2.12 – North-western waters: CMSY-BSM fitting run 4. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

For all the runs the residuals showed no particular trend (Figures 2.13, 2.14, 2.15, 2.16). The retrospective analysis does not show any instability signal (Figures 2.17, 2.18, 2.19 and 2.20).

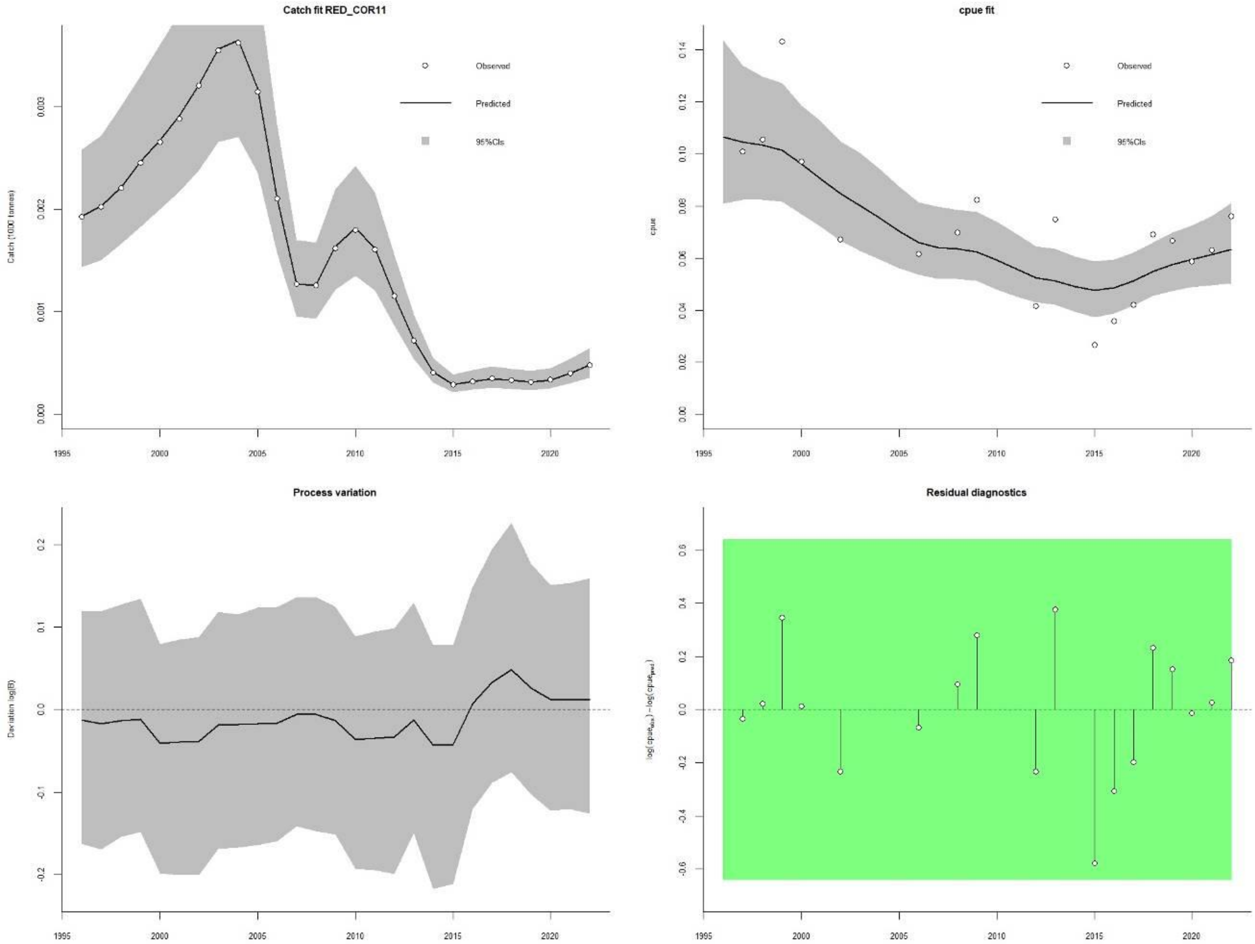


Figure 2.13 – North-western waters: CMSY BSM fitting run 1 and residuals diagnostics.

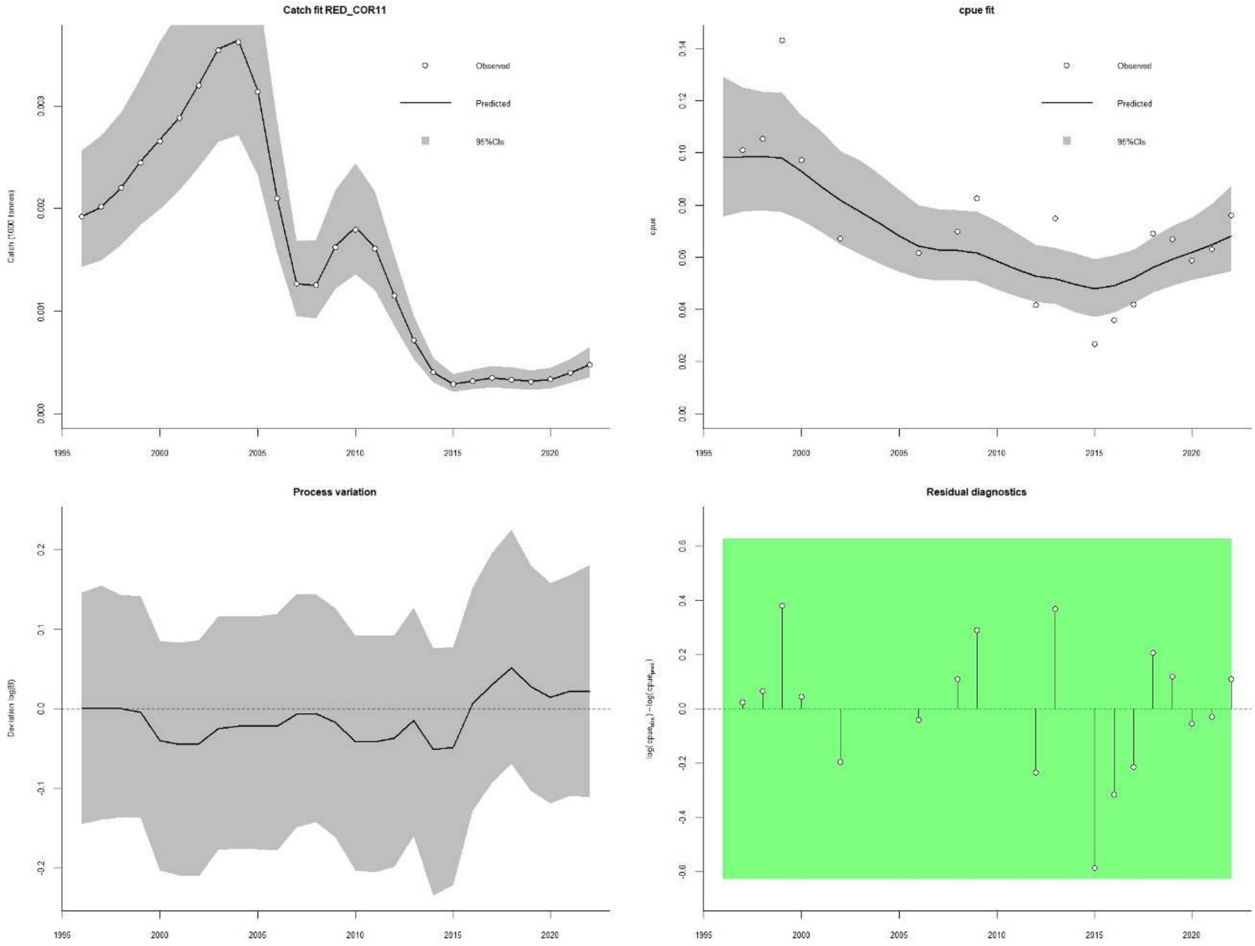


Figure 2.14 – North-western waters: CMSY BSM fitting run 2 and residuals diagnostics.

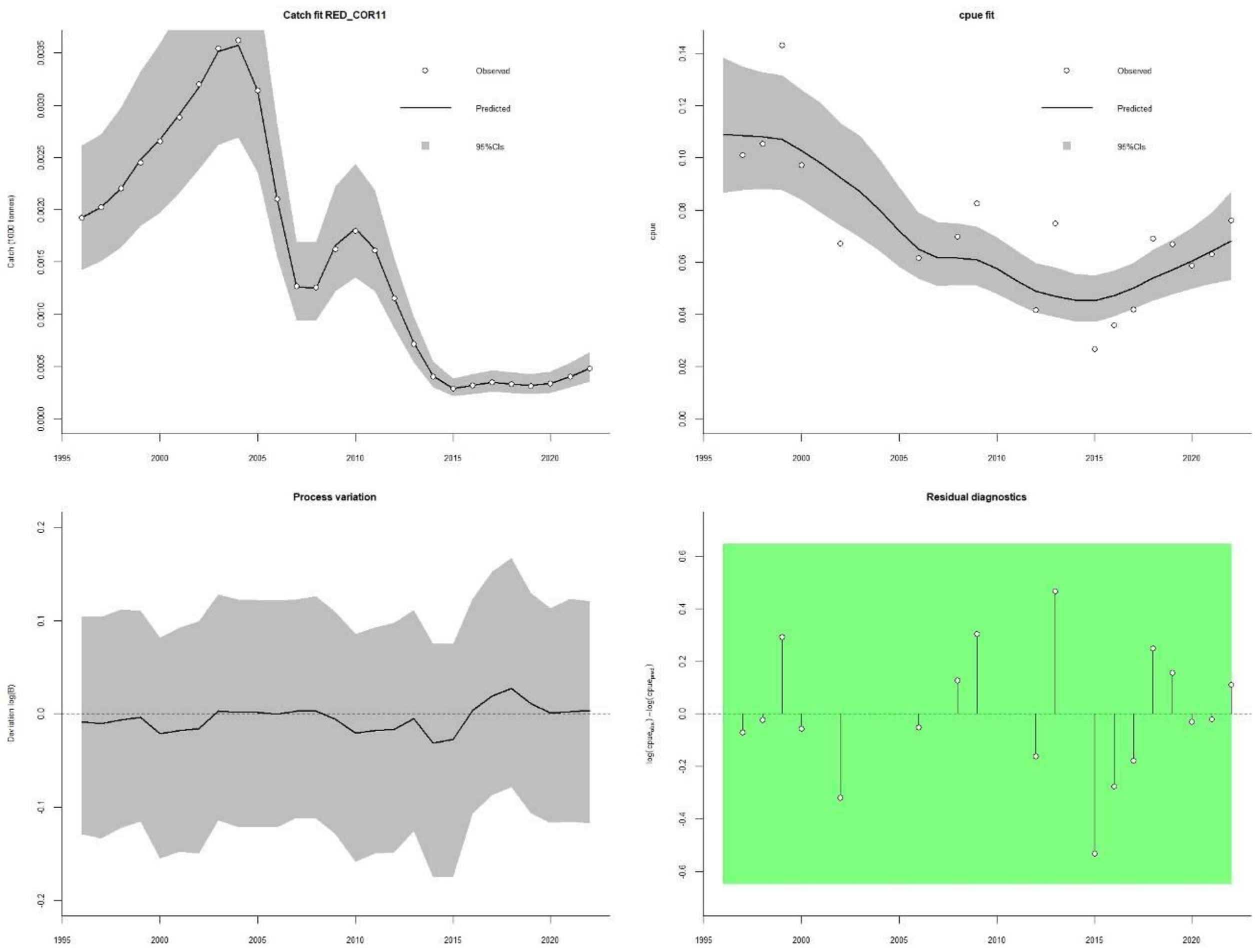


Figure 2.15 – North-western waters: CMSY BSM fitting run 3 and residuals diagnostics.

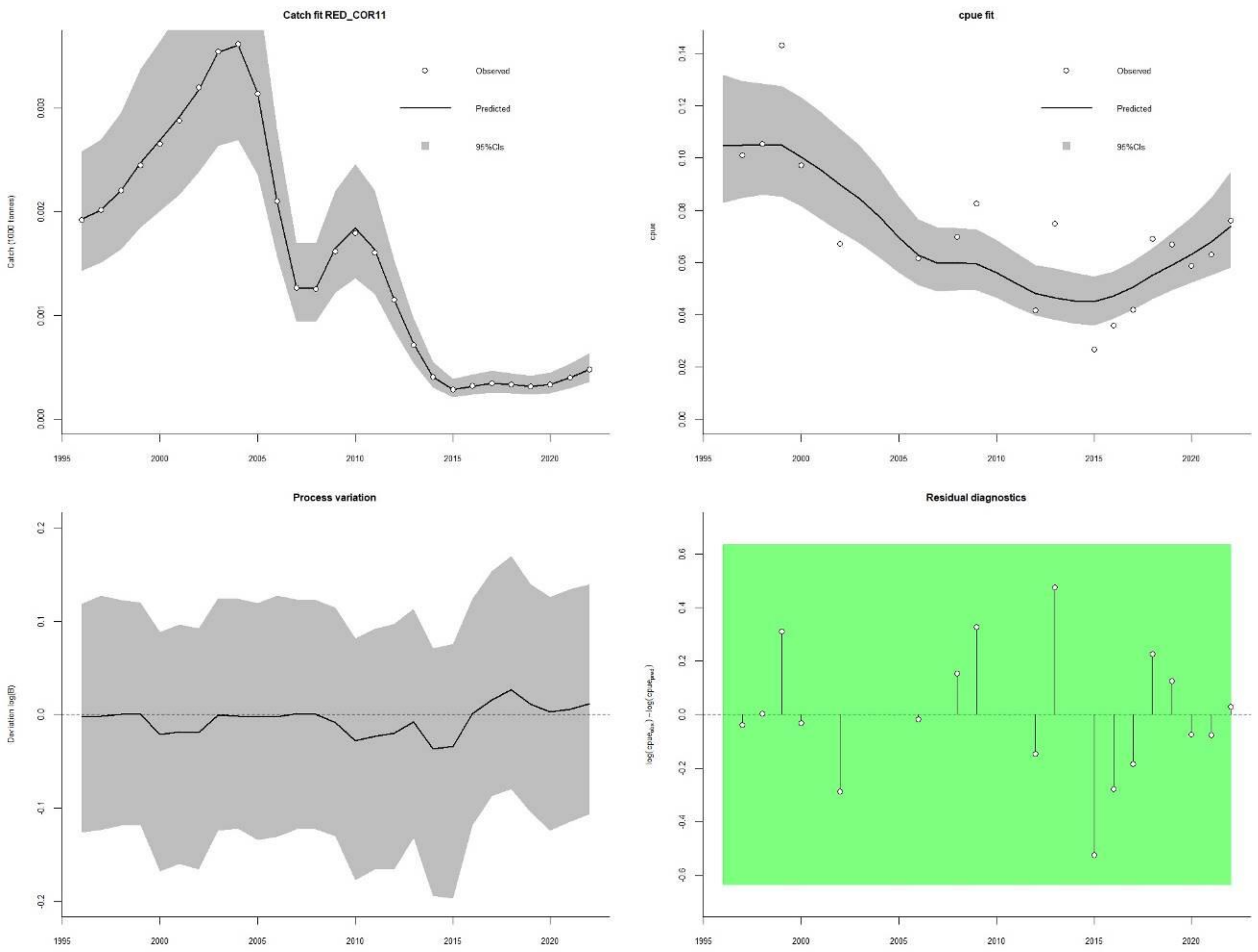


Figure 2.16 – North-western waters: CMSY BSM fitting run 4 and residuals diagnostics.

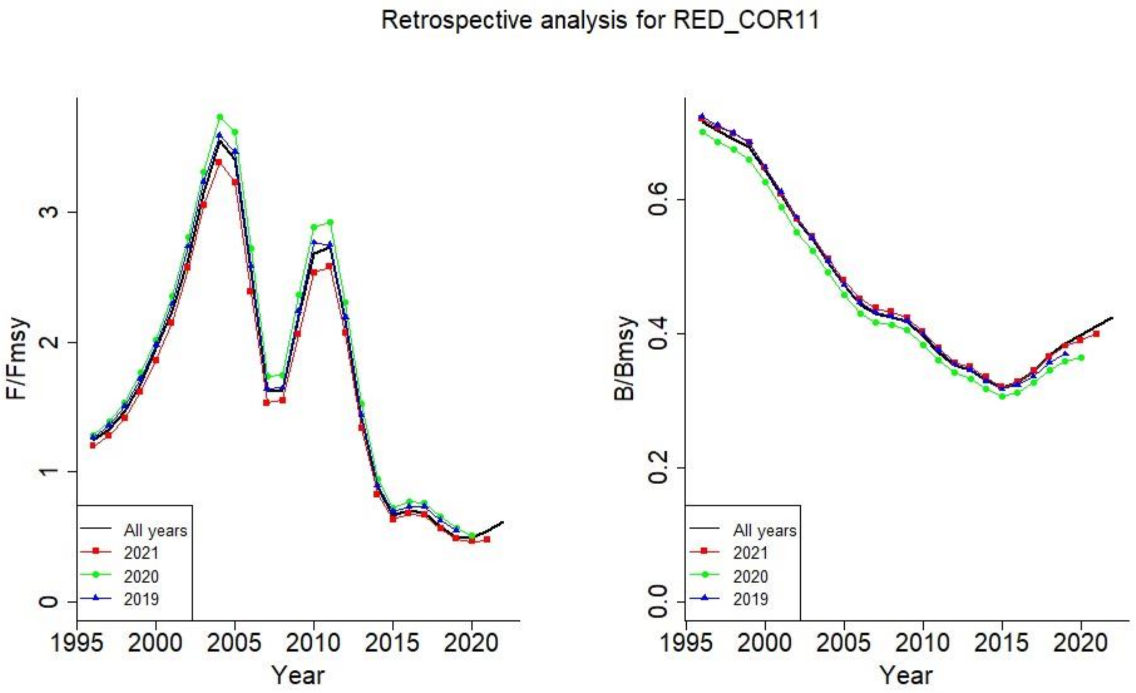


Figure 2.17 – North-western waters: CMSY-BSM retrospective analysis run 1.

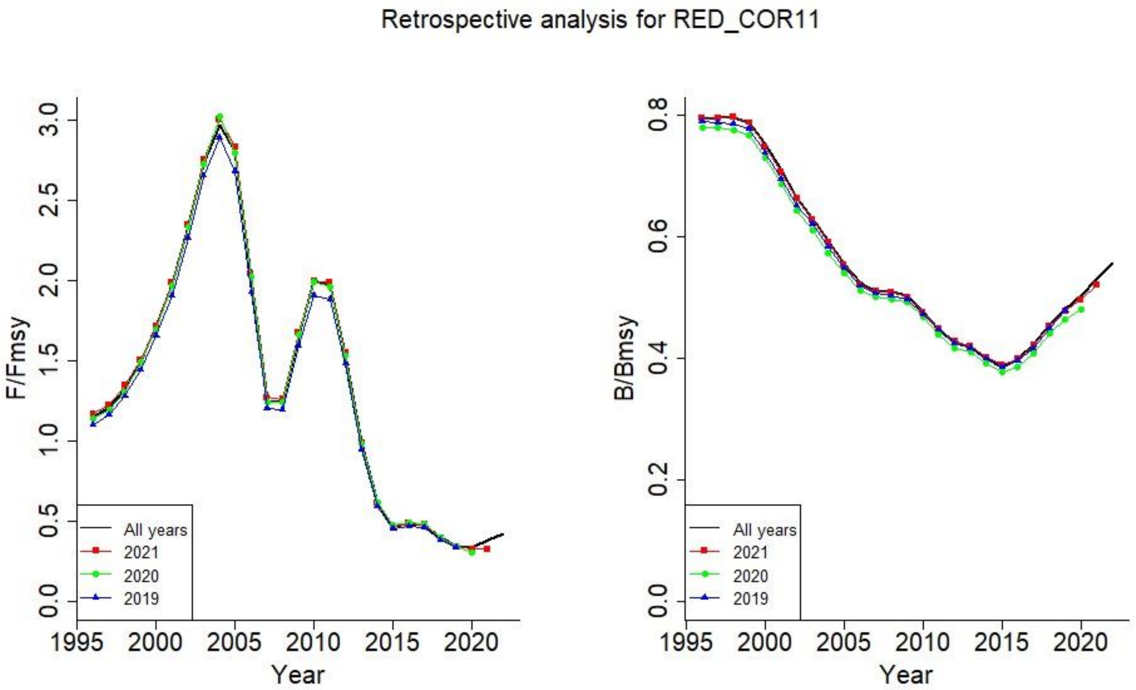


Figure 2.18 – North-western waters: CMSY-BSM retrospective analysis run 2.

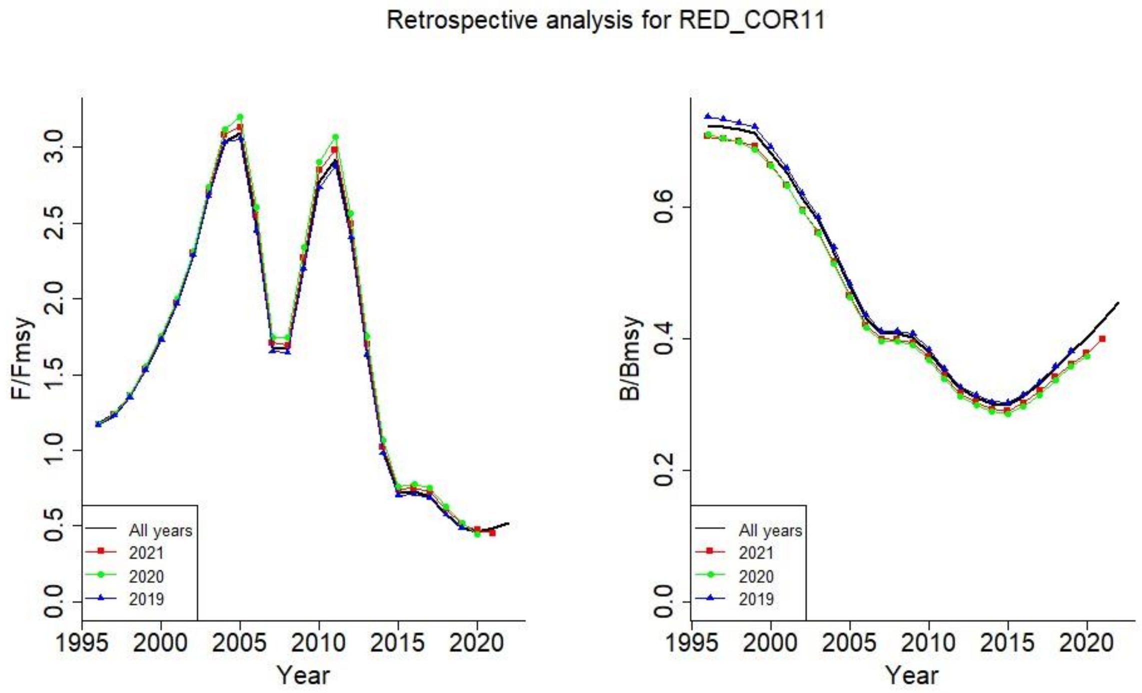


Figure 2.19 – North-western waters: CMSY-BSM retrospective analysis run 3.

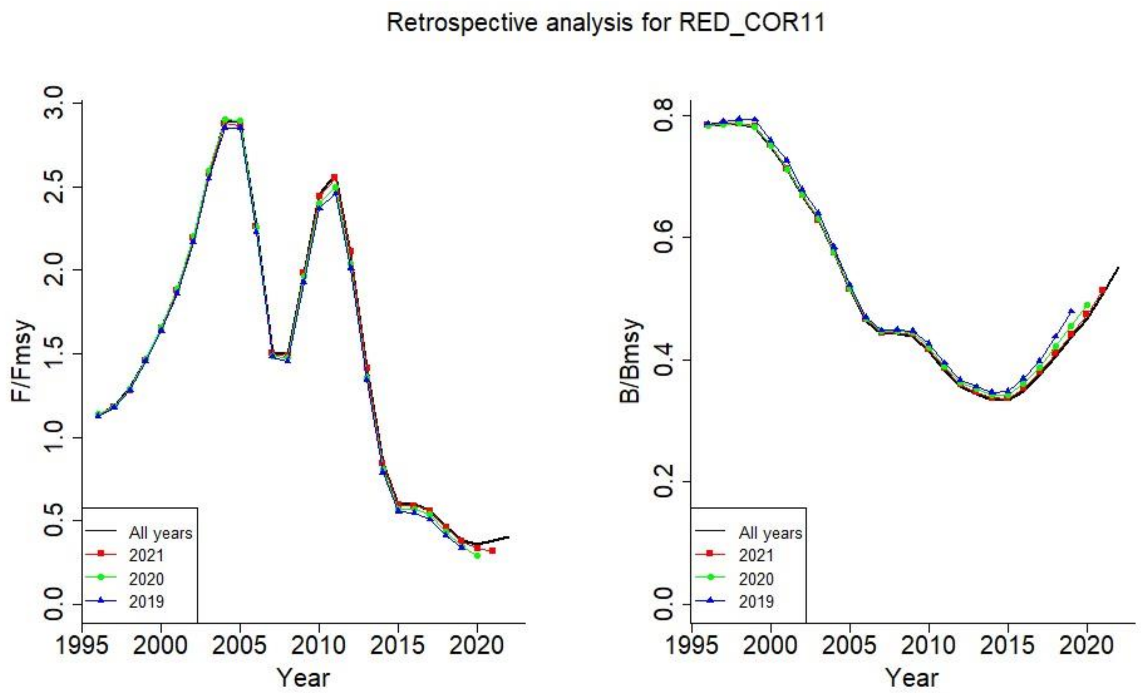


Figure 2.20 – North-western waters: CMSY-BSM retrospective analysis run 4.

