Ecosystem modeling to evaluate the ecological sustainability of small-scale fisheries: A case study from El Hierro, Canary Islands

Article *in* Ocean & Coastal Management · September 2022

DOI: 10.1016/j.ocecoaman.2022.106297

5 authors, including:

José Carlos Mendoza
Instituto Español de Oceanografia
11 PUBLICATIONS 119 CITATIONS

Modino Raquel
Universidad de La Laguna
59 PUBLICATIONS 496 CITATIONS

Pablo Martín-Sosa
Instituto Español de Oceanografia
53 PUBLICATIONS 411 CITATIONS

José Carlos Hernández
Universidad de La Laguna
138 PUBLICATIONS 2,189 CITATIONS

Ocean and Coastal Management 228 (2022) 106297

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Ecosystem modeling to evaluate the ecological sustainability of small-scale fisheries: A case study from El Hierro, Canary Islands

José Carlos Mendoza [a,*], Raquel de la Cruz-Modino [b], Carmelo Dorta [c], Pablo Martín- Sosa [d], José Carlos Hernández [a]

[a] Departamento de Biología Animal, Edafología y Geología, Universidad de La Laguna. c/ Astrofísico Francisco Sánchez s/n, 38206, La Laguna, Santa Cruz de Tenerife, Spain

[b] Instituto de investigación Social y Turismo (ISTUR), Camino La Hornera, 37. Facultad de Derecho, Módulo D-02, Apartado 456, 38200, La Laguna, Santa Cruz de Tenerife, Spain

[c] Gobierno de Canarias, Dirección General de Pesca, Avda. Francisco La Roche, 35, Edf. Usos Múltiples I, planta 11, 38071, Santa Cruz de Tenerife, Spain

[d] Centro Oceanográfico de Canarias. Instituto Español de Oceanografía - CSIC. c/ Farola del Mar, 22, Dársena pesquera, 38180, Santa Cruz de Tenerife, Spain

ARTICLE INFO

Keywords:
Ecopath with ecosim
Canary islands
Scenario modeling
Fisheries management
Small-scale fisheries

ABSTRACT

This paper examines various fishery management scenarios based on the recovery of small-scale fisheries (SSF) following a submarine volcanic eruption in 2011 in El Hierro Island (Canary Islands, Spain). After this catastrophic event, the SSF composition of La Restinga fishing community was affected by socio-economic and demographic changes. The uncertainty derived from this situation provides an opportunity to evaluate the fisheries' sustainability and advice on different management options under an ecosystem-based approach. The Ecopath with Ecosim modeling framework was used to build a model of El Hierro Island, where the versatile and traditional multispecies small-scale fleet of La Restinga operates. Our main goal is to improve traditional fisheries, based on the relevance of key local fisheries and multi-specific fishery strategies in the light of scientific knowledge. Temporal simulations for the next decade were analyzed by creating scenarios of alternative fishing effort distributions based on the fishing trends observed in El Hierro small-scale community of La Restinga after a natural hazard. The outcomes of this modeling prototype show the vulnerability of some littoral and demersal species, the resilience of migratory species, and the sustainability of SSF diversification practices. These results could develop an adaptive and co-management strategy with the local fishing community to preserve the small-scale fishing system and marine resources.

1. Introduction

In recent decades scientists have driven fishery management to achieve the long-term sustainability of fishing resources. Small-scale fisheries (SSF) provide food security and livelihoods around the world (FAO 2020) and are an integral component of coastal economies in many countries and insular areas (Kolding et al., 2014; De Lara and Corral, 2017), such as La Restinga (El Hierro Island) in the Canary Islands (Spain). Small-Scale Fisheries (SSF) in the area where this study was carried out (Fig. 1), may be considered under the general Small-Scale Fisheries EU's definition.[1] Those are characterized by their small boats, under 12 m, and not using towed gears (Macfadyen et al., 2011; Pascual-Fernández et al., 2020; Percy and O'Riordan 2020). SSF represent approximately 86% of the EU fishing fleet in 2019 (EC 2020). In the Canary Islands, the legal category of 'small-scale gears' encompasses most of the small-scale fleet, not fully overlapping with the EU category (Pascual-Fernández et al., 2020). The Archipelago, jointly with Galicia and Andalusia, constitute the region with the most small-scale vessels in Spain. In addition, the SSF fleet represents 85% of the total fleet of the region (Pascual-Fernández et al., 2020).

In La Restinga, the only fishing community of El Hierro Island, fisheries revenues have been estimated higher than 1 M€, and

* Corresponding author.
E-mail address: jmendozd@ull.edu.es (J.C. Mendoza).

[1] Based on Council Regulation (EC) No 1198/2006 of the European Fisheries Fund: "1. For the purpose of this Article, 'small-scale coastal fishing' means fishing carried out by fishing vessels of an overall length of fewer than 12 m and not using towed gear as listed in Table 3 in Annex I of Commission Regulation. (EC) No 26/2004 of 30 December 2003 regarding the fishing vessels register of the Community". Later the European Maritime and Fisheries Fund Regulation 508/2014, reproduces the same definition.

https://doi.org/10.1016/j.ocecoaman.2022.106297
Received 8 November 2021; Received in revised form 17 June 2022; Accepted 20 July 2022
Available online 26 August 2022

approximately 57 different species are targeted along the year (Dorta and Martín-Sosa, 2022). However not all species are landed has the same relevance, for example the parrotfish (*Sparisoma cretense*) brings in about 23% of the total incomes, followed by the wahoo (*Acanthocybium solandri*) and the red bream (*Beryx splendens*) at 21 and 14% respectively (Pascual-Fernández et al., 2018). These fisheries may be considered essential (Dorta and Martín-Sosa, 2022) and may be fished in conjunction with different tuna species (e.g., *Katsuwonus pelamis, Thunnus albacares, Thunnus alalunga, Thunnus thynnus*), and other epi- and mesodemersal species such as *Muraena augusti, Serranus atricauda, Plesionika* spp or *Ruvettus pretiosus.* During 2011 a massive fish mortality occurred after a submarine volcanic eruption located in El Hierro coast (Brito et al., 2012; De Paz et al., 2013). All commercial fishing activities stopped during 6 months (Pascual-Fernández et al., 2015) in the entire Island waters. At the end of this fishing ban, the small-scale fishers voluntarily adopted some additional fishing management measures through their *cofradía*[2] (fishers' organization) (Bavinck et al., 2015). Overall, restrictions remained for 462 days, with specific limitations for *B. splendens*, *S. cretense* and *A. solandri* (De la Cruz Modino and Piñeiro-Corbeira, 2022).

In the Canary Islands, different studies have analyzed the activity of SSF (Brito and Dorta 1998; González 2008; González et al., 2020; Pascual-Fernández et al., 2020, Dorta and Martín-Sosa, 2022); as well as the recovery status of El Hierro coastal fishing communities (Brito et al.,

