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Assessing the Stock Dynamics of Elasmobranchii off the Southern Coast of Sicily by Using Trawl Survey Data

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Abstract: Elasmobranchii (sharks and rays), which have peculiar and vulnerable life-history traits, are highly threatened by fishing activities. Indeed, between 53% and 71% of Mediterranean elasmobranch species are at risk of extinction. In this context, using the abundance MSY (AMSY) model, the present study provides an assessment of 20 batoids and 16 shark species in the Strait of Sicily, sampled during a bottom trawl survey from 1995 to 2020. Overall, the outputs underline a progressively improving condition for shark and ray assemblages of both shelf and eurybathic zones. As for slope-dwelling species, a horseshoe-shaped dynamic, characterized by a progressive decrease in relative harvesting pressure and an increase in relative biomass followed by an increase in fishing pressure and decrease in biomass, was detected. The dynamics of the Elasmobranchii living in the Strait of Sicily appear to be affected by changes in the fishing patterns of trawlers, showing a shift from shallow water to bathyal fishing grounds and targeting deep-water red shrimp. In this context, it seems wise to limit the impact of deep-water fisheries on Elasmobranchii by reducing fishing efforts and implementing ad hoc management measures aimed at safeguarding these vulnerable species.

Keywords: AMSY; assemblage; fishing impact; MEDITS; rays; sharks; stock assessment

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1. Introduction

Elasmobranchii, which have peculiar and vulnerable life-history traits (low fecundity, delayed sexual maturity, long lifespan, low growth rates), are considered to be very sensitive to the impact of fishing pressure [1–3] and are generally thought to have lower productivity than bony fish [4,5]. These characteristics are reflected in the poor sustainability of shark and ray fishing [6–8]. As a matter of fact, in many areas of the world, a decline in cartilaginous stocks are generally recognised to be mainly due to increased fishing efforts [2,3]. In addition, habitat degradation and climate change have also played fundamental roles in the decline of Elasmobranchii populations [9–11].

In recent years, a decline in these stocks has also been evidenced in several areas of the Mediterranean [12–14], characterised by high fishing pressure and a poor exploitation pattern, i.e., a high catch of undersized specimens [15,16]. Indeed, between 53% and 71% of Mediterranean Elasmobranchii species are at risk of extinction and many have an elevated and worsening threat status regionally (Mediterranean Sea) compared to their global status [17]. For example, nine of the 16 shark species reported at Food and Agriculture Organization (FAO) Mediterranean landings are more threatened at the regional than the global level [8]. Major commercial bony fish species in the Mediterranean (e.g., *Merluccius merluccius*, *Mullus barbatus*, *Encraulis encrasiculos*) have been routinely evaluated within the frameworks of regional scientific bodies using complex stock assessment models based on extensive sets of data covering time series of total removals, catch at length or age, relative or absolute abundance indices, fishing efforts and information on life-history parameters [18].

Given the poor reliability of catch data and the lack of long time series, it is not possible to analytically assess the status of Elasmobranchii species using well-fitting complex models, as is already done for bony fish. However, for stocks that have reliable catch time series and catch rates, the use of surplus production models is a suitable approach to estimate stock status and exploitation, putting the dynamics of the stocks within the framework of biological reference points [19]. Classically, this approach needs a reliable and contrasted time series of catches and specific effort (e.g., [20]). Bonfil [21] reported that using a surplus production model was a good approach for stock assessment in Elasmobranchii fisheries.

It must be pointed out that there are currently very few examples of fisheries where Elasmobranchii are the target species, at least in the Mediterranean Sea. Indeed, only sporadic fishing activities target Elasmobranchii species, such as in the northern Adriatic Sea and in the Strait of Sicily, where vessels using gillnets target smooth-hound sharks (*Mustelus* spp.), dogfish sharks (*Squalus* spp.) and guitarfishes (*Rhinobatos* sp.) [7,22–26]. Some seasonal fisheries targeting piked dogfish *S. acanthias* operate in Bulgaria [27–29]. Most pelagic species are caught by driftnets for tuna and swordfish, and demersal species are caught by gillnets or mainly bottom trawls [26,30–32]. Larger individuals of some species (e.g., *M. mustelus*, *Raja clavata*, *R. miraletus*) that have commercial value are caught for food consumption, while small individuals and species with no commercial value are discarded [7,8,33].