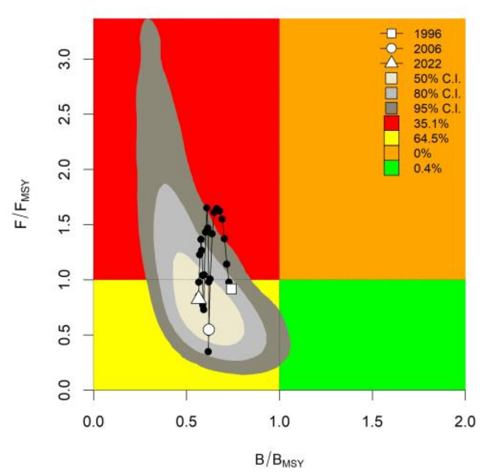
Among the runs explored, run 3 shows the lowest prior/posterior variance ratio (PPVR), and thus the most improved posterior knowledge relative to prior knowledge (Table 2.5).

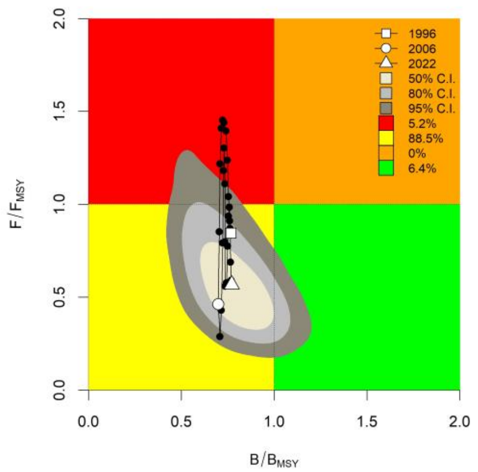
Table 2.5 – North-western waters. CMSY-BSM prior/posterior variance ratio by run.

Run	F	K	MSY	B/K 1996	B/K 2006	B/K 2022	avg
1	0.82	1.4	0.35	0.33	0.17	0.23	0.55
2	0.89	1.5	0.37	0.28	0.12	0.59	0.63
3	**0.5**	**0.55**	**0.13**	**0.28**	**0.08**	**0.17**	**0.29**
4	0.49	0.58	0.15	0.28	0.08	0.55	0.36

Northern Sardinian waters stock

In Northern waters all CMSY runs show that the stock is in overexploitation, with biomass below the safe biological limits, and overexploited with fishing mortality higher than F_{MSY} (Figure 2.21.a). The CMSY-BSM results, that integrate also the CPUE information, provide the same information with more uncertainty (Figure 2.21.b).





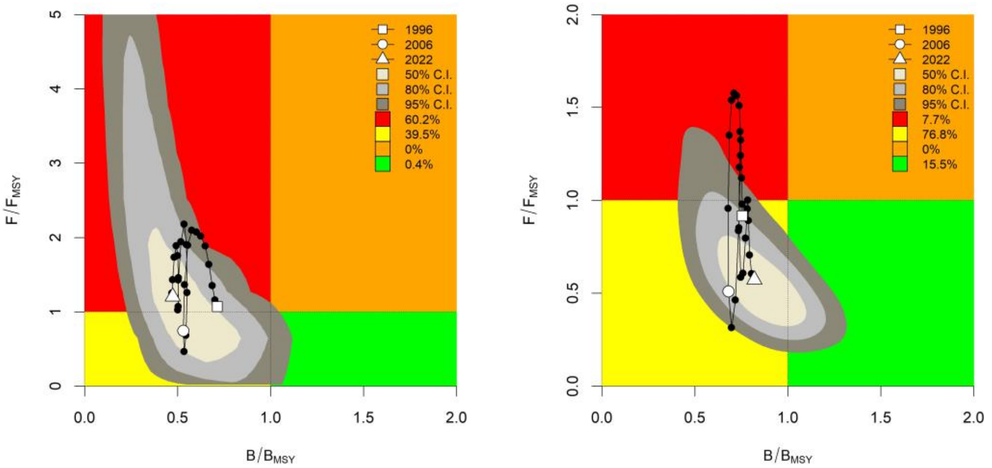


Figure 2.21.a - Kobe plots (CMSY) across the different scenarios in Northern waters. First row: run1 and run2; second row: run 3 and run 4. Run 1: Resilience very low, depletion medium-strong-strong. Run2: Resilience very low, depletion medium-strong-medium. Run3: Resilience low, depletion medium-strong-strong. Run4: Resilience low, depletion medium-strong- medium.

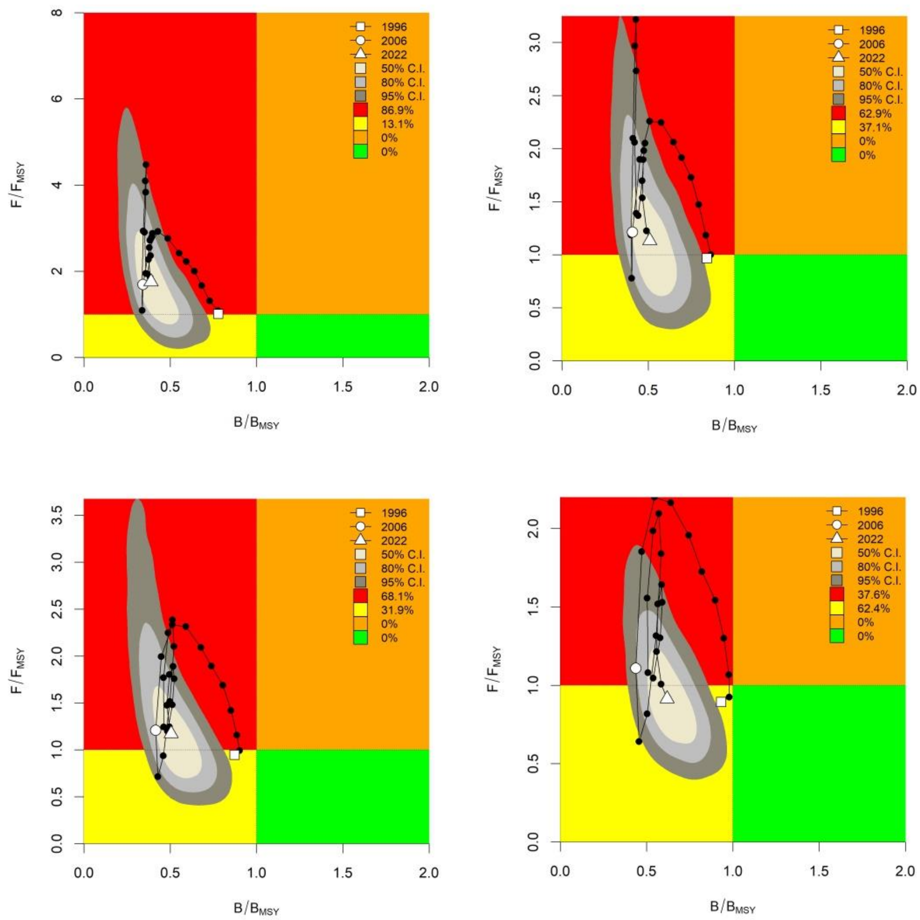


Figure 2.21.b - Kobe plots (CMSY-BSM) across the different scenarios in Northern waters. First row: run1 and run2; second row: run 3 and run 4. Run 1: Resilience very low, depletion medium-strong-strong. Run2: Resilience very low, depletion medium-strong-medium. Run3: Resilience low, depletion medium-strong-strong. Run4: Resilience low, depletion medium-strong- medium.

In this case, too, the integration of CPUE information through BSM shows an improvement in the fitting of B/K and F/F_{MSY} time series (Figures 2.22, 2.23, 2.24, 2.25). The results of the CMSY-BSM model showed that the fitting of the r and K, independently if using or not the CPUE, is more stable when assuming very low resilience (Figures 2.22, 2.23, 2.24, 2.25).

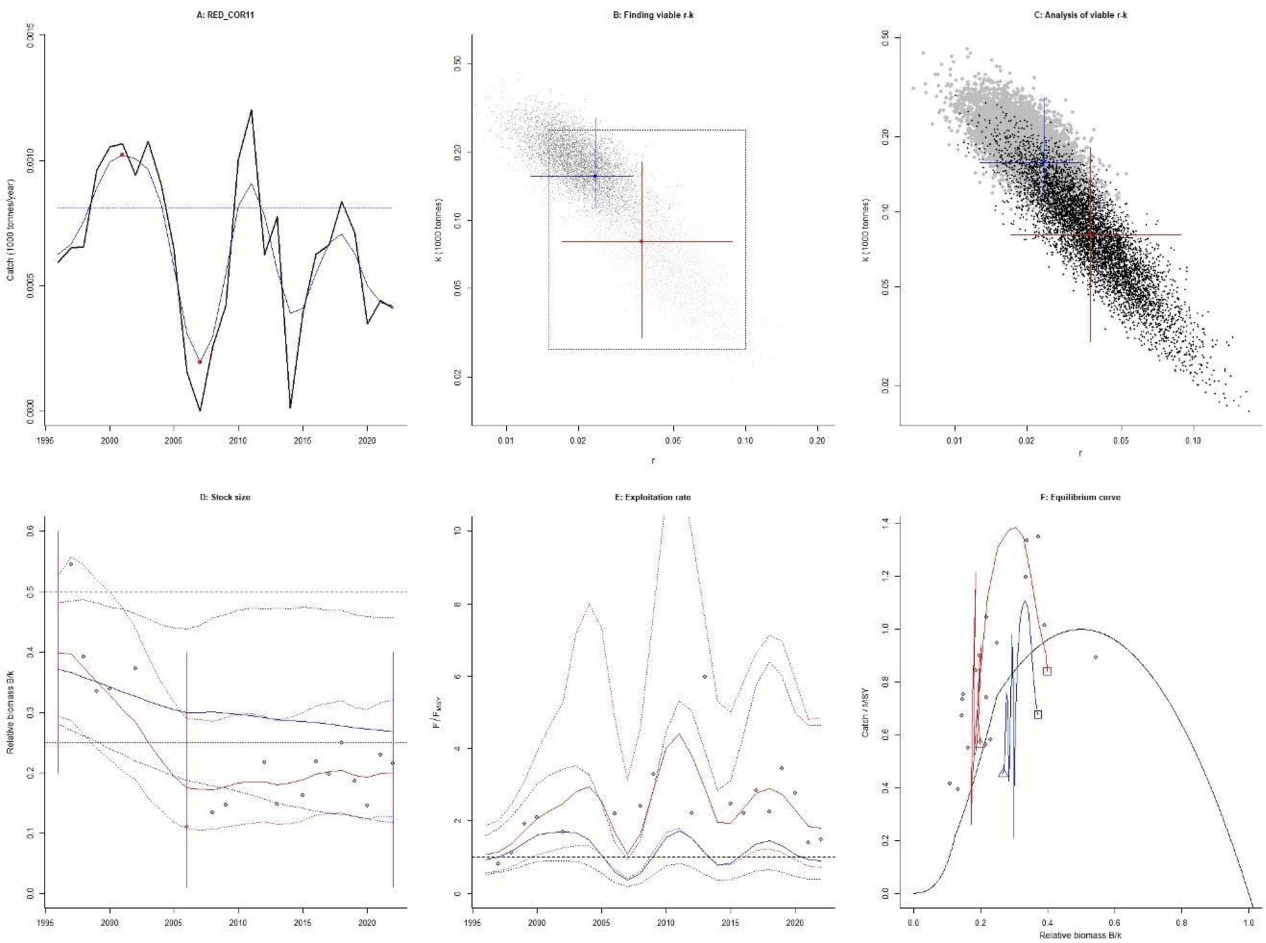


Figure 2.22 – Northern waters: CMSY-BSM fitting run 1. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

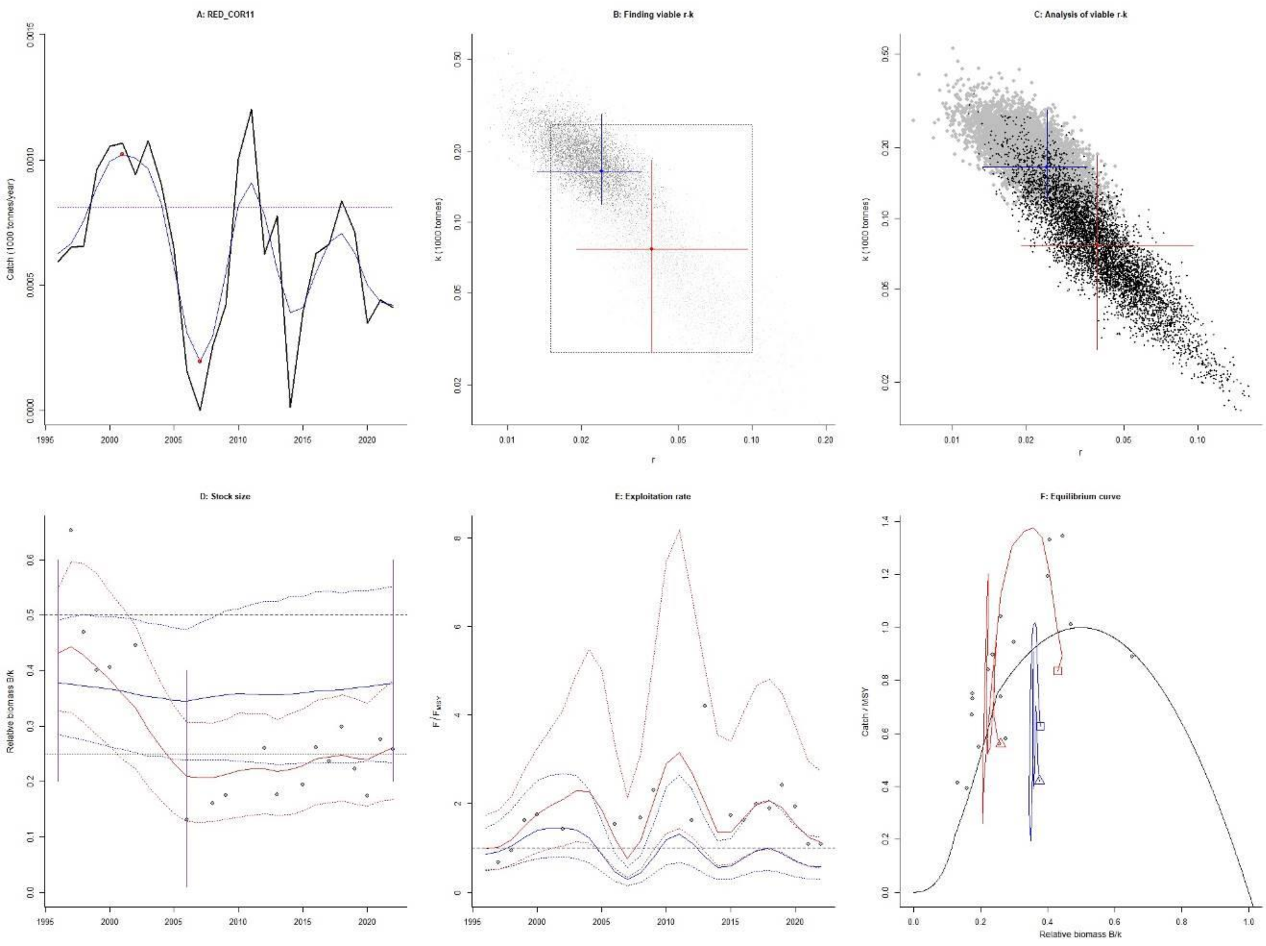


Figure 2.23 – Northern waters: CMSY-BSM fitting run 2. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

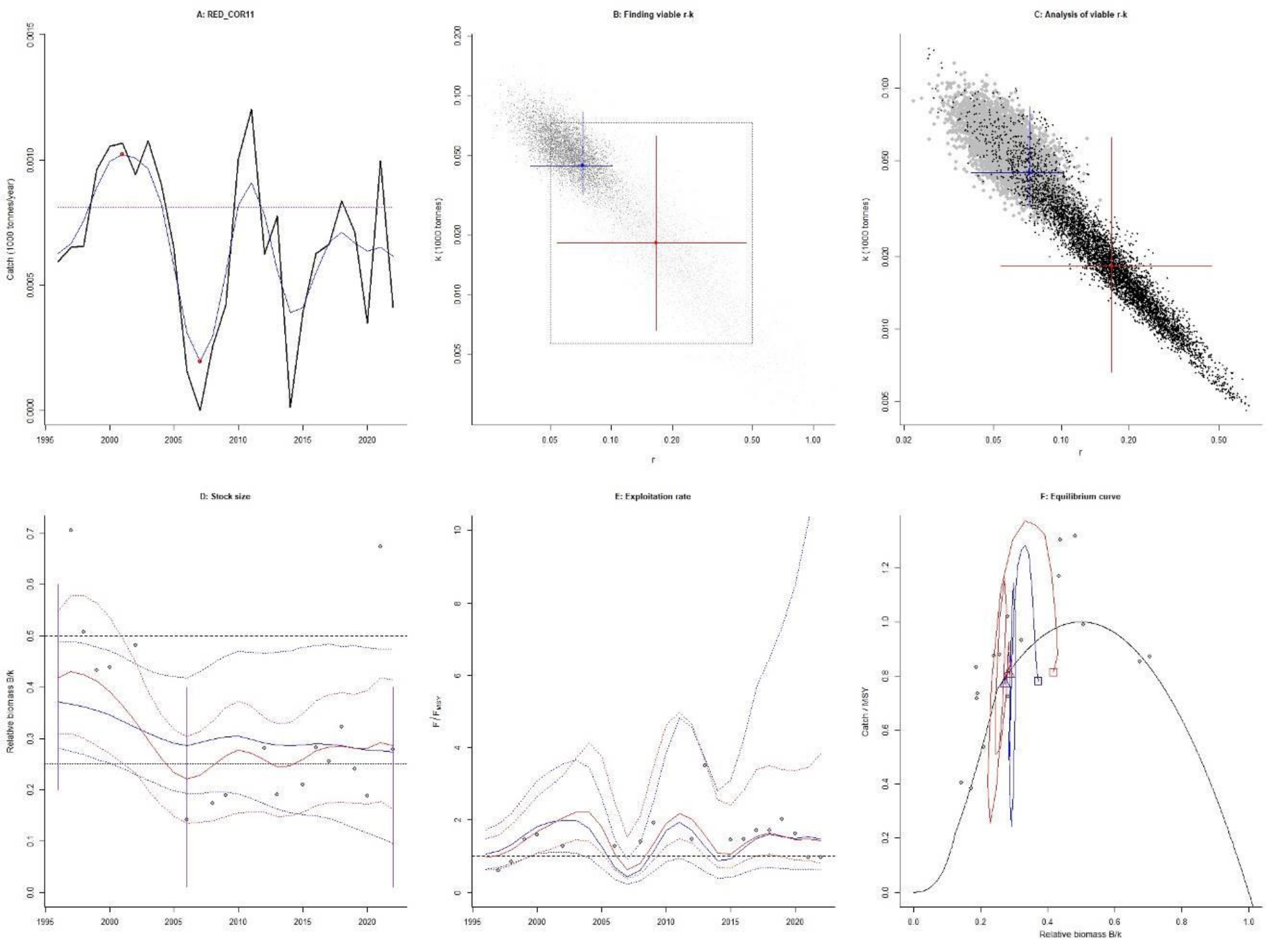


Figure 2.24 – Northern waters: CMSY-BSM fitting run 3. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

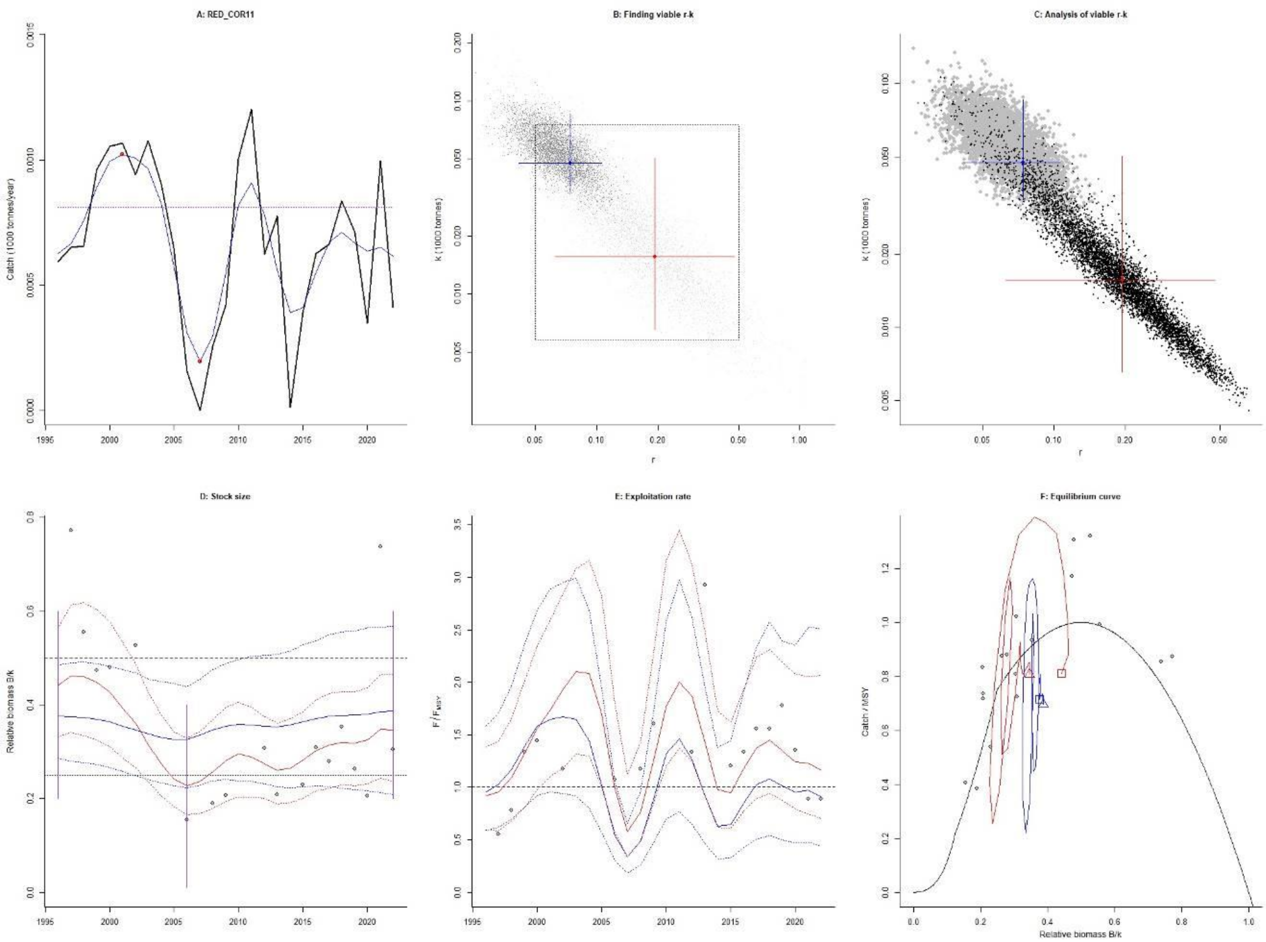


Figure 2.25 – Northern waters: CMSY-BSM fitting run 4. Blue lines indicate the CMSY estimates without CPUE information, while the red lines the BSM results, including CPUE.

For all the runs the residuals showed no particular trend (Figures 2.26, 2.27, 2.28, 2.29). The retrospective analysis shows some instability in runs 3 and 4 when excluding the last two years, with the first 2 runs showing more stable results (Figures 2.30, 2.31, 2.32, 2.33).

