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Scientific and Fisher's Knowledge-Based Ecological Risk Assessment: Combining Approaches to Determine the Vulnerability of Fisheries Stocks

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Abstract: Small-scale fishing is a multi-gear activity that focuses on a wide range of species. As there is a considerable diversity of species, it is often difficult to keep track of all of those that are caught, and due to the lack of data or poor quality, most stock statuses are currently unknown around the world. Therefore, local ecological knowledge provided by fishers has been regarded as a valuable source of information to bridge these crucial gaps. This study assesses the vulnerability status of 22 fishing stocks in the Azores, through productivity and susceptibility analyses (PSAs) using two independent data sources: *conventional scientific knowledge* and *fishers' knowledge* data. We created four PSAs with separate and integrated data sources. Although we found some differences in the vulnerability scores and rankings, the risk outputs of the PSAs using independent and integrated sources of data generally match, reflecting a similar pattern trend. The findings of this work suggest that integrating FK may be an alternative to provide good fisheries' assessment outcomes in the absence of CSK. Overall, this research supports the inclusion of fishers' knowledge in vulnerability assessments as not only beneficial in the absence of data, but also as a supplement to data that can improve management advice.

Keywords: small-scale fisheries; local ecological knowledge; productivity-susceptibility analyses; data-limited fisheries; Azores fisheries

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1. Introduction

Small-scale fisheries (SSFs) play an important role worldwide; they are widespread fishing activities carried out in various manners and environments, which are responsible for food security and poverty reduction, and directly and indirectly support the livelihoods of millions of people [1,2]. SSFs account for 90% of employment in marine fisheries and contribute to more than half of global fish catches [2]. In general, a SSF is a multi-gear enterprise that targets a wide range of species, depending on their availability and season [3].

In the European Union (EU), 84% of the fishing fleet belongs to SSFs, generating around 53% of jobs in the fishing industry and accounting for a quarter of the catch value, directly providing approximately 100,000 jobs, and contributing to the local and regional economic growth [4]. Portugal is one of the European countries with the largest fishing fleet, totalling 7655 fishing boats, which account for 9.23% of the EUs' fleet [5,6].

In the Azores Archipelago, a Portuguese autonomous region, the fishing fleet comprises 711 fishing boats, representing 8.49% of the total Portuguese fleets [5,6]. Azorean fisheries are primarily small-scale and artisanal with 88% of fishing boats being under 12 m, having open and closed decks and limited power. These fleets target a wide range of fisheries resources, mainly demersal species [7,8]. These fisheries represent one of the main economic activities in the Azores, employing over 4000 people, accounting for nearly 27.8% of the overall exports, and providing a significant source of revenue for residents on several islands of the archipelago [6,9]. Azorean fisheries have increased in relevance over the past years, both in terms of landings and revenue, with demersal species landings accounting for more than 50% of the total annual value landed in the region [7,8].

About 1883 marine species have been found in the Azores region, with 138 species, such as algae, molluscs, crustaceans, echinoderms, and fish that are commercially exploited throughout the last decade [8,10]. Among these species, 22 stocks have recently been identified as priority species for assessment and monitoring under the EU Marine Strategy Framework Directive (MSFD; Descriptor 3) and the United Nations Sustainable Development Goal 14 (SDG; Indicator 14.4.1) [8].

As SSFs exploit a wide range of species, monitoring which ones are caught can be problematic. The biological data collection for most resources exploited by fisheries is insufficient to estimate the stock levels, which requires substantial data sets [11]. Considering the absence of conventional scientific knowledge (CSK) data from surveys or monitoring programs about fishing stocks, local ecological knowledge (LEK) held by fishers, has been regarded as a valuable source of information, which may help to overcome these limitations [12–14].

Fishers' knowledge (FK) constitutes empirical knowledge of the biological and ecological features of fish populations, accumulated through time by fishers, as resource users [15,16]. This knowledge consists of experience-based observations of the natural resources and ecosystem, and their incorporation into assessment programs could reduce the existing knowledge gaps and provide more information for management and conservation efforts [14,17–19]. FK can, therefore, provide valuable information about species' monitoring, abundance, distribution, seasonal changes, and spatial/temporal shifts, which are sensitive to ecosystem changes [20–22].

The productivity and susceptibility analyses approach (PSAs) is a data-poor framework that uses semi-quantitative risk assessments to determine the vulnerability of the fisheries stocks [23]. It is a flexible tool that can benefit from including both the CSK and FK data in its assessment, thereby reducing the lack of information about target stocks [18,19]. PSAs are efficient because they can analyse multiple stocks at the same time and identify species that require additional management attention, due to their highly vulnerable score on the fishing impacts. They are widely used by decision-makers around the world, as they identify species with the highest risk of fishing impact [23–29]. Recently, Torres et al. [30] performed a PSA focusing on the vulnerability of Azorean coastal fish species.

Within this context, considering the characteristics and the socioeconomic importance of SSFs in the Azores region and the wide diversity of its fishery resources—about many of which there exists no basic information regarding the biological traits and life cycle, needed to perform traditional stock assessments—we proposed a case study with 22 priority marine stocks commercially exploited in the Azores, using a PSA framework that includes both independent CSK and FK as input data to estimate the stock vulnerability and to determine whether there is any overlap between their outcomes. This case study emerges, focusing on 22 priority stocks and evaluating and analysing the outcomes of the PSA, using independent and integrated data sources to determine the potential utility of FK when management recommendations are needed but CSK data on fish populations is limited or insufficient.

2. Materials and Methods

2.1. Data Acquisition and Target Species

The 22 priority stocks in the Azores were selected for this work (Table 1). To obtain data for productivity and susceptibility attributes within the CSK PSA, we performed a literature review of the biological and ecological attributes and the fishing aspects of the selected stocks. The literature used for each productivity and susceptibility attribute is described in Sections 2.2.1 and 2.2.2. To obtain the productivity and susceptibility values for each attribute of the FK PSA, a structured questionnaire was developed to assess the FK and score in terms of both the productivity and susceptibility information for each stock (Supplementary Materials). The questionnaires were administered individually, to avoid group method biases [19]. This questionnaire included 27 close-ended items, regarding sociodemographic information, as well as ecological and biological knowledge of the stocks.

Table 1. The 22 priority marine stocks commercially exploited by small-scale fisheries in the Azores. IUCN categories: data deficient (DD), least concern (LC), near threatened (NT), vulnerable (VU).