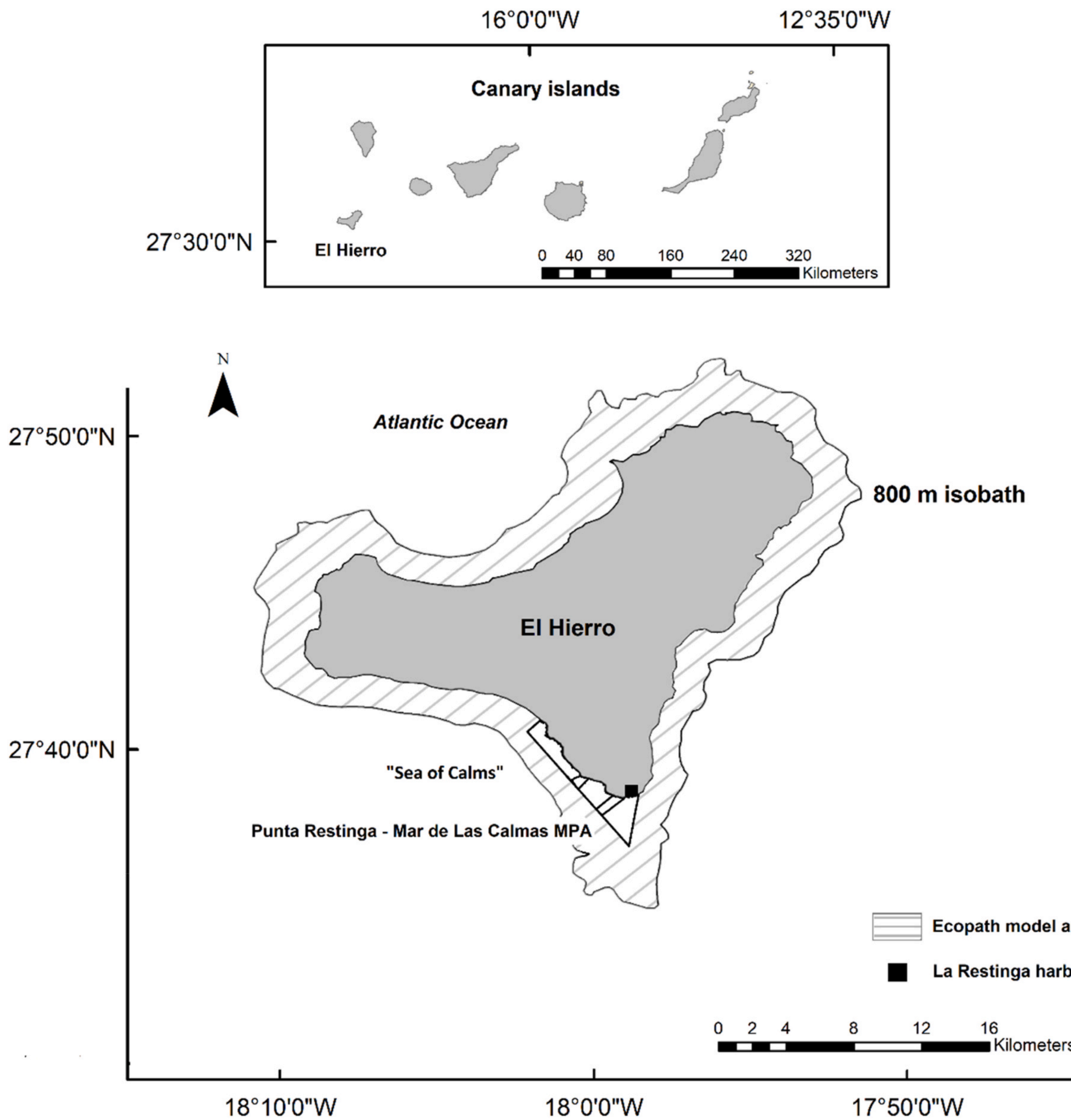

Fig. 1. Location of El Hierro Island and the fishing harbour of La Restinga. The striped pattern represents the modeled area where the small-scale fisheries of La Restinga mainly operates.

[2] Spanish local fishing organizations, called 'cofradias', participate in different aspects of fisheries resource management. They can influence the regulation of fishing activities in their local coastal area, constituting an early example of communal resource management (Bavinck et al., 2015).

2013) and the small-scale fishing activity in La Restinga (De la Cruz Modino and Piñeiro-Corbeira, 2022). However, the lack of data on fish stocks and/or reference indicators of marine resource status can make the design of long-term sustainable strategies unfeasible (Santamaría et al., 2014). A lack of efficient systems for collecting data increases the complexity of advice for SSF management. This situation is particularly problematic in cases when facing rapid environmental changes introduced by global trends and/or disrupted events such as natural hazards (e.g., submarine volcanic eruption, landslides) or anthropogenic unexpected impacts (e.g., oil-spill, chemical spill). The ecosystem-based approach is suitable to address questions about the status of fishing resources and SSF management after natural disasters.

This paper uses the well-established ecosystem modeling approach EwE (Christensen and Walters, 2004; Christensen et al., 2008; Heymans et al., 2016) to explore several hypothetical fishing scenarios following the fisheries closure in the waters of El Hierro, after the submarine volcano eruption. Specifically, we (i) design and parameterize a mass-balance model in Ecopath, (ii) parameterize the prototype of dynamic interactions in Ecosim and fit it to available catch time series, (iii) to simulate the implementation of some scenarios reflecting different SSF strategies, and (iv) to evaluate the sustainability of key fisheries in the study area in the light of the scenarios proposed.

In the Canary Islands, the ecosystem-based approach to SSF (García 2003) was proposed for the first time in 2015 for the island of Gran Canaria (Canary Islands) (Couce-Montero et al., 2015, 2019). Mendoza et al. (2020) built an EwE model for El Hierro coastal waters to test the resilience of its Marine Protected Area (MPA) after the 2011 the submarine volcanic eruption. This study mainly focuses on exploring and comparing spatial recovery trends of species in protected and unprotected areas. However, it does not examine the impacts of the changes on the SSF community of La Restinga, after the fishing closure mentioned above. A decade later, some changes in the small-scale fleet composition of the fishing community took place, considering socio-economic and demographic modifications (i.e., fishers retired, fish's markets changes). Consequently, this new situation constitutes an opportunity to evaluate the SSF of the area based on an EwE ecosystem approach to ensure the sustainability of the local SSF resources and provide a "snapshot" for future discussions and management proposals. We believe that the current scenario in La Restinga maybe a suitable context to improve scientific knowledge transfer for SSF social and environmental sustainability and maintenance.

2. Material and methods

Methodologies for fishery management have been implemented from an ecosystem-based approach using ecological models (Plagányi 2007). Given the complexity of ecosystem processes, this analytical alternative has been used to explore new fishing management strategies, considering the ecosystem as a whole. In this regard, Ecopath with Ecosim (EwE) software (EwE; Christensen and Walters 2004; Heymans et al., 2016) is the most widely used ecosystem modeling approach. The EwE approach is increasingly used in fishery management, incorporating multiple gears and species target combinations in the analysis. Moreover, EwE can address questions about the impacts of fishing on non-target species and the unintended side effects of fishing. In the last decades, EwE models have analyzed different management actions in SSF, and some of these published models have focused on exploring the possible impacts of fishing on the structure and functioning of ecosystems (Pinnegar and Polunin 2004; Tsehaye and Nagelkerke, 2008; Philippsen et al., 2019; Lira et al., 2021). Other models have examined alternative fishing management options to recover exploited marine resources (Fouzai et al., 2012; Cisneros-Montemayor et al., 2020) and assess optimal harvesting strategies using social and economic criteria (Arreguín-Sánchez et al., 2004). Therefore, this software offers a management tool to address decision-making in SSF.

2.1. Study area and local small-scale fishing community of La Restinga

El Hierro is the westernmost and youngest island of the Canary Islands (Spain). La Restinga fishing village, on the island's southwest coast, was founded in the 1940s by a few fishing families (Pascual-Fernández et al., 2018). The waters surrounding El Hierro contain abundant fishing resources (Bortone et al., 1991), and most communities of marine species occur within a short and abrupt volcanic basin. 500 m-deep are close, approximately one mile from the shore. The study area covers 227.3 km^2 and represents a rocky reef ecosystem up to 800 m in depth (Fig. 1). It includes epipelagic and mesopelagic communities of a scant rocky shelf, interconnected by a seabed slope habitat. The fishers of the local small-scale fleet work along the coastline, from 0 to 600 m in depth, except during seasonal tuna catches. Traditionally, fishers used to "rest coastal marine resources" through a combination of demersal and pelagic fisheries over the years. In the words of an old fisher, the "best reserve" was the tuna fishery period, called *zafra* (De la Cruz Modino 2004; 2012; Jentoft et al., 2012), when the majority of fishers abandoned demersal fisheries to catch different tuna species and large pelagic species (Table A1), which were available cyclically.

In 2010 there were approximately 23 fishing productive units in El Hierro and 39 fishers, mainly based in La Restinga (Pascual-Fernández and De la Cruz Modino, 2011). A fishing productive unit in SSF integrates a group of people involved in the economic activity of fishing (e.g., catching, processing, and distribution) and who can play different roles (De la Cruz Modino and Piñeiro-Corbeira, 2022; Piñeiro-Corbeira et al., 2022). These units' composition is linked to recruitment strategies traditionally correlated with close kinship and diverse forms of affinity, depending on the circumstances (Pascual Fernández 1991). Furthermore, production units have the means of production (e.g., boats, gears, and technology) necessary to develop their activity. For example, a production unit may have more than one boat (De la Cruz Modino 2012). Finally, productive units accumulate knowledge, know-how and skills through generations, allowing them to situate themselves in the marine environment, locate the target species and catch them, optimizing the use of the workforce and the means of production (Andersen and Wadel 1972) -See De la Cruz Modino and Piñeiro-Corbeira, 2022.

Compared to other Canarian fishing villages, there has been a historic and important revamping of the fishing workforce in this community, related to the institutional support from the local public administration (Pascual-Fernández et al., 2018) and the good commercial conditions provided by a local fishing cooperative named *Pescarestinga*[3]. Younger fishers usually start fishing with family members and relatives. Without the support and knowledge of older fishers, some of them may be restricted to fishing near the shore more intensively, because of the skills and knowledge needed to develop many of the pelagic and deep-sea fisheries with hook-and-line gears. In 2018 an average of 37 fishers were active on the Island, operating 33 boats and organized into 25 productive fishing units, mainly located in La Restinga. There is almost a third new productive unit made up exclusively of young fishers. In addition, young fishers who are not originally from family fisherfolk or La Restinga SSF community constitute a third of fishers.