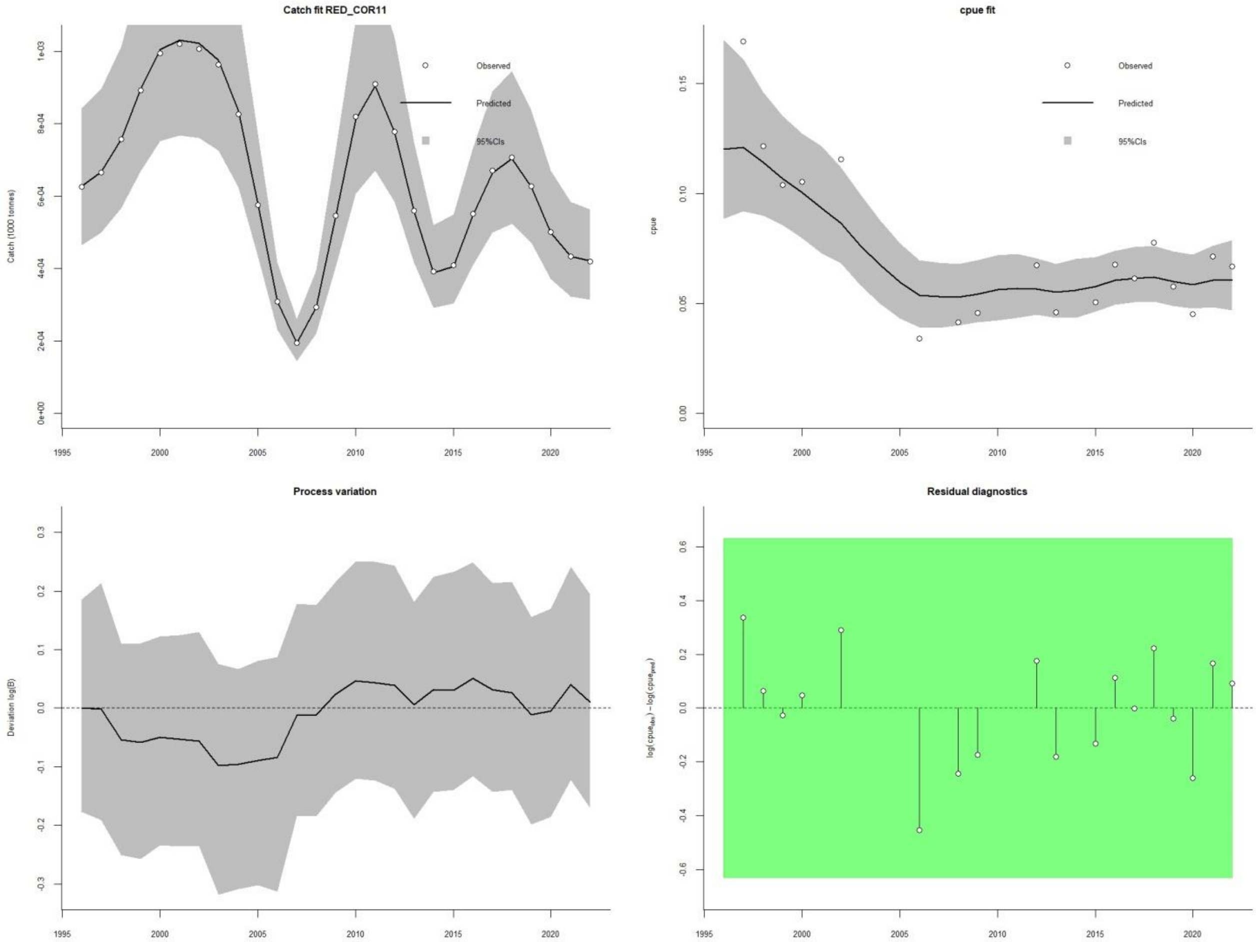


Figure 2.26 – Northern waters: CMSY BSM fitting run 1 and residuals diagnostics.

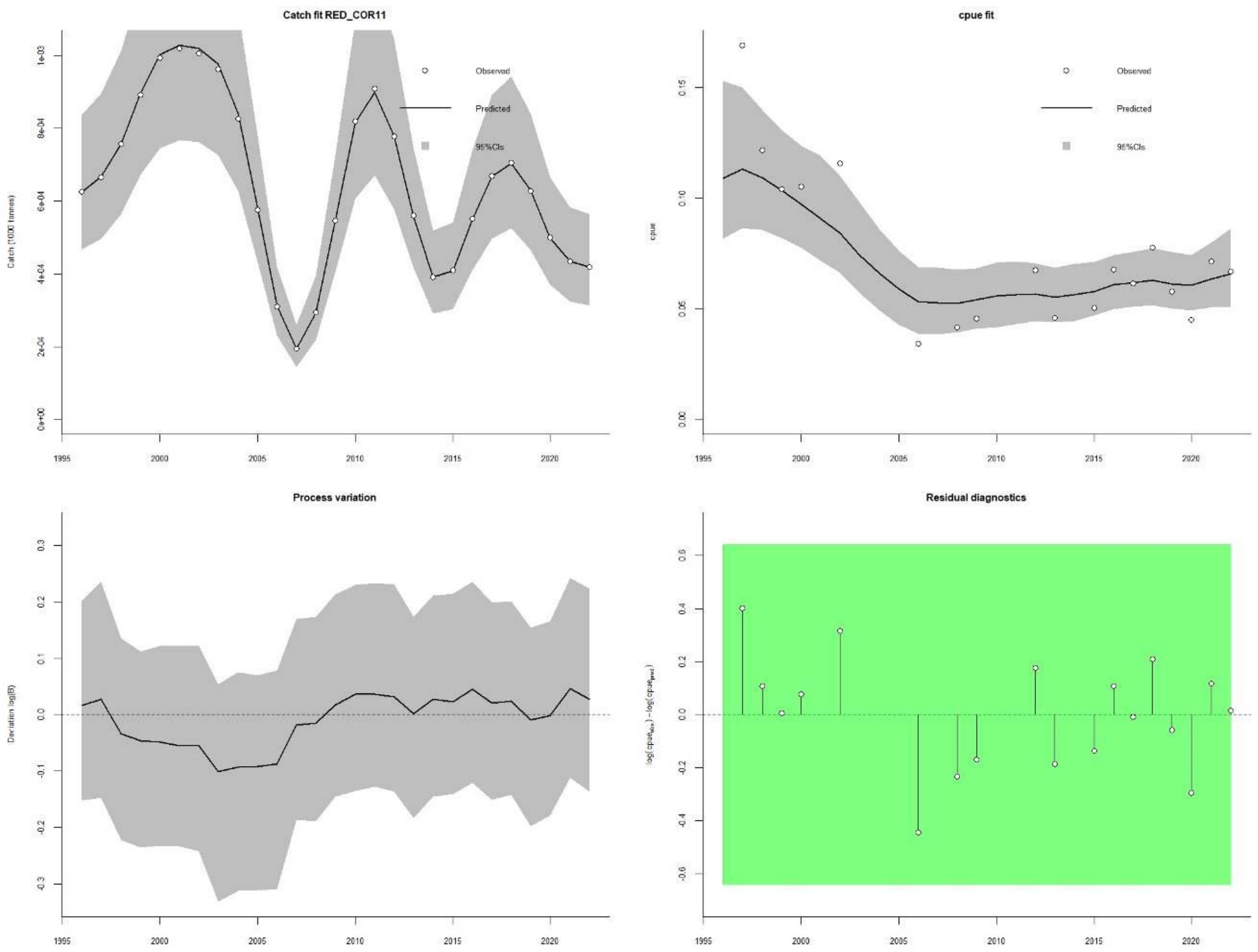


Figure 2.27 – Northern waters: CMSY BSM fitting run 2 and residuals diagnostics.

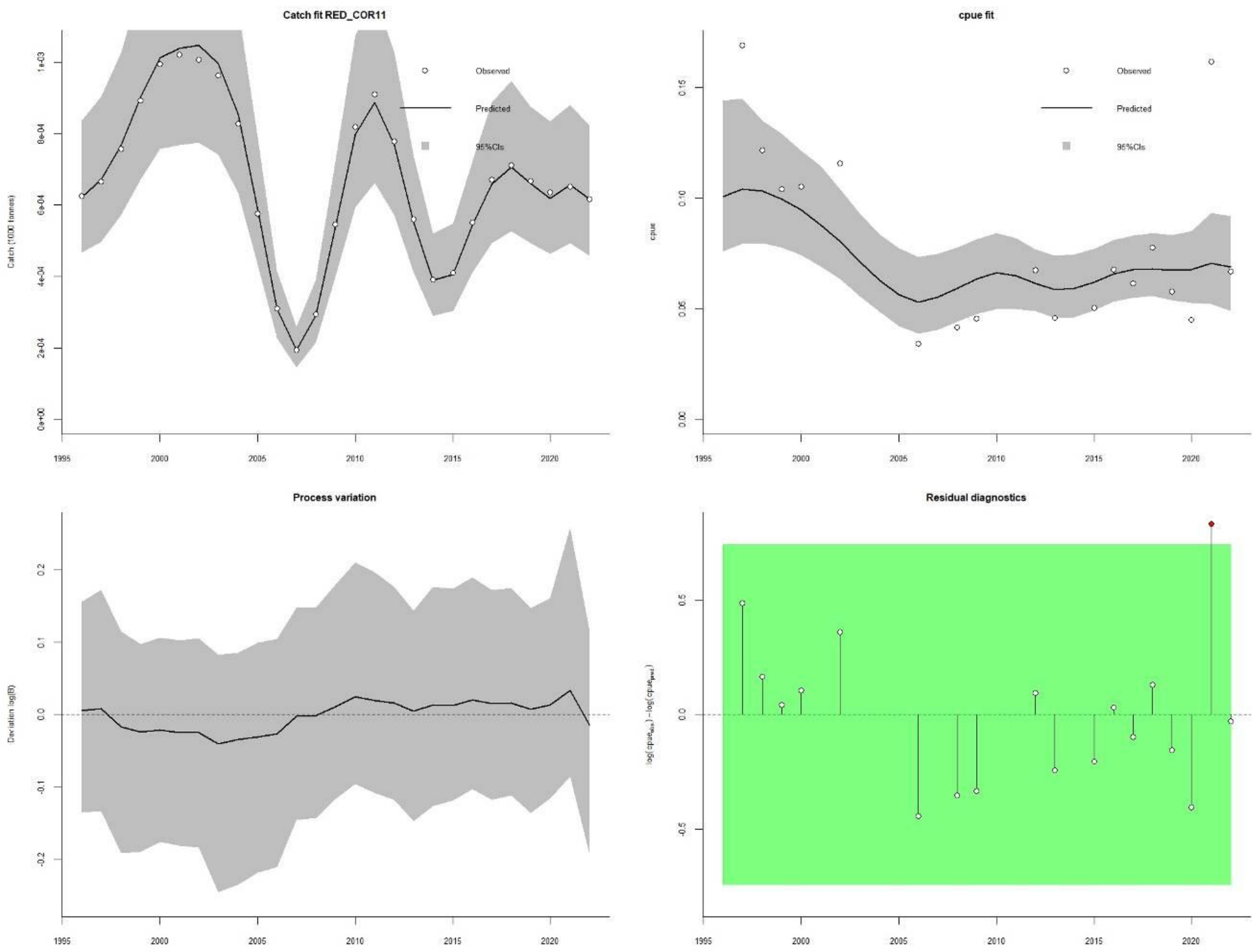


Figure 2.28 – Northern waters: CMSY BSM fitting run 3 and residuals diagnostics.

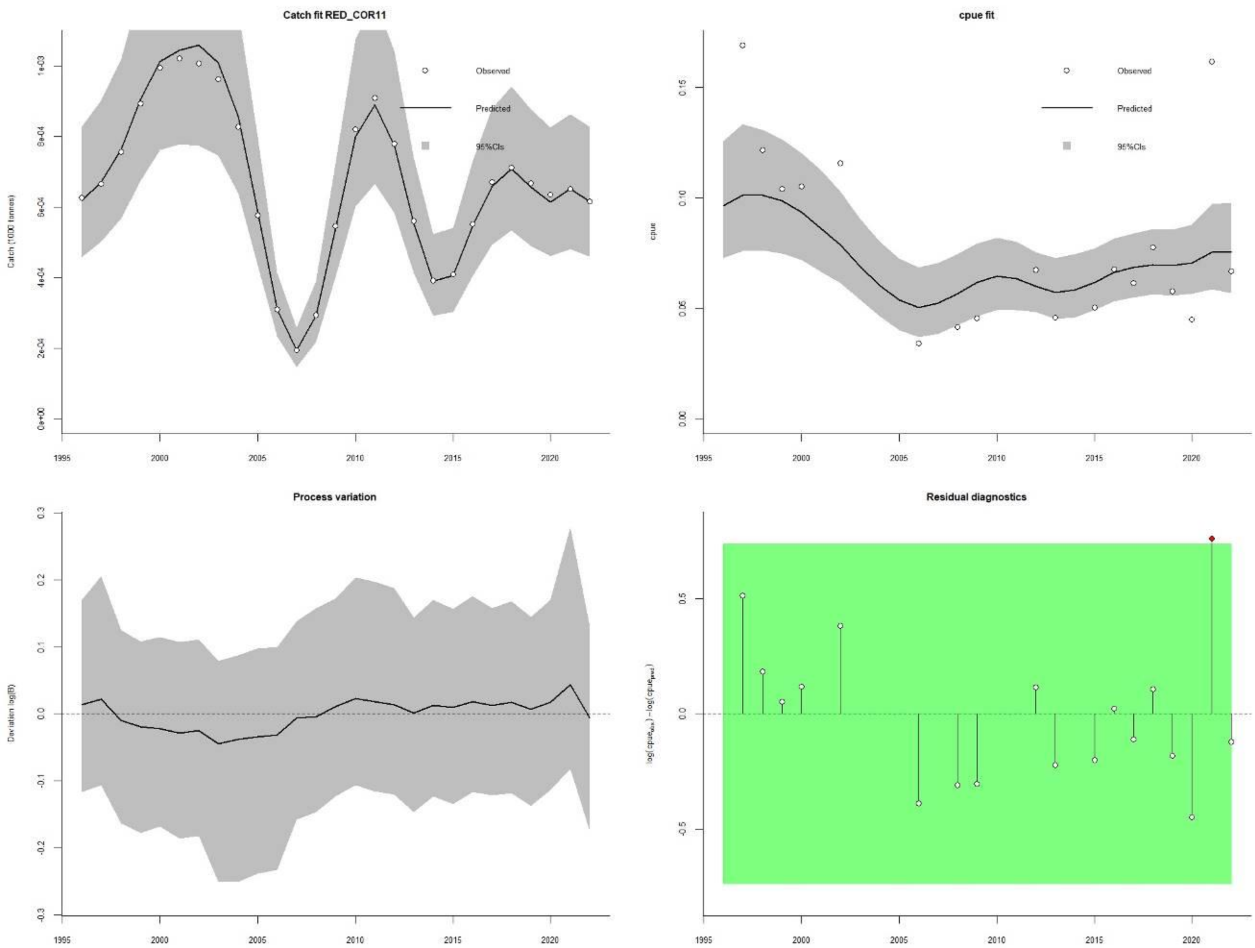


Figure 2.29 – Northern waters: CMSY BSM fitting run 4 and residuals diagnostics.

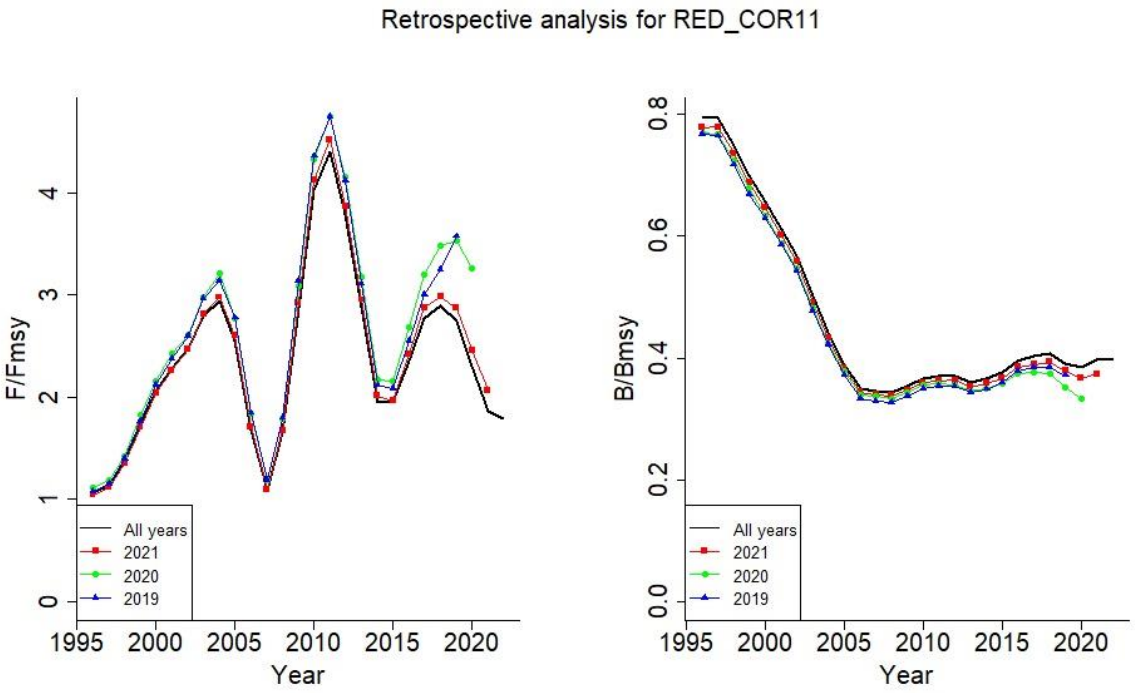


Figure 2.30 – Northern waters: CMSY-BSM retrospective analysis run 1.

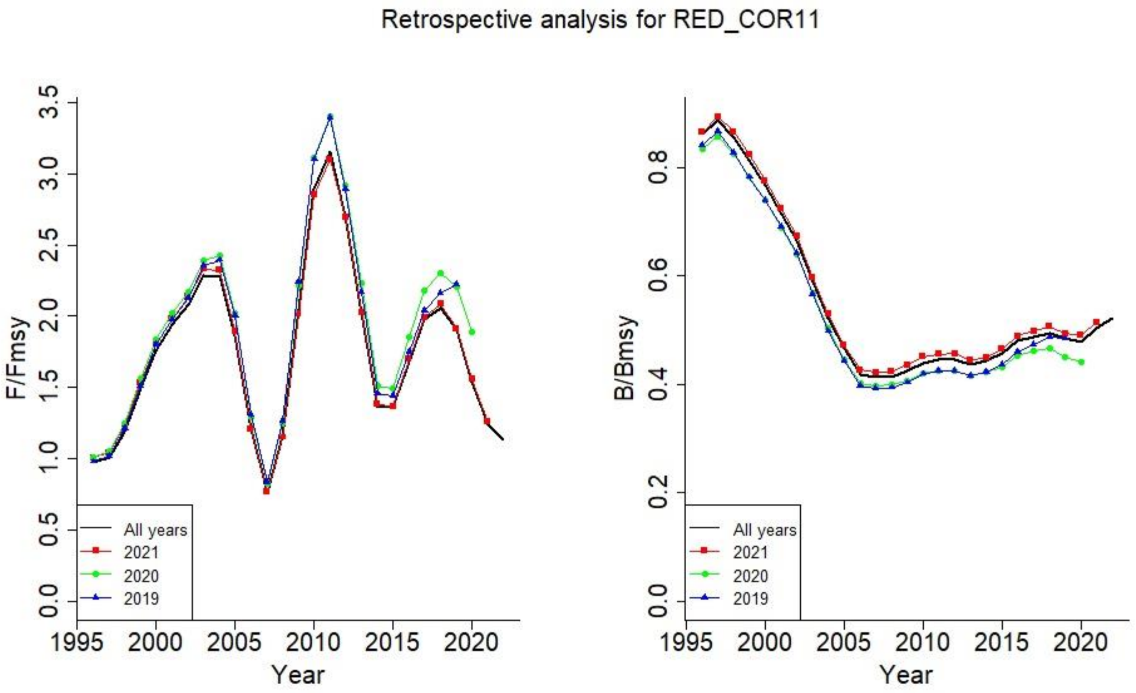


Figure 2.31 – Northern waters: CMSY-BSM retrospective analysis run 2.

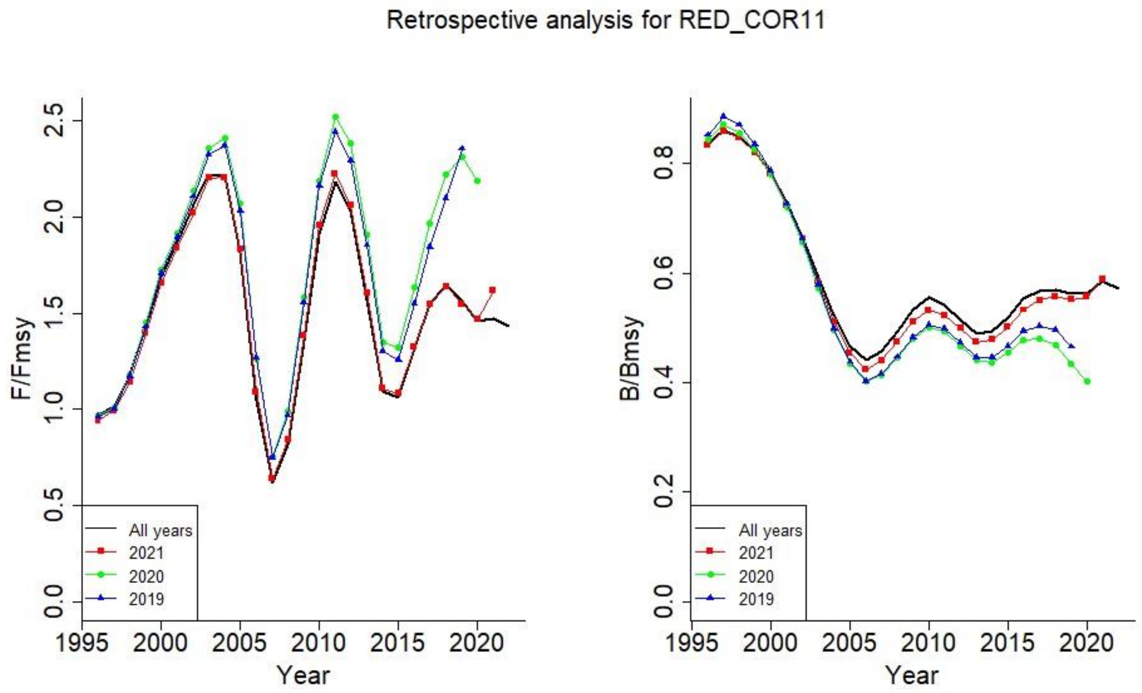


Figure 2.32 – Northern waters: CMSY-BSM retrospective analysis run 3.

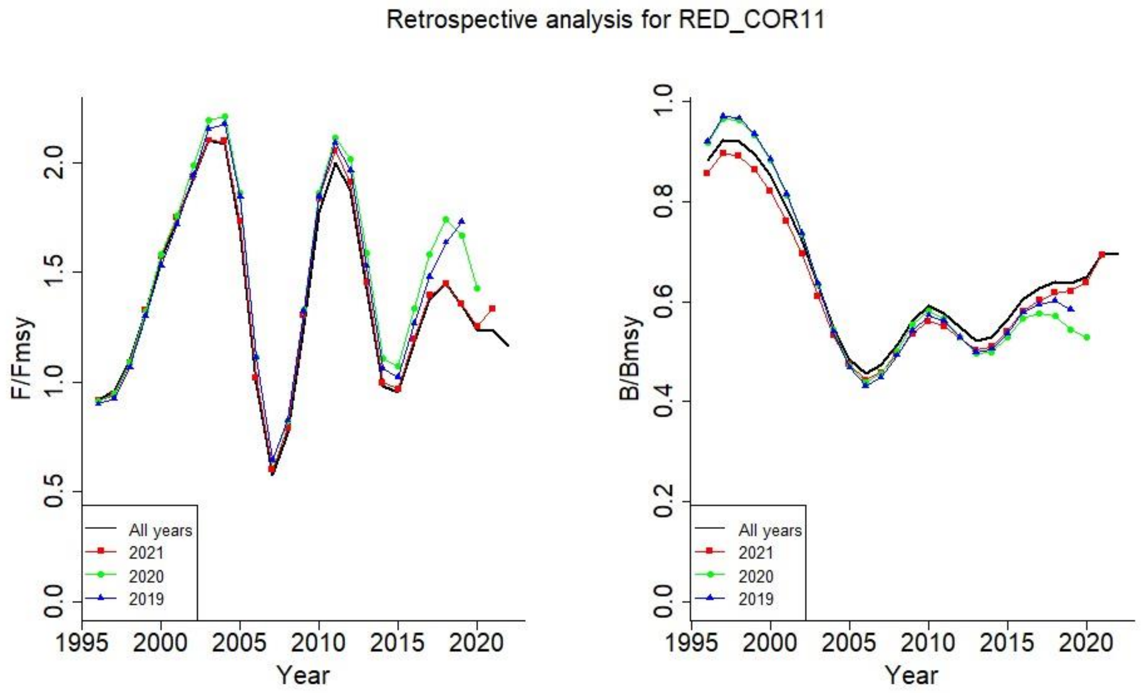


Figure 2.33– Northern waters: CMSY-BSM retrospective analysis run 4.