Family	Species	Author	Common Name	FAO Code	IUCN
Rajidae	*Raja clavata*	Linnaeus, 1758	Thornback ray	RJC	NT
Congridae	*Conger*	Linnaeus, 1758	European conger	COE	LC
Carangidae	*Seriola* spp.		Amberjacks nei	AMX	
Trichiuridae	*Aphanopus carbo*	Lowe, 1839	Black scabbardfish	BSF	LC
Scorpaenidae	*Pontinus kuhlii*	Bowdich, 1825	Offshore rockfish	POI	DD
Sparidae	*Pagrus pagrus*	Linnaeus, 1758	Red porgy	RPG	LC
Phycidae	*Phycis phycis*	Linnaeus, 1766	Forkbeard	FOR	DD
Scorpaenidae	*Scorpaena scrofa*	Linnaeus, 1758	Red scorpionfish	SER	LC
Moridae	*Mora moro*	Risso, 1810	Common mora	RIB	LC
Trichiuridae	*Lepidopus caudatus*	Euphrasen, 1788	Silver scabbardfish	SFS	LC
Sebastidae	*Helicolenus dactylopterus*	Delaroche, 1809	Blackbelly rosefish	BRF	LC
Berycidae	*Beryx splendens*	Lowe, 1834	Splendid alfonsino	BYS	NT
Sparidae	*Pagellus bogaraveo*	Brünnich, 1768	Blackspot seabream	SBR	NT
Berycidae	*Beryx decadactylus*	Cuvier, 1829	Alfonsino	BXD	NT
Serranidae	*Serranus atricauda*	Günther, 1874	Blacktail comber	WSA	DD
Loliginidae	*Loligo forbesii*	Steenstrup, 1856	Veined squid	SQF	LC
Scombridae	*Scomber colias*	Gmelin, 1789	Atlantic chub mackerel	MAZ	LC
Scaridae	*Sparisoma cretense*	Linnaeus, 1758	Parrotfish	PRR	LC
Carangidae	*Trachurus picturatus*	Bowdich, 1825	Blue jack mackerel	JAA	LC
Scyllaridae	*Scyllarides latus*	Latreille, 1803	Mediterranean slipper lobster	YLL	DD
Palinuridae	*Palinurus elephas*	Fabricius, 1787	Common spiny lobster	SLO	VU
Patellidae	*Patella aspera*	Röding, 1798	Rough limpet	LQY	

Fishers were invited to respond to items about any of the 22 species that they were familiar with. Since SSFs in the Azores have a variety of target species, fishers usually replied to items for more than one species. Participants were fully anonymised, consenting adults who were informed of the studies' purpose and could interrupt their participation at any given moment, following the European Union regulations and ethical research guidelines [31,32]. Sampling the participants was accomplished in two ways: through convenience sampling of the fishers, that were questioned in person by researchers, or by sending the questionnaire to fisher associations who would then administer it to the consenting fishers.

2.2. Vulnerability Approach

Vulnerability is here defined as the level of impact, resulting from fishing activities that a population or stock can withstand, meant to reflect whether the fishing mortality exceeds the biological limits at which the species can renew itself, highlighting the stocks that are the most vulnerable to overfishing [24,33]. The vulnerability was assessed, using the PSA and was determined by the function of the weighted productivity and susceptibility attributes (see Section 2.3). The assumption of the approach is that the vulnerability of a given stock to overexploitation by a fishery is assessed by a function between these two groups of attributes: productivity, which is defined as a group of attributes that reflect the life history features and reflect the rate of the increased population in the stock, and susceptibility, which is defined as a group of attributes that reflect the interaction between stocks and fishing activities and may influence the reduction/removal portion of a population in the stock [23,33–35].

Each attribute of productivity and susceptibility is scored within the low (1), moderate (2), and high (3) score systems. Where for productivity, 1 indicates a relatively low productivity and a potentially high risk and 3 indicates a relatively high productivity and a potentially low risk, while for susceptibility, 1 indicates a relatively low susceptibility and a potentially low risk and 3 indicates a relatively high susceptibility and a potentially high risk [23,24]. To score each attribute of productivity and susceptibility on a scale of three levels, the quantiles of the value distribution between the stocks assessed were used when the thresholds were not available in the literature (see Sections 2.2.1 and 2.2.2) [27,29]. The average score of productivity and susceptibility attributes per stock was used to estimate the vulnerability. This combination generates a single overall vulnerability score per stock, obtained by calculating the Euclidean distance from the origin of the PSA scatterplot, according to the following equation:

$$v = \sqrt{\left[(P - X_0)^2 + (S - Y_0)^2\right]} \tag{1}$$

where P is the total productivity score, S is the total susceptibility score, v is the vulnerability score, X_0 and Y_0 are the origin coordinates of the biplot.

The results were then displayed on an x-y scatterplot with the risk categories ranking (low, moderate, and high risk). The risk category of the stocks was defined by ranking the vulnerability scores relative to each other using quantiles [27]. The low-risk category includes species that are less vulnerable to fishing impacts than species in the moderate and high-risk categories, which are progressively more vulnerable and require more attention [23,24,33,34].

This study performed four PSAs: one with the CSK data, (PSA-1), another with the FK data (PSA-2), and the two remaining PSAs integrated both sources of data—one included the CSK productivity and the FK susceptibility data (PSA-3), while the last one used the FK productivity and the CSK susceptibility data (PSA-4).

The questions in the questionnaire for the FK PSA were formulated in an indirect manner using language that was understandable to fishers to access their knowledge of the biology and ecologies of the chosen stocks. The questionnaire was adapted to fit the PSA approach. In other words, since the PSA is a tool that scores its attributes in a three-level scoring system, fishers were invited to score questions using the same scale, except for questions related to species' size and feeding ecology. When size related questions were answered in weight, they were transformed into length through the weight-length relationship, according to the following equation:

$$L = \sqrt[b]{W/a} \tag{2}$$

where L is length, W is weight, and a and b are the parameters of the length-weight relationship. These parameters were obtained from the available scientific literature (CITAR Synopsis).

For items related to the feeding ecology, questions were asked about what each species usually eats in its natural environment. For answers related to the feeding ecology to fit within the three-level PSA scores, the answers were divided into three groups: (1) indications that species' main food preference was algae were treated as a lower trophic level; (2) generalist species with different dietary preferences, were attributed an intermediate trophic level; (3) specialized species whose main dietary items were fish and/or crustaceans and/or mollusks, were attributed a higher trophic level.

In the PSAs with the CSK and FK input data. The thresholds within the low (1), moderate (2), and high (3) score systems were defined using the quantile distribution of the 22 stocks [27,29]. When data on the attributes were missing, they were not used in the productivity and susceptibility final score computations [27].