In terms of governance, on the whole Island, fisheries are generally managed by the *cofradía,* which determines the gears allowed jointly

[3] The cooperative manages most of the landings and organizes their sale, both in El Hierro and in the other Canary Islands such as Tenerife (Pascual-Fernández et al., 2018). The role of the cooperative, built-in 1990 (Galván-Tudela 1990, 2003; De la Cruz Modino 2012), has been essential to ensure the marketing of the tuna fisheries due to the limits of the insular market and the remoteness of this SSCF community that increment the commercialization cost. Producer organizations and small cooperatives also play an important role in tuna fisheries' commercialization in the other Canary Islands (e.g., Tenerife Island) (Pascual-Fernández et al., 2019).

with the regional government. The cooperative, *Pescarestinga*, is also instrumental in promoting and ensuring some fisheries, such as tuna fisheries, throughout the year. Almost 90% of the fishing productive units employ hook-and-line gears, widely used for the *S. cretense* fishery, epidemersal, slope, mesodemersal fisheries, trolling, and tuna fisheries. However, the latter fishing relies on purse seine, which is only used to catch live bait. Approximately 40% of all fishing productive units use the harpoon exclusively for wahoo (*A. solandri*), and trolling is also used for this fishery. 25% of productive fishing units deploy traps for catching either moray eels or shrimp, and more than 40% are shellfish gatherers. The studied fishing area is exploited by the multiple and traditional fishing gears mentioned above. Most small-scale fishers target various species, including pelagic and demersal resources (see the target and complementary species in Table A1 and S1). In terms of total catches (weight) for 2010, the most important species were the *A. solandri*, *S. cretense,* and the skipjack tuna *Katsuwonus pelamis* account for more than 50% of total landings (Martín-Sosa et al., 2010). However, catches by weight of pelagic species vary every year depending on related migratory processes (Arrizabalaga et al., 2002).

2.2. Modeling El Hierro small-scale fisheries

2.2.1. Input data and model parametrization

The ecosystem model of El Hierro was developed using the Ecopath with Ecosim (EwE) modeling software 6.6 (https://ecopath.org/) (Christensen and Walters 2004; Christensen et al., 2008). The mass balance model (Ecopath) of El Hierro Island (0–800 m) was established using the year 2010 as the reference point, before the start of volcanic eruption (October 2011). This year was chosen as a baseline because it provided the best quality data about fishing effort and catches. However, input data of catches from recreational fishing were not considered in the model due to the lack of empirical local data available on El Hierro Island (Castro et al., 2019; Bilbao-Sieyro et al., 2022).[4] The limits of the modeled area were defined using a combination of geo-referenced bathymetric layers within an Arcview GIS system. El Hierro Small-Scale Fisheries (EHSSF) model was composed of 28 functional groups including single species (Table 1). The composition of the functional groups was based on their feeding habits and ecological roles (Tuya et al., 2004) or aggregated as simple species of interest for key fisheries.

The epipelagic functional groups' (0–40 m) biomasses (B) were obtained from the monitoring abundances of marine species around El Hierro using scuba diving surveys (Table A1). Monitoring the abundance of marine organisms in the shallow rocky bottom ecosystems off El Hierro has been ongoing since 1997 and conducted by the University of La Laguna. Input biomass data for target fishing groups (0–800 m) were obtained using an estimation method for open fish populations. Specifically, we used the assessment package (Sraplus - Catch-only SIR model) developed in Ovando et al. (2021). Production (P/B) and consumption (Q/B) rates were estimated using empirical equations taken from FishBase (Froese and Pauly 2010) or other ecological models previously developed for the Canary Islands (Couce-Montero et al., 2015, 2019; Mendoza et al., 2020). The diet matrix composition (Table S2) was assembled from published feeding habit studies in the archipelago or other Atlantic regions. For tuna and other pelagic fishes, with seasonal migrations, we set a fraction of the diet as import based on the months that this functional group feeds outside the studied fishing area.

[4] There are few studies that have evaluated in depth recreational fishing's impact on the MPA and La Restinga coast, and there are no any studies carried out in the coastal areas of El Hierro Island. There is only one fishing tourist enterprise operating in the island. Angling from the shore is popular in La Restinga coast, recreational fishers are mostly local anglers and domestic tourists. However, they are highly seasonal, from June to September mainly (De la Cruz Modino and Piñeiro-Corbeira, 2022).

Table 1
Basic estimates of El Hierro Small-Scale Fisheries (EHSSF) model (2010). Parameters definitions: TL = trophic level, B = biomass (tonnes/km^2), P/B = production/biomass (year^{-1}), Q/B = consumption/biomass (year^{-1}), EE = ecotrophic efficiency and P/Q = production/consumption. In bold, parameters estimated by the model.

Functional group	TL	B	P/B	Q/B	EE	P/Q
1. Detritus	**1.000**	17.10			**0.368**	
2. Macroalgae	**1.000**	15.030	10.31		**0.196**	
3. Phytoplankton	**1.000**	7.325	166.8		**0.729**	
4. Zooplankton	**2.000**	8.879	57.64	128.7	**0.818**	**0.448**
5. Limpets	**2.000**	0.0261	1.743	10.16	**0.693**	**0.172**
6. Polychaeta	**2.000**	0.006	3.337	21.92	**0.000**	**0.152**
7. Echinoderms	**2.017**	0.300	0.485	2.669	**0.886**	**0.182**
8. Benthic meiofauna	**2.197**	1.989	9.100	26.46	**0.324**	**0.344**
9. Gastropods	**2.347**	0.274	4.469	17.64	**0.890**	**0.253**
10. Benthic decapods	**2.366**	0.469	3.852	18.28	**0.759**	**0.211**
11. *Sparisoma cretense*	**2.370**	0.539	0.732	7.100	**0.635**	**0.103**
12. Sparids	**2.489**	1.972	0.976	7.500	**0.897**	**0.130**
13. Non-fished epidemersal invertivorous fishes	**2.474**	1.718	0.960	7.447	**0.904**	**0.129**
14. Non-fished epidemersal piscivorous fishes	**3.296**	1.387	0.550	4.523	**0.369**	**0.122**
15. Deep Scattering Layer (DSL)	**2.750**	32.20	**5.707**	14.40	0.950	**0.396**
16. Pandalid shrimps	**2.952**	0.235	1.150	7.500	**0.409**	**0.153**
17. Small pelagics	**3.206**	**25.99**	0.711	7.368	0.950	**0.103**
18. Medium pelagics	**3.292**	**9.712**	1.230	8.109	0.950	**0.152**
19. Demersal cephalopods	**2.963**	0.044	2.856	7.895	**0.939**	**0.362**
20. Slope carnivorous fishes	**3.050**	0.422	1.050	4.884	**0.518**	**0.214**
21. Slope Scorpionfishes	**3.812**	0.051	0.775	4.356	**0.203**	**0.178**
22. Epidemersal carnivorous fishes	**3.358**	0.392	0.485	3.450	**0.098**	**0.141**
23. Epidemersal planktivorous fishes	**2.895**	0.153	0.723	5.425	**0.092**	**0.133**
24. Morays	**3.202**	0.340	0.458	3.737	**0.286**	**0.123**
25. Pelagic cephalopods	**3.349**	**7.520**	1.865	16.200	0.950	**0.115**
26. *Seriola* spp	**3.609**	0.163	0.777	3.500	**0.267**	**0.222**
27. *Beryx splendens*	**3.721**	1.408	0.890	4.100	**0.401**	**0.217**
28. Mesodemersal fishes	**3.710**	0.668	0.621	4.138	**0.317**	**0.150**
29. *Acanthocybium solandri*	**4.235**	2.425	1.225	7.850	**0.104**	**0.156**
30. *Katsuwonus pelamis*	**3.963**	3.382	2.054	15.34	**0.033**	**0.134**
31. Tunas and large pelagics	**4.093**	2.707	1.285	12.56	**0.059**	**0.102**
32. Marine mammals	**4.273**	0.771	0.042	14.97	**0.000**	**0.003**

Multi-species SSF were included in the model as different fishing gears and techniques used by La Restinga fishers (Martín-Sosa et al., 2010). We had included ten distinct categories representing each fishery (Table S1): (1) *S. cretense*; (2) Epidemersal; (3) Slope and (4) Mesodemersal fishery; (5) Purse seine; (6) Harpoon/Trolling; (7) Shrimp and (8) Moray traps; (9) Tuna and large pelagic fisheries and (10) Shellfish Gatherers. Data on catches were taken from reported landings in 2010 (Macarofood project - Interreg-MAC/2.3d/015) and scaled by each fishing gear area (bathymetric range) around the Island. The pedigree routine was used to assign the ranges of percent uncertainty of the input parameters (B, P/B, Q/B, diet, and catch values). Pedigree values for each key input value were used to calculate the quality of the model defined by the pedigree index. Please refer to supplementary data for further details on sources and references of the input data, diet matrix, pedigree index, and model parametrization.