Among the explored runs, run 1 shows the lowest prior/posterior variance ratio (PPVR) on average, and thus the most improved posterior knowledge relative to prior knowledge (Table 2.6).

Table 2.6 – Northern waters. BSM prior/posterior variance ratio by run.

Run	F	K	MSY	B/K 1996	B/K 2006	B/K 2022	avg
1	**1.01**	**0.92**	**0.29**	**0.34**	**0.27**	**0.25**	**0.51**
2	1.03	1.02	0.33	0.27	0.2	0.58	0.57
3	1.43	1.75	0.14	0.33	0.15	0.2	0.67
4	1.12	1.78	0.11	0.27	0.14	0.42	0.64

SPiCT: stochastic surplus production model in continuous time

North-western Sardinian waters stock

SPiCT results, reported in the kobe plot representation as CMSY, show that the North-western red coral stock is exploited below F_{MSY}, while the status of the stock biomass is still below the biological safe limits (B_{msy}) (Figure 2.34).

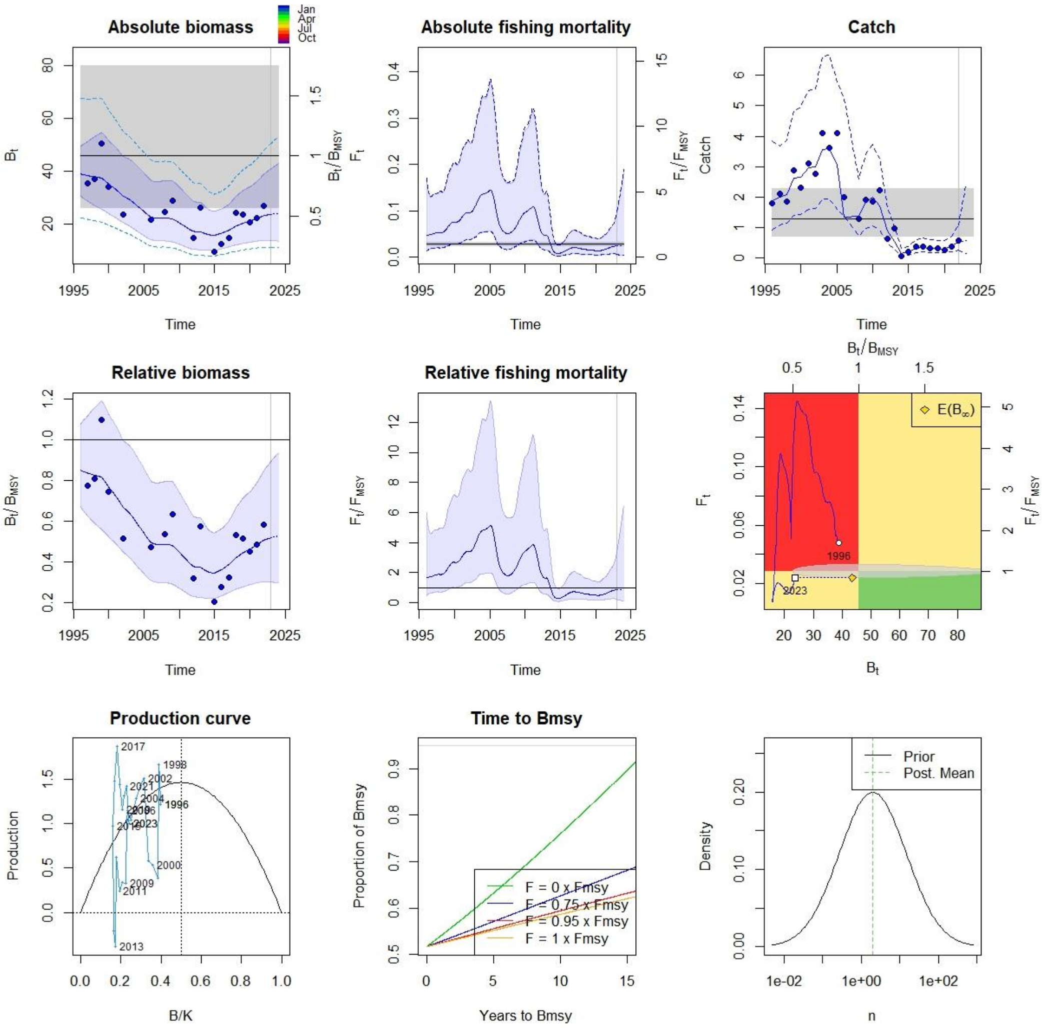


Figure 2.34 - SpiCT results North-western waters. Upper row: Median (blue solid line) of biomass and fishing mortality with 95% CI (blue shaded area) and observed (blue points) and estimated catch with 95% CIs. Middle row: Median (blue solid line) of relative biomass and relative fishing mortality with 95% CI (blue shaded area) and Kobe plot of relative fishing mortality versus relative biomass. Bottom row: Production curve (left), time to reach Bmsy among different F scenarios and comparison of prior and posterior distributions of sdi.

The residuals diagnostics do not show any particular violation of the model assumptions, except the normality of the catch distribution through the Shapiro test (Figure 2.35).

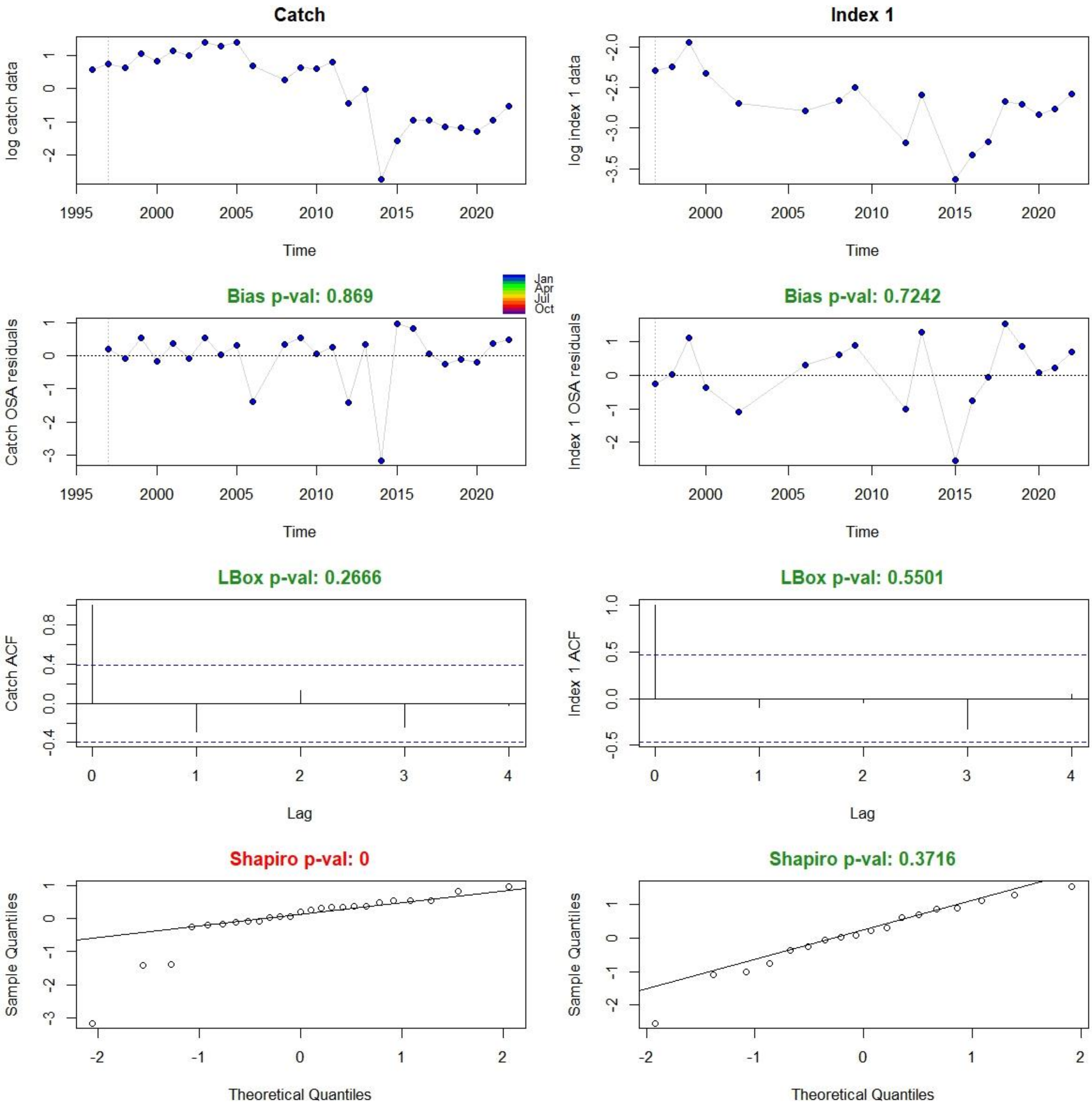


Figure 2.35 – North-western waters: SpiCT residuals diagnostics. The first column contains information related to catch data and the second column contains information related to the index data. The rows contain: 1. Log of the input data series. 2. OSA (one-step ahead) residuals with the p-value of a test for bias (i.e. that the mean of the residuals is different from zero) 3. Empirical autocorrelation of the residuals. Two tests for significant autocorrelation is performed. A Ljung-Box simultaneous test of multiple lags (here 4), and tests for individual lags shown by dashed horizontal lines in the plot. 4. Tests for normality of the residuals both as a QQ-plot and with a Shapiro test.

The retrospective analysis does not show any particular instability signal. Mohn's ρ (rho)[5], a diagnostic statistic used to evaluate the retrospective consistency of a fish stock assessment model, is in the acceptable range, with absolute value below 0.3. Mohn's ρ measures the systematic bias in the model's estimates of key parameters (like biomass or fishing mortality) when data from recent years are sequentially removed (Figure 2.36).

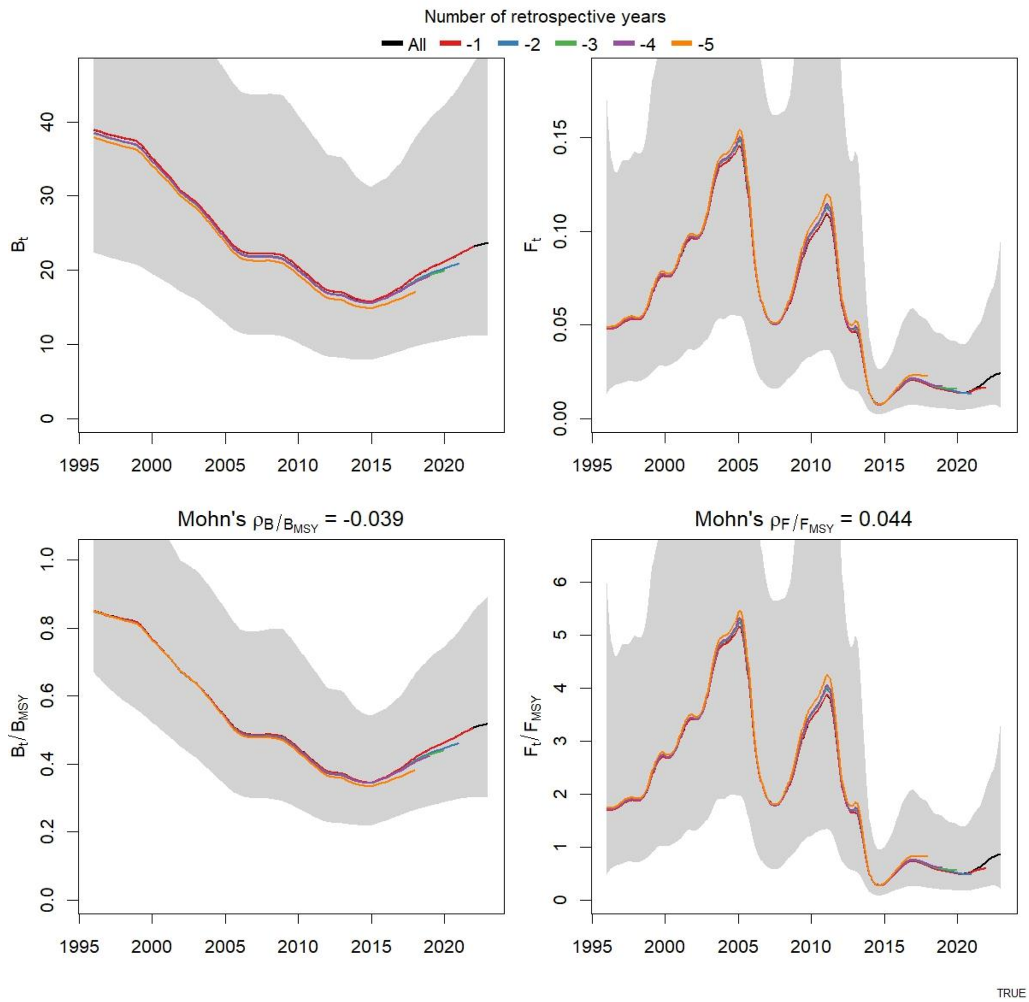


Figure 2.36 – North-western waters: SpiCT retrospective analysis.

---

[5] Mohn's ρ is valuable for detecting retrospective patterns that may indicate model misspecification, such as incorrect assumptions about selectivity or natural mortality (CAPAM-IATTC, workshop *"Model Diagnostics in Integrated Stock Assessments"* organized from January 31 to February 3, 2022).

The performance of the runs is reported in Table 2.8.

Table 2.8 – North-western waters: Performance of SPiCT runs following the SPiCT checklist.

Check list	Check	Status North-western
1	Convergence	√
2	All variance parameters of the model parameters are finite	√
3	No violation of model assumptions	Yes, except the violation on quantile of catch
4	Consistent patterns in the retrospective analysis	√
5	Realistic production curve	Bmsy/K=0.5
6	High assessment uncertainty	logsdb=0.0085; logsdc=0.415; logsdi=0.249; logsdf=0.767; B/Bmsy om=0 and F/F_{MSY} om = 1
7	Initial values do not influence the parameter estimates	all 30 runs converged

Northern Sardinian waters stock

SPiCT results show that the Northern red coral stock is exploited above F_{MSY} and that the status of the stock biomass is still below the biological safe limits (B_{msy}), indicating a worse situation respect to the North-western stock (Figure 2.37).

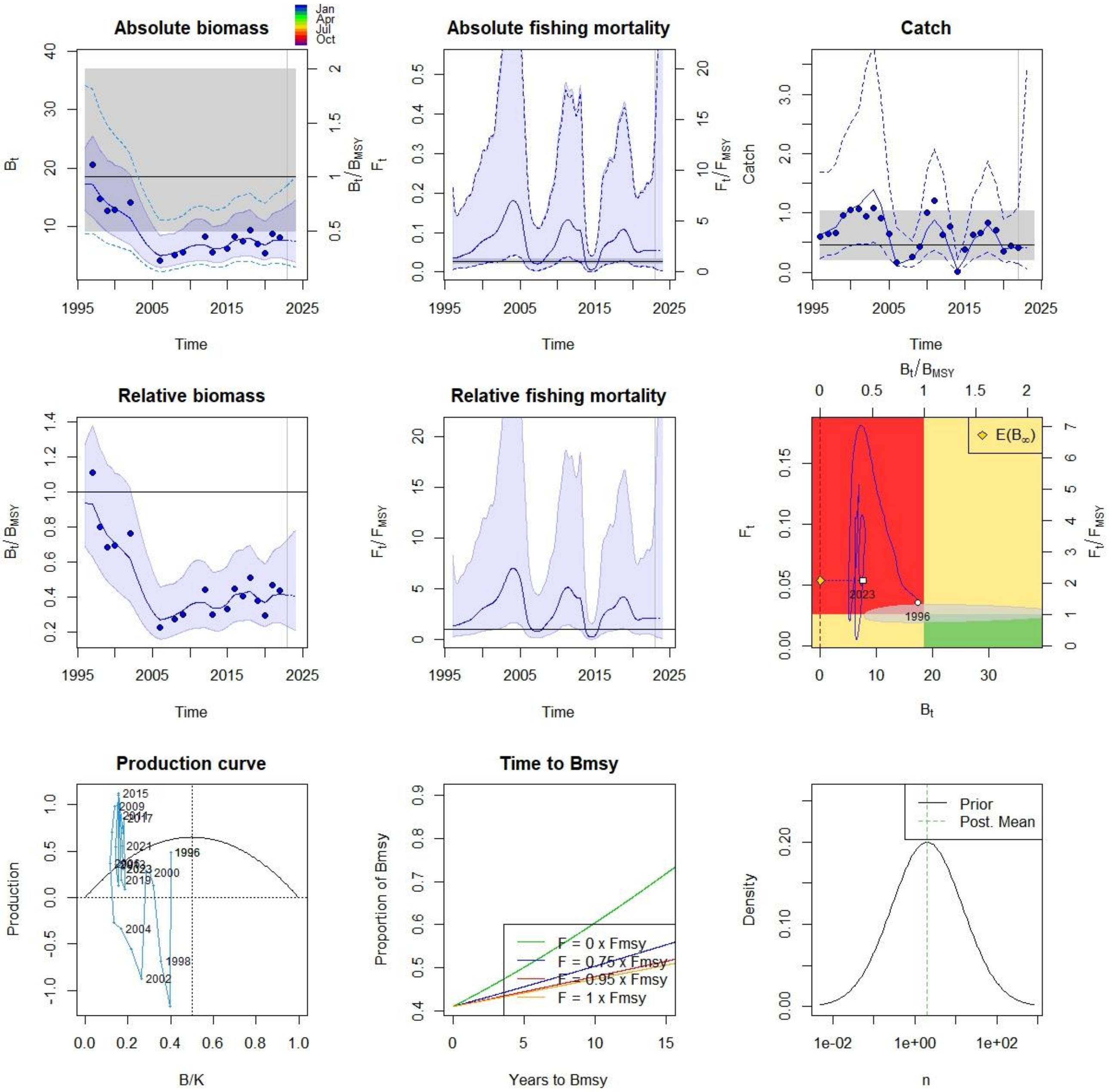


Figure 2.37 - SpiCT results North-western waters. Upper row: Median (blue solid line) of biomass and fishing mortality with 95% CI (blue shaded area) and observed (blue points) and estimated catch with 95% CIs. Middle row: Median (blue solid line) of relative biomass and relative fishing mortality with 95% CI (blue shaded area) and Kobe plot of relative fishing mortality versus relative biomass. Bottom row: Production curve (left), time to reach Bmsy among different F scenarios and comparison of prior and posterior distributions of sdi.

Also in this case, the residuals diagnostics do not show any particular violation of the model assumptions, except the normality of the catch distribution through the Shapiro test (Figure 2.38).

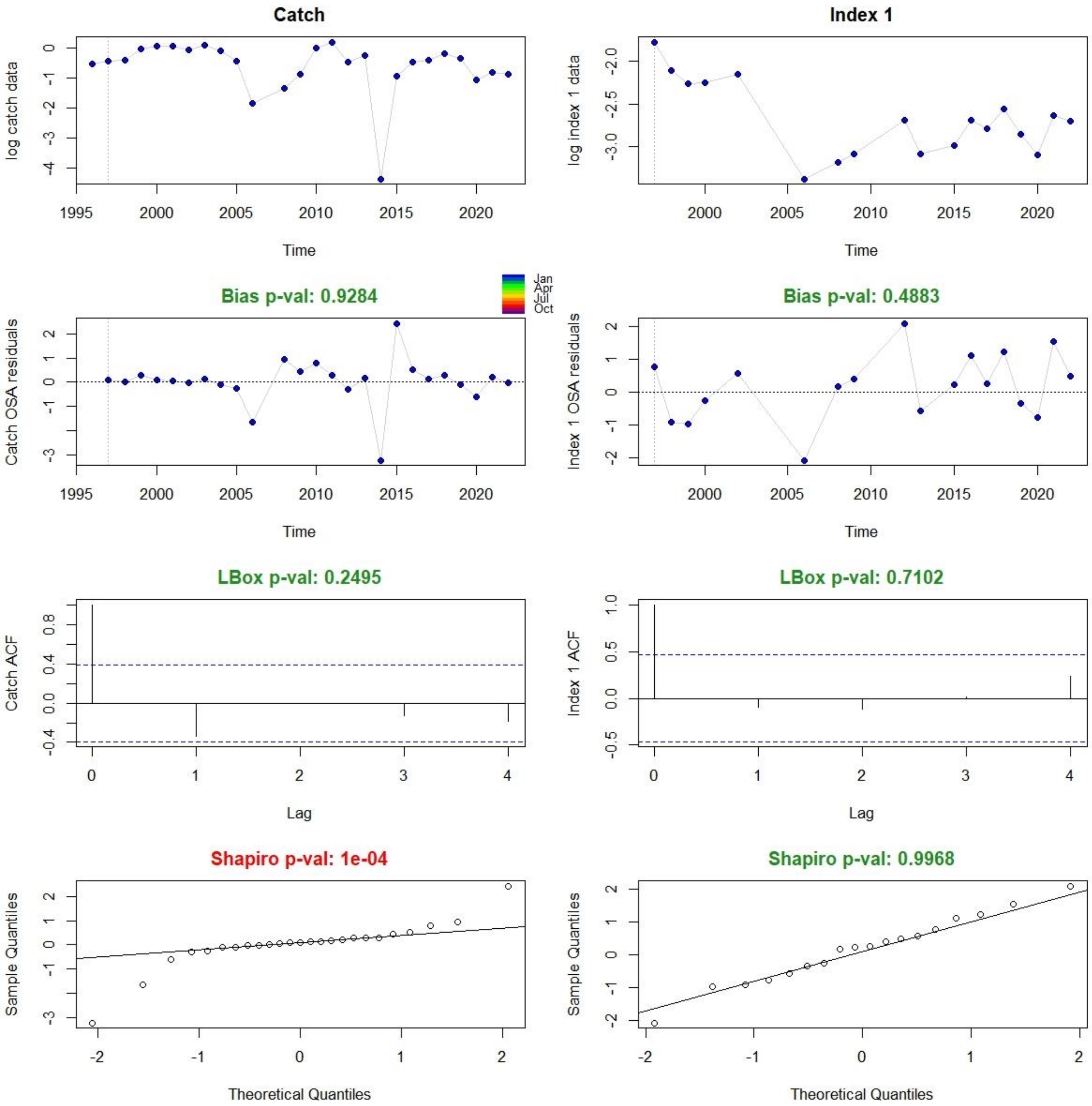


Figure 2.38– Northern waters: SpiCT residuals diagnostics. The first column contains information related to catch data and the second column contains information related to the index data. The rows contain: 1. Log of the input data series. 2. OSA (one-step ahead) residuals with the p-value of a test for bias (i.e. that the mean of the residuals is different from zero) 3. Empirical autocorrelation of the residuals. Two tests for significant autocorrelation is performed. A Ljung-Box simultaneous test of multiple lags (here 4), and tests for individual lags shown by dashed horizontal lines in the plot. 4. Tests for normality of the residuals both as a QQ-plot and with a Shapiro test.

The retrospective analysis does not show any instability signal and the Mohn's rho coefficients are in the acceptable range, with absolute value below 0.3 (Figure 2.39).