2.2.1. Productivity Attributes

Nine attributes related to life-history traits were selected to be used in the productivity of all PSAs, selected following Patrick et al. [24] and Lucena-Frédou et al. [27]. Information to score each attribute was obtained from the literature (CSK PSA) and from interviews with fishers (FK PSA). Detailed descriptions of the attributes are presented below and the details of the scores can be seen in Tables 2 and 3 for the CSK and FK PSAs, respectively.

Table 2. Productivity attributes for the conventional scientific productivity and susceptibility analysis and the thresholds of scoring used to estimate the stock vulnerability in the Azores. Source, a: Patrick et al. [24]; b: Lucena-Frédou et al. [27].

Attributes	Ranking			Source
	High (3)	Moderate (2)	Low (1)	
von Bertalanffy growth coefficient (k, cm·year^{-1})	>0.12	0.07–0.12	<0.07	a, b
Maximum size (L_{max}, cm)	<53.00	53.00–88.25	>88.25	a, b
Size at first maturity (L_{50}, cm)	<23.87	23.87–34.05	>34.05	a, b
Intrinsic growth rate (r)	>0.50	0.31–0.50	<0.31	a, b
Mean trophic level (TL)	<3.75	3.75–4.13	>4.13	a, b
L_{50}/L_{max}	<0.43	0.43–0.48	>0.48	b
Maximum age (A_{max}, year^{-1})	<11	11–20.00	>20.00	a, b
Age maturity (A_{mat}, year^{-1})	<2.23	2.23–4.50	>4.50	a

Table 3. Productivity attributes for the fishers' knowledge productivity and susceptibility analysis and the thresholds of the scoring used to estimate stock vulnerability in the Azores. Source, a: Patrick et al. [24]; b: Lucena-Frédou et al. [27].

Attributes	Ranking			Source
	High (3)	Moderate (2)	Low (1)	
Maximum size (L_{max}, cm)	<49.78	49.78–86.20	>86.20	a, b
Size at first maturity (L_{50}, cm)	<23.87	23.87–34.05	>34.05	a, b
L_{50}/L_{max}	<0.37	0.37–0.53	>0.53	b
Intrinsic growth rate (r)	>2.47	1.75–2.47	<1.75	a, b
Fecundity	>2.93	2.60–2.93	<2.60	a, b
Mean trophic level (TL)	<2.93	2.93–2.98	>2.98	a, b
von Bertalanffy growth coefficient (k, cm·year^{-1})	>2.32	1.54–2.32	<1.54	a, b

1. von Bertalanffy growth coefficient (k, cm·y^{-1}): The rate at which a species reaches its maximum size. It has a positive relationship with productivity, the higher the value of k, the higher the stock's productivity. Short-lived species have a higher k value and produce more than long-lived species, which have a lower k value and productivity [24]. The values were obtained in the literature [8,36,37].
2. Maximum size (L_{max}, cm): The maximum size of a species is related to its productivity; large species have a long-life expectancy and, as a result, low productivity [24]. The values were obtained from the literature [36].
3. Size at first maturity (L_{50}, cm): Length at which 50% of individuals can reproduce. This parameter is negatively correlated with productivity as long-lived species that grow slowly take longer to reach L_{50}. The values were obtained from the literature [36]. The CSK values were used in both the CSK and FK PSAs.
4. Intrinsic growth rate (r): The intrinsic rate of the population growth or maximum population growth without fishing at a small size [27,36]. FishBase was used (assessed in June 2022) to obtain the r values because this information is not available at the regional level.
5. Mean trophic level (TL): This reflects the species' trophic position and involvement in trophic web interactions. Higher trophic levels are less productive than lower trophic levels, so the TL is negatively correlated with productivity [24]. The values were obtained from the literature [36].

6 L_{50}/L_{max}: This ratio reflects the relative investment in somatic and reproductive growth. Species with small sizes reach L_{50} in relatively larger sizes, compared to their maximum size, while large species reach L_{50} in smaller sizes and continue to grow [27].

7 Maximum age (A_{max}, year^{-1}): Maximum age reported, inversely correlated with productivity. High values of A_{max} reflect a low productivity. The values were obtained from the literature [36].

8 Age maturity (A_{mat}, year^{-1}): Long-lived species tend to have higher ages and take longer to reach the age at 50% maturity, compared to short-lived species, thus have a lower productivity. The values were obtained from the literature [36].

9 Fecundity: This attribute is related to the number of eggs produced by a female for a given spawning event or period [24]. This attribute was adapted to fit in the FK PSA. Fishers were asked which species they considered had low, moderate, or high fecundity. Low fecundity may indicate a low population productivity.

2.2.2. Susceptibility Attributes

Twelve attributes related to distribution, abundance, behaviour, and fishery aspects were selected to be used in the susceptibility of all PSAs. They were selected following Patrick et al. [24], and Roux et al. [18], and we also introduced four new attributes—two in the CSK and two in FK attributes. The information to score each attribute was obtained from the literature (CSK PSA) and from interviews with fishers (FK PSA). Detailed descriptions of the attributes are presented below and the details of the scores can be seen in Tables 4 and 5 for the CSK and FK PSAs, respectively.

Table 4. Susceptibility attributes for the conventional scientific knowledge productivity and susceptibility analysis and the thresholds of the scoring used to estimate the stock vulnerability in the Azores. Attribute thresholds were defined using a quantile method, except for attributes with * that were scored following the literature, and attributes with ** defined by the present study. Source, a: Patrick et al. [24]; b: Lucena-Frédou et al. [27].

Attributes	Ranking			Source
	Low (1)	Moderate (2)	High (3)	
F/M *	<0.5	0.5–1	>1	b
Z/K *	<0.5	0.5–1	>1	b
SPR *	>0.4	0.2–0.4	<0.2	a
Value of the fishery	<2.25	2.25–9.34	>9.34	a
Stock size **	Stocks with increased trends	Stocks with stable trends	Stocks with negative trends	Present study
Stock identity **	Migratory stocks	Stocks with uncertainty about local/regional distribution	Stocks with local/regional stock units	Present study
Management strategy *	Stocks with TAC and subject to other management and conservation measures	Stocks with only TAC or other conservation and management measures	Stocks with neither TAC nor other conservation and management measures	a

Table 5. Susceptibility attributes for the fishers' knowledge productivity and susceptibility analysis and the thresholds of the scoring used to estimate the stock vulnerability in the Azores. Attributes were defined with a quantile method, except for attributes with * that were scored following the literature and attributes with ** defined by the present study. Source, a: Patrick et al. [24]; b: Roux et al. [18].