Furthermore, many genera, such as *Dipturus* and *Centrophorus*, are not easy to identify taxonomically [34–36] and can hybridize with each other, such as *M. mustelus* with *M. punculatus* [37] or *R. montagui* with *R. polystigma* [38]. These characteristics imply that catch statistics from most areas of the Mediterranean are unreliable in terms of specific composition and catches, limiting the application of fishery-dependent methods [8,39]. The scant reliability of fishery-dependent data in Elasmobranchii stock assessment is more common in the Mediterranean than in other areas of the world where stock evaluation is more advanced, such as the Atlantic Ocean (e.g., [40,41]).

Because of the well-known difficulties in setting up an effective commercial catch monitoring system for Mediterranean fisheries (the multiplicity of species caught, fishing systems and landing points) [42,43], since the 1980s, research in the region has relied on trawl surveys to obtain standardised information on the distribution, abundance, and demography of demersal species [44–46]. In particular, the international bottom trawl survey in the Mediterranean (MEDITS) is the main source of fishery-independent information covering trawls at depths between 10 and 800 m from as many as 10 coastal countries [47,48]. There are numerous examples of analyses of Elasmobranchii data collected by trawl surveys in the Mediterranean [49,50]. However, such analyses have so far been limited to the study of the temporal variations in abundance, demography, and spatial distribution of the main species.

Comparing trawl surveys carried out in the Adriatic Sea from 1948 to 1998, Jukic–Peladic et al. [51] provided information on the changes that occurred in the composition and distribution of demersal fish, including Elasmobranchii, over the 50-year period. The main change was a decrease in Elasmobranchii diversity and occurrence; the same decrease was also reported for other Mediterranean areas [50,51]. Some differences were found in relative occurrence and abundance by species; small-sized species, such as the small-spotted catshark (*Scyliorhinus canicula*) and the brown ray (*R. miraletus*), were frequently collected in both surveys, while some species (bigger shark species and other rays) had disappeared or were rarely found during the last survey of the time series.

Despite the consensus on the poor exploitation status of almost all Mediterranean Elasmobranchii stocks, the abundance indices in some areas of the Mediterranean have shown stable or even increasing trends, indicating signs of a slight recovery. Geraci et al. [52] analysed the distribution and abundance of 37 demersal species of chondrichthyans—

chimaera, sharks, and batoids—collected by MEDITS trawl surveys from 1994 to 2013 in the south of Sicily (Geographical Sub-Area (GSA) 16) and reported that most of them were in a steady-state, with a recovering trend from 2001 to 2009 for sharks and from 2001 to 2010 for batoids. Marongiu et al. [53] examined the occurrence, abundance, and size trends of 25 demersal chondrichthyans collected by MEDITS surveys carried out around Sardinian waters between 10 and 800 m depth from 1994 to 2015 and showed that temporal trends of abundance indices were stable or increasing. Almost all species displayed a stable size structure, apart from *R. brachyura* and *D. oxyrinchus*, which showed a statistically increasing trend. Very recently, Froese et al. [54] proposed a new method to fit the surplus production model (abundance maximum sustainable yield (AMSY)) that estimates relative population size when no catch data are available. In the present study, the stock status of the main Elasmobranchii species living in the Strait of Sicily was analysed through MEDITS biomass indices collected in the last 25 years using the AMSY model; the aggregate status of shark and batoid species was analysed as well.

2. Materials and Methods

2.1. Study Area

The investigated area (Figure 1) is located in the northern part of the Strait of Sicily, an ecologically important area in the Mediterranean Sea [55,56] identified as GSA 16 [57]. The area covers about 31,000 km^2 and is characterized by the presence of two wide and shallow banks (<100 m), one in the west (Adventure Bank) and one in the east (Malta Plateau), and a wide portion of water with a depth generally greater than 200 m [58].