2.2.2. Balancing procedure and fitting to time series

We performed a top-down balance strategy starting from the groups with higher trophic levels to obtain the mass-balance Ecopath model.

The pedigree information guided the balancing procedure of the most uncertain parameters (low quality). Before the fitting procedure, the general model structure was checked and calibrated using a pre-balancing (PREBAL) analysis (Link 2010) to test the ecological coherence of ecosystem input data (Heymans et al., 2016). The balanced Ecopath model was tuned by time series of fishing efforts (2010–2018) and calibrated with the catch (2007–2020) and biomass (2010–2019) time series to reconstruct historical trends. A forcing function based on phytoplankton production (2010–2017) was incorporated to explore model fits. We used the automated stepwise fitting tool (Scott et al., 2016) to test alternative scenarios combining fishing impacts, different vulnerabilities for a prey-predator relationship, and primary production anomalies. The search routine estimates the vulnerability parameters and primary production functions that show the "best fit" between Ecosim outputs and observed data. The "best fit" model is the one that determines the minimum difference between predicted and observed data using the weighted sum of squared differences (SS) and the Akaike Information Criterion (AICc; Burnham and Anderson 2002). The automated stepwise routine was used to identify a satisfactory number and combination of vulnerability and primary production anomaly parameters that simplify the 'Fit to Time Series' routine (Walters et al., 1997). The most sensitive predator-prey interactions were identified within primary production anomalies. More information on the PREBAL analysis and fitting to time series are provided in the supplementary data (Figs. S2, S3, and S4).

2.2.3. Fishing scenario analyses

Once the El Hierro Small-Scale Fishery (hereafter EHSSF) model was satisfactorily fitted to historical time series data, we tested four hypotheticals SSF scenarios related to the observed post-volcanic fishing trends in the community of La Restinga. This approach combines quantitative and qualitative methods, focusing on the SSF activities and the recent changes in the fishing productive units (Fig. S1). Specifically, the model evaluated the temporal variation of SSF strategies for different fishing effort scenarios over the next decade.

The defined percentages in fishing effort scenarios were based on the characterization of La Restinga fishing community. Four simulations were carried out for a period from 2018 to 2031 under different scenarios on the 2010 Ecopath model: (1) *Fishing at baseline levels (2010):* The first scenario was developed to maintain the fishing effort at baseline levels (2010), considering that fishing catches can be self-regulated by the SSF community through the *cofradía*. (2) *A younger fisher community:* The second scenario was based on implementing the existing generational succession with a local ecological knowledge loose (Fig. S1) defined by an increase (+50 and + 100%) in fishing effort in single-species fisheries and a decrease (−50%) in multispecies fisheries. This scenario allowed us to explore target species dynamics and explore optimization of fishery sustainability. (3) *Promoting multispecies fisheries:* The third scenario simulated the SSF units involved in multispecies fisheries for an increase (+50 and + 100%) in the fishing effort and a decrease (−50%) of single species fishing effort. (4) *Fishing at maximum sustainable yield (MSY):* Finally, a Maximum Sustainable Yield (MSY) scenario suggested by EwE for single target species was tested to complement and compare fishery strategies. The ecosystem-based estimates of the MSY metrics for the target species were estimated through an EwE built-in function. This approach allows the biomass dynamics of non-target species to respond when changing target species biomass (Walters et al., 2005). The obtained values of "Fmsy" were applied to the target species instead of the current fishing mortality for the coming years. A detailed summary of the fishing strategies scenarios is presented in Table 2.

Table 2
List of prototype fishing scenarios proposed for EHSSF model.

		The fishing effort multiplier factor	Impacted functional group
Scenario 1. Fishing at baseline levels (2010)		x1	All fished functional groups
Scenario 2. Younger fisher community (YFC)	**2.1**	x0.5	*Sparisoma cretense*
	2.2	x1.5	Morays
	2.3	x2	Pandalid shrimps
			Acanthocybium solandri
			Katsuwonus pelamis
			Beryx splendens
Scenario 3. Promoting multispecies fisheries (PMF)	**3.1**	x0.5	Epidemersal carnivorous fishes
	3.2	x1.5	Slope carnivorous fishes
	3.3	x2	Mesodemersal fishes
			Tunas and large pelagics
			Sparids
			Seriola spp.
	Current F (2018)	**EwE Fmsy**	**Impacted functional group**
Scenario 4. Maximum Sustainable Yield (MSY)	0.327	0.390	*Sparisoma cretense*
	0.158	0.240	Morays
	0.043	0.179	Pandalid shrimps
	0.655	0.911	*Acanthocybium solandri*
	1.397	1.537	*Katsuwonus pelamis*
	0.680	0.695	*Beryx splendens*

3. Results

3.1. Ecosystem structure and uncertainty of the model

The uncertainty of input data for the present model resulted in a pedigree index of 0.489 (Table S3). The trophic network of the EHSSF model showed the links and flows among the different functional groups and related fishing gears (Fig. 2). The functional groups of the modeled ecosystem were distributed in trophic levels from 1 to 4.2.

The resulting Ecopath model was balanced and calibrated according to best practices suggested by Heymans et al., (2016). The fitting procedure of the balanced Ecopath model obtained the best fit model (AICc = 348) when fishing and vulnerability estimates for most sensitive prey-predator interactions were incorporated into the calibration analysis. The historical trends were reasonably replicated by the fitted model predictions (Figs. S3 and S4). Regarding the ability of the model to reproduce functional groups with pelagic habits and catch fluctuations, we observed the highest differences in the sum of squared differences (SS) between observed and predicted data (Fig. S3). In terms of observed biomass, the model output fitted satisfactorily when focusing in essential species (*Sparisoma cretense*), while for others, such as *Epidemersal carnivorous fishes,* moderate deviations were evident (Fig. S4).

3.2. Future small-scale coastal fisheries simulations (2018–2031)

3.2.1. Scenario 1: fishing at baseline levels (2010)

The results of the first scenario simulation for single and multi-species fisheries, where relative biomasses begin at different levels, resulted in a constant or oscillatory biomass trend (migratory species) reaching a balance at the end of the biomass projections. The baseline trend allowed a reference point for comparison with other fishing effort scenarios (Figs. 3 and 4).

3.2.2. Scenario 2: a younger Fisher community

Under these scenarios (YFC 1.5 and YFC 2), the model predicted a moderate decrease in the relative biomass in single-species fisheries, except for pandalid shrimps, *Acanthocybium solandri* and *Katsuwonus*

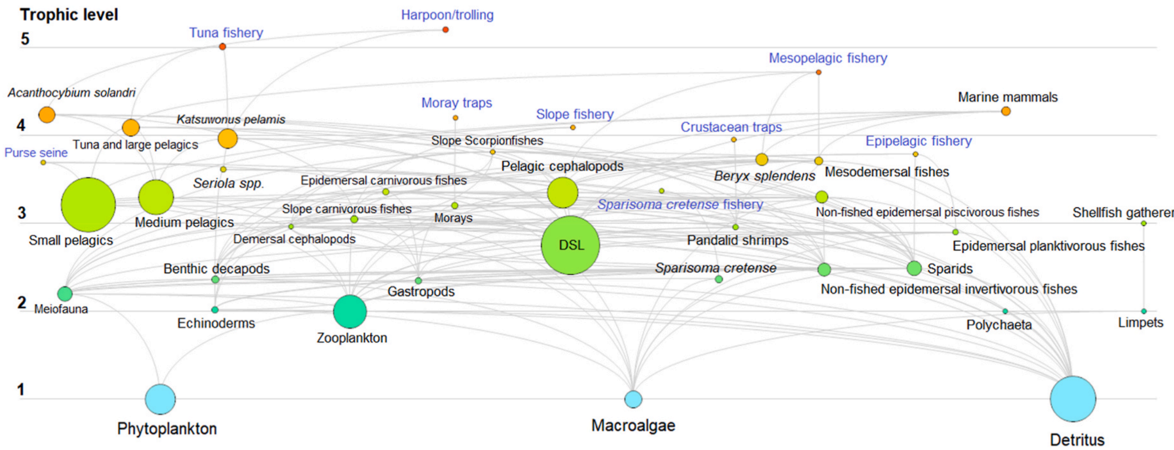

Fig. 2. Flow diagram of the 32 functional groups and artisanal fishing gears included in EHSSF model, representing the year 2010. The size of each circle is proportional to the biomass of each functional group and lines represent the links between each group.