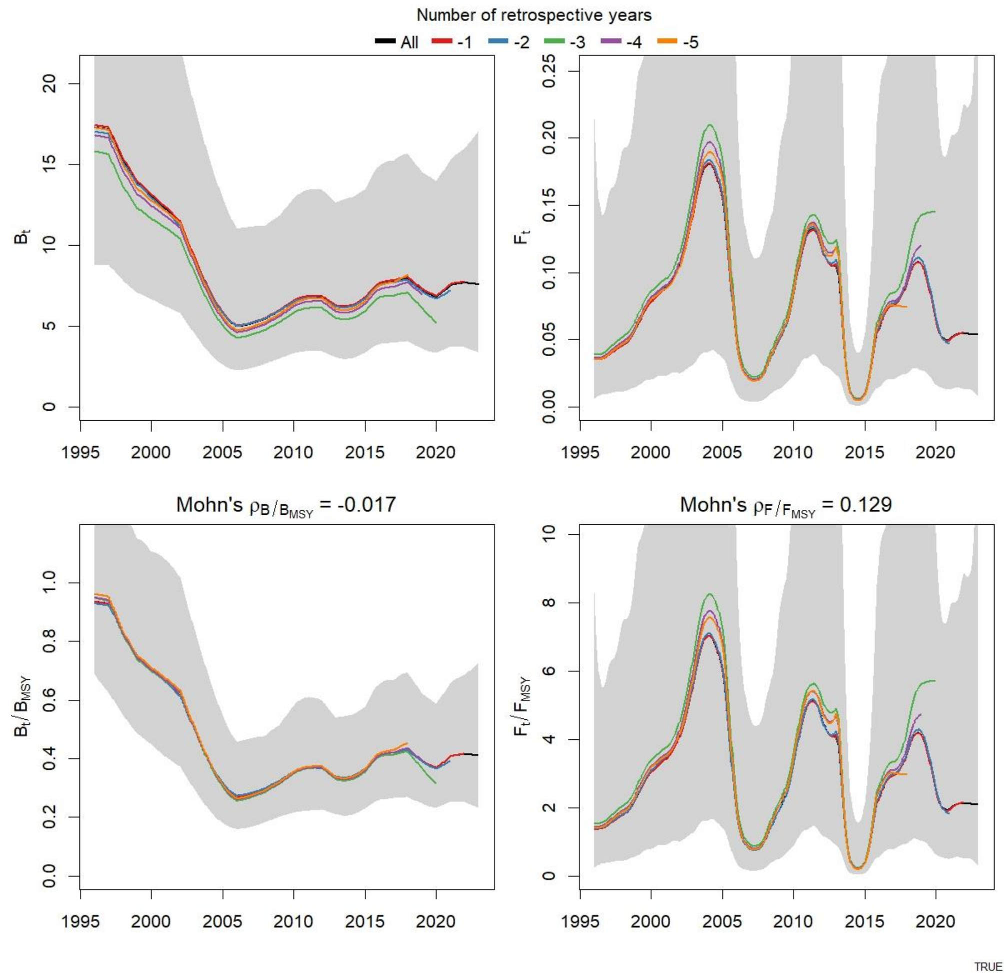


Figure 2.39 – Northern waters: SpiCT retrospective analysis.

The performance of the runs is reported in Table 2.9.

Table 2.9 – Northern waters: Performance of SPiCT runs following the SPiCT checklist.

Check list	Check	Northern
1	Convergence	√
2	All variance parameters of the model parameters are finite	√
3	No violation of model assumptions	Yes, except the violation on quantile of catch

Check list	Check	Northern
4	Consistent patterns in the retrospective analysis	√
5	Realistic production curve	Bmsy/K=0.5
6	High assessment uncertainty	logsdb=0.13; logsdc=0.56; logsdi=0.17; logsdf=1.18; B/Bmsy om=0 and F/F_{MSY} order of magnitude = 2
7	Initial values do not influence the parameter estimates	all 30 runs converged

Length-Based Spawning Potential Ratio

North-western Sardinian waters stock

LBSPR results show that the fishing mortality estimated on the basis on basal diameter frequency distributions is more than twice of the natural mortality and that the spawning potential ratio is well below the reference value of 0.4 that is considered risk adverse for many species (Clark, 2002) with an increasing trend since 2014 (Table 2.11, Figure 2.40).

Table 2.11 – LBSPR results North-western waters. Selectivity parameters $BD_{50\%}$ (size at first capture) and $BD_{95\%}$ (size at which the 95% of individuals are caught). F/M ratio and SPR (spawning potential ratio).

	North-western waters			
	BD50	**BD95**	**F/M**	**SPR**
2007	7.65	9.61	2.59	0.1
2008	7.71	9.69	2.62	0.1
2009	7.81	9.85	2.59	0.11
2012	7.93	10.02	2.48	0.12
2013	8.04	10.25	2.33	0.13
2014	8.22	10.57	2.22	0.15
2015	8.49	10.77	2.26	0.14
2023	8.76	10.97	2.28	0.15

	North-western waters			
	BD50	**BD95**	**F/M**	**SPR**
average	8.08	10.22	2.42	0.13

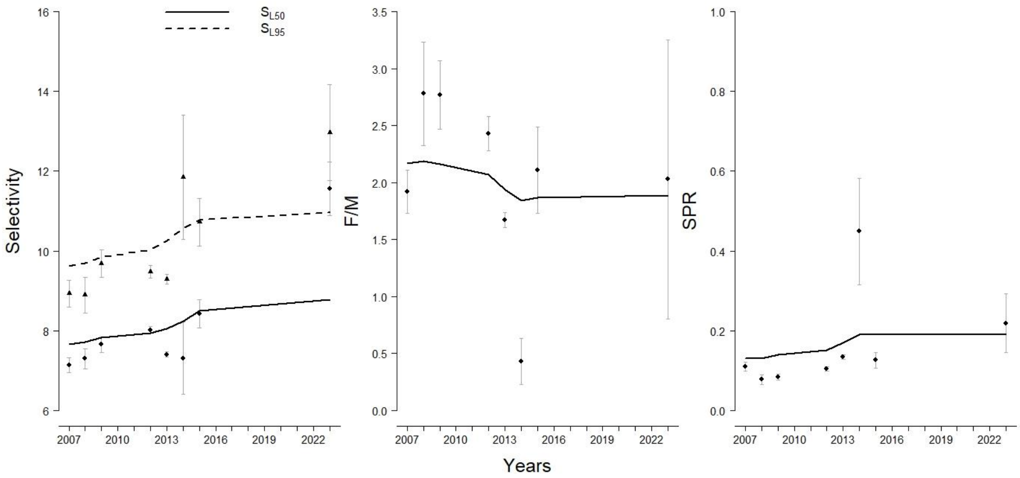


Figure 2.40 - LBSPR results in North-western waters.

The results, perturbed including uncertainty on the key biological parameters, show that the size at first capture is quite stable around 8 mm along the sampled years, except in 2023 having a $BD_{50\%}$ around 12 mm. The ratio between F and M is between 2 and 4 along the years, except 2014, showing a marked lower value slightly above 1.5. The most part of SPR realizations are below 0.25, showing that also including uncertainty the stock spawning stock is importantly deteriorated (Figure 2.41).

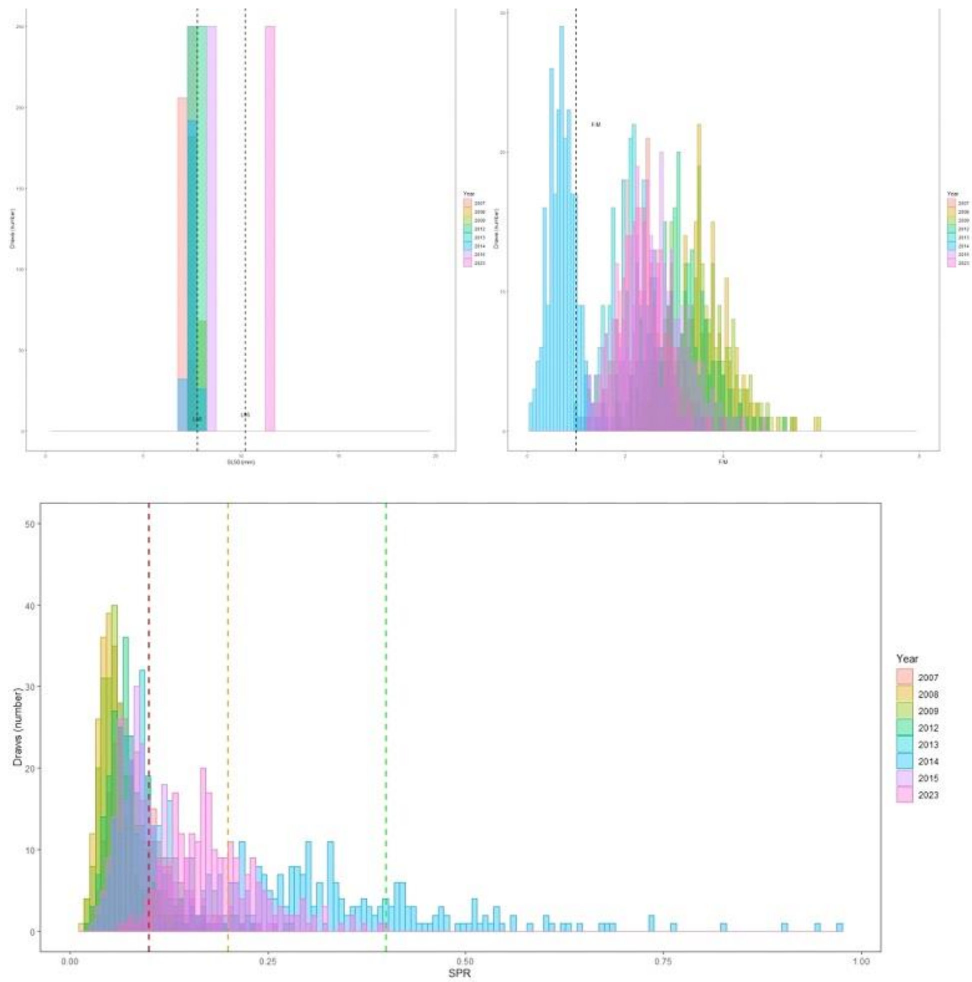


Figure 2.41 - LBSPR results in North-western waters, including uncertainty.

The results of the scenarios, combining the different sizes at first capture with the different ratios of F/M, indicate that for North—western waters, to achieve a SPR between 0.3 and 0.4 (yellow cells in Figure 2.42) while fishing at an F level equal to 2.5 times the natural mortality, it would be necessary to increase the size at first capture to 15 mm of basal diameter. On the other hands, the MCRS adopted by the Sardinia Autonomous Region in the previous years (= 10 mm) would return an SPR higher than 0.3 only reducing the fishing mortality to the same level of the natural mortality (Figure 2.41).

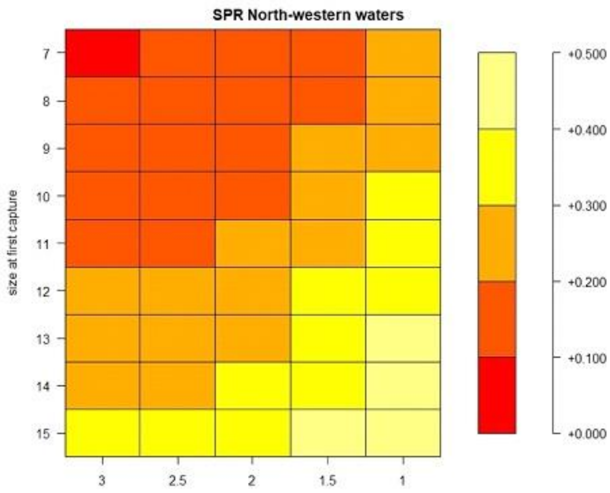


Figure 2.42 - LBSPR SPR results in North-western waters. On the x axis there are the ratios F/M tested, while on the y-axis there are the size at first capture explored in the LBSPR simulations.

Northern Sardinian waters stock

LBSPR results show also for Northern waters that the estimated fishing mortality is twice of the natural mortality and that the spawning potential ratio (=0.08) is well below the reference value of 0.4 (Table 2.12), indicating that the spawning stock in this area is more deteriorated than in North-western waters.

Table 2.12 - LBSPR results Northern waters. Selectivity parameters $BD_{50\%}$ (size at first capture) and $BD_{95\%}$ (size at which the 95% of individuals are caught). F/M ratio and SPR (spawning potential ratio).

Year	Northern waters			
	BD50	**BD95**	**F/M**	**SPR**
2012	5.70	7.05	2.02	0.08

The results of the scenarios, combining the sizes at first capture and the ratios of F/M, show that for Northern waters, in order to have a SPR between 0.3 and 0.4 fishing at an F level equal to twice the natural mortality it would be necessary to increase the size at first capture at 13 m of basal diameter, slightly lower than the one indicated by the same analysis in North-western waters (14 mm). Consistently with the North-western results, using the MCRS of 10 mm basal diameter it would be necessary to reduce the fishing mortality to the same level of the natural mortality to achieve an SPR between 0.3 and 0.4 (Figure 2.43).

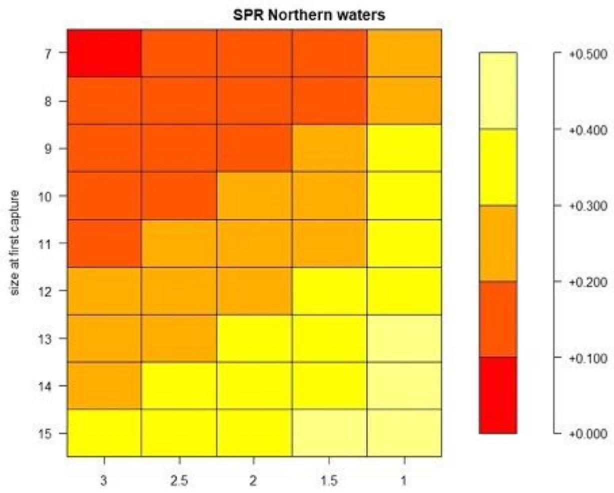


Figure 2.43 - LBSPR SPR results in Northern waters. On the x axis there are the ratios F/M tested, while on the y-axis there are the size at first capture explored in the LBSPR simulations.

2.4 Conclusions

In this chapter a detailed description of the data available on the red coral resources in Northern-western and Northern Sardinian waters was provided. The presence of a quite long time series of landing data by port from logbook and the number of fishers, authorized annually to harvest the resource, allowed to apply two global production models, one data-poor (CMSY) and one data-rich (SPiCT), separately for the two areas. The data, including commercial catch basal diameter structures and age data, represent a unique case in Mediterranean Sea of amount of information for this species. The ageing of 62 colonies, characterized by a range of basal diameters, allowed to statistically test the difference in the growth rate between the two areas and to estimate a linear growth model for the two areas separated. This source of information, integrated with the size at first maturity derived from literature allowed to estimate a natural mortality rate and to apply a data-poor methodology, LBSPR, to take advantage of the scientific monitoring data to estimate the status of the spawning stock potential.

It should be noticed that both CMSY and SPiCT provided for the two study areas very consistent results, showing a better situation in North-western waters with respect to Northern waters. This is also consistent with the LBSR results, showing a SPR lower in Northern waters.

The results presented in this chapter represent the first stock assessment carried out in Mediterranean Sea for the red coral and have been presented and validated during the GFCM WGSAD January 2022, December 2022, 2023 and 2024, contributing to provide for the first time information of the status of this important resource in Sardinia. The official stock assessment reports have been published on the GFCM web page, here: https://www.fao.org/gfcm/data/safs/fr/

Moreover, in the context of the GFCM REDCORAL program (https://www.fao.org/gfcm/researchprogramme-redcoral/en/), the assessment was presented to the Working Group on Red Coral (WGREDCORAL, https://www.fao.org/gfcm/technical-meetings/detail/en/c/1681847/) in April 2024, and contributed to the discussion the issues related to existing and additional measures as well as their possible implementation and potential development, providing technical elements for management and a toolbox of measures for the consideration of the SAC in 2024.

A paper describing the results presented in this chapter was also submitted to the ICES Journal of marine Science and is under revision.

Chapter 3: Exploitation status of spiny lobster in Asinara MPA

3.1 Introduction

Figure 3.1 – Individual of *P. elephas*.

P. elephas (Figure 3.1), is a conspicuous and ecologically important decapod crustacean inhabiting rocky reef ecosystems across the eastern Atlantic and Mediterranean Sea (Diaz et al. 2001). Its distinctive spiny exoskeleton and absence of large chelae on the first walking legs are defining characteristics of the Palinuridae family. Understanding its biology, ecology and distribution is paramount for effective fisheries management and conservation efforts, particularly given its high economic value. *P. elephas* is a highly prized species in European fisheries, fetching high market prices due to its culinary value and relatively limited availability (Porcu et al. 2022). Targeted fisheries operate across its distribution range, employing traps (pots), gillnets, and trammel nets. The economic importance is significant at local and regional levels, supporting coastal livelihoods.

Biologically, *P. elephas* is characterized by slow growth and late maturation. Sexual maturity is typically attained at carapace lengths (CL) of 80-100 mm, a process that can span several years depending on environmental factors such as temperature and food availability (Garrabou et al., 2011).

The species' slow life history makes it highly susceptible to overexploitation (Santos et al. 2022).

In Sardinia, the spiny lobster (*P. elephas*) is primarily targeted by the small-scale coastal fleet using passive gears, notably trammel nets and lobster traps, typically deployed in rocky and coastal habitats at depths ranging from 30 to 150 meters. These fishing gears are low-impact and highly selective, making them suitable for artisanal fisheries operating within marine protected areas and traditional fishing zones (Follesa et al., 2009).

Several studies in Sardinia have evaluated the benefits of Marine Protected Areas (MPAs) on the conservation and fishery recovery of spiny lobster. Follesa et al. (2009) documented movement patterns of tagged lobsters within the Su Pallosu MPA, confirming site fidelity and localized behavior, which support the effectiveness of area-based management. Building on this, Follesa et al. (2011) demonstrated positive spillover effects in the same MPA, where increased densities and catch rates were observed in adjacent fishing grounds, indicating that protection within the MPA benefits surrounding fisheries. Porcu et al. (2022) focused their study on two Fully Protected Areas (FPAs) in Sardinia: Su Pallosu and Buggerru. Their research analyzed reproductive parameters of *P. elephas* populations within these FPAs and their surrounding commercial zones, highlighting the effectiveness of FPAs in enhancing reproductive output and supporting conservation efforts.

Additionally, Mulas et al. (2022) analyzed movement patterns of 744 tagged lobsters across 12 Fully Protected Areas (FPAs) around Sardinia, finding that most individuals exhibited limited movement, reinforcing the importance of strategically placed MPAs in safeguarding sedentary species like *P. elephas*. Collectively, these studies demonstrate that MPAs are vital tools for the sustainable management of spiny lobster populations in the Mediterranean.

Asinara Island Marine Protected Area

The Marine Protected Area (MPA) of Asinara Island (Figure 3.2), encompassing approximately 108 km², is spatially organized into zones with varying levels of environmental protection:. Zone A, where all access is prohibited, constitutes about 5% of the MPA and is located in three specific stretches of sea: between

Punta dello Scorno and Punta del Porco, between Punta l'Arroccu and Punta Galetta, and between Punta Pedra Bianca and Punta Agnadda (Anonymous, 2023). Zones B and C cover the majority of the MPA, accounting for approximately 65% and 30% respectively (Anonymous, 2023).

Since the establishment of the MPA by decree on August 13, 2002, all fishing activities around Asinara Island have been prohibited for all seafarers, with a specific exception granted to small-scale fishers from Porto Torres and Stintino who can obtain authorization for fishing at a distance greater than 150 meters from the coast and outside the fully protected Zone A areas (Anonymous, 2023). Furthermore, a decree from the Ministry of the Environment dated November 28, 1997, already established an absolute ban on trawling within three nautical miles along the west coast of the island (from Punta dello Scorno to Punta Salippi) and within the 50-meter bathymetric depth along the eastern and southern coasts from Punta dello Scorno to Punta Salippi (Art. 5), thus excluding this fishing method from the permitted activities within the MPA (Anonymous, 2023).

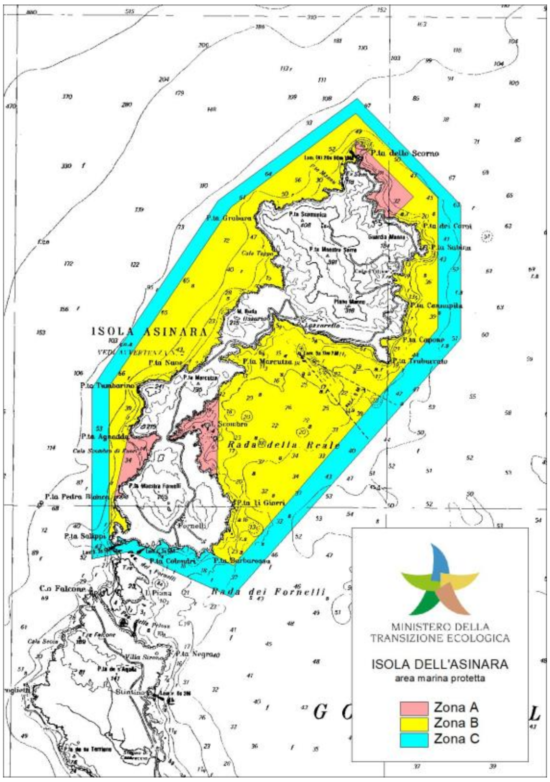


Figure 3.2 – Asinara Island Marine Protected Area indicating the zones A, B and C.

3.2 Materials and Methods

The Department of Life and Environmental Sciences at the University of Cagliari (under the coordination of Prof. Maria Cristina Follesa), has been actively involved in monitoring programs within the Asinara Island Marine Protected Area (MPA). These initiatives focus on evaluating the ecological and fishery impacts of protection measures, particularly concerning demersal resources like the European spiny lobster.

Under my PhD period, data from biological sampling program carried out in the Asinara MPA for the years 2020, 2022, 2023 and 2024 was used to provide a preliminary assessment for the spiny lobster resource in this area. The data were collected by vessels using trammel nets and operating in zones B, C and around the MPA.

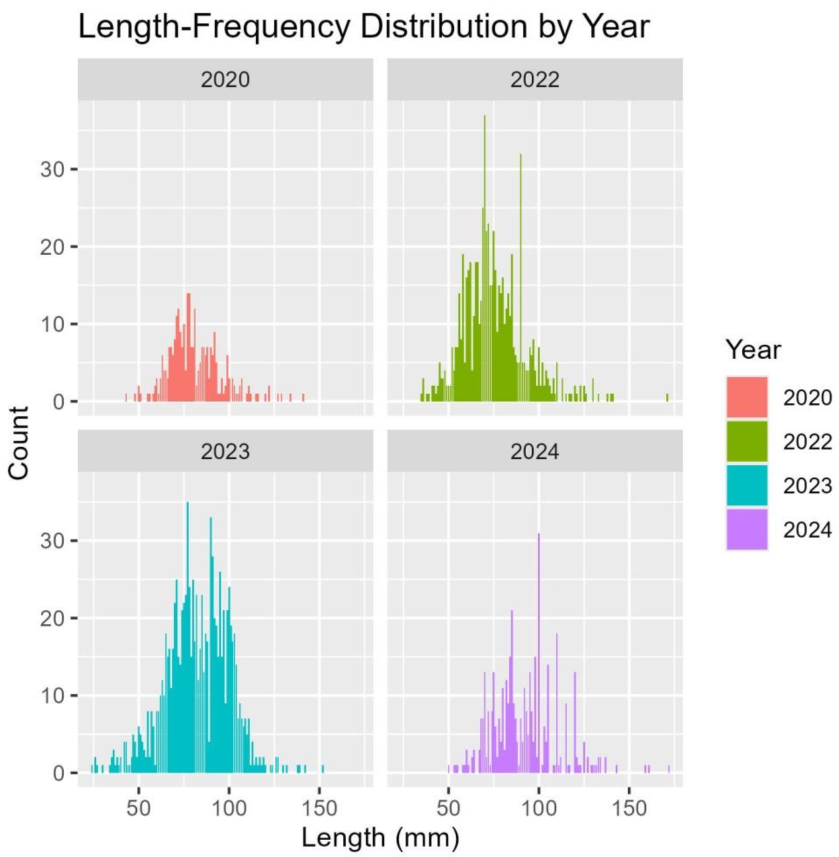


Figure 3.3 – carapace length-frequency distributions of spiny lobster collected under the monitoring program in Asinara island MPA.

The growth parameters are available from Follesa et al. (2007), while the size at first maturity is collated from Porcu et al. 2022 (Table 3.1).

Table 3.1 – Growth and maturity parameters used for the spiny lobster assessment in Asinara MPA.

Parameter	Sex	Value
CL_{inf} (mm)	Females	125
K	Females	0.19
t_0	Females	-0,37
$CL_{50\%m}$ (mm)	Females	82.6
CL_{inf} (mm)	Males	167
K	Males	0.13
t_0	Males	-0.401
$CL_{50\%m}$ (mm)	Males	82.5

A scalar value for natural mortality was derived through the Barefoot ecologist app (http://barefootecologist.com.au/shiny_m) using the parameters in Table 3.1. The obtained values by area are reported in Table 3.2, indicating the 4 methods included in the average.

Tab. 3.2- Scalar values for M estimated with barefootecologist.com.au/shiny_m for the spiny lobster assessment in Asinara MPA.

Method	M
Then_VBGF	0.37
Hamel_k	0.23
Jensen_k 1	0.20
Jensen_k 2	0.21
average	0.25

Considering the available data and information for the spiny lobster in the Asinara MPA, the LBSPR model was applied. For the theoretical description of LBSPR methodology, refer to chapter 2.2.2 of this thesis.

3.3 Results

Length-Based Spawning Potential Ratio

The results of LBSPR model highlight that, under the assumption of steady state, the spawning potential of the stock appears deteriorated with SPR values below 0.2, with an improvement in the last year with a value of 0.3. However, this value is still below the reference value of 0.4 that is considered risk adverse for many species (Clark, 2002).