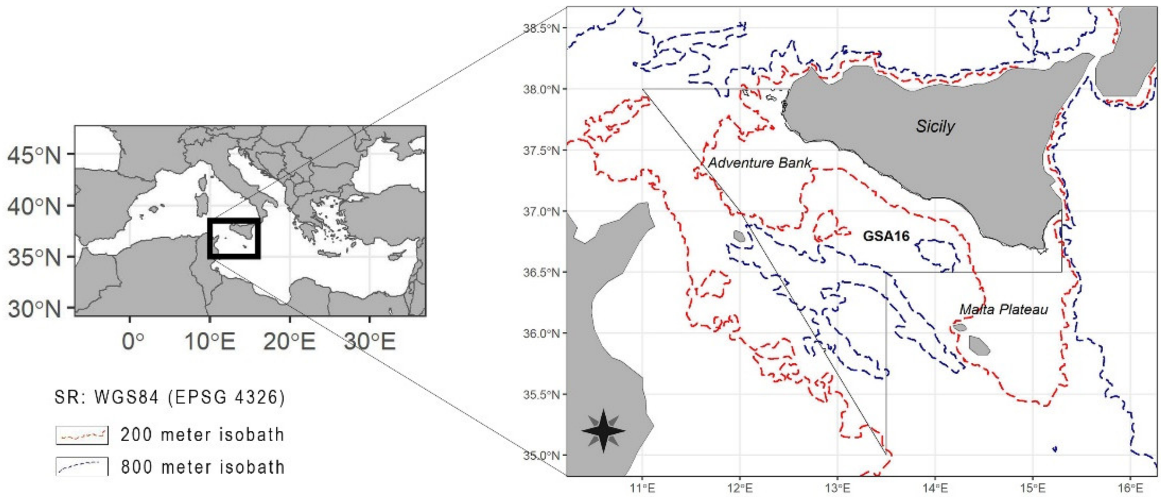

Figure 1. Investigated area, highlighted in the black square.

This area represents one of the most important fishing grounds for demersal species, exploited mainly by trawl fisheries [55]. In particular, the trawling fleet exploits the deeper fishing ground, targeting deep-water crustaceans such as *Aristaeomorpha foliacea*, *Aristaeus antennatus*, and *Nephrops norvegicus* [59,60], as well as the shallow fishing ground, targeting mainly *M. barbatus*, *M. surmuletus*, sparids and cephalopods [43,61]. Among these fishing typologies, an important component of commercial and discarded bycatch comprises cartilaginous fishes [62].

2.2. Data Sources

In the present study, data were gathered through two sources of the European Data Collection Framework (EU-DCF). Considering that cartilaginous fishes do not represent a target species for bottom trawling and the landing data are scattered and biased [8], to perform the preliminary assessment of these species, data gathered through the MEDITS survey for the time series 1995 to 2020 were used. MEDITS is carried out annually during late spring/summer in several areas of the Mediterranean Sea using a standardized sampling methodology [48]. MEDITS surveys are conducted during the daytime according to a stratified sampling scheme with a random drawing pattern inside the following bathymetric limits: 10–50 m (stratum a), 51–100 m (b), 101–200 m (c), 201–500 m (d) and 501–800 m (e); 30- and 60-min daylight hauls were performed on the shelf (10–200 m) and slope (201–800 m) grounds, respectively. Since the number of hauls by survey varied over time, the biomass index was calculated considering the same number of hauls for each stratum. To do this, the minimum number of performed hauls during the time period was considered for each stratum using the resampling without replacement procedure with 99 iterations. Considering the data paucity for some cartilaginous species, it was decided to assemble the species according to the following approach: (i) first, the species were divided into two main groups, batoids and sharks, and (ii) each main group was divided according to the same depth distribution considering the following strata: 10–200, 200–800 and 10–800 m. The most frequent species, understood as those with a percentage of positive hauls per stratum higher than 15%, were also evaluated individually, except for *D. oxyrinchus*, because it represented the bulk of the slope batoid assemblage (Table S1).

The percentage of positive hauls was calculated as follows:

$$\%\ positive\ hauls = \frac{n_{hauls}}{N_{hauls}} * 100 \quad (1)$$

where n_{hauls} is the total number of hauls per stratum in which the species was caught and N_{haul}s is the total number of hauls per stratum. The choice to assess the species in combination was also based on a report in the literature showing a difference in biomass dynamics of aggregated fish species with respect to a summed single species [63]. Moreover, for each identified group, the biomass index (*BI*; kg/km^2) for each species was calculated as a percentage as follows:

$$\%\ BI = \frac{BI_i}{BI_{tot}} * 100$$

where BI_i is the biomass index of species *i* and BI_{tot} is the sum of *BI* values of Elasmobranchii species caught in each identified taxonomic/bathymetric group. Lastly, to relate stock dynamics with fishing pressure, we obtained the nominal fishing effort trends (expressed as the number of days at sea per fishing capacity in kW) of trawlers registered in GSA 16 with an overall length of <24 m, >24 m, and both combined. Since there was a change in target species for the Sicilian fleet, which moved from the classical Mediterranean mixed trawling to deepwater fishing targeting high-priced crustaceans [61], an index representative of the fishing pattern was calculated. This index represents the ratio of the landing of *Mullus* spp., *Octopus vulgaris* and *Eledone moschata*, species indicative of shelf trawling, and of *A. foliacea*, *A. antenatus* and *N. norvegicus*, species indicative of slope trawling, to the total yield, from the official data of commercial landing of trawlers from 2004 to 2020 (DCF source). Trends in these indices can be related to changes in fishing patterns targeting shallow or deep-water demersal resources.