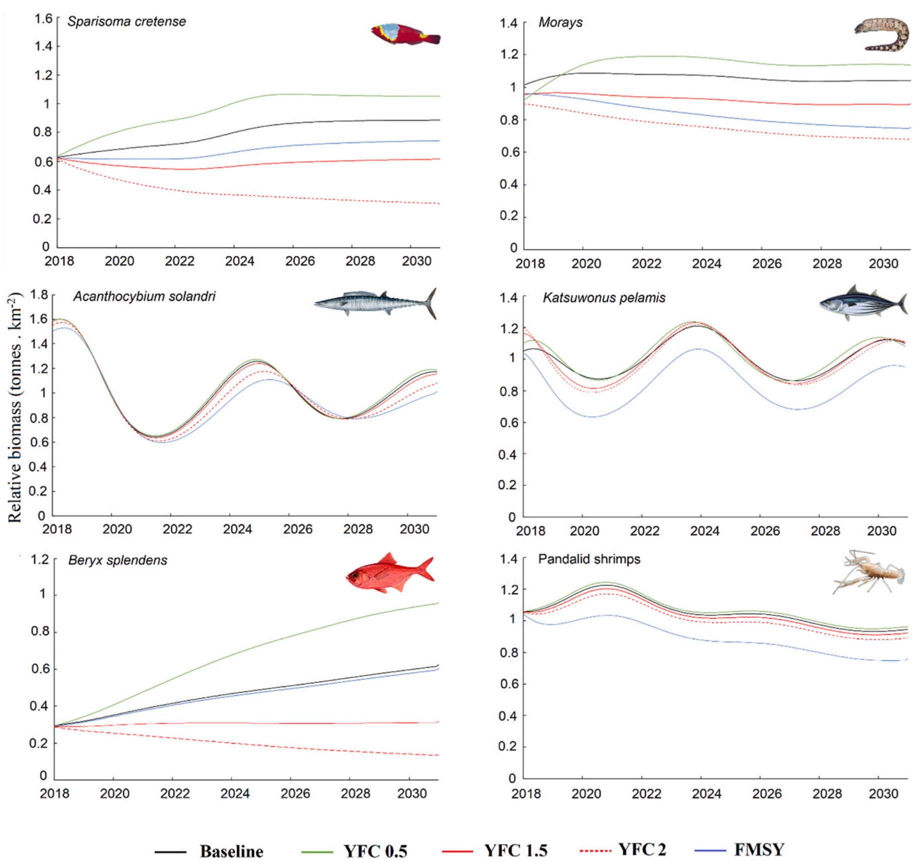

Fig. 3. Relative biomass trends of functional groups related to single species techniques in EHSSF model. YFC (1.5, 2 and 0.5): Younger fishery community; MSY: Maximum sustainable yield.

pelamis, which could cope with different levels (+50% and +100%) of higher fishing efforts. Biomass decreasing responses of most single species groups were different from the baseline scenario 2010 (Fig. 3). For example, model results indicated more complex responses, where we expected a lower decline for the parrotfish *S. cretense* fisheries. However, the increased fishing pressure on the *B. splendens* behind in the baseline scenario yielded their decline, as expected. On the contrary, due to the reduction scenario of −50% in fishing effort (YFC 0.5), overall benefits were expected for single species. *B. splendens, S. cretense,* and Morays exhibited higher relative biomass increases than pelagic species. Based on our understanding of the dynamics in the model, it seems to be due to the uncertainties in the migration parameterisation of *K. pelamis or A. solandri.*

3.2.3. Scenario 3: Promoting multispecies fisheries

Under these scenarios (PMF 1.5 and PMF 2), our results, in general, showed evident negative effects on relative biomasses compared to the baseline scenario. Slope carnivorous and mesodemersal fishes showed a noted decline in biomass of approximately 50% when fishing effort was doubled (Fig. 4). There was also a strong negative trend for the amberjack, *Seriola* spp., a complementary species to the tuna and large pelagic fishery. However, the trends projected a lower reduction for tuna

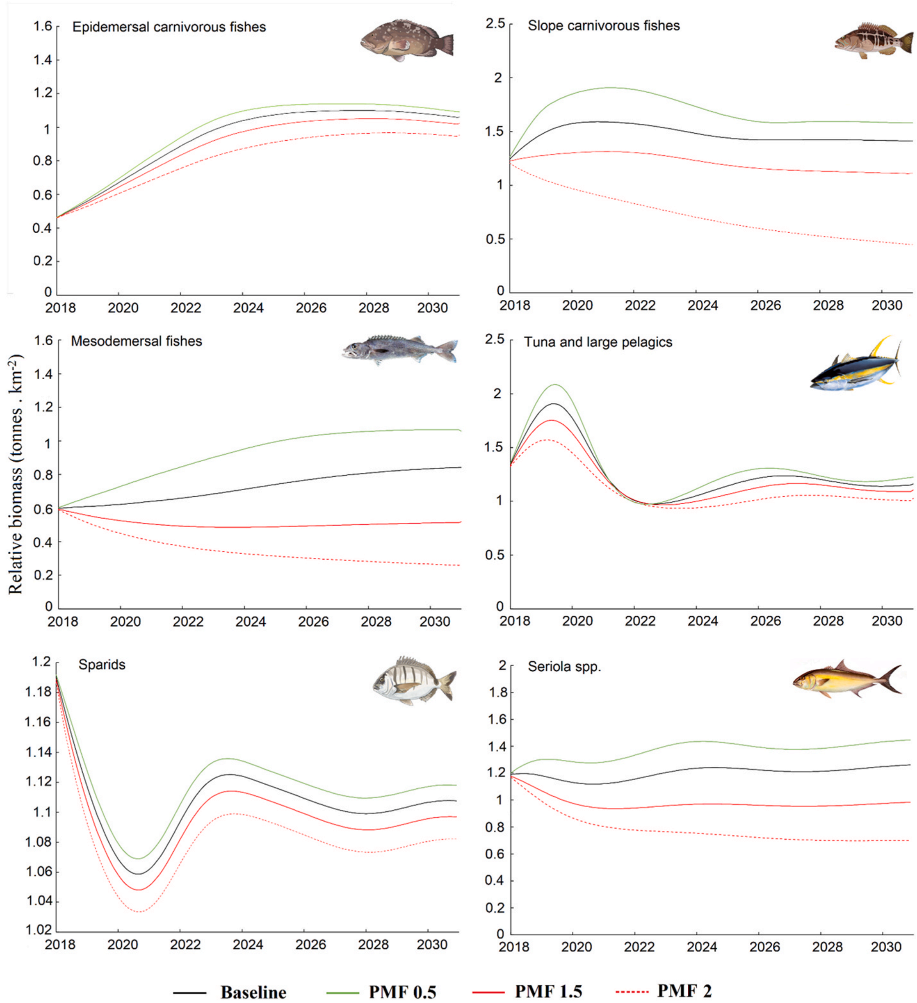

Fig. 4. Relative biomass trends of functional groups related to multi-species fisheries in EHSSF model. BL: Baseline scenario; PMF (1.5, 2 and 0.5): Promoting multispecies fisheries.

and large pelagics, sparids and epidemersal carnivorous functional groups. On the contrary, under PMF 0.5 scenario, multispecies functional groups increased their relative biomasses to reduce −50% in the fishing effort as expected, highlighting the positive trends for slope carnivorous fishes, mesodemersal fishes and *Seriola* spp. increasing the initial biomass over time in the 2018–2031 projection.

3.2.4. Scenario 4: fishing at maximum sustainable yield (MSY)

Fishing at maximum sustainable yield for single-species fisheries showed a slight decrease in biomass levels in the *S. cretense* fishery compared to the baseline 2010 scenario. Contrastingly, the MSY trend lines for *K. pelamis, A. solandri,* morays, and pandalid shrimps were below baseline trends in the next 13 years of simulation (Fig. 4). The demersal fish *B. splendens* did not show large changes in biomass with a baseline trend as a reference point.

4. Discussion

The present study attempted to create an EwE model incorporating our best biological and social information knowledge to interpret the effects of potential changes in the EHSSF derived from a natural hazard. The EHSSF model is a prototype focused on SSF management representing trophic dynamics in the coastal waters of El Hierro, because small-scale fishers from La Restinga may fish in the entire island coasts. Our results have detected the most vulnerable target species to fishing effort changes over the next few years. Therefore, the outcomes of this study provide an assessment of current SSF fishery trends and a prototype tool for understanding the optimal fishing management scenarios for the future. Although the SSF management is challenging due to its dynamism and complexity (Pauly 2011), the EwE modeling approach can represent different case-specific fisheries, heterogeneity, diversity, and interactions. However, reaching a realistic design and a more advanced model requires combining scientists' knowledge across disciplines and sectors, and integrating a detailed social dimension in fisheries.