Attributes	Ranking			Source
	High (3)	Moderate (2)	Low (1)	
Overlap area	>2.17	2.00–2.17	<2.00	b
Seasonal migration *	Seasonal migration increase the overlap with the fishery	Seasonal migration does not substantially affect the overlap with the fishery	Seasonal migration decreases the overlap with the fishery	a
Schooling, aggregation, and other behaviors	>2.65	2.15–2.65	<2.15	a
Value of the fishery	>9.34	2.25–9.34	<2.25	a
Management strategy *	Stocks with TAC and subject to other management and conservation measures	Stocks with only TAC or other conservation and management measures	Stocks with neither TAC nor other conservation and management measures	a
Length trends **	>2.10	1.96–2.10	<1.96	Present study
Lands trends **	>2.26	2.12–2-26	<2.12	Present study

1 F/M ratio: The ratio between the fishing mortality (F) and the natural mortality (M). This relationship shows the relative impact of the fishing pressure on stocks, with the relative value providing a magnitude of fishing exploration [38,39]. A high F/M value, larger than 1, indicates a high susceptibility [24]. The values were obtained from the literature (calculated by Medeiros-Leal et al. *under review*).

2 Z/K ratio: The total mortality (Z) ratio and the von Bertalanffy growth coefficient (k). The in yield-per-recruit analysis, this is a natural parameter. Z/k is linked to many survival patterns, such as how the number of survivors varies with size and/or age. A stock with a high Z/k value, of more than 1, has a lower chance of surviving and therefore is more vulnerable (Pauly, 1984). The values were obtained from the literature [36,37,40] (calculated by Medeiros-Leal et al. *under review*).

3 Spawning potential ratio (SPR): The SPR can be used as an alternative reference point for biomass, suggesting a proxy for biomass spawners [41]. The values were obtained from the literature (calculated by Medeiros-Leal et al. *under review*).

4 Value of the fishery: Stocks with higher economic value are thought to be more vulnerable to overfishing due to the increased effort. The value of initial commercialization per kg was used to determine the value of the fishery [24]. The values were obtained from the literature [36].

5 Stock size: Stock size is a new attribute included and concerns the abundance trends in the most recent five years. Stocks that show negative trends are supposed to be more susceptible. The values were obtained from the literature [8].

6 Stock identity: This is a new attribute that is related to stock distribution, whether migratory or local/regional stock units. Local stocks are more susceptible than shared or migratory stocks. This information was obtained from the literature [36].

7 Management strategy: Stocks that are subject to various fisheries management actions and catch control measures have a lower likely susceptibility. This information was obtained from the literature [36].

8 Overlap area: This attribute aims to address the proportion of the overall overlap area between the preferred fishing location and habitat type [18].

9 Seasonal migration: Seasonal migrations to or from the fishery region for spawning or feeding might influence the overlap between the stock and fishing [24].

10 Schooling, aggregation, and other behaviours: Individual or stock-level behaviours, in response to fishing can affect catchability [24].
11 Length trends: This is a new attribute that was based on the fisher's perception of a species length trends. Species that show decreased length trends are likely to be more susceptible.
12 Landing trends: This is a new attribute that was based on the fishery perception of a species' landing trends. Species that show decreased landing trends are likely to be more susceptible.

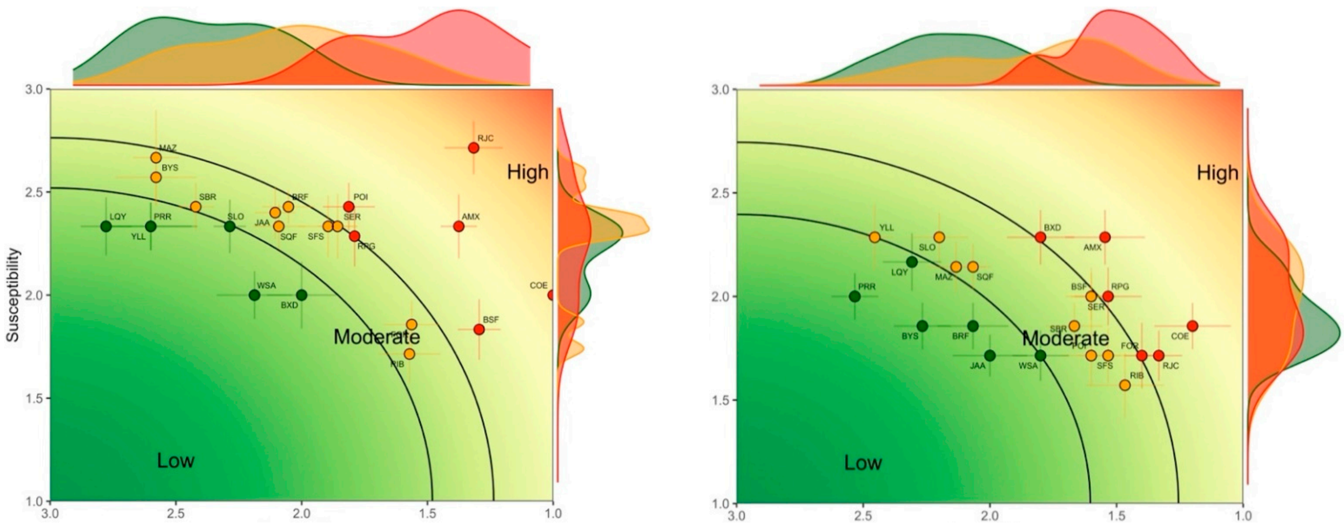
2.3. Weights and Uncertainty

Following Lucena-Frédou et al. [27] and Lira et al. [29], a baseline scenario was set up with productivity attributes where L_{max}, k, and *r* with a weight value of 3, since they are important resilience attributes to the stocks, while a default weight 2 was provided to other productivity and susceptibility attributes. From this baseline scenario, 10,000 simulations were run, in which, for the productivity and susceptibility attributes, a random sample of the integer weights, between 1 and 3, were assigned to test the sensitivity of vulnerability scores and the classifications with different weights. For each species, the standard deviations of the vulnerability values, as well as the empirical probability of being categorised as having a low, moderate, or high vulnerability, were computed [29]. All analyses used the R core Team software [42].