2.3. Stock Assessment Models

The AMSY model was applied to assess the stock status of sharks and batoids considered in the present study [54]. AMSY is a data-limited model that estimates fisheries reference points (F/F_{MSY}, B/B_{MSY}) using time series of catch per unit effort (CPUE) from commercial fisheries or scientific surveys, as well as prior ranges of resilience (r) and relative stock size (B/K, ranging between 0 and 1). The model uses this information to test a high number of combinations of resilience (r) and carrying capacity (K) for their compatibility with these inputs. All r–K combinations that are compatible with time series of plausible (never negative, never too high) predicted catches are identified by a Monte Carlo approach. A detailed description of the theory and equations behind AMSY is provided by Froese et al. [54]. In the present study, the model was run considering a biomass index time series from 1995 to 2000. In particular, the assessment was carried out considering the following: (i) a shorter time series of 2004–2020 for *Squalus blainville* because the data from

1995 to 2003 were not reliable, and (ii) *M. mustelus* and *M. punctulatus* being combined in the shelf assemblage due to some mistakes in identification [20,31]. The different levels of exploitation in terms of F/F_{MSY} and B/B_{MSY} were classified by using the Mediterranean threshold reported by Demirel et al. [64]: severely depleted ($B \leq 0.2\ B_{MSY}$), critical condition ($B \leq 0.5\ B_{MSY}$, $F > F_{MSY}$), exploited outside safe biological limits ($B \leq 0.5\ B_{MSY}$), subject to overfishing ($F > F_{MSY}$), recovering ($B < B_{MSY}$, $F \leq F_{MSY}$) and healthy ($B > B_{MSY}$, $F \leq F_{MSY}$).

2.4. Prior Selection

The biologically plausible values of r were based on the resilience classification reported by FishBase [65]. However, for many species, only qualitative r priors were found, which were translated into quantitative values using the values provided by Froese et al. [54]. In addition, considering that each analysed group included several species, it was decided to use the most frequent r values. Considering that the r values of many species were based on very few assessments, a sensitivity analysis of prior r values was performed, with the aim of quantifying the effect of the priors on the reference point estimations. Concerning the priors for relative stock size, driven by expert knowledge and a long history of fishing exploitation, which was more intense from the second half of the 20th century in the Strait of Sicily [66,67], it was decided to set B/K priors in the first year of the time series from very small to about half. In this way, it was also possible to detect the potential influence of these B/K priors on the reference point estimations. The best model was chosen based on the estimation of r/K priors and on the retrospective analysis (Figure S1), which was applied to remove three years.

3. Results

A total of 20 batoids and 16 shark species were assessed in the investigated area (Table S1). According to the Mediterranean International Union for Conservation of Nature (IUCN) Red List, among the batoid species, five are reported as Least Concern, five as Near Threatened, two as Vulnerable, two as Endangered and three as Critically Endangered, and for three species, no assessment is available. Among the sharks, two species were assessed as Data Deficient, three as Least Concern, one as Near Threatened, five as Vulnerable, two as Endangered, and one as Critically Endangered, and for two species, no assessment is available (Table S1). The outputs of the AMSY model are reported in (Tables 1 and S2), and the results for each group and species are reported in the following sections.

Table 1. Outputs and prior values used to fit the AMSY model. *r*.est, estimated resilience; K.est, estimated carrying capacity; CI, 95% confidence interval; H, healthy; O, overfished; C, critical.