The Ecopath model was built based on local fishing studies with source data of an overall reasonable quality, especially considering the normally low data availability for slope and mesopelagic habitats. However, some observed biomass information such as the mesopelagic habitat would be desirable to validate and improve the simulations. Further studies confirmation and refinement of these input parameters could help to increase the capacity of the model. In general, model outputs seemed appropriated for the purpose of the study since the pedigree index was within the overall mean of published EwE models (Colléter et al., 2015). The developed model was able to reproduce the historical catch and biomass trends for the main target functional groups after setting up the simulations representing the effects of fishing.

The EwE simulations of the model attempted to reproduce the current SSF scenarios fed by the available sociodemographic data into different hypothetical small-scale fishery scenarios based on the fishing effort. The exploration in detail of long-term fishing scenarios reveals important changes in the biomass of several groups. Some of those are considered essential for the SSF maintenance in La Restinga fishing community (Dorta and Martín-Sosa, 2022), and they are key for the small-scale fishing activity maintenance. In particular, we focused on the essentiality importance order as follows: *S. cretense, A. solandri, K. pelamis,* Tuna and large pelagics fishes, *B. splendens*, Slope carnivorous fishes, Pandalid shrimps and Morays.

In general, the analysis of *Sparisoma cretense*, the most emblematic and fast-growing population (Petrakis and Papacontastinous 1990) highlight the importance of fishing effort controls to increase stock biomass as the main driver for this fishery in the Canary Islands (Tuya et al., 2006). Despite the responses of *S. cretense* to fishing effort, the fishery tends towards sustainability considering the life traits and the recovery capacity after a submarine volcano eruption (Mendoza et al., 2020) of this specie. We also recognize the efforts made by local fishermen during the post-volcanic stage, on limiting this fishery. However, following the temporal results (YFC and MSY scenarios) and the uncertainty of the model we suggest avoiding in long-term higher increases of fishing effort than those explored in the *S. cretense* fishery.

The *Acanthocybium solandri* fishery showed a sustainable result even with increasing annual catches in recent years. However, the oceanic habits and the high mobility of this species could decrease the reliability, as is well-known, of migratory-pelagic temporal trends in the modeling approach (Christensen and Walters, 2004). In this field, we valuate the maintenance of artisanal or traditional low-impact of the harpoon employed for the wahoo fisheries facing other techniques.

In a similar manner, *Katsuwonus pelamis* and tuna species seasonal fishery reveal a high capacity to withstand an increased fishing pressure. These migratory and wide-ranging species may be affected by conditions outside the study area (Martell 2004). Also, tuna fisheries in the Canary Islands are highly dependent on market conditions and subsidies due to the insularity and remoteness of the seafood market (Carmona 2022; Pascual-Fernández et al., 2019). Therefore, this trend could be more uncertain than other explored temporal simulations. However, considering the YFC, PMF and MSY trends within the natural fishing closure due to seasonality and the multiple fishing gear combination, we suggest promoting the exploitation of this species instead of the more vulnerable shelf-based fisheries.

One of the most popular fishes in recent years, *Beryx splendens,* could become a vulnerable species soon if fishing mortality of this resource increases substantially. This target species belongs to the mesodemersal fishery area, where the population status of *B. splendens* and associated fish species is largely unknown in this bathymetric area (500–800 depth). Stock assessment of deep-water species is considerably more complicated than shelf-based species (Large et al., 2001). With the uncertainty of this high mobility species (Wiff et al., 2012), the fishing pressure after the volcanic eruption (Brito et al., 2013), and considering the lack of valued information for this functional group we suggest keeping the current level of fishing mortality. In other Atlantic fisheries (Gulf of Guinea), a rapid fish stock depletion of *B. splendens* was observed using demersal longlines (Salmerón et al., 2015). In the past, specific regulations have been implemented to protect this fishing resource from the longlines in El Hierro (BOC-A-1997-084-792). Similarly, the conservation of low-impact fishing gears employed by the SSF of La Restinga could support the viability of the future *B. splendens* fishery in El Hierro. In addition, we recommend the monitoring of this essential EHSSF with direct surveys to validate the explored scenarios.

The slope fishery area includes essential species such as *Serranus atricauda* and also keystone species (Valls et al., 2015) as ecological indicators of a healthy ecosystem: *Balistes capriscus* and *Bodianus scrofa* (Hernández 2017; Mendoza and Hernández, 2019; Mendoza et al., 2020). A depletion of slope fishes could threaten the trophic balance of the ecosystem, even damaging trophic migratory connections between epipelagic and mesopelagic habitats. In this regard, the migration among habitats for different species of slope carnivorous fishes could increase the uncertainty of the biomass estimates. The limited information on biomass in the temporal dimension suggests to strengthening of the conservation of these fishes by maintaining the current fishing level efforts. An increase of the fishing effort to the main target specie (*S. atricauda)* could impact negatively into the complementary species and threaten the sustainability of this fishery. The regulation and monitoring of this fishery should be essential in promoting resource persistence and stability.

The other functional group that benefits under this scenario is the pandalid shrimps, mainly represented by *Plesionika narval.* This abundant and widespread species is probably favored by its reproductive biology (González et al., 1997) and the reduced number of fishing productive units using shrimp traps in La Restinga harbor. According to the EHSSF model results and the low annual catches this fishery could be promoted; however, this depends on market options related mainly to demand of the service sectors.

Finally, the last essential specie (Morays) and also strongly related to the services sector showed a positive scenario for younger fishermen. The redistribution of the fishing effort towards moray traps may be an optimal and sustainable management strategy when necessary. Although different vulnerable species are included in this functional group, more accuracy in landings databases would be desirable.

The results of the changing fishing trends after the submarine volcanic crisis suggest the need to evaluate the catches and promote a biomass monitoring of essential species when fishing effort increases above baseline levels. These mainly involves the slope carnivorous fishes, mainly represented by *S. atricauda* and mesodemersal fishes, including *B. splendens*. In addition, we recommend focusing current fishing efforts on migratory species during the summer months and those that have shown an apparent capacity to withstand more fishing pressure, such as morays and pandalid shrimps. We also recommend improving fishing strategies that strengthen multi-species fisheries, which would enhance the SSF system's resilience and be cautious with vulnerable species such as the slope fishes. We think that support for fishers' multiple enrolments, which allows them to fish in different boats, would benefit multi-species fisheries. However, it is still necessary to know which factors influence the SSF community regarding the distribution of fishing effort among the different small-scale fishing productive units and which questions limit young fishers' recruitment strategies for larger fishing productive units.

5. Conclusions

This advice-oriented trophic model represents a new step in understanding the functioning of the SSF of El Hierro and ecosystem-based related management questions. However, the current version of the ecosystem model should be used with caution until biomass estimates of deep-sea habitats are validated with survey data. Our findings indicate that management scenarios explored in this model are helpful to develop an adaptive and co-management strategy, together with the SSF community, towards optimal fishery exploitation and preserving the sustainability of the marine resources of El Hierro.

One of the most successful strategies identified is the combination among fisheries during the year. This fishing community of La Restinga has shown its ability to diversify through multiple species combinations, changing technology, flexibility in time spent fishing and boat crew members' composition, and market developments. Therefore, any management measures to be considered as successful to reach the sustainability of essential fisheries depend on interactions among these heterogeneous factors. In this sense, we need to incorporate additional tools to assess the variation of the socio-economic aspects in the temporal and spatial modeling, with the main goal to maintain the ecosystem model actualized.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgments

We would like to thank all researchers from the 'Universidad de La Laguna' who helped us to build this ecological model as well as Professor José J. Pascual-Fernández who led the "Instituto Universitario de Investigación Social y Turismo" (ISTUR) and supported the paper's preparation. We would also like to acknowledge Macarofood project (Interreg-MAC/2.3d/015) for providing fisheries landings data with the support of the European Regional Development Fund and the European Project FoodE funding from the European Union's Horizon 2020 research and innovation program under grant agreement No. 862663. This study was partially founded by Cajacanarias Foundation and Fundación Bancaria "La Caixa" through the "Proyecto para el fortalecimiento de la capacidad de adaptación y recuperación en la población de La Restinga (El Hierro, Islas Canarias)" [2017REC23] carried out with research funds from the CajaCanarias Foundation and the La Caixa Banking Foundation. RCM was also partially funded by Ramón Areces Foundation through the XVII Call for Social Research Grant, founding reference "CISP17A5887''.

Appendix A. Supplementary data

Supplementary data to this chapter can be found online at http://doi.org/10.1016/j.ocecoaman.2022.106297.