3. Results

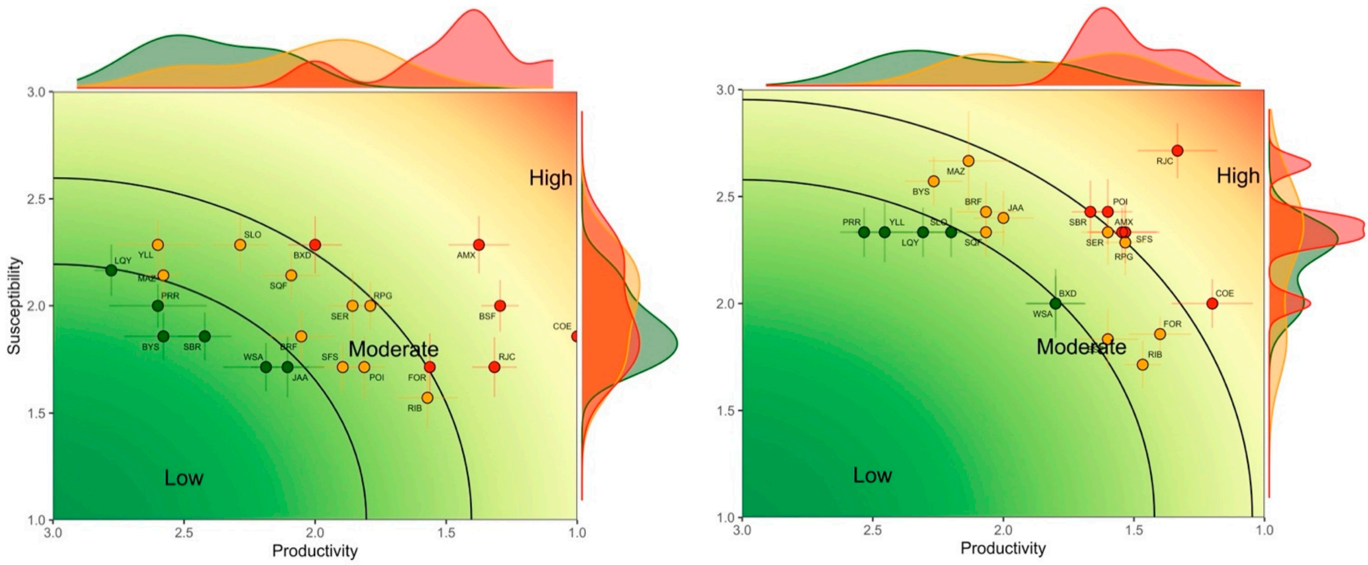
To obtain the FK data needed to perform the PSAs, questionnaires were administered to fishers on five Azorean islands (Corvo: 5, Faial: 7, Graciosa: 12, São Jorge: 7, São Miguel: 22). The average fisher's age was 46.11 (±10.12) years, and the average fishing experience was 20.94 (±13.39) years. Since the SSFs in the Azores are multispecies and multi-gear, most fishers answered items regarding multiple species.

Examining Figure 1—which depicts the vulnerability scores for the 22 species—for all four PSAs, most species were grouped in the graphs' upper sections, showing a moderate to high susceptibility score. Moreover, the same figures show a large and spread-out productivity score. In general, the productivity and susceptibility parameters from PSA-2 show more grouped values, when compared with PSA-1, although some patterns remain consistent.



(**a**) (**b**)

Figure 1. *Cont.*



(**c**) (**d**)

Figure 1. Overall distribution of the vulnerability scores of the 22 fish stocks explored by small-scale fisheries, estimated with (**a**) analytical scientific data—PSA-1, (**b**) fishers' knowledge data PSA-2, (**c**) analytical productivity and fishers' knowledge susceptibility PSA-3, and (**d**) fishers' knowledge productivity and analytical susceptibility PSA-4. The colour scale reflects the lowest (green) and highest (red) vulnerability scores. The range lines at each point show the standard deviation to each productivity and susceptibility axis with 10,000 runs. The density plots show the total variation for the productivity and susceptibility in each risk category.

The results of all four PSAs performed are presented in Table 6. The most vulnerable species is *Raja clavata* (v = 2.40—in the PSA-1) and the least vulnerable is *Pagellus bogaraveo* (v = 1.03—in the PSA-3). Considering the four PSAs, in each PSA, six species were classified as high risk, specifically, PSA-1: *Seriola* spp., *Aphanopus carbo*, *Conger conger*, *Pontinus kuhlii*, *R. clavata*, and *Pagrus pagrus*; PSA-2: *Seriola* spp., *Beryx decadactylus*, *C. conger*, *Phycis phycis*, *R. clavata*, and *P. pagrus*; PSA-3: *Seriola* spp., *A. carbo*, *B. decadactylus*, *C. conger*, *P. phycis*, and *R. clavata*; and PSA-4: *Seriola* spp., *C. conger*, *P. kuhlii*, *R. clavata*, *P. bogaraveo*, and *Lepidopus caudatus*.

In PSA-1 and PSA-2, with an independent source of information, six stocks were considered high risk, six moderate risk, and three low risk categories in each one of the PSAs. When the data sources were combined, PSA-3 and PSA-4, a similar trend in risk categories was observed; six stocks were classified as high risk, ten as moderate risk, and six as low risk, each. Some stocks are shared in the same risk category (high, moderate, and low) in the different PSAs performed.

PSA-2 and PSA-4 showed the most uncertain results in the risk probability, and PSA-1 and PSA-3 show a similar pattern (Figure 2). In PSA-1, the six species categorized as high risk had a larger than 70% chance of being classified as such, and five species at low risk had a larger than 75% chance of being classified as such. In PSA-2, the three highest and lowest risk species show a larger than 80% chance of being classified as such.

Table 6. Productivity (*P*), susceptibility (*S*), and vulnerability (*v*) scores for the different PSAs performed on the 22 marine stocks in the Azores. PSA-1: conventional scientific knowledge (CSK) PSA; PSA-2: fisher knowledge (FK) PSA; PSA-3: CSK P × FK S PSA; PSA-4: FK P × CSK S PSA. M.A.: number of missing attributes per species.