Stock	*r* Prior (CI)	B/K Prior (CI)	*r*.est	K.est	K.est (CI)	B/B_{MSY}	B/B_{MSY} (CI)	F/F_{MSY}	F/F_{MSY} (CI)	Stock Status
Batoids										
Batoids (10–200 m)	0.015–0.8	0.01–0.4	0.70	14.9	12.0–20.5	1.43	0.79–2.61	0.50	0.05–1.16	H
Batoids (200–800 m)	0.015–0.8	0.2–0.6	0.55	6.7	5.7–7.9	0.77	0.43–1.38	1.48	0.44–2.93	O
Batoids (10–800 m)	0.015–0.8	0.2–0.6	0.63	105.1	92.8–120.8	1.35	0.75–2.48	0.61	0.10–1.25	H
R. clavata	0.05–0.8	0.01–0.6	0.74	64.1	56.6–74.5	1.50	0.82–2.72	0.38	0.05–0.84	H
R. miraletus	0.05–0.8	0.2–0.6	0.56	45.9	36.1–58.2	0.21	0.12–0.39	5.8	1.72–6.65	C
Sharks										
Sharks (10–200 m)	0.015–0.8	0.01–0.4	0.83	26.4	22.5–32.6	1.34	0.75–2.41	0.66	0.10–1.74	H
Sharks (200–800 m)	0.015–0.8	0.01–0.6	0.59	58.3	46.5–73.4	0.65	0.36–1.17	1.70	0.55–3.3	O
G. melastomus	0.05–0.5	0.01–0.4	0.45	40.2	31.9–54.2	0.53	0.29–0.94	2.19	0.73–4.03	O
E. spinax	0.015–0.8	0.01–0.6	0.46	5.9	3.9–8.6	0.49	0.27–0.89	1.95	0.45–4.18	C
Sharks (10–800 m)	0.015–0.8	0.01–0.6	0.64	68.9	60.4–81.8	1.56	0.87–2.85	0.40	0.04–0.95	H
S. blainville	0.015–0.5	0.2–0.6	0.43	50.7	43.1–61.0	1.35	0.77–2.48	0.68	0.08–1.53	H
S. canicula	0.05–0.8	0.2–0.6	0.51	29.7	21.7–44.6	1.26	0.69–2.27	0.73	0.09–1.71	H

3.1. Batoids

As for the batoids, as shown in Figure 2, *Dasyatis pastinaca* and *R. asterias* represented the most abundant species of the shelf (10–200 m), and *D. oxyrinchus* in almost all time series represented 100% of the biomass of the slope (200–800), with other species being quite rare, while *R. clavata* and *R. miraletus* represented the most abundant species in the eurybathic zone (10–800 m). From 1995 to 2001, *R. miraletus* represented the most abundant batoid species, with a peak of 71.7% in 1997. Subsequently, from 2002, *R. clavata* became the most abundant species, with a peak of 75.9% in 2019.

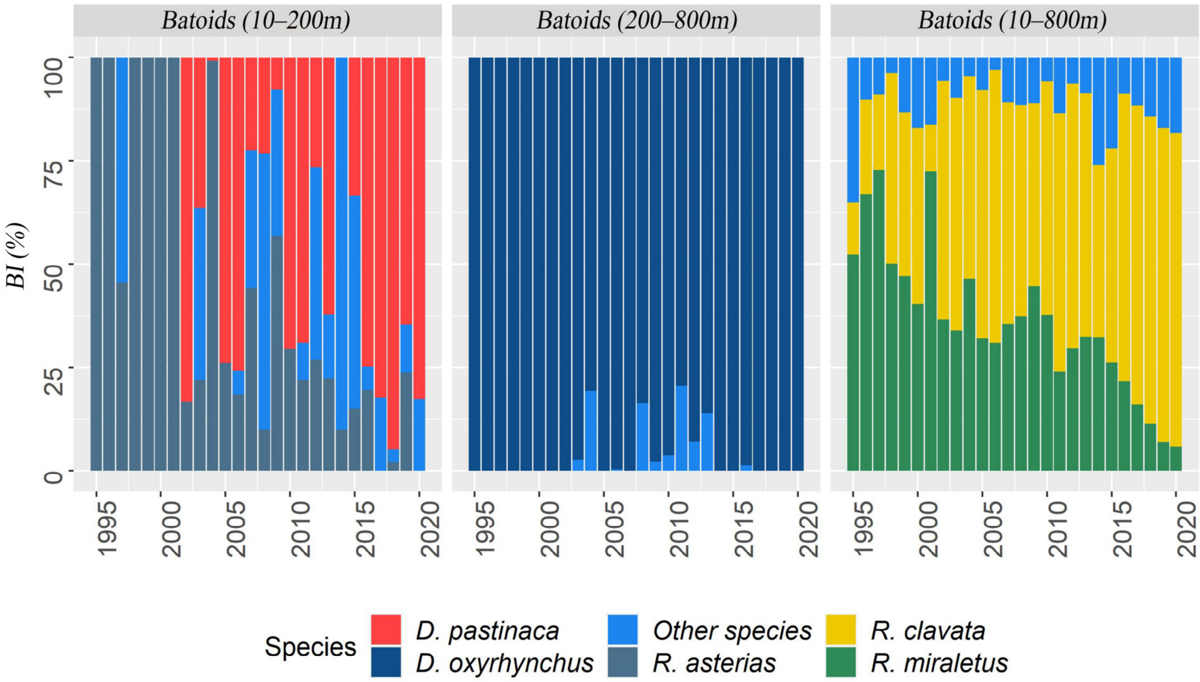

Figure 2. Biomass index (%) of a single skate/ray species among total batoids per depth stratum over the years.