References

Andersen, R., Wadel, C., 1972. Comparative Problems in Fishing Adaptations. North Atlantic Fishermen. St. John's ISER, pp. 141–165.
Arreguín-Sánchez, F., Hernández-Herrera, A., Ramírez-Rodríguez, M., Pérez-España, H., 2004. Optimal management scenarios for the artisanal fisheries in the ecosystem of La Paz Bay, Baja California Sur, Mexico. Ecol. Model. 172 (2–4), 373–382.
Arrizabalaga, H., López-Rodas, V., Ortiz de Zárate, V., Costas, E., Gonzaléz-Garcés, A., 2002. Study on the migrations and stock structure of albacore (*Thunnus alalunga*) from the Atlantic Ocean and the Mediterranean Sea based on conventional tag release-recapture experiences. Collect Vol Sci Pap ICCAT 54 (4), 1479–1494.
Bavinck, M., Jentoft, S., Pascual-Fernández, J.J., Marciniak, B., 2015. Interactive coastal governance: the role of pre-modern Fisher organizations in improving governability. Ocean Coast Manag. 117, 52–60.
Bilbao-Sieyro, A., Pérez-González, Y., Martín-Sosa, P., Castro-Hernández, J.J., Jiménez-Alvarado, D., Pascual-Fernández, J.J., 2022. Marine recreational fisheries in the canary islands: state of knowledge, preliminary results. In: Biology and Life Sciences Forum, vol. 13. Multidisciplinary Digital Publishing Institute, p. 7. No. 1.
BOC-A-1997-084-792. Decreto 90/1997, de 9 de junio, por el que se excepciona la aplicación del artículo 5 del Decreto 154/1986, de 9 de octubre, de regulación de artes y modalidades de pesca en aguas interiores del Archipiélago Canario, para la práctica de la pesca con palangre en las aguas interiores del litoral de las islas de Fuerteventura y El Hierro. http://www.gobiernodecanarias.org/boc/archivo/1997/084/pda/001.html.
Bortone, S.A., Van Tassell, J.L., Brito, A., Falcón, J.M., Bundrick, C.M., 1991. A visual assessment of the inshore fishes and fishery resources off El Hierro, Canary Islands: a baseline survey. Sci. Mar. 58 (3), 529–541.
Brito, A., Hernández, J.C., Clemente, S., Sangil, C., Falcón, J.M., Balsalobre, M., 2012. Informe preliminar sobre el impacto del volcán submarino de El Hierro en la biodiversidad y los recursos litorales. Grupo de investigación BIOECOMAC, Universidad de La Laguna, p. 137.
Brito, A., Hernández, J.C., Clemente, S., Dorta, C., 2013. Estado actual de la biodiversidad y los recursos marinos costeros en la Reserva Marina de La Restinga-Mar de las Calmas (El Hierro). Grupo de investigación BIOECOMAC, Universidad de La Laguna, p. 48.
Brito, A., Dorta, C., 1998. Programa de Gestión de las Pesquerías Artesanales de La Restinga, PGPAdRE. Departamento de Biología Animal (Ciencias Marinas). Universidad de La Laguna. Consejería de Agricultura, Pesca y Alimentación del Gobierno de Canarias, p. 71 pp. + anexos.
Burnham, K.P., Anderson, D.R., 2002. A Practical Information-Theoretic Approach. Model Selection and Multimodel Inference, second ed. Springer, New York, p. 2.
Carmona, X., 2022. Changes in the Spanish fish-canning industry since Spain's entry to the European Union. Ocean Coast Manag. 216, 105972.
Castro, J.J., Divovich, E., de Molina Acevedo, A.D., Barrera-Luján, A., Riera, R., 2019. Reconstruction of marine small-scale fisheries captures in the canary islands (NE atlantic ocean) from 1950 to 2010. Sci. Mar. 83 (1), 7–17.
Christensen, V., Walters, C.J., 2004. Ecopath with Ecosim: methods, capabilities and limitations. Ecol. Model. 172, 109–139.
Christensen, V., Walters, C.J., Pauly, D., Forrest, R., 2008. Ecopath with Ecosim version 6. User guide. Len Oce Futs Proj 235.
Cisneros-Montemayor, A.M., Zetina-Rejón, M.J., Espinosa-Romero, M.J., Cisneros-Mata, M.A., Singh, G.G., Melo, F.F.R., 2020. Evaluating ecosystem impacts of data-limited artisanal fisheries through ecosystem modelling and traditional Fisher knowledge. Ocean Coast Manag. 195, 105291.
Colléter, M., Valls, A., Guitton, J., Gascuel, D., Pauly, D., Christensen, V., 2015. Global overview of the applications of the Ecopath with Ecosim modeling approach using the EcoBase models repository. Ecol. Model. 302, 42–53.
Couce-Montero, L., Christensen, V., Castro, J.J., 2015. Effects of small-scale and recreational fisheries on the Gran Canaria ecosystem. Ecol. Model. 312, 61–76.
Couce-Montero, L., Christensen, V., Bilbao Sieyro, A., Pérez González, Y., Jiménez-Alvarado, D., Castro, J.J., 2019. Temporal and spatial predictions of effect of alternative fishing policies for the Gran Canaria marine ecosystem. J. Fish. Biol. 94 (6), 882–895.
De la Cruz Modino, R., 2004. Patrimonio Natural y reservas marinas. PASOS Rev. Tur. Patrim. Cult. 2 (2), 179–192.
De la Cruz Modino, R., 2012. Turismo, pesca y gestión de recursos. *Aportaciones desde La Restinga y L'Estartit*. Ministerio de Educación, Cultura y Deporte, Madrid.
De la Cruz Modino, R., Piñeiro-Corbeira, C., et al., 2022. Small but strong: socioeconomic and ecological resilience of a small European fishing community affected by a submarine volcanic eruption. Ocean Coast Manag. 223.
De Lara, D.R.M., Corral, S., 2017. Local community-based approach for sustainable management of artisanal fisheries on small islands. Ocean Coast Manag. 142, 150–162.
De Paz, P.L.P., Sangil, C., de Soto, N.A., Hernández, J.C., Clemente, S., Hernández, P.A., 2013. El Hierro: volcán de naturaleza y melancolía. In: Afonso-Carrillo, E.J. (Ed.), El Hierro: nacimiento de un volcán. Instituto de Estudios Hispánicos. Puerto de La Cruz, ISBN 978-84-616-5651-6, pp. 13–53, 179.
Dorta, C., Martín-Sosa, P., 2022. Fishery essentiality: a short-term decision-making method based on economic viability as a tool to understand and manage data-limited small-scale fisheries. Fish. Res. 246, 106171.
European Commission, Joint Research Centre, Scientific, Technical and Economic Committee for Fisheries, 2020. The 2020 annual economic report on the EU fishing fleet (STECF 20-06). https://data.europa.eu/doi/10.2760/500525.
FAO, 2020. El estado mundial de la pesca y la acuicultura 2020. La sostenibilidad en acción. Roma.
Fouzai, N., Coll, M., Palomera, I., Santojanni, A., Arneri, E., Christensen, V., 2012. Fishing management scenarios to rebuild exploited resources and ecosystems of the Northern-Central Adriatic (Mediterranean Sea). J. Mar. Syst. 102, 39–51.
Froese, R., Pauly, D., 2010. FishBase.
Galván-Tudela, A., 1990. Pescar en grupo": de los azares ambientales a los factores institucionales (La Restinga, El Hierro). Eres (Serie de Antropología) 2, 39–60.
Galván-Tudela, A., 2003. Sobre las culturas de la mar: prácticas y saberes de los pescadores de La Restinga. El Pajar: Cuaderno de Etnografía Canaria (15), 108–117.
García, S.M., 2003. The Ecosystem Approach to Fisheries: Issues, Terminology, Principles, Institutional Foundations, Implementation and Outlook (No. 443). FAO.
González, J.A., 2008. Memoria científico-técnica final sobre el Estado de los Recursos Pesqueros de Canarias (REPESCAN). Instituto Canario de Ciencias Marinas, Agencia Canaria de Investigación, Innovación y Sociedad de la Información, Gobierno de Canarias. Telde (Las Palmas), p. 210.
González, J.A., Tuset, V.M., Lozano, I.J., Santana, J.I., 1997. Biology of *Plesionika narval* (Crustacea, Decapoda, pandalidae) around the canary islands (eastern central atlantic). Estuar. Coast Shelf Sci. 44 (3), 339–350.
González, J.A., González-Lorenzo, G., Tejera, G., Arenas-Ruiz, R., Pajuelo, J.G., Lorenzo, J.M., 2020. Artisanal fisheries in the Canary Islands (Eastern-central Atlantic): description, analysis of their economic contribution, current threats, and strategic actions for sustainable development. Acta Ichthyol. Piscatoria 50, 269–289.
Hernández, J.C., 2017. Influencia humana en las fluctuaciones poblacionales de erizos de mar. Rev. Biol. Trop. 65 (1–1), S23–S34.
Heymans, J.J., Coll, M., Link, J.S., Mackinson, S., Steenbeek, J., Walters, C., Christensen, V., 2016. Best practice in Ecopath with Ecosim food-web models for ecosystem-based management. Ecol. Model. 331, 173–184.
Jentoft, S., Pascual-Fernandez, J.J., De la Cruz Modino, R., Gonzalez-Ramallal, M., Chuenpagdee, R., 2012. What stakeholders think about marine protected areas: case studies from Spain. Hum. Ecol. 40 (2), 185–197.
Kolding, J., Béné, C., Bavinck, M., 2014. Small-scale fisheries: importance, vulnerability and deficient knowledge. Governance of marine fisheries and biodiversity conservation 317–331.
Large, P.A., Hammer, C., Bergstad, O.A., Gordon, J.D.M., Lorance, P., 2001. Options for the Assessment and Management of Deep-Water Species in the ICES Area. Scientific council meeting.
Link, J.S., 2010. Adding rigor to ecological network models by evaluating a set of pre-balance diagnostics: a plea for PREBAL. Ecol. Model. 221, 1580–1591.
Lira, A.S., Lucena-Fredou, F., Le Loc'h, F., 2021. How the fishing effort control and environmental changes affect the sustainability of a tropical shrimp small scale fishery. Fish. Res. 235, 105824.
Macfadyen, G., Salz, P., Cappell, R., 2011. Characteristics of Small-Scale Coastal Fisheries in Europe. Policy Department: Structural and Cohesion Policies, European Parliament, Fisheries, p. 162.