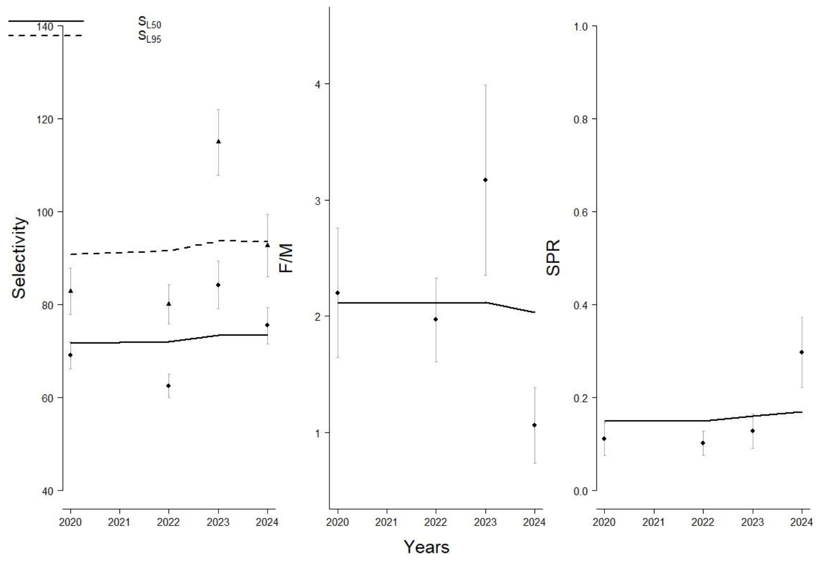


Figure 3.4 – Selectivity parameters (SL50% and SL95%), F/M ratio and Spawning Potential Ratio (SPR) estimated for spiny lobster in the Asinara MPA in the years 2020, 2022, 2023 and 2024.

These results would still show a situation of overexploitation and this is consistent with what shown by the model about the size of first capture (around 71 mm of carapax length) that is well below the size at first maturity (82 mm) (Figure 3.5).

The model is able to fit the length-frequency distributions in a satisfactory way, contributing to provide a reliable overview of the status of the resource in the Asinara MPA (Figure 3.6).

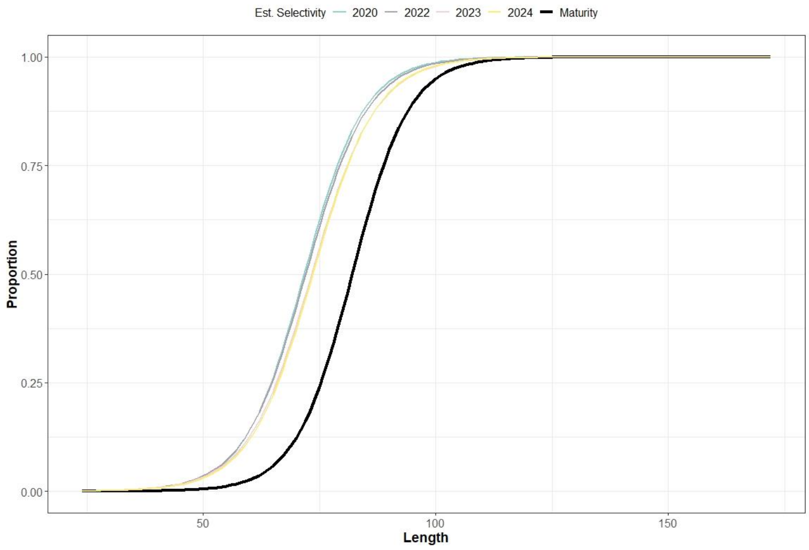


Figure 3.5 – Estimated selectivity function (logistic) and maturity ogive in the years 2020, 2022, 2023 and 2024.

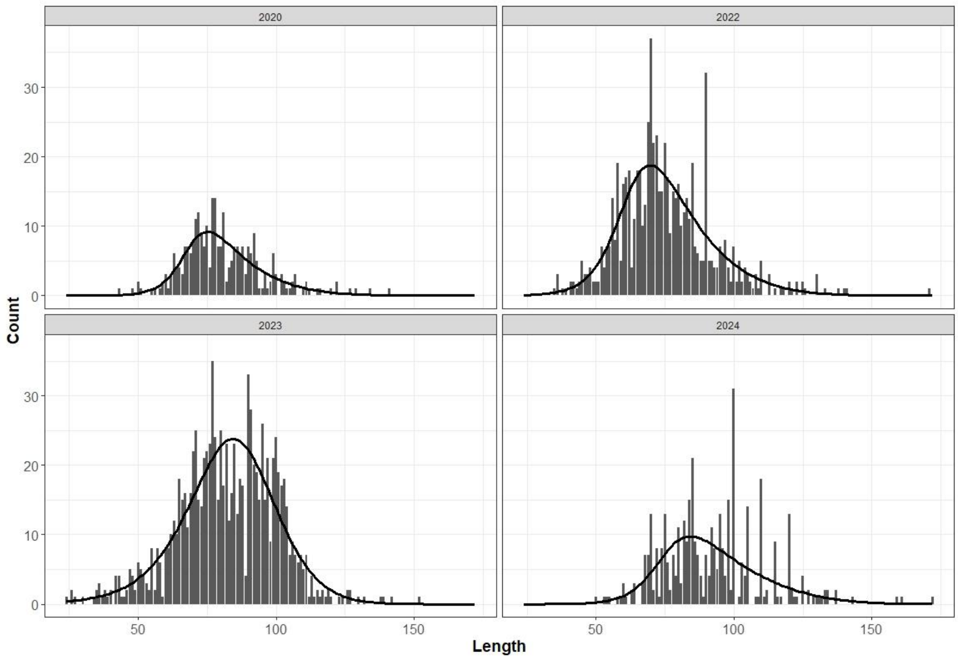


Figure 3.6 – LBSPR results: Fitting of the observed length-frequency distributions in the years 2020, 2022, 2023 and 2024 for the spiny lobster in Asinara MPA.

3.4 Conclusions

This chapter details the assessment conducted on the spiny lobster stock within the Asinara Island Marine Protected Area (MPA). Although this analysis represents a preliminary stage, it marks the first instance since the MPA's establishment in 2002 that the status of its resources has been evaluated through a stock assessment model.

Indeed, the findings presented in this chapter, derived from the utilization of data collected under the MPA's monitoring program and their integration with biological information sourced from scientific literature, have proven instrumental in gauging the effectiveness of the implemented spatial management measures aimed at stock recovery.

Over the four years of monitoring, the application of LBSPR method, a data-poor approach particularly valuable in contexts with limited detailed fisheries information, revealed that the spawning potential ratio of the spiny lobster stock remains significantly below the established reference level considered sustainable. This indicates a state of high overexploitation, primarily attributed to a size at first capture that is smaller than the size at first maturity. This condition suggests that the current fishing practices do not allow the stock to adequately regenerate once individuals are harvested.

Notwithstanding the overall picture, an encouraging signal was observed in 2024, characterized by an increase across all analyzed indicators, although they still fall short of the desired reference thresholds. This positive signal necessitates further verification in the coming years through the continued monitoring of this valuable resource, with the aim of confirming a trend reversal and evaluating the long-term impact of the implemented protection measures.

Discussion

Exploitation status of red mullet (Linnaeus, 1758) in Sardinian waters

In fisheries management, timely and robust stock assessments are essential for ensuring the sustainable exploitation of marine resources. When such assessments are absent—particularly for key demersal species that contribute significantly to regional fisheries—the consequences can be severe for both the ecosystem and the socio-economic stability of coastal communities (FAO, 2024).

The primary goal of my PhD research was to enhance understanding of the exploitation status of key species supporting fisheries in Sardinian waters. This involved reviewing the main reports and outputs from Mediterranean stock assessment working groups (GFCM and STECF), with particular focus on identifying species that had not yet been evaluated within the relevant scientific *fora*.

Within this context, *M. barbatus* stock in GSA 11 had never been formally assessed, despite its inclusion in the EU Data Collection Framework since 2002 and the availability of substantial biological and fishery data. This lack of assessment represented a notable gap in the evaluation of demersal fisheries exploited by the Sardinian fleet, which are regularly reviewed by STECF under the Western Mediterranean Multiannual Management Plan (e.g. STECF 2020; STECF 2021a).

One of the primary risks of lacking stock assessments is the undetected overexploitation of a resource. Without accurate estimates of biomass, fishing mortality and recruitment trends, managers are left without the scientific basis needed to implement effective regulations. This can result in excessive fishing pressure that pushes a stock beyond its biological limits. Prolonged overfishing may lead to a stock collapse, from which recovery could take decades—or may never occur—particularly for long-lived, slow-growing demersal species. A collapse not only disrupts the marine ecosystem but also threatens the livelihoods of fishers who depend on the resource, leading to long-term economic and social consequences.

A seminal case is represented by the collapse of the Atlantic cod in Newfoundland (Canada) in the early 1990s, due to the intense industrial fishing throughout the 20th century, combined with mismanagement and overestimation of stock size. This is considered as one of the most dramatic stock collapses in history. The Canadian government imposed a moratorium in 1992, putting over 30,000 people out of work. Moreover, cod populations have still not fully recovered more than 30 years later (Hutchings and Myers, 1994; Hamilton and Butler, 2001).

On the other hand, the absence of stock assessments may also result in lost opportunities. In cases where a resource is in good condition or underexploited, but not evaluated, precautionary management may limit catches unnecessarily. This leads to underutilization of available resources, reducing the economic potential of fisheries and possibly leading to the misallocation of effort toward other, more vulnerable species.

The North Sea plaice (*Pleuronectes platessa*) is a notable example of a demersal stock that, after decades of overexploitation, underwent a strong recovery due to the implementation of precautionary management strategies, including Total Allowable Catches (TACs), effort controls and technical measures such as increased mesh sizes. By the mid-2010s, scientific advice from ICES indicated that the plaice stock had reached levels above B_{MSY}. However, despite the positive stock status, catch opportunities remained relatively restricted due to cautious quota increases and the species being managed in a mixed fishery with North Sea sole, which was slower to recover. This led to several years of underutilization, where fleets were unable to fully exploit the sustainable yield of plaice, representing a case of lost fishing opportunities driven by cross-stock management constraints and lagging policy adaptation (Bogaards et al. 2007).

This situation illustrates how underexploitation, often rooted in conservative management or technical mismatches, can delay the full realization of socio-economic benefits even when biological sustainability is achieved.

Another case of possible loss of fishing opportunities is represented by the Small-scale coastal fisheries (SSCF) in the Mediterranean. Characterized by multi-gear, multi-species and often seasonal operations, SSCF target a wide variety of demersal and small pelagic species, typically within a few nautical miles from shore. Despite their importance, many of these fisheries remain underassessed and underregulated, particularly for low-commercial or data-poor species (GFCM, 2020). This data deficiency has led to uncertain stock status and often overly precautionary measures, which in turn result in lost fishing opportunities, especially where resilient or underexploited species are not properly managed. At the same time, SSCF face increasing challenges such as competition with industrial fleets, climate change and the degradation of critical coastal habitats (Tsikliras et al., 2015). Strengthening data collection, participatory governance, and tailored management plans for SSCF is essential to unlock their full potential while ensuring ecological sustainability and socio-economic resilience.

In Sardinia, the small-scale coastal fleet plays a vital role in the regional fisheries sector, both economically and culturally. Representing the majority of active vessels on the island, these artisanal fisheries are primarily family-run and operate with low-impact gear such as gillnets, trammel nets, longlines and traps, typically within a few nautical miles of the coast. The fleet targets a wide range of demersal and benthic species, including octopus, spiny lobster, cuttlefish, red mullet and seabreams, reflecting the island's ecological diversity and seasonal dynamics (DCF data). Beyond their direct economic contribution, small-scale fisheries in Sardinia are deeply embedded in local coastal communities, often forming the basis for food security, cultural identity and tourism-related activities such as pescatourism. However, they face growing challenges, including competition for space with industrial fleets, declining access to certain resources, and limited representation in decision-making processes. Recent management efforts—such as co-management experiments, marine protected areas (e.g., Asinara), and the inclusion of SSCF in EU and GFCM frameworks—highlight a shift toward more inclusive and sustainable governance (GFCM, 2020; GFCM, 2022).

It should be noticed that in the specific case of Western Mediterranean Sea MAP, some specific measures – catch limits of hake- have been defined also for the small-scale fleet to reduce the fishing mortality rate on

European hake that is the main target of MAP. Indeed the Council Regulation (EU) 2025/219 established a maximum catch limit of European hake for Union fishing vessels using gillnets and trammel in Union waters of the Western Mediterranean Sea (GSAs 8, 9, 10 and 11) for 2025 equal to 261 tons, corresponding to a reduction of 15% respect to the 2023 Italian landing of hake in GSAs 8, 9, 10 and 11. Thus, it is expected a further reduction of the fishing mortality also for red mullet stocks in Western Mediterranean Italian GSAs, leading to a further deterioration of the economic performance of the small-scale fleets operating in the area.

Failing to recognize the sustainable yield of a healthy stock can restrict income for the fishing sector and limit the development of value-added activities along the supply chain.

As fisheries management plans increasingly adopt measures to reduce fishing effort and limit catches—particularly to rebuild overexploited stocks—it becomes essential to introduce new, sustainable fishing opportunities that can help mitigate the socio-economic impacts of these restrictions. In the context of the Western Mediterranean Multiannual Management Plan (EU Regulation 2019/1022), significant effort reductions have been implemented to protect demersal stocks such as hake. However, without providing viable alternatives, these restrictions risk eroding the economic viability of coastal fisheries (STECF, 2021b).

The stock assessment of red mullet in GSA 11 carried out during my PhD thesis highlights the possibility to compensate the losses due to effort reduction and catch limits, both for trawlers and small-scale fleets, while providing new fishing opportunities on red mullet stock.

Introducing new fishing opportunities—such as targeting underexploited or resilient species, allowing low-impact gears in restricted areas, or enabling seasonal diversification—can improve stakeholder acceptance, enhance food security and ensure the continuity of traditional fisheries. By aligning new fishing opportunities with ecological sustainability and local socioeconomic needs, management plans can balance resource conservation with livelihood resilience.

In Sardinia, participatory approaches have increasingly been integrated into the management of demersal fisheries, especially within Marine Protected Areas (MPAs). A prominent example is the Asinara MPA, where local fishers, scientists and park managers have engaged in co-management processes to define spatial restrictions, seasonal closures, and sustainable catch. These collaborative efforts have led to enhanced compliance, recovery of key resources and increased stakeholder trust (Follesa et al., 2009; GFCM, 2021). This highlights how participatory governance can strengthen the ecological and economic sustainability of demersal fisheries in Mediterranean contexts, particularly where small-scale fisheries are central to coastal livelihoods.

The results achieved in the red mullet stock assessment in GSA 11 presented in chapter 1 are in agreement with the status of the red mullet stocks in Tyrrhenian Sea (GSA 9 and 10) that are evaluated as sustainable exploited (https://www.fao.org/gfcm/data/safs/fr/). The decrease in the fishing mortality estimated by the XSA model is also in line with the decrease in the fishing opportunities set by the Western Mediterranean MAP for Sardinian fleets in terms of fishing days (European Union, 2019). The achievement of $F_{0.1}$ for the red mullet stock in 2021 has been favored by the faster growth rate of the red mullet respect to hake that allowed to achieve the reference point in less than one species lifespan.

One of the key limitations of the stock assessment presented in chapter 1 lies in the use of a single method to estimate natural mortality, which, although widely applied, introduces a degree of uncertainty that may affect the robustness of the stock assessment results. Natural mortality is a fundamental parameter in age-structured models, yet it is not directly observable and often estimated indirectly through empirical relationships based on life-history traits. Relying on a single model may overlook the variability and uncertainty inherent in M estimation, especially given the potential differences in growth, habitat, and environmental pressures across stocks or regions. Future studies could utilize a more comprehensive approach—such as taking the average of multiple natural mortality assumptions (e.g., Pauly, Hoenig, Gislason, and Chen & Watanabe) or conducting a sensitivity analysis to explore how different M values influence key outputs—could enhance the credibility and transparency of the assessment. The CAPAM Workshop on Natural Mortality (Hamel et al., 2023) emphasized the critical importance of evaluating M uncertainty and recommended ensemble approaches or sensitivity testing as standard practice in stock assessment. Incorporating this variability would not only improve the reliability of model predictions but also strengthen the scientific basis for management advice.

Another limitation of this research is the absence of biomass reference points (such as B_{MSY}, B_{lim}, or B_{pa}) and the lack of short-term forecast scenarios, which constrains the ability to fully evaluate the status of the assessed stocks in relation to key conservation and management thresholds (ICES, 2021). This gap limits the direct integration of the results into harvest control rules (HCRs) or multiannual management frameworks, which often rely on biomass-based indicators for adaptive regulation (EU, 2019) for exploring expected stock trajectories under varying exploitation levels and management strategies (Hilborn & Walters, 1992).

However, it should be considered that after the 2021 (reference year of the assessment) further effort reductions to trawlers have been applied by the MAP, thus, it is expected that the fishing mortality is currently well below the reference point, stabilizing further the underexploitation of the stock and enhancing the biomass level.

A refining for the stock assessment carried out in chapter 1 could be to estimate the biomass reference point assuming a constant recruitment to verifying the biomass status respect to reference points.

Another important limitation concerns the application of only a single stock assessment method; while the chosen approach provides useful outputs, it does not allow for cross-validation or the quantification of structural uncertainty. The implementation of Statistical Catch-at-Age (SCAA) models represents a logical further development. These models offer enhanced flexibility, incorporate observation and process error, and enable the integration of various data types within a likelihood-based framework, ultimately improving the reliability and management relevance of assessments (Methot & Wetzel, 2013; Maunder & Punt, 2013).

Take home message

This PhD thesis addressed a major gap in Mediterranean fisheries science by delivering the first formal stock assessment of red mullet in GSA 11. Despite its economic importance and available data, the species had remained unassessed, exposing risks of overfishing or underutilization. The results reveal sustainable opportunities even under management restrictions. Small-scale coastal fisheries, central to Sardinia's economy and culture, require tailored strategies and better integration into policy frameworks. Strengthening science-based management is key to aligning conservation goals with socio-economic resilience in coastal communities.

Exploitation status of two C. rubrum sub-populations in Sardinian waters

Within the principal objective of my PhD, that was to enhance the understanding of the status of commercial resources in Sardinian waters, there was the evaluation of the status of one of the iconic resources of the Sardinian fishery, the precious red coral. This discussion critically evaluates the status of Sardinian red coral resources, addressing the limitations of traditional stock assessment methods through the application of data-poor models and providing novel insights into the species' population dynamics and management implications.

This longevous, sciaphilous and sessile octocoral exhibits crucial life-history characteristics—slow growth rate, late sexual maturity, and a potential lifespan exceeding a century (Garrabou and Harmelin, 2002; Marschal et al., 2004)—that necessitate careful consideration in exploitation status evaluations using stock assessment models.

While previous studies have applied stock assessment models to experimental data, including the Yield per recruit models (Tsounis et al., 2007) and the Leslie-Lewis tables by length (Hughes, 1984; Santangelo et al., 2007, Bramanti et al., 2009), these works often suffered from limitations inherent in their reliance on the steady-state hypothesis. Given the potential for this octocoral to live over 100 years, assessments based on data spanning only eight young age classes inherently lacked information on a significant portion of the population, particularly the more fecund and economically valuable older individuals.

Based on the comprehensive literature review conducted during this PhD, traditional age-structured stock assessment models, such as Yield per Recruit (YPR), are deemed unsuitable for accurately evaluating red coral populations due to several inherent ecological and methodological constraints.

Firstly, the sessile nature of red coral violates the fundamental dynamic pool assumption outlined by Caddy (1995), which presupposes a uniform distribution of both the resource and fishing effort. In contrast, red coral exhibits a spatially heterogeneous distribution, and fishing effort is not uniformly distributed across its habitat. Furthermore, red coral populations cannot be treated as single, well-mixed units, as is often assumed for demersal species. The limited dispersal capacity and strong site fidelity prevent the kind of mixing that would make the entire stock equally accessible to fishing gear.

Previous applications of Leslie-Lewis matrix models based on length were also constrained by the incomplete representation of the species' full size range and lifespan in the available data, thus compromising the reliability of these models.

This PhD research addressed these limitations by employing a new generation of data-poor models (Carruthers et al., 2014), specifically designed for stock assessment when data are sparse or when species characteristics hinder traditional cohort tracking.

Three distinct models were applied to data from the two study areas: (1) two global production models, CMSY (data-poor) and SPiCT (data-moderate), to capitalize on the approximately 30-year landing time series; and (2) one length-based data-poor model (LBSPR) to utilize the basal diameter frequency distributions collected over eight years under the Autonomous Region of Sardinia's monitoring programs.

To implement the length-based model, growth and natural mortality parameters were reviewed in the context of existing literature and integrated with new, unpublished age readings. This allowed for the estimation of two distinct growth models for the two populations. Although the growth models are not statistically different, the observed basal diameter and height size-frequency distributions indicate distinct morphologies between the two populations. Colonies from northern waters exhibited smaller heights compared to those from the north-western region. This disparity could be attributed to the differing wind patterns and hydrodynamic regimes characteristic of the two areas, potentially influencing growth morphology. Specifically, colonies in northern Sardinia tended to be more compact, whereas those along the north-western coast displayed a more elongated and slender morphology. The availability of age data allowed to better inspect the growth process.

The linear model is commonly used in literature to describe the coral growth (e.g. Sherwood and Edinger, 2008; Sinclair et al., 2011; Farmer et al., 2015) and was demonstrated to return better performances across different growth functions for deep corals (Carbonara et al. submitted). The estimation of the growth rate, consistent with the findings from other studies in Western Mediterranean (Garrabou and Harmelin, 2002; Gallmetzer et al., 2010), allowed us to derive the exponential rate of approach (K) to the asymptotic basal diameter, a key parameter for estimating natural mortality rates using life-history trait-based methods. Although the aged colonies in our samples ranged from 5.8 to 12.7 mm in basal diameter, corresponding to an age range of 16-47 years, the observation of larger colonies (38-41 mm basal diameter), present only in historical collections (with a maximum of 45 mm observed in the private Cap de Creus collection by Garrabou and Harmelin, 2002) provided crucial information on the species' growth potential.

These data, collected during on-board monitoring programs, were used to derive a proxy for the asymptotic basal diameter, which was then integrated with the K value derived from age readings. The age data demonstrated a higher growth rate in the North-western colonies. The difference on morphological features of the two populations led us to treat the two areas separately. This differentiation allowed us to account for the spatial patchy distribution of the resource.

Leveraging the availability of a relatively long landing time series and comprehensive data on the annual number of fishing authorizations, which enabled the derivation of a CPUE time series, we applied two widely used global production models: CMSY and SPiCT. These models are commonly employed in stock assessment working groups within ICES, STECF and GFCM. Bouch et al. (2021) conducted a comparative analysis of these two models using data-rich stock assessments from ICES working groups. Their findings indicated that CMSY tends to overestimate relative fishing mortality and underestimate relative stock biomass, while SPiCT exhibits the opposite trend. They also noted that CMSY assessments were less reliable when the default depletion prior deviated from ICES assessments, and while SPiCT assessments showed better correlation with ICES assessments, they often failed to accurately estimate the scale of F/F_{MSY} or B/B_{MSY}.

To mitigate these issues, we not only applied both models but also, but we tested a range of depletion and resilience scenarios in CMSY and set a medium depletion hypothesis in SPiCT at the beginning of the time series, aligning with the CMSY scenarios that yielded the best diagnostics and retrospectives.

The two models, CMSY and SPiCT, yielded highly consistent results for both study areas, indicating a more favorable stock status in North-western waters compared to Northern waters. Specifically, while the biomass of both stocks is below the reference level, the North-western red coral is exploited below F_{MSY}, whereas the Northern stock is exploited above F_{MSY}. This finding is also consistent with the LBSPR results, which showed a lower Spawning Potential Ratio in Northern waters.

Furthermore, this PhD thesis provides practical insights for the management of the resource in Sardinia. Indeed, through LBSPR method, it was possible to evaluate the effectiveness of the current minimum conservation reference size (MCRS) established at GFCM level (7 mm, Recommendation GFCM/43/2019/4) and alternative MCRS (8-15 mm basal diameter) with respect to different fishing pressure levels. Our findings demonstrate that the current MCRS is insufficient to ensure sustainable exploitation of the stock in the two areas analysed. To achieve sustainable exploitation in North-western Sardinian waters with the current fishing effort, an increase in the MCRS to 15 mm basal diameter would be necessary. Alternatively, a reduction of the MCRS to 14 mm combined with a 20% reduction in fishing effort, or a reduction of the MCRS to 12 mm with a 40% effort reduction, are also proposed. In Northern waters, although the current SPR is lower than in North-western waters, the fishing pressure is also lower; this determine that, it would be necessary to increase the MCRS to 13 mm under the current fishing pressure, or alternatively, to increase the MCRS to 12 mm and reduce fishing effort by 25%. However, the samples by basal diameter available in this area are limited to data from 2012, therefore, the stock status in this sub-area since 2012 may have changed. Ongoing research projects initiated by the Autonomous Sardinian Region will help to assess the stock status in this sub-area.