The BI showed an overall increasing trend for shelf and eurybathic batoids, with the highest values of 19.30 kg/km^2 in 2016 and 129.6 kg/km^2 in 2010. Slope batoids showed a fluctuating trend, with a decrease in the last two years and the highest biomass of 6.15 kg/km^2 registered in 2011. As for single species, the BI trend of *R. clavata* indicated an overall increase throughout the time series, with the highest value of 79.4 kg/km^2 in 2010; *R. miraletus* showed a fluctuating BI trend until 2014, with the highest value of 53.1 kg/km^2 in 2010, followed by an abrupt decrease to 2.9 kg/km^2 in 2020 (Figure 3).

Concerning the stock dynamics, a progressively improving condition was found for the assemblages of both shelf and eurybathic batoids (Table 1, Figure 4). When the main single species of the eurybathic assemblage is considered, it is notable that the improving state of *R. clavata* corresponded to the worsening of the *R. miraletus* stock status. Conversely, the batoid assemblage living on the slope showed an initial overexploited state, followed by a progressive decrease in relative harvesting pressure and an increase in relative biomass until 2011; then, from 2012, a new phase of increased fishing pressure and decreased biomass drove the assemblage to a state similar to the starting one, following a horseshoe-shaped dynamic. The sensitivity analysis indicated that the models were quite robust for all considered batoids. These results were further corroborated by retrospective analysis, except for *R. clavata*, which showed a slight shift in the removal years (Figure S1).

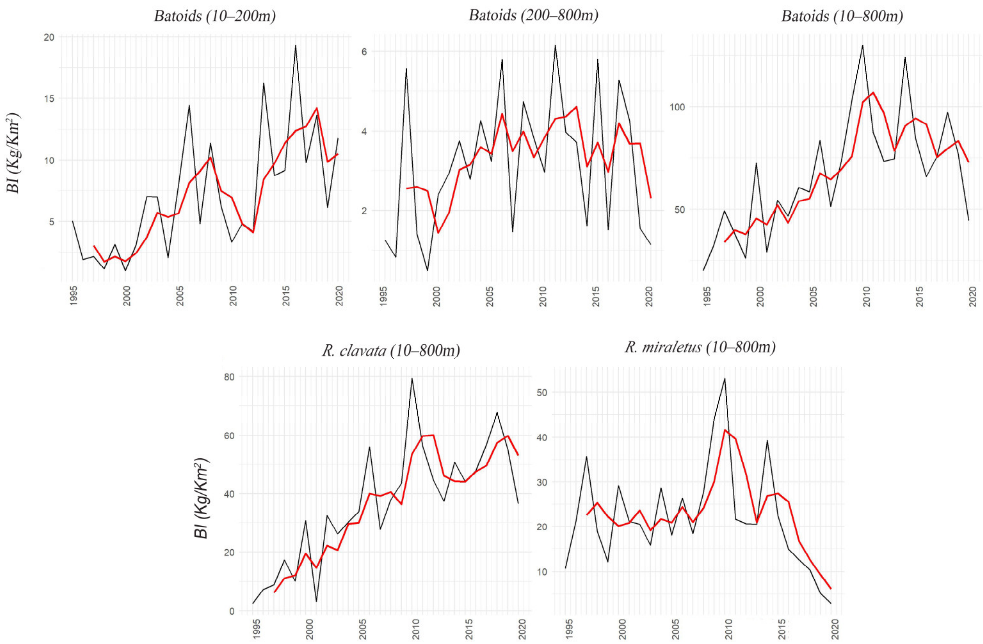

Figure 3. Trend of observed (black lines) MEDITS survey biomass index (kg/km^2) over the years and 3-year rolling mean (red lines) for batoids in the Strait of Sicily.