Scientific Name	FAO Code	PSA-1						PSA-2						PSA-3						PSA-4					
		M.A.	***p***	***S***	***v***	**Risk**	**Rank**	**M.A.**	***p***	***S***	***v***	**Risk**	**Rank**	**Code**	***p***	***S***	***v***	**Risk**	**Rank**	**M.A.**	***p***	***S***	***v***	**Risk**	**Rank**
Seriola spp.	AMX	6	1.37	2.33	2.10	high	3	2	1.54	2.28	1.94	high	2	5	1.37	2.28	2.07	high	2	3	1.54	2.33	1.97	high	5
Helicolenus dactylopterus	BRF	0	2.05	2.42	1.71	moderate	10	0	2.06	1.85	1.26	low	19	0	2.05	1.85	1.27	moderate	15	0	2.06	2.42	1.70	moderate	13
Aphanopus carbo	BSF	1	1.29	1.83	1.89	high	4	2	1.60	2.00	1.72	moderate	7	1	1.29	2.00	1.97	high	3	2	1.60	1.83	1.62	moderate	15
Beryx decadactylus	BXD	1	2.00	2.00	1.41	low	18	0	1.8	2.28	1.75	high	5	1	2.00	2.28	1.62	high	5	0	1.80	2.00	1.56	low	17
Beryx splendens	BYS	0	2.57	2.57	1.62	moderate	13	0	2.26	1.85	1.12	low	21	0	2.57	1.85	0.95	low	22	0	2.26	2.57	1.73	moderate	11
Conger conger	COE	1	1.00	2.00	2.23	high	2	0	1.20	1.85	1.99	high	1	1	1.00	1.85	2.17	high	1	0	1.20	2.00	2.05	high	2
Phycis phycis	FOR	1	1.56	1.85	1.67	moderate	11	0	1.40	1.71	1.75	high	6	1	1.56	1.71	1.60	high	6	0	1.40	1.85	1.81	moderate	10
Trachurus picturatus	JAA	1	2.10	2.40	1.66	moderate	12	0	2.00	1.71	1.22	low	20	0	2.10	1.71	1.14	low	18	1	2.00	2.40	1.72	moderate	12
Patella aspera	LQY	8	2.77	2.33	1.35	low	21	2	2.30	2.16	1.35	low	18	5	2.77	2.16	1.18	low	17	5	2.30	2.33	1.50	low	20
Scomber colias	MAZ	1	2.57	2.66	1.71	moderate	9	0	2.13	2.14	1.43	moderate	15	0	2.57	2.14	1.21	moderate	16	1	2.13	2.66	1.87	moderate	9
Pontinus kuhlii	POI	1	1.81	2.42	1.85	high	5	0	1.60	1.71	1.57	moderate	12	1	1.81	1.71	1.38	moderate	12	0	1.60	2.42	2.00	high	3
Sparisoma cretense	PRR	3	2.60	2.33	1.39	low	19	0	2.53	2.00	1.10	low	22	2	2.60	2.00	1.07	low	20	1	2.53	2.33	1.41	low	22
Mora moro	RIB	2	1.57	1.71	1.59	moderate	15	0	1.46	1.57	1.63	moderate	9	2	1.57	1.57	1.53	moderate	8	0	1.46	1.71	1.69	moderate	14
Raja clavata	RJC	0	1.31	2.71	2.40	high	1	0	1.33	1.71	1.81	high	3	0	1.31	1.71	1.82	high	4	0	1.33	2.71	2.39	high	1
Pagrus pagrus	RPG	0	1.78	2.28	1.76	high	6	0	1.53	2.00	1.77	high	4	0	1.78	2.00	1.57	moderate	7	0	1.53	2.28	1.95	moderate	7
Pagellus bogaraveo	SBR	0	2.42	2.42	1.54	moderate	16	0	1.66	1.85	1.58	moderate	11	0	2.42	1.85	1.03	low	21	0	1.66	2.42	1.95	high	6
Scorpaena scrofa	SER	3	1.85	2.33	1.75	moderate	7	0	1.60	2.00	1.72	moderate	8	2	1.85	2.00	1.51	moderate	9	1	1.60	2.33	1.93	moderate	8
Lepidopus caudatus	SFS	1	1.89	2.33	1.73	moderate	8	0	1.53	1.71	1.63	moderate	10	0	1.89	1.71	1.31	moderate	14	1	1.53	2.33	1.98	high	4
Palinurus elephas	SLO	6	2.28	2.33	1.51	low	17	0	2.20	2.28	1.51	moderate	13	2	2.28	2.28	1.47	moderate	10	4	2.20	2.33	1.55	low	19
Loligo forbesii	SQF	7	2.09	2.33	1.61	moderate	14	0	2.06	2.14	1.47	moderate	14	3	2.09	2.14	1.46	moderate	11	4	2.06	2.33	1.62	moderate	16
Serranus atricauda	WSA	2	2.18	2.00	1.28	low	22	0	1.80	1.71	1.39	low	17	1	2.18	1.71	1.08	low	19	1	1.80	2.00	1.56	low	18
Scyllarides latus	YLL	10	2.6	2.33	1.39	low	20	2	2.45	2.28	1.39	moderate	16	6	2.60	2.28	1.34	moderate	13	6	2.45	2.33	1.44	low	21