Martell, S., 2004. Dealing with migratory species in ecosystem models. Back to the Future: Advances in Methodology for Modelling and Evaluating Past Ecosystems as Future Policy Goals. Fish Cen Res Rep 12 (1), 41–44.
Martín-Sosa, P., Cansado, S., Boza, C., González-Lorenzo, J.G., Falcón, J.M., Villegas, N., 2010. Información pesquera en el entorno de la Reserva Marina de Punta de La Restinga – Mar de Las Calmas (El Hierro). Periodo 2003-10. *IEO, Centro Oceanográfico de Canarias*. Informe, p. 19. + Anexos.
Mendoza, J.C., Hernández, J.C., 2019. Modelo trófico del ecosistema rocoso litoral de la isla de El Hierro, islas Canarias. Scientia Insularum. Año 2019, número 2.
Mendoza, J.C., Clemente, S., Hernández, J.C., 2020. Modeling the role of marine protected areas on the recovery of shallow rocky reef ecosystem after a catastrophic submarine volcanic eruption. Mar. Environ. Res. 155, 104877.
Ovando, D., Free, C.M., Jensen, O.P., Hilborn, R., 2021. A history and evaluation of catch-only stock assessment models. Fish and Fish 23 (3), 616–630.
Pascual-Fernández, J.J., 1991. Entre el mar y la tierra. Los pescadores artesanales canarios. Tenerife: Interinsular Canaria, Print, 1991.
Pascual-Fernández, J.J., De la Cruz Modino, R., 2011. Conflicting Gears, Contested Territories: MPAs as a Solution. World Small-Scale Fisheries Contemporary Visions, pp. 205–220.
Pascual-Fernández, J.J., Chinea-Mederos, I., De la Cruz-Modino, R., 2015. Marine protected areas, small-scale commercial versus recreational Fishers: governability challenges in the Canary Islands, Spain. In: Interactive Governance for Small-Scale Fisheries. Springer, Cham, pp. 397–412.
Pascual-Fernández, J.J., De la Cruz Modino, R., Chuenpagdee, R., Jentoft, S., 2018. Synergy as strategy: learning from La Restinga, canary islands. Maritain Stud. 17 (1), 85–99.
Pascual-Fernández, J.J., Pita, C., Josupeit, H., Said, A., Garcia Rodrigues, J., 2019. Markets, distribution and value chains in small-scale fisheries: a special focus on Europe. In: Transdisciplinarity for Small-Scale Fisheries Governance. Springer, Cham, pp. 141–162.
Pascual-Fernández, J.J., Pita, C., Bavinck, M., 2020a. Small-Scale Fisheries in Europe: Status, Resilience and Governance. Springer, Cham.
Pascual-Fernández, J.J., Florido-del-Corral, D., De la Cruz-Modino, R., Villasante, S., 2020b. Small-scale fisheries in Spain: diversity and challenges. In: Small-Scale Fisheries in Europe: Status, Resilience and Governance. Springer, Cham, pp. 253–281.
Pauly, D., 2011. Foreword, p 15-17. In: Chuenpagdee, R. (Ed.), World Small-Scale Fisheries Contemporary Vision. Euburon, Delft.
Percy, J., O'Riordan, B., 2020. The EU common fisheries policy and small-scale fisheries: a forgotten fleet fighting for recognition. Small-scale fisheries in Europe: status. Resilience and Governance 23, 23.
Petrakis, G., Papaconstantinou, C., 1990. Biology of *Sparisoma cretense* in the dodecanese (Greece). J. Appl. Ichthyol. 6 (1), 14–23.
Philippsen, J.S., Minte-Vera, C.V., Coll, M., Angelini, R., 2019. Assessing fishing impacts in a tropical reservoir through an ecosystem modeling approach. Rev. Fish Biol. Fish. 29 (1), 125–146.
Piñeiro-Corbeira, C., Barrientos, S., Aswani, S., Pascual-Fernández, J.J., De la Cruz Modino, R., 2022. Can Local Knowledge of Small-Scale Fishers Be Used to Monitor and Assess Changes in Marine Ecosystems in a European Context? In: Misiune, I., Depellegrin, D., Egarter Vigl, L. (eds) Human-Nature Interactions. Springer, Cham, pp. 299–314.
Pinnegar, J.K., Polunin, N.V., 2004. Predicting indirect effects of fishing in Mediterranean rocky littoral communities using a dynamic simulation model. Ecol. Model. 172 (2–4), 249–267.
Plagányi, É.E., 2007. Models for an Ecosystem Approach to Fisheries (No. 477). Food and Agriculture Organization of the United Nations.
Salmerón, F., Báez, J.C., Macías, D., Fernandez-Peralta, L., Ramos, A., 2015. Rapid fish stock depletion in previously unexploited seamounts: the case of *Beryx splendens* from the Sierra Leone Rise (Gulf of Guinea). Afr. J. Mar. Sci. 37 (3), 405–409.
Santamaría, M.T.G., Falcón, J.M., Jiménez, S., Villegas, N., González, J.F., 2014. Gepeto Project. Case Study 7: Artisanal Fisheries in the Canary Islands. Centro Oceanográfico de Canarias. *3 de abril 2014*. Technical report.
Scott, E., Serpetti, N., Steenbeek, J., Heymans, J.J., 2016. A stepwise fitting procedure for automated fitting of Ecopath with Ecosim models. Software X 5, 25–30.
Tsehaye, I., Nagelkerke, L.A., 2008. Exploring optimal fishing scenarios for the multispecies artisanal fisheries of Eritrea using a trophic model. Ecol. Model. 212 (3–4), 319–333.
Tuya, F., Boyra, A., Sánchez-Jerez, P., Barberá, C., Haroun, R.J., 2004. Relationships between rocky-reef fish assemblages, the sea urchin *Diadema antillarum* and macroalgae throughout the Canarian Archipelago. Mar. Ecol. Prog. Ser. 278, 157–169.
Tuya, F., Ortega-Borges, L., Sanchez-Jerez, P., Haroun, R.J., 2006. Effect of fishing pressure on the spatio-temporal variability of the parrotfish, *Sparisoma cretense* (Pisces: scaridae), across the Canarian Archipelago (eastern Atlantic). Fish. Res. 77 (1), 24–33.
Valls, A., Coll, M., Christensen, V., 2015. Keystone species: toward an operational concept for marine biodiversity conservation. Ecol. Monogr. 85 (1), 29–47.
Walters, C., Christensen, V., Pauly, D., 1997. Structuring dynamic models of exploited ecosystems from trophic mass balance assessments. Rev. Fish Biol. Fish. 7, 139–172.
Walters, C.J., Christensen, V., Martell, S.J., Kitchell, J.F., 2005. Possible ecosystem impacts of applying MSY policies from single-species assessment. ICES J. Mar. Sci. 62 (3), 558–568.
Wiff, R., Quiroz, J.C., Gatica, C., Contreras, F., Paramo, J., Barrientos, M.A., 2012. Uncertain population dynamic and state variables of alfonsino (*Beryx splendens*). Lat Am J Aquat Res 40 (1), 201–212.