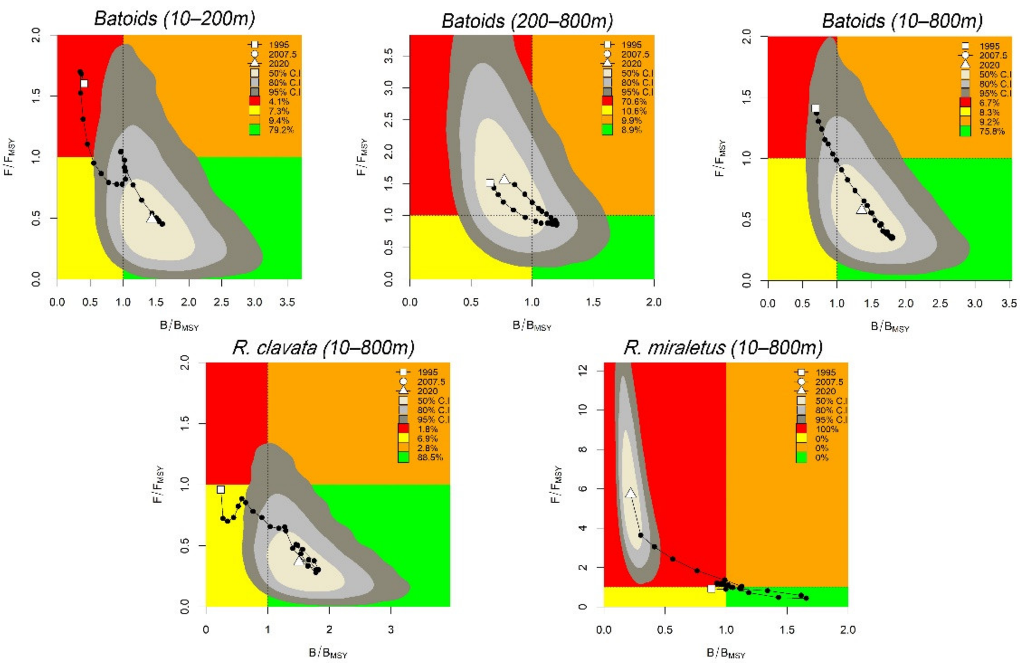

Figure 4. Dynamics of batoid stocks in GSA16 estimated by the AMSY model. F/F_{MSY} versus B/B_{MSY}. Quadrants are colour-coded: red: stocks that are both overfished (low relative biomass) and subject to overfishing (high exploitation rate) ($B \leq B_{MSY}$; $F \geq F_{MSY}$); orange: relative biomass is quite high but the exploitation rate is high ($B \geq B_{MSY}$; $F \geq F_{MSY}$); yellow: recovering stocks ($B \leq B_{MSY}$; $F \leq F_{MSY}$); green: stocks subject to a sustainable exploitation rate and with healthy stock biomass that can produce high yields close to MSY ($B \geq B_{MSY}$; $F \leq F_{MSY}$). Shaded areas indicate confidence intervals at 50% (light grey), 80% (grey) and 95% (dark grey) of the reference points during the last year.

3.2. Sharks

Concerning the shark assemblages, species belonging to the genus *Mustelus* presented higher biomass index values on the shelf, although in 1998 the biomass index of *S. stellaris* achieved a value of about 75%. Among the slope sharks, *Galeus melastomus* represented the most abundant species, followed by *C. uyato* and *Etmopterus spinax*. Among eurybathic species, *S. canicula* and *S. blainville* were the most representative, both achieving values higher than 75% in each year of the considered time series, with peaks of 100% (Figure 5).

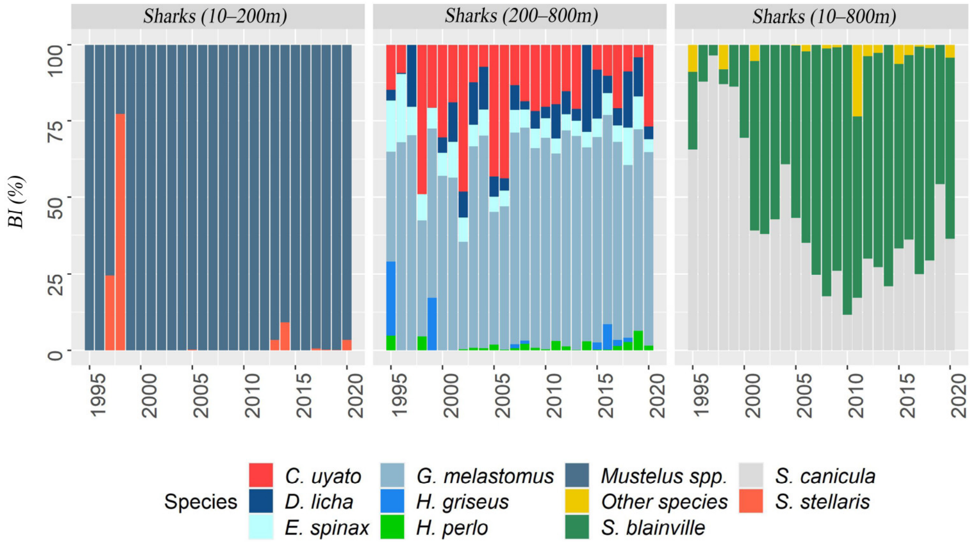

Figure 5. Biomass index (%) of a single shark species among total sharks per depth stratum over the years.