The findings of this PhD work on red coral highlight the crucial role of basal diameter frequency distributions, obtained through data collection at landing sites and on board as part of the monitoring program launched by the Autonomous Region of Sardinia (Carugati et al., 2020), in facilitating the integration of global production models with the length-based Spawning Potential Ratio method. Data collected by the monitoring on board were particularly valuable for the detection of larger colonies, which are often underrepresented in the samples collected at landing site.

A promising avenue for future research would be the ageing of the biggest colonies with radiocarbon techniques, that has proven more effective in dating bigger colonies (Carbonara et al., submitted) for other coral genus; indeed, in those cases, the age reading based on bands counting challenges the reliability in the presence, periodicity and reproducibility of results.

During this PhD research, we also had the opportunity to apply LBSPR model in other areas (Croatia, Corsica, Greece) in the context of the GFCM Red Coral program. In these applications, the life history parameters estimated for Sardinia were used, due to the lack of available data. Based on our research, which was designed to account for the local specificities of the populations and fisheries, it would be advisable to estimate population-specific life-history parameters.

Several limitations of the red coral stock assessment results warrant highlighting. As emphasized by the GFCM WGSAD 2024 (GFCM 2024), there is the need to better explore the suitability of employing a Maximum Sustainable Yield (MSY) strategy for harvesting this resource, given its very low intrinsic rate of population increase. Indeed, Therefore, caution is advised in using surplus production assessment models (SPICT, CMSY) for monitoring stock status and evaluating management strategies over short-term cycles. The extended time lag between management interventions and observable population responses (potentially spanning decades) is likely to impede the reliability of surplus production models in accurately estimating productivity and surplus yield from aggregated catch and nominal effort data. Consequently, the WGSAD proposed that a more in-depth evaluation of approaches for providing assessment and management advice on red coral would necessitate a dedicated specialist group, lacking the necessary capacity and expertise to support the development of a tailored, adaptive management framework (e.g., based on rational harvesting combined with monitoring of individual colonies' reproductive potential).

Another limitation is that global production models rely heavily on the assumption that the nominal CPUE is proportional to abundance, without standardization for confounding factors (area, depth, season and fishing tactics) that can all bias the abundance trend. To ensure the informativeness of CPUE data regarding abundance trends, a further development of this work involves conducting plausibility checks to assess whether sustained periods of increasing CPUE fall within the expected range of the maximum population growth potential.

A general direction for future research to enhance the reliability of red coral assessments, is evaluating the generation of abundance data through dedicated ROV surveys to obtain fishery-independent tuning indices to be used in the assessment.

A final objective of my PhD was to provide a quantitative socio-economic evaluation of the impact of a range of management measures on the fishery. However, although several socio-economic data were collected under the GFCM Red Coral research program, due to time constraints it was not feasible to parameterize the BEMTOOL bio-economic model (Rossetto et al. 2015; Russo, Bitetto et al., 2017) for this purpose. Therefore, a future direction for this research, involves the socio-economic evaluation of alternative combination of MCRS and fishing mortality levels, integrating the stock assessment results obtained in this PhD into BEMTOOL, as already done in the context of the Western Mediterranean MAP on demersal fisheries since many years (STECF, 2021b, 2022 and 2023).

Take home message

This PhD thesis addressed a major gap in Mediterranean fisheries science, applying data-poor and intermediate assessment models (CMSY, SPiCT, LBSPR) to **evaluate the status of red coral in Sardinian waters**, while addressing the limitations of traditional age-structured models for long-lived, sessile species.

This represent the **first validated assessment in Mediterranean Sea** for red coral.

The study identified clear biological and exploitation differences between **northern and north-western** populations, supported by **distinct morphology**.

Using long-term landings, CPUE, and basal diameter data, area-specific growth models were developed, revealing **unsustainable exploitation under the current 7 mm MCRS**. Alternative MCRS and effort reduction scenarios were proposed to achieve sustainability, tailored to each area's dynamics.

The integration of **onboard monitoring** and age data proved crucial for capturing older colonies and improving model reliability.

Future improvements include **standardizing CPUE**, **implementing ROV surveys**, and using **radiocarbon ageing** for better precision.

This work offers a **scientific foundation for adaptive and area-specific management**.

Exploitation status of spiny lobster in Asinara MPA

The establishment of Marine Protected Areas (MPAs) represents a cornerstone strategy for the conservation of marine biodiversity and the sustainable management of fisheries resources (Gaines et al., 2010). Within this framework, a fundamental yet often challenging aspect is the rigorous evaluation of the resources targeted for protection and the subsequent verification of the MPA's effectiveness in achieving its conservation objectives (García-Charton et al., 2008). This study addresses this critical need by presenting the first stock assessment of the spiny lobster (*P. elephas*) population within the Asinara Island MPA since its establishment in 2002. The findings, derived from the application of a data-poor stock assessment model over four years of monitoring, provide crucial initial insights into the status of this ecologically and economically valuable species within this protected area.

The importance of evaluating the resources within MPAs cannot be overstated. MPAs are often implemented with the explicit goal of promoting the recovery and long-term sustainability of specific species or habitats (Halpern et al., 2009). Without robust assessments, it remains difficult to ascertain whether the implemented management measures are indeed yielding the desired outcomes. Baseline assessments and subsequent monitoring are essential to establish a benchmark against which future changes can be measured and to provide evidence-based feedback on the efficacy of the MPA's design and regulations (Vandeperre et al., 2011). Chapter 3 contributes directly to this need by providing the first quantitative evaluation of the spiny lobster stock within the Asinara Island MPA, offering a crucial starting point for future monitoring and adaptive management strategies.

Despite the ecological and economic significance of the spiny lobster across the Mediterranean Sea, comprehensive stock assessments for this resource remain relatively scarce. Much of the available information often pertains to localized studies or focuses on specific aspects of its biology and ecology. A notable study by Santos et al. (2022) conducted off the Azores archipelago utilized a yield-per-recruit assessment to evaluate the status of the European spiny lobster. Their findings highlighted a state of overexploitation, largely attributed to fishing pressure impacting the reproductive potential of the stock.

The application of the Length-Based Spawning Potential Ratio (LBSPR) method revealed that the spawning potential ratio of the spiny lobster stock within and around the MPA is significantly below the established reference level, indicative of a state of high overexploitation. A key factor contributing to this situation appears to be the size at first capture being consistently smaller than the size at first maturity. This mismatch implies that a significant proportion of the spiny lobster population is being harvested before individuals have had the opportunity to reproduce, thereby hindering the stock's ability to recover and maintain a healthy reproductive output. This finding aligns with general concerns regarding size-selective fishing and its detrimental impacts on the reproductive capacity of lobster populations (Santos et al. 2022).

It is crucial to underscore that this work represents a significant advancement in our understanding of the spiny lobster status in the Sardinian context. To the best of our knowledge, this study constitutes the first documented stock assessment of *P. elephas* conducted in the waters surrounding Sardinia. Furthermore, within the specific context of the Asinara Island MPA, this research marks the first quantitative evaluation of the effectiveness of this protected area in safeguarding its spiny lobster resources since its establishment. This baseline assessment provides essential information for future comparisons and for evaluating the long-term impact of the MPA's management strategies on this valuable species. The initial positive signal observed in 2024, with an increase in all indicators, warrants careful attention and continued monitoring to ascertain whether this trend signifies a genuine recovery or merely reflects inter-annual variability.

Looking towards future research and the refinement of our understanding, several avenues for further development emerge. The current assessment relied on a data-poor method (LBSPR) due to the limited temporal extent of the monitoring data. As the MPA's monitoring program continues to accumulate more years of data on the size structure of the spiny lobster population, it will become feasible to apply more data-intensive stock assessment methodologies. These could include age-structured models or surplus production models that incorporate time series of catch and effort data, potentially providing a more nuanced and precise evaluation of the stock's status and trends (Hilborn & Walters, 1992).

Furthermore, the retrieval and analysis of historical and ongoing landing data from fisheries operating within and around Sardinian waters could significantly enhance our understanding of the broader impact of the Asinara Island MPA. Integrating such data with spatial information on fishing effort could enable the application of global production models at a wider spatial scale, encompassing not only the MPA itself but also the surrounding fishing grounds. This would allow for a more comprehensive evaluation of the MPA's effectiveness in a regional context, considering potential spillover effects (where increased abundance within the MPA leads to higher catches in adjacent areas, Follesa et al. 2011) and its contribution to the overall sustainability of spiny lobster fisheries in Sardinian waters.

In conclusion, this initial stock assessment of the spiny lobster within the Asinara Island MPA provides critical baseline information on the status of this important resource. The finding of overexploitation, linked to the issue of size at first capture, underscores the need for careful consideration of existing fishing regulations and potential adjustments to ensure the protection of juvenile and pre-reproductive individuals. The study's significance lies in being the first stock assessment for this species in Sardinian waters and the first evaluation of the MPA's effectiveness for spiny lobster conservation. The continued monitoring efforts and the future integration of more extensive data sets, including landing information, will be crucial for refining our understanding of the stock dynamics and for optimizing the management strategies within the Asinara Island MPA and the broader Sardinian fisheries context. This research serves as a vital step towards ensuring the long-term conservation and sustainable utilization of this valuable marine resource.

Take home message

This PhD thesis delivers the **first stock assessment of *P. elephas* within the Asinara Island MPA** since its creation in 2002.

Findings reveal a state of **overexploitation**, with many individuals caught before reaching maturity. Our work establishes a critical baseline for long-term monitoring and adaptive management. It also fills a significant data gap in Sardinian and broader Mediterranean spiny lobster research. Initial **signs of recovery observed in 2024** are **promising** but require ongoing evaluation. The use of LBSPR in a data-poor context proves effective for early assessments. Future work should **integrate more comprehensive models and landing data**. Such approaches will enhance MPA performance evaluation and regional fisheries sustainability.

Concluding remarks

This PhD thesis has significantly enhanced the knowledge of the exploitation status of key marine resources within Sardinian waters, addressing critical gaps in fisheries science and providing essential information for sustainable management.

The research delivered the first formal stock assessment of red mullet in GSA 11, revealing sustainable opportunities for both trawlers and small-scale fleets, even under management restrictions (chapter 1). This study emphasizes the importance of informed stock assessments to prevent overfishing or underutilization and to support the socio-economic resilience of Sardinia's coastal communities.

Furthermore, the thesis provided the first validated assessment of red coral in the Mediterranean Sea, applying data-poor models to overcome the limitations of traditional methods for this long-lived, sessile species. The findings highlighted distinct biological and exploitation differences between northern and north-western populations, demonstrating unsustainable exploitation under the current minimum conservation reference size. The research proposes alternative management scenarios, including adjusted size limits and effort reductions, tailored to each area's dynamics (chapter 2).

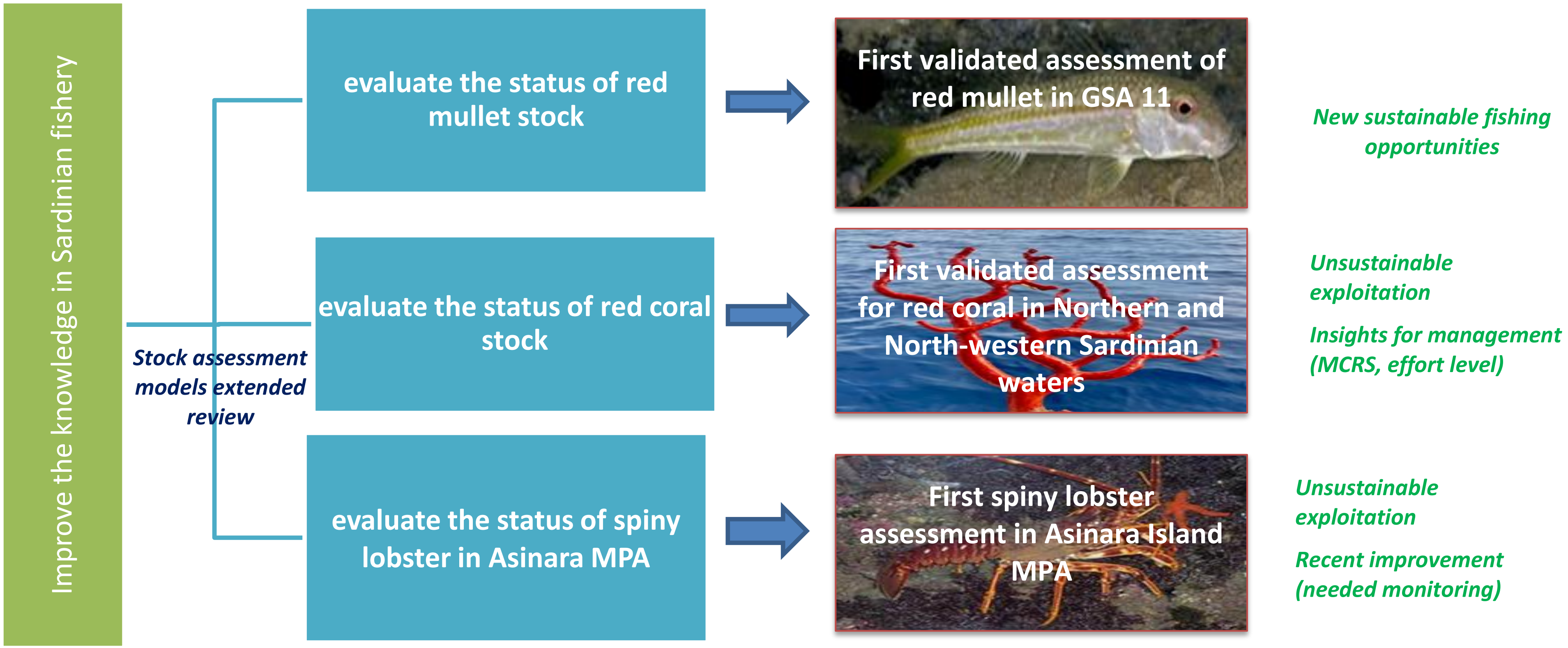
Finally, the study presented the first stock assessment of spiny lobster within the Asinara Island MPA, revealing a state of overexploitation and the urgent need for adjusted size-at-capture regulations to protect the reproductive potential of this valuable resource. This baseline assessment is crucial for long-term monitoring and adaptive management, contributing to both regional fisheries sustainability and MPA performance evaluation (chapter 3).

Looking ahead, future research developments should focus on several key areas. For the red mullet assessment, incorporating a wider range of natural mortality estimation methods, developing biomass reference points and the application of other stock assessment models would enhance the robustness and applicability of the findings. In the context of red coral, future work should prioritize the standardization of

CPUE data, the implementation of ROV surveys to generate fishery-independent abundance indices, and the application of radiocarbon dating techniques to improve the accuracy of age estimations, particularly for larger colonies. Additionally, integrating the stock assessment results into bio-economic models would provide valuable insights into the socio-economic impacts of the proposed alternative management strategies. For the spiny lobster within the Asinara MPA, continued monitoring efforts and the integration of more extensive data sets, including historical landing information and fishing effort data, are essential for refining stock dynamic understanding and optimizing management strategies both within and outside the MPA.

Collectively, this research underscores the necessity of strengthening science-based management and employing appropriate assessment methods to balance conservation goals with the sustainable utilization of marine resources and the resilience of Sardinian coastal communities.

In the following scheme are summarized the achievements of this PhD thesis starting from its objectives.


Improve the knowledge in Sardinian fishery
Stock assessment models extended review
evaluate the status of red mullet stock
evaluate the status of red coral stock
evaluate the status of spiny lobster in Asinara MPA
First validated assessment of red mullet in GSA 11
First validated assessment for red coral in Northern and North-western Sardinian waters
First spiny lobster assessment in Asinara Island MPA
New sustainable fishing opportunities
Unsustainable exploitation
Insights for management (MCRS, effort level)
Unsustainable exploitation
Recent improvement (needed monitoring)

References

Baranov, F. I. (1918). On the question of the biological basis of fisheries. Izvestiya otdela rybovodstva i nauchno-promyslovykh issledovanii, 1(1), 81–128.

Bavestrello, G., Bo, M., Bertolino, M., Betti, F., & Cattaneo-Vietti, R. (2015). Long-term comparison of structure and dynamics of the red coral metapopulation of the Portofino Promontory (Ligurian Sea): a case-study for a Marine Protected Area in the Mediterranean Sea. Marine Ecology, 36(4), 1354-1363.

Bogaards, H., Borges, L., Machiels, M., Kraak, S., & Rijnsdorp, A. (2007). Fisheries-independent estimates of trends in North Sea plaice (Pleuronectesplatessa) abundance: a Bayesian analysis of research vessel survey data.

Books, O., & Books, O. (1999). Impacts of mobile fishing gear: the biodiversity perspective. In American Fisheries Society Symposium (Vol. 22, pp. 31-40).

Bramanti, L., Magagnini, G., De Maio, L., & Santangelo, G. (2005). Recruitment, early survival and growth of the Mediterranean red coral Corallium rubrum (L 1758), a 4-year study. Journal of Experimental Marine Biology and Ecology, 314(1), 69-78.

Bramanti L., Iannelli M., Santangelo G. (2009) Mathematical modelling for conservation and management of gorgonians corals: youngs and olds, could they coexist? Ecological Modelling 220 (2009) 2851–2856.

Bramanti, L., Vielmini, I., Rossi, S., Tsounis, G., Iannelli, M., Cattaneo-Vietti, R., ... & Santangelo, G. (2014). Demographic parameters of two populations of red coral (Corallium rubrum L. 1758) in the North Western Mediterranean. Marine biology, 161, 1015-1026.

Caddy, J.F., & Mahon, R. (1995). Reference points for fisheries management. FAO Fisheries Technical Paper No. 347. Rome: FAO. Retrieved from https://openknowledge.fao.org/items/4fb59221-195f-444f-86cb-574d50ce4aa5

Cadrin, S. X., & Dickey-Collas, M. (2015). Stock assessment methods for sustainable fisheries. ICES Journal of Marine Science, 72(1), 1–6.

Cannas, R., F. Caocci, M. C. Follesa, E. Grazioli, C. Pedoni, P. Pesci, F. Sacco & A. Cau, 2010. Multidisciplinary data on the status of red coral (Corallium rubrum) resource in Sardinian seas (central western Mediterranean). In Bussoletti, E., D. Cottingham, A. Bruckner, G. Roberts & R. Sandulli (eds), Proceedings of the International Workshop on Red Coral Science, Management, and Trade: Lessons from the Mediterranean NOAA Technical Memorandum CRCP-13. NOAA, Silver Springs, MD: 40–57.

Carbonara, P., Intini, S., Modugno, E., Maradonna, F., Spedicato, M. T., Lembo, G., ... & Carnevali, O. (2015). Reproductive biology characteristics of red mullet (Mullus barbatus L., 1758) in Southern Adriatic Sea and management implications. Aquatic Living Resources, 28(1), 21-31.

Carbonara, P., Intini, S., Kolitari, J., Joksimović, A., Milone, N., Lembo, G., ... & Sion, L. (2018). A holistic approach to the age validation of Mullus barbatus L., 1758 in the Southern Adriatic Sea (Central Mediterranean). Scientific Reports, 8(1), 13219.

Carbonara, P., & Follesa, M. C. (Eds.). (2019). Handbook on Fish Age Determination: A Mediterranean Experience. Studies and Reviews No. 98. Rome: FAO.

Carbonara P., Chimienti G., Bellodi A., Bakiu R., Bitetto I., Calcagnile L., D'Elia M., Follesa M. C., Morello E. B., Nastasi A., Palmisano M., Zupa W., Quarta G. Age and growth of bamboo coral Isidella elongata (Esper, 1788): a Mediterranean Vulnerable Marine Ecosystem indicator taxa. (submitted)

Carruthers, T. R., Punt, A. E., Walters, C. J., et al. (2014). Evaluating methods for setting catch limits in data-limited fisheries. Fisheries Research, 153, 48–68.

Carugati, L., Cau, A., Follesa, M. C., Melis, R., Moccia, D., Porcu, C., Salvadori, S., & Cannas, R. (2020). Onboard Scientific Observers Provide a Realistic Picture of Harvesting and Management Priorities for the Precious Red Coral (Corallium rubrum L.). Frontiers in Marine Science, 7, 482.

Cattaneo-Vietti, R., Bavestrello, G., Bo, M., Canese, S., Vigo, A., and Andaloro, F. (2017). Illegal ingegno fishery and conservation of deep red coral banks in the Sicily channel (Mediterranean Sea). Aquat. Conservation: Mar. Freshw. Ecosyst. 27 (3), 604–616. doi: 10.1002/aqc.2731

Cattaneo-Vietti, R., Bo, M., Cannas, R., Cau, A., Follesa, C., Meliadò, E., ... & Bavestrello, G. (2016). An overexploited Italian treasure: past and present distribution and exploitation of the precious red coral Corallium rubrum (L., 1758)(Cnidaria: Anthozoa). Italian Journal of Zoology, 83(4), 443-455. doi: 10.1080/11250003.2016.1255788

Cau, A., Paliaga, E. M., Cannas, R., Deiana, G., Follesa, M. C., Sacco, F., ... & Orru, P. E. (2015a). Preliminary data on habitat characterization relevance for red coral conservation and management. Italian Journal of Geosciences, 134(1), 60-68.

Chen, S., & Watanabe, S. (1989). Age dependence of natural mortality coefficient in fish population dynamics. Nippon Suisan Gakkaishi (Japanese Journal of Fisheries Science), 55(2), 205–208.

Clark, William G. (2002). "F 35% revisited ten years later." North American Journal of Fisheries Management 22.1: 251-257.

Cochran, W. G. (1953). Sampling Techniques. New York: John Wiley & Sons.

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Ben Rais Lasram, F., Aguzzi, J., ... & Voultsiadou, E. (2010). The biodiversity of the Mediterranean Sea: estimates, patterns, and threats. PloS one, 5(8), e11842.

Community Fleet Register- European Commission. Retrieved from https://webgate.ec.europa.eu/fleet-europa/index_en;jsessionid=ToZpLA_fsbZZMSSvIeMCoEszROYlARwz1-LDf307rc4wYekR1yml!-9922059 , consulted at 16/04/2025.

CREA (2021) - Annuario dell'Agricoltura italiana 2019, vol. LXXIII, in www.crea.gov.it/documents/68457/0/Annuario_2019.pdf/6db61aad-9e3f-ab883703-aae67ed29f9c?t=1622045006635

Dieter, B. E., Wion, D. A., & McConnaughey, R. A. (2003). Mobile fishing gear effects on benthic habitats: a bibliography. NOAA Technical Memorandum NMFS AFSC, (135), 216.

Dick, E. J., & MacCall, A. D. (2011). Depletion-Based Stock Reduction Analysis: A catch-based method for determining sustainable yields for data-poor fish stocks. Fisheries Research, 110(2), 331–341.

Espinosa, F., Ostalé-Valriberas, E., Maestre, M., González, A. R., Ouerghi, A., Sghaier, Y. R., & Bazairi, H. (2019). Sighting of a red coral [Corallium rubrum (Linnaeus, 1758)] population living at Gibraltar Strait. Regional Studies in Marine Science, 29, 100641.

European Commission. 2010. Commission decision of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters. Official Journal of the European Union L 232:14.

European Parliament, Council of the European Union. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for Community action in the field of marine environmental policy (Marine Strategy Framework Directive). Official Journal of the European Union L 164:19.

European Union. (2013). Regulation (EU) No 1380/2013 of the European Parliament and of the Council on the Common Fisheries Policy.

European Union, 2017. Commission Implementing Decision (EU) 2016/1251 on the DCF.

European Union. (2019). Regulation (EU) 2019/1022 of the European Parliament and of the Council of 20 June 2019 establishing a multiannual plan for the fisheries exploiting demersal stocks in the western Mediterranean Sea. Official Journal of the European Union.

Fadragas, O. M., & Stefánsson, G. (2005). Assessment of the Spiny Lobster (Panulirus argus, Latreille, 1804) in Northeastern Cuban Waters. [Unpublished manuscript]. United Nations University Fisheries Training Programme.

FAO (2009). International Guidelines for the Management of Deep-Sea Fisheries in the High Seas. Rome, Italy, https://openknowledge.fao.org/items/c552376c-a207-46a1-a49a-91a79c213989

FAO (2020). The State of World Fisheries and Aquaculture 2020. https://openknowledge.fao.org/server/api/core/bitstreams/170b89c1-7946-4f4d-914a-fc56e54769de/content

FAO (2024). The State of World Fisheries and Aquaculture 2024. Food and Agriculture Organization of the United Nations. http://openknowledge.fao.org/items/06690fd0-d133-424c-9673-1849e414543d

FAO (2022). The State of World Fisheries and Aquaculture 2022. Food and Agriculture Organization of the United Nations. https://www.fao.org/3/cc0461en/cc0461en.pdf

Follesa, M.C., Cuccu D., Cannas R., Sabatini A., Cau A., 2007a. Emigration and retention of Palinurus elephas (Fabricius, 1787) in a central western Mediterranean marine protected area. Scientia Marina 71, 279–285.