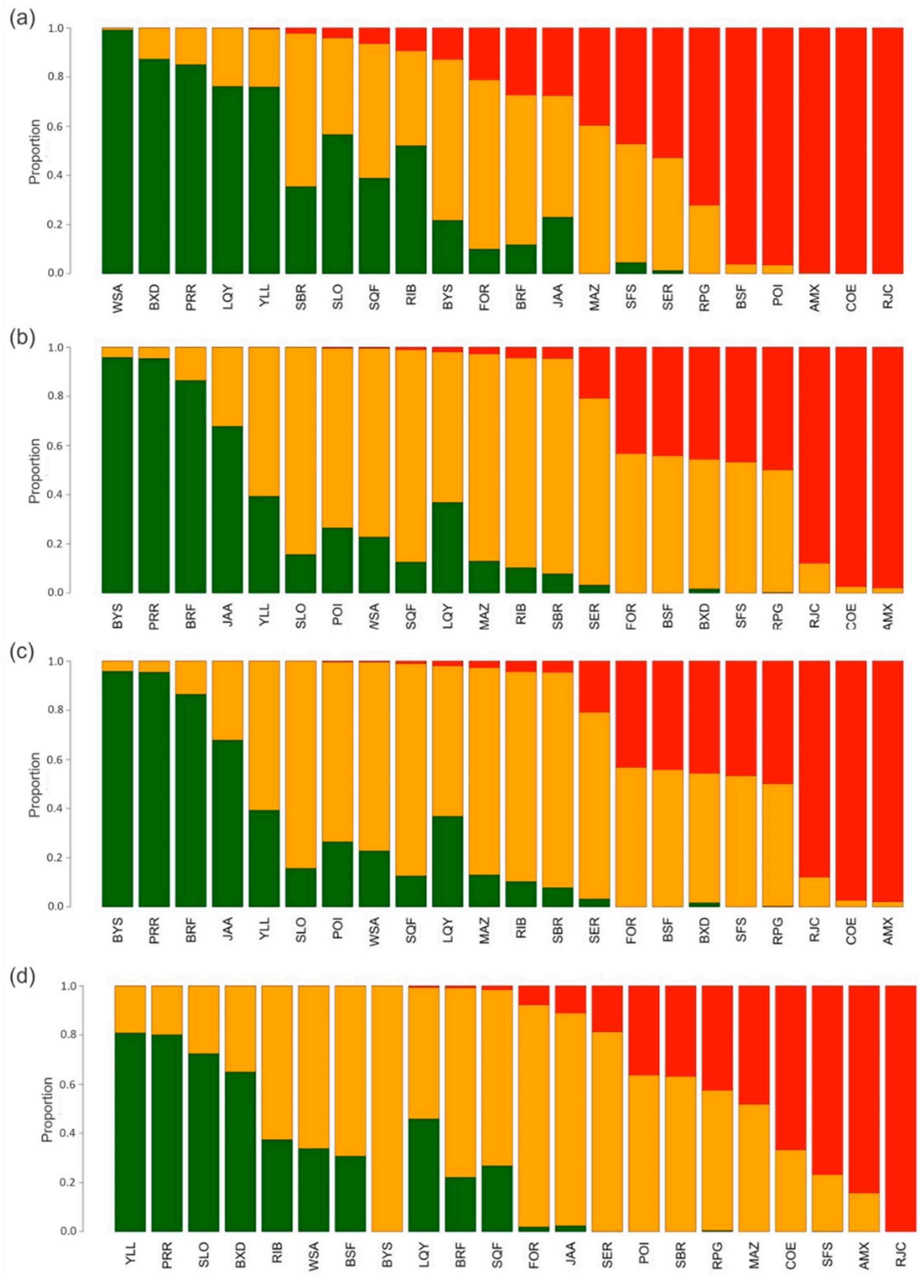


Figure 2. Overall probability of risk from the uncertainty simulations of 22 fish stocks exploited by small-scale fisheries, estimated with (**a**) analytical scientific data—PSA-1, (**b**) fishers' knowledge data PSA-2, (**c**) analytical productivity and fishers' knowledge susceptibility PSA-3, and (**d**) fishers' knowledge productivity and analytical susceptibility PSA-4. Species are distributed from left to right, according to the vulnerability rank: low (green), yellow (moderate) high (red).

4. Discussion

4.1. Applicability of the PSAs

Alternative approaches, such as the PSAs, are effective in data-poor fisheries scenarios where numerous species are caught, and many of which lack the information necessary to undertake more quantitative methods [23,24]. It is a useful and flexible tool that accepts data from various sources, both quantitative and qualitative, and requires only basic information regarding the productivity and susceptibility attributes of a given stock [23,24,27,43].

The approach has certain limitations and should be used with caution. A PSA does not provide traditional stock assessment reference points and may be considered a conservative approach that misclassifies some stocks, when compared with more quantitative approaches [26]. Additionally, a conservative scoring approach overclassifies species risks when the highest score is assigned to the missing attributes [23,44]. Despite some limitations, the PSA is widely used in data-poor fisheries and may be useful in situations when the fisheries include a range of target species with limited biological and ecological information for assessing stocks with traditional stock assessments [18,27]. It evaluates many different stocks at the same time and provides information on which stocks are more at risk from fishing impacts and require more attention. This information enables policymakers and stakeholders to focus their management and conservation efforts on high-risk stocks [23,24].

The PSA approach has been applied globally to various marine animals [25,27,29,43,45–48] and is recommended by the Marine Stewardship Council for fishery certifications [49], the Australian Fisheries Management Authority [23], the International Commission for the Conservation of Atlantic Tunas (ICCAT) [27,50], it is used by the Expert Groups of the International Council for the Exploration of the Sea [51], and are used to manage US fish stocks [24].

Even though PSAs require little information, basic life history and fisheries data required to perform a PSA is simply unavailable for certain stocks, or available data is considered outdated. To overcome these difficulties, this work performed four PSAs with two independent data sources, the CSK and FK data, and used the combined data to test whether, in the absence of the CSK data, gaps in knowledge can be filled in by the FK to obtain similar risk category outcomes. Few attempts have been made to try to integrate the CSK and FK and most previous research employs the FK in the susceptibility attributes [18,19], or only one productivity attribute [18] and the reconstruction of historical data [52].

4.2. Combining the CSK and FK PSAs

The difference in the four PSAs performed in this work arises from the data used, in which PSA-1 was performed with only the CSK data source and here, it is used as a baseline to compare a preliminary validation of the results of other PSAs that use the FK, PSA-2, and combine the CSK and FK, PSA-3, and PSA-4. The findings from this research suggest that including alternative data sources in PSAs, such as the FK, can provide helpful information for assessing the stock vulnerability in the absence of the CSK data. Furthermore, the outcomes of the combination of the CSK and FK in the PSAs, generally coincide with the risk outcomes of PSAs with only the CSK data, even for stocks that are still little known to science. The CSK and FK can provide different and independent source data that, combined, can be helpful to assess stocks that lack information, by filling the gaps and increasing the confidence in the outcomes [18,19]. However, due to a PSA's limitations, these results should be evaluated with caution and used prudently to adopt precautionary management strategies.

With few exceptions, the results of PSA-2, PSA-3, and PSA-4 generally follow the same trend as PSA-1. The fact that the CSK and FK were in accord, in this case, may suggest that the FK inclusion in the analysis may be reliable. The addition of the FK in this scenario may be an alternative for complementing the PSA assessments by filling in information gaps for species, for which fundamental data are unavailable [18,19]. By including the FK, instead of precautionary approaches, lacking the attributes, borrowing information from similar taxa, or "best guess", which can create bias in the results, the PSA can improve the assessment and reduce the inherent uncertainties [23,44,53,54].

Local ecological knowledge data from fishers can provide adequate perspectives on the ecological and biological features of stocks [14,53]. The FK insights are gathered by resource users throughout a lifetime of interaction with the natural systems, and this knowledge can be accumulated through generations and passed down orally by cultural transmission [15,54]. Some studies have shown the benefits of including the FK and/or stakeholders' knowledge in different models, such as food web models [55], GIS-based protocols for local knowledge mapping [56], and the historic reconstruction of fisheries catches in marine protected areas [57]. Despite its potential as a valuable source of information for fisheries resource management and conservation, the FK is still frequently left out of assessments, management processes, and decision-making [19].

To assess the FK, we used individual questionnaires, instead of focus group methods with fishers, to minimise the potential group biases [19,58,59]. Even though questionnaires were effective in collecting data, PSA-2 findings were more uncertain in their probability risk, when compared with the PSA-1. Different factors may have influenced these results, namely the fact that, as elsewhere [60,61], some Azorean fishers have a tense relationship with the scientific community and tend to view interviews regarding fishing activities as untrustworthy.

The 1–3 score level method used in the questionnaire to score items, was chosen to fit in the PSA approaches that use three-level scores, but it also proved adequate in avoiding responses with extreme values or imprecise answers, a common feature of questionnaires with Azorean fishers. However, questions, such as "first maturation size" were hard for fishers to answer, resulting in insufficient responses and subsequently being eliminated from the PSA-2 analyses, replaced instead by the CSK. Many fishers may not be confident in stating the level of species' maturity or feeding ecology. This is likely due to the first sale of fish in the Azores carried out without gutting the fish, hampering the fishers' ability to determine whether the species' gonads are mature. Even so, in this research, we used the mean trophic level attribute during the analysis because it could be validated with PSA-1.

Given the PSA's flexibility in introducing alternative attributes and information [19,58], we recommend that the choice of attributes and construction of the FK questionnaire should take into consideration the most readily available and easily accessible information for each fishery and fishers' local social contexts. The two new attributes inserted in this work, the length trends and landing trends, can be good examples of important signals of susceptibility in the local context. This type of FK can help design experiments and analyses, which could better identify stock changes over time by disentangling the different drivers of change. In addition, adding the FK to the PSA susceptibility attributes, could make results more representative of the local conditions [18].

Improving the FK data collection may aid research outcomes, given that this knowledge is ready to use and is easier and less costly to obtain than the biological data [59]. Since the PSAs work with bins rather than exact values, they allow the FK to be included in the assessment without harm [24]. Reviewing the scientific results with the fishing community could also improve future research outcomes, enhance the fisher engagement by further integrating them into fisheries science processes, and could promote future implementation and compliance with management measures [62,63].

The proposed use of the CSK and FK and their combination into PSAs, is a first attempt to incorporate the FK in the evaluation of the Azorean fisheries and provides some preliminary indications that the FK can improve the PSA outcomes. Although there may need further validation of this approach, with simulation tests and/or expansion of the data, we believe that this approach is valid to determine if an unassessed stock presents a low, moderate, or high risk to the fisheries' impacts.

4.3. Vulnerability of the Azorean Stocks

In our case study in the Azores, the risk category outcomes in all PSAs demonstrate a similar pattern overall. Ten species did not change their risk category, among different PSAs. The following species were consistently classified as (1) high risk: *Seriola* spp., *C. conger*, and *R. clavata*; (2) moderate risk: *Scomber colias*, *Mora moro*, *Scorpaena scrofa*, and *Loligo forbesii*; and (3) low risk: *Patella aspera*, *Sparisoma cretense*, and *Serranus atricauda*. The species *R. clavata*, *C. conger*, and *Seriola* spp., were in the top six high-risk category in all PSAs. *A. carbo*, *P. pagrus*, *P. kuhlii*, *B. decadactylus*, and *P. phycis* were classified as high risk in at least two PSAs and *L. caudatus* and *P. bogaraveo* were classified as high risk in one PSA. These stocks were screened out as high-risk stocks, which although classified at different ranks and different PSAs, they were highlighted as having the same high-risk category.

These high-risk outcomes were expected, due to a combination of moderate to low productive characteristics, such as the species' life history features, a medium/long life span (>15 years), and low spawning rates, and additionally due to the high susceptibility stocks with low biomass also considered as intensively exploited [27,33,64]. High vulnerability scores mainly result from the relationship between low productivity and high susceptibility attributes and might lead to an increased chance of stock vulnerability [27].

In general, these risk categories' outcomes seem to be adequate since we did not find a larger range of vulnerability scores in any of the PSAs performed [65,66]. This might be linked to the fact that most information about the selected species' productivity and susceptibility attributes is available in the scientific literature and in the collected FK data [65]. Extreme values of vulnerability are often related to a high risk of stock overexploitation or false positives/negatives when the risk is overestimated or underestimated and may indicate a bias in the assessment [23,27,66].

For a few species, namely *Seriola* spp., *Scyllarides latus*, *Palinurus elephas*, *L. forbesii*, and *P. aspera*, limited information regarding the available productivity and susceptibility attributes exist, lacking at least six attributes in PSA-1. However, in PSA-2, almost all attributes were filled in. Despite this difference between the data sources and the number of attributes with available information, vulnerability values of PSA-2, PSA-3, and PSA-4 show similar outcomes to PSA-1. This result suggests the FK can be used as additional information to fill in the lack of the CSK.

The largest inconsistency was found in *B. decadactylus,* classified as low risk in PSA-1 and high risk in PSA-2, and in *P. bogaraveo*, classified as low risk in PSA-3 and high risk in PSA-4. Inconsistencies in the assessment outcomes of these species may arise from this inherent difference between the CSK and FK information. Unlike the fisheries' independent data, which focus heavily on the stocks' biological/ecological aspects, the FK data is shaped by the different perceptions of these resources, influenced not only by the alternative lenses through which these resources are viewed, but also by potential conflicts between the fisheries' stakeholders [18,67]. In this case, the inconsistencies might reflect existing conflicts between fishers and stakeholders, given that these stocks of high economic importance for fishers have recently suffered a decrease in their TAC. Fauconnet et al. [68] have documented the disagreements in which Azorean fishers see management measures as inadequate for their fisheries. This has direct implications for the results and management strategies. Future assessments should take these factors into consideration, or risk being scientifically and socially undermined.

PSA-1 was performed using regional data for the attributes, except for the r attribute. Since the FK reflects local ecological conditions and perceptions about fisheries and stocks, the use of different scales in the assessment may introduce biases [19]. Yet, according to Jara et al. [19] differences in the PSAs using the FK result mostly come from different spatial scales. Even though this study adopted an independent source of data and different spatial scales, the results obtained follow a similar pattern. However, since those authors show that the use of the FK assessment can improve the assessment at the local level, we recommend that these scales should be examined at the local level in future studies using the FK, considering that fishing pressure patterns might be different between the different western, central, and eastern groups of islands in the Azores.

5. Conclusions

The small-scale demersal fisheries of the Azores catch a variety of species, but only a limited number of species groups have data for traditional stock assessments, and for many of these species, the state of their stocks is still unknown, due to a lack of data [8]. This is the reality for most small-scale fisheries around the world. The findings of this work suggest that integrating the FK may be a reliable alternative to provide good fisheries assessment outcomes in the absence of the CSK. The use of the FK is recommendable in data-poor stocks, to fill the gaps in knowledge when data are lacking for a fully CSK PSA. However, the outcomes should be used carefully and used only for ranking stocks to define the priority species for future research, monitoring and precautionary management. Although we found some differences in the vulnerability scores and rankings, the risk category outcomes of our study case reflect a similar pattern trend. The FK perceptions of stocks can include biological, ecological, and socioeconomic considerations in the assessment to achieve broader and more comprehensive results for the prioritization of monitoring programs, assessment, and management efforts for high-risk stocks. This work can handily and efficiently be replicated in different small-scale fisheries around the world, and, as a result, directly impact the decision-making, local or regional management strategies, and fishing policies.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142214870/s1, Questionnaire.

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