Follesa, M. C., Cuccu, D., Cannas, R., & Cau, A. (2007b). On the growth of the European spiny lobster, Palinurus elephas from Sardinian waters (central western Mediterranean Sea). New Zealand Journal of Marine and Freshwater Research, 41(4), 377-383.

Follesa, M. C., Cuccu, D., Cannas, R., Sabatini, A., Deiana, A. M., & Cau, A. (2009). Movement patterns of the spiny lobster Palinurus elephas (Fabricius, 1787) from a central western Mediterranean protected area. Scientia Marina, 73(3), 499–506.

Follesa, M.C., Cannas R., Cau Al., Cuccu D., Gastoni A., Ortu A., Pedoni C., Porcu C., Cau A. 2011. Spillover effects of a Mediterranean marine protected area on the European spiny lobster Palinurus elephas resource. Aquatic Conservation Marine Freshwater Ecosystem 21, 564–572.

Follesa, M. C. (2012). La duplice valenza delle aree di ripopolamento attivo di Palinurus elephas: utili siti di sperimentazione e potenti strumenti gestionali (Doctoral dissertation, Universita'degli Studi di Cagliari).

Follesa M.C., Cannas R., Pedoni C., Pesci P., Cau A. (2013). Deep water red coral from the island of Sardinia (north-western Mediterranean): a local example of sustainable management. Marine and freshwaters research 64(8):706-715. (DOI: 10.1071/MF12235; ISSN: 13231650)

Follesa, M.C., & Carbonara, P. (Eds.). (2019). Atlas of the maturity stages of Mediterranean fishery resources. FAO. Rome. 268 pp.

Froese, R., Winker, H., Gascuel, D., Sumaila, U. R., & Pauly, D. (2016). Minimizing the impact of fishing. Fish and fisheries, 17(3), 785-802.

Froese, R., Demirel, N., Coro, G., Kleisner, K., & Winker, H. (2017). Estimating fisheries reference points from catch and resilience. Fish and Fisheries, 18(3), 506–526.

Froese R, Winker H, Coro G, Palomares M-L, Tsikliras AC, Dimarchopoulou D, Touloumis K, Demirel N, Vianna GMS, Scarcella G, Schijns R, Liang C, Pauly D (2023). New developments in the analysis of catch time series as the basis for fish stock assessments: The CMSY++ method. Acta Ichthyologica et Piscatoria, 53, 173–189. https://doi.org/10.3897/aiep.53.105910

Gaines, S. D., White, C., Carr, M. H., & Palumbi, S. R. (2010). Designing marine reserve networks for both conservation and fisheries management. Proceedings of the National Academy of Sciences, 107(43), 18286-18293.

Gallmetzer, I., Haselmair, A., & Velimirov, B. (2010). Slow growth and early sexual maturity: bane and boon for the red coral Corallium rubrum. Estuarine, Coastal and Shelf Science, 90(1), 1-10.

García-Charton, J. A., Pérez-Ruzafa, A., Marcos, C., Claudet, J., Badalamenti, F., Benedetti-Cecchi, L., ... & Planes, S. (2008). Effectiveness of European Atlanto-Mediterranean MPAs: Do they accomplish the expected effects on populations, communities and ecosystems?. Journal for Nature Conservation, 16(4), 193-221.

Garrabou J, Harmelin G. 2002. A 20-year study on life-history traits of a harvested long-lived temperate coral in the NW Mediterranean: insights into conservation and management needs. J Anim Ecol 71:966–78.

Gazale, V., Tarricone, E., Carboni, D., & Messina, G. (2022). Chapter Fishing and territory. Status and perspectives of Sardinia artisanal fisheries. The case of traditional fishery in Asinara Island MPA.

GFCM (2020). The State of Mediterranean and Black Sea Fisheries 2020. FAO. https://openknowledge.fao.org/handle/20.500.14283/cb2429en

GFCM (2022a). The State of Mediterranean and Black Sea Fisheries 2022. FAO. https://openknowledge.fao.org/items/53c4dd52-0c42-464d-bdb5-3a4c7c545fb5

GFCM (2022b) Working Group on Stock Assessment of Demersal species (WGSAD) 17-28 January 2022. Available: https://gfcm.sharepoint.com/:b:/g/EG/EZ7FiUEcRqNNuOS6xnIuHyUB5DFg11jP0B8B633UWm3E4Q

GFCM (2022c) Working Group on Stock Assessment of Demersal species (WGSAD) 12-17 December 2022. Available: https://gfcm.sharepoint.com/:b:/g/EG/EWDhdeu5Sc5Djm0HatRs4-UBfVshM38Xhx4DlMlIXsioZg

GFCM (2023) Working Group on Stock Assessment of Demersal species (WGSAD) 11-16 December 2023. Available: https://gfcm.sharepoint.com/:b:/g/EG/EYPznp_voZ5LhY06qnYfLH4Bv5RH9BRITyOXANtBjFlwQQ

GFCM (2024) Working Group on Stock Assessment of Demersal species (WGSAD) 9-14 December 2023. Available: https://gfcm.sharepoint.com/:b:/g/EG/EcWFk5MJR-JBpOv8GUQ8gBEBjVvM7qZ6J59ZiWqinrjwUg

Gharsalli, M., & Kitakado, T. (2022). Management Strategy Evaluation for the Common Spiny Lobster, Palinurus elephas (Fabricius, 1787), Stock in Tunisia. Asian Fisheries Science, 35(1).

Giannoulaki M., A. Belluscio, F. Colloca, S. Fraschetti, M. Scardi, C. Smith, P. Panayotidis, V. Valavanis M.T. Spedicato (2013) Mediterranean Sensitive Habitats. DG MARE Specific Contract SI2.600741, Final Report, 557 p.

Goñi, R., Reñones, O., & Quetglas, A. (2003). Size at maturity, fecundity and reproductive potential of a protected population of the spiny lobster Palinurus elephas (Fabricius, 1787) from the western Mediterranean. Marine Biology, 143(3), 583–592

Gulland, J.A. (1983). Fish Stock Assessment: A Manual of Basic Methods. FAO/Wiley.

Halpern, B. S., Lester, S. E., & Kellner, J. B. (2009). Spillover from marine reserves and the replenishment of fished stocks. Environmental Conservation, 36(4), 268-276.

Hamel, O. S., Ianelli, J. N., Maunder, M. N., & Punt, A. E. (2023). Natural mortality: Theory, estimation and application in fishery stock assessment models. Fisheries Research, 261, 106638.

Hamilton, L. C., & Butler, M. J. (2001). Outport adaptations: Social indicators through Newfoundland's cod crisis. Human Ecology Review, 8(2), 1–11.

Hilborn, R., & Walters, C. J. (1992). Quantitative Fisheries Stock Assessment: Choice, Dynamics and Uncertainty. Springer.

Hordyk, A. R., Ono, K., Valencia, S. R., Loneragan, N. R., & Prince, J. D. (2015). A novel length-based empirical estimation method of spawning potential ratio (SPR), and tests of its performance, for small-scale, data-poor fisheries. ICES Journal of Marine Science, 72(1), 217–231.

Hughes P. T. (1984) Population Dynamics Based on Individual Size Rather than Age: A General Model with a Reef Coral Example. The American Naturalist: Vol. 123, No. 6.

Hutchings, J. A., & Myers, R. A. (1994). What can be learned from the collapse of a renewable resource? Atlantic cod, Gadus morhua, of Newfoundland and Labrador. Canadian Journal of Fisheries and Aquatic Sciences, 51(9), 2126–2146.

ICES (2005). Working Group on the Assessment of Demersal Stocks in the North Sea and Skagerrak (WGNSSK), 6–15 September 2005, ICES Headquarters, Copenhagen. ICES Document CM 2006/ACFM: 09. 958 pp ICES (2021). General context of ICES advice. ICES Advice 2021, Book 1.https://ices-library.figshare.com/articles/report/General_context_of_ICES_advice/18667649?file=33450299

ICES (2020). Plaice (Pleuronectes platessa) in Subarea 4 (North Sea). ICES Advice. https://ices-library.figshare.com/articles/report/Plaice_Pleuronectes_platessa_in_Subarea_4_North_Sea_and_Subdivision_20_Skagerrak_/18638240?file=33417641

ICES (2024). Benchmark workshop 3 on the development of MSY advice using SPiCT (WKBMSYSPiCT3). ICES Scientific Reports. Report. https://doi.org/10.17895/ices.pub.24998858.v1

IPCC, 2019: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 755 pp. https://doi.org/10.1017/9781009157964.

MacCall, A. D. (2009). Depletion-Corrected Average Catch: A simple formula for estimating sustainable yields in data-poor situations. ICES Journal of Marine Science, 66(10), 2267–2271.

Marschal, C., Garrabou, J., Harmelin, J. G., & Pichon, M. (2004). A new method for measuring growth and age in the precious red coral Corallium rubrum (L.). Coral reefs, 23(3), 423-432.

Martell, S., & Froese, R. (2013). A simple method for estimating MSY from catch and resilience. Fish and Fisheries, 14(4), 504–514.

Maunder, M. N., & Punt, A. E. (2013). A review of integrated analysis in fisheries stock assessment. Fisheries Research, 142, 61–74.Pope, J.G. (1972). An investigation of the accuracy of virtual population analysis using cohort analysis. ICNAF Research Bulletin, 9: 65–74.

Methot, R. D., & Wetzel, C. R. (2013). Stock Synthesis: A biological and statistical framework for fish stock assessment and fishery management. Fisheries Research, 142, 86–99.

Pauly, D., Christensen, V., Guénette, S., et al. (2002). Towards sustainability in world fisheries. Nature, 418(6898), 689–695.

Pedersen, M. W., & Berg, C. W. (2017). A stochastic surplus production model in continuous time (SPiCT). Fish and Fisheries, 18(2), 226–243.

Pope, J.G. (1972). An investigation of the accuracy of virtual population analysis using cohort analysis. International Commission for the Northwest Atlantic Fisheries (ICNAF) Research Bulletin, 9, 65–74.

Porcu C., Follesa M.C., Cannas R., Cau A., Soldovilla G., Pesci P. Cau A. (2017). Reproductive patterns in deep versus shallow populations of the precious Mediterranean gorgonian Corallium rubrum (Linnaeus, 1758) (Sardinia, Central-Western Mediterranean). Medit. Mar. Sci., 18/1, 2017, 64-76

Prager, M. H. (1994). A suite of extensions to a nonequilibrium surplus-production model. Fishery Bulletin, 92(2), 374–389.

Priori, C., Mastascusa, V., Erra, F., Angiolillo, M., Canese, S., & Santangelo, G. (2013). Demography of deep-dwelling red coral populations: Age and reproductive structure of a highly valued marine species. Estuarine, coastal and shelf science, 118, 43-49.

Puga, R., de León, M. E., & Cruz, R. (1991). Reclutamiento de puerulos de langosta (Panulirus argus) a la plataforma cubana. Revista de Investigaciones Marinas, 12(1–3), 66–75.

Rjeibi O. (2012). Biologie et dynamique des populations de la langouste rouge Palinurus elephas pêchée sur les côtes tunisiennes. Thèse de doctorat de l'Institut National Agronomique de Tunisie spécialité Halieutique, Tunisie. 281 pp.

Rosenberg, A. A., Kleisner, K. M., Afflerbach, J., Anderson, S. C., Dickey-Collas, M., Cooper, A. B., ... & Ye, Y. (2014). Developing new approaches to global stock status assessment and fishery production potential of the seas. Science, 345(6193), 360–365.

Rossetto M., Bitetto I., Spedicato M. T., Lembo G., Gambino M., Accadia P., Melià P. 2014. Multicriteria decision-making for fisheries management: A case study of Mediterranean demersal fisheries. Marine Policy, 53, 83–93.

Russo, T., Bitetto, I., Carbonara, P., Carlucci, R., D'Andrea, L., Facchini, M.T., Lembo, G., Maiorano, P., Sion, L., Spedicato, M.T., Tursi, A. and Cataudella, S. 2017. A Holistic Approach to Fishery Management: Evidence and Insights from a Central Mediterranean Case Study (Western Ionian Sea). Front.Mar.Sci., 4:193, https://doi.org/10.3389/fmars.2017.00193

Santangelo G, Abbiati M, Giannini F, Cicogna F. (1993). Red coral fishing trends in the western Mediterranean Sea during the period 1981–1991. Scientia Marina 57: 139–143.

Santangelo, G., Carletti, E., Maggi, E., & Bramanti, L. (2003). Reproduction and population sexual structure of the overexploited Mediterranean red coral Corallium rubrum. Marine Ecology Progress Series, 248, 99-108.

Santangelo G., Bramanti L., Iannelli M. (2007) Population dynamics and conservation biology of the over-exploited Mediterranean red coral. Journal of Theoretical Biology 244 (2007) 416–423.

Santos, R., Peixoto, U. I., Medeiros-Leal, W., Sequeira, R. M., Novoa-Pabon, A., & Pinho, M. (2022). Demographics and yield–Per–Recruit Assessment of the vulnerable spiny lobster Palinurus elephas in the Azores—Implications for Conservation and Fisheries Management. Biology, 11(3), 474.

Shepherd, J.G. (1999). Extended survivors analysis: an improved method for the analysis of catch-at-age data and abundance indices. ICES Journal of Marine Science, 56(5), 584–591

Sparre, P., & Venema, S. C. (1998). Introduction to tropical fish stock assessment. Part 1: Manual. FAO Fisheries Technical Paper No. 306/1, Rev. 2. Food and Agriculture Organization of the United Nations, Rome.

Spedicato, M. T., Massutí, E., Merigot, B., et al. (2019). The MEDITS trawl survey specifications in an ecosystem approach to fishery management. Scientia Marina, 83(S1), 9–20.

STECF (2020). Stock Assessments: demersal stocks in the western Mediterranean Sea (STECF-20-09). EUR 28359 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27165-9, doi:10.2760/286667, JRC122993

STECF (2021a). Stock Assessments: demersal stocks in the western Mediterranean Sea (STECF-21-11). Publications Office of the European Union, Luxembourg, 2021, EUR 28359 EN, ISBN 978-92-76-46116-6, doi:10.2760/046729, JRC127744

STECF (2021b). Evaluation of the fishing effort regime in the Western Mediterranean – part VI (STECF-21-13). Publications Office of the European Union, Luxembourg, 2021, EUR 28359 EN, ISBN 978-92-76-43488-7, doi:10.2760/121901, JRC126965

STECF (2022). Evaluation of maximum catch limits and closure areas in the Western Mediterranean (STECF-22- 01). EUR 28359 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-51980-5, doi:10.2760/657891, JRC129243.

STECF (2023). Evaluation of fishing effort and catch regime for demersal fisheries in the western Mediterranean Sea (Part XI). Publications Office of the European Union. https://op.europa.eu/en/publication-detail/-/publication/7f18a379-57de-11ec-91ac-01aa75ed71a1/language-en

Stefánsson, G. 1992. Note on the stock-dynamics and assessments of the Icelandic cod. ICES.C.M.1992/G:71.

Toma, M., Bo, M., Cattaneo-Vietti, R., Canese, S., Canessa, M., Cannas, R., Cardone, F., Carugati, L., Cau, A., Corriero, G., Follesa, M. C., Mercurio, M., Greco, S., Andaloro, F., & Bavestrello, G. (2022a). Basin-scale occurrence and distribution of mesophotic and upper bathyal red coral forests along the Italian coasts. Mediterranean Marine Science, 23(3), 484–498.

Toma M, Bo M, Giudice D, Canese S, Cau A, Andaloro F, Angiolillo M, Greco S and Bavestrello G (2022b) Structure and status of the Italian red coral forests: What can a large-scale study tell? Front. Mar. Sci. 9:1073214. doi: 10.3389/fmars.2022.1073214

Torrents, O., & Garrabou, J. (2011). Fecundity of red coral Corallium rubrum (L.) populations inhabiting in contrasting environmental conditions in the NW Mediterranean. Marine Biology, 158, 1019-1028.

Torrents, O., Garrabou, J., Marschal, C., & Harmelin, J. G. (2005). Age and size at first reproduction in the commercially exploited red coral Corallium rubrum (L.) in the Marseilles area (France, NW Mediterranean). Biological Conservation, 121(3), 391-397.

Tsikliras, A. C., Dinouli, A., Tsiros, V.-Z., & Tsalkou, E. (2015). The Mediterranean and Black Sea fisheries at risk from overexploitation. PLoS ONE, 10(3): e0121188.

Tsounis, G., Rossi, S., Gili, J. M., & Arntz, W. (2006). Population structure of an exploited benthic cnidarian: the case study of red coral (Corallium rubrum L.). Marine biology, 149, 1059-1070.

Tsounis, G., Rossi, S., Gili, J.M., Arntz, W.E. (2007). Red coral fishery at the Costa Brava (NW Mediterranean): case study of an over harvested precious coral. Ecosystems, 10, 975-986

Tsounis, G., Rossi, S., Grigg, R. W., Santangelo, G., Bramanti, L., and Gili, J. M. (2010). The exploitation and conservation of precious corals. Oceanogr. Mar. Biol.: Annu. Rev. 48, 161–212. doi: 10.1201/EBK1439821169

Underwood, E. C., Viers, J. H., Klausmeyer, K. R., Cox, R. L., & Shaw, M. R. (2009). Threats and biodiversity in the mediterranean biome. Diversity and Distributions, 15(2), 188-197.

Vandeperre, F., Higgins, R. M., Sánchez-Meca, J., Maynou, F., Goñi, R., Martín-Sosa, P., ... & Santos, R. S. (2011). Effects of no-take area size and age of marine protected areas on fisheries yields: a meta-analytical approach. Fish and Fisheries, 12(4), 412-426.

Vølstad, J. H., Afonso, P. S., Baloi, A. P., de Premegi, N., Meisfjord, J., & Cardinale, M. (2014). Probability-based survey to monitor catch and effort in coastal small-scale fisheries. Fisheries research, 151, 39-46.

Acknowledgements

My PhD journey has been an extraordinary voyage, made possible by the support, guidance and encouragement of many people and institutions. To all those who have contributed to this work, I wish to express my most sincere gratitude.

First and foremost, I wish to thank Prof. Follesa, for always believing in my abilities, even in the most challenging moments. Thank you for your unwavering patience, for the invaluable feedback, for transmitting your immense passion to me, and for opening the doors to a new and fascinating world during these three years. Thank you for guiding me towards the achievement of pioneering results in the Mediterranean. This adventure has been wonderful!

A special thank you goes to my colleague and friend Pierluigi Carbonara. His contagious enthusiasm for research, his guidance (expressed with his unmistakable energy and vivacity), and his constant willingness to exchange ideas have been essential for the attainment of this milestone. My gratitude for all of this will never end. A heartfelt thank you to Maria Teresa Spedicato and Giuseppe Lembo, for sharing their incredible passion for the sea and fishery science with me since 2009. I would not be where I am today without their guidance.

I also wish to thank the Reviewers and Members of my doctoral Committee. Thank you for the time dedicated to me, for the precious feedback, and for the willingness shown in evaluating this work. Your contributions and your helpful suggestions have been crucial in refining my research and presenting it more effectively.

This research has benefited from the collaboration with several institutions and researchers. In particular, I am grateful to the University of Cagliari (Department of Life and Environmental Sciences), the Autonomous Region of Sardinia, and COISPA. I sincerely thank Alessandro Cau, of the Department of Life and Environmental Sciences, for the careful revision of my article on red coral and for the valuable advice on how to shape the work for publication. Heartfelt thanks also to Paola Pesci, for the constant support in collecting data from biological samplings and for her help throughout this journey.

A special thank you also goes to my colleagues at Coispa: Walter, for his unshakeable encouragement in the most difficult moments, and Cosmidano, for his constant and precious availability. Thanks to Lola, whose precious suggestions, serenity, and smile were a great support during the thesis preparation.

On a personal level, I wish to thank my family and friends for the love, support, and encouragement that they have constantly offered me during this long journey. To my parents, I express my profound gratitude for always believing in me, even when doubts assailed me.

Infinite thanks go to the reasons for my life, Nicolò, and to our two jewels, Rocco and Miriam. To my husband Nicolò, in particular, goes a special thank you for encouraging me to embark on this adventure, for enduring my nervousness, and for always encouraging and supporting me, during the long nights and in the early hours of the day, when I took advantage of the children's sleep to dedicate myself to the thesis.

Thanks to Gino, who with his smile and his cheerfulness has always instilled serenity in me and spurred me to move forward; and to Daniela, the sister I never had but always wanted. Your irrepressible irony and your joy of living have helped me to see things from a different perspective, especially in the most difficult moments.

I wish to dedicate this PhD thesis to Lia, who was and always will be like a second mother to me. You were unable to witness the completion of this journey, but this work is for you. For always urging me to aim high and to never settle, with your constant sweetness and kindness.

Il mio percorso di Dottorato è stato un viaggio straordinario, reso possibile dal sostegno, dalla guida e dall'incoraggiamento di molte persone e istituzioni. A tutti coloro che hanno contribuito a questo lavoro, desidero esprimere la mia più sincera gratitudine.

Innanzitutto, desidero ringraziare la Prof.ssa Follesa, per aver sempre creduto nelle mie capacità, anche nei momenti più difficili. Grazie per la sua pazienza, per il prezioso feedback, per avermi trasmesso la sua immensa passione e per avermi aperto le porte di un mondo nuovo e affascinante in questi tre anni. Grazie per avermi guidato/a nel raggiungimento di risultati pionieristici nel Mediterraneo. Questa avventura è stata meravigliosa!

Un ringraziamento speciale va al mio collega e amico Pierluigi Carbonara. Il suo contagioso entusiasmo per la ricerca, la sua guida (espressa con la sua inconfondibile energia e vivacità) e la sua costante disponibilità a confrontarsi sulle idee sono stati essenziali per il conseguimento di questo traguardo. La mia riconoscenza per tutto questo non avrà mai fine. Un sentito ringraziamento a Maria Teresa Spedicato e Giuseppe Lembo, per aver condiviso con me la loro incredibile passione per il mare e la scienza della pesca sin dal 2009. Non sarei dove sono oggi senza la loro guida.

Desidero inoltre ringraziare i Revisori e i Membri del mio collegio di dottorato. Grazie per il tempo dedicatomi, per la loro preziosa opinione e per la disponibilità dimostrata nella valutazione di questo lavoro. I vostri contributi e i vostri utili suggerimenti sono stati determinanti nel perfezionare la mia ricerca e nel presentarla in modo più efficace.

Questa ricerca ha beneficiato della collaborazione con diverse istituzioni e ricercatori. In particolare, sono grata all'Università di Cagliari (Dipartimento di Scienze della Vita e dell'Ambiente), alla Regione Autonoma della Sardegna e a COISPA. Ringrazio sentitamente Alessandro Cau, del Dipartimento di Scienze della Vita e dell'Ambiente, per l'attenta revisione del mio articolo sul corallo rosso e per i preziosi consigli sul taglio da *dare al lavoro in vista della pubblicazione. Un grazie di cuore anche a Paola Pesci, per il supporto costante nella raccolta dei dati dai campionamenti biologici e per l'aiuto in questo percorso.*

Un ringraziamento speciale va anche ai miei colleghi di Coispa: Walter, per il suo tenace incoraggiamento nei momenti più ardui, e Cosmidano, per la sua costante e preziosa disponibilità. Grazie a Lola, i cui preziosi suggerimenti, serenità e sorriso sono stati di grande aiuto durante la preparazione della tesi.

A livello personale, desidero ringraziare la mia famiglia e i miei amici per l'amore, il sostegno e l'incoraggiamento che mi hanno costantemente offerto durante questo lungo percorso. Ai miei genitori, esprimo la mia profonda gratitudine per aver sempre creduto in me, anche quando i dubbi mi assalivano.

Un grazie infinito va alle ragioni della mia vita, Nicolò, e ai nostri due gioielli, Rocco e Miriam. A mio marito Nicolò, in particolare, va un ringraziamento speciale per avermi spronata ad intraprendere questa avventura, per aver sopportato il mio nervosismo e per avermi sempre incoraggiata e sostenuta, nelle lunghe notti e nelle prime ore del giorno, quando approfittavo del sonno dei bambini per dedicarmi alla tesi.

Grazie a Gino, che con il suo sorriso e la sua allegria mi ha sempre infuso serenità e la spinta ad andare avanti; e a Daniela, la sorella che non ho mai avuto ma che ho sempre desiderato. La tua irrefrenabile ironia e la tua gioia di vivere mi hanno aiutata a vedere le cose da una prospettiva diversa, soprattutto nei momenti più difficili.

Desidero dedicare questa tesi di Dottorato a Lia, che è stata e sarà sempre per me una seconda mamma. Non hai potuto assistere al completamento di questo percorso, ma questo lavoro è per te. Per avermi sempre spronata a puntare in alto e a non accontentarmi mai, con la tua costante dolcezza e simpatia.