The BI trend showed fluctuations for shelf assemblages (highest value of 41.6 kg/km^2 in 2004), a dome-shaped curve for slope species (highest value of 62.1 kg/km^2 in 2009) and an increasing trend for eurybathic sharks (highest value of 84.6 kg/km^2 in 2018). As for single species, a dome-shaped curve was recorded for *G. melastomus* (highest value of 40.7 kg/km^2 in 2008) and *E. spinax* (highest value of 3.81 kg/km^2 in 2009), which was less pronounced for the latter. A fluctuating trend in the whole time series was recorded for *S. canicula* (highest value of 23.6 kg/km^2 in 2018) and *S. blainville* (highest value of 60.8 kg/km^2 in 2014) (Figure 6).

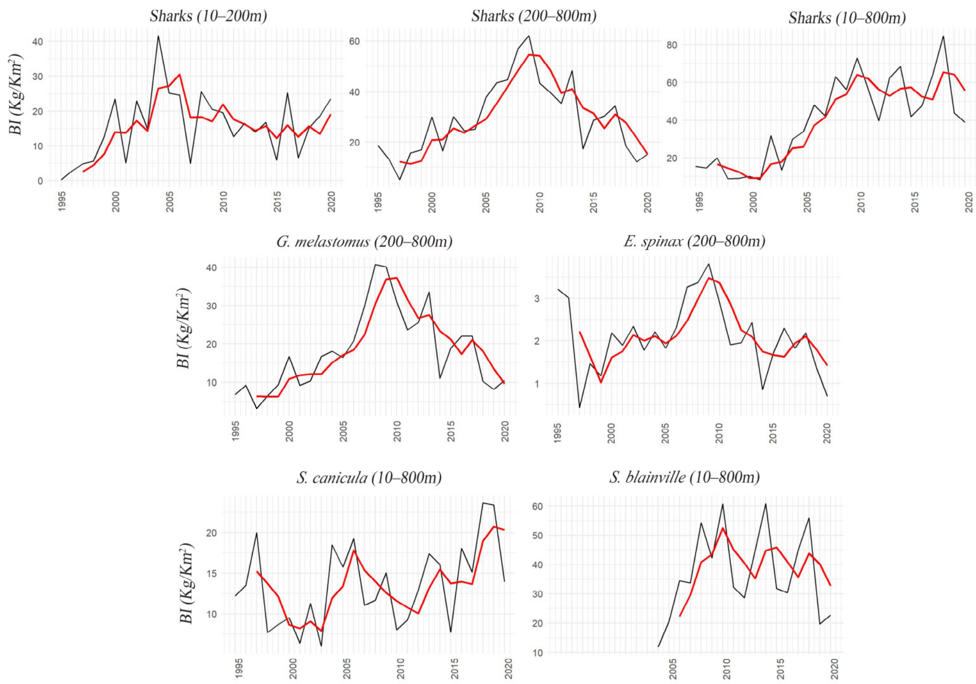

Figure 6. Trend of observed (black lines) MEDITS survey biomass index (kg/km^2) over the years and 3-year rolling mean (red lines) for sharks in the Strait of Sicily.

Regarding the assemblage of shelf sharks, good status in terms of relative biomass and harvesting has been detected since 2000 (Figure 7). On the other hand, a horseshoe pattern, with an improved assemblage condition from 1995 to 2008 followed by a worsening state up to 2020, was detected in the slope shark assemblage. This pattern was also found in the dynamics of the two main species comprising the slope shark assemblage, *G. melastomus* and *E. spinax*; the latter was in a state of overfishing and overexploitation during the whole examined time series. Regarding the eurybathic shark assemblage, a progressively improved status throughout the time series was detected. Similar dynamics were found for *S. blainville*, while for *S. canicula*, a more complex oscillating pattern was estimated in periods characterised by overfishing and overexploitation alternating with periods with sustainable relative biomass and harvesting value (Figure 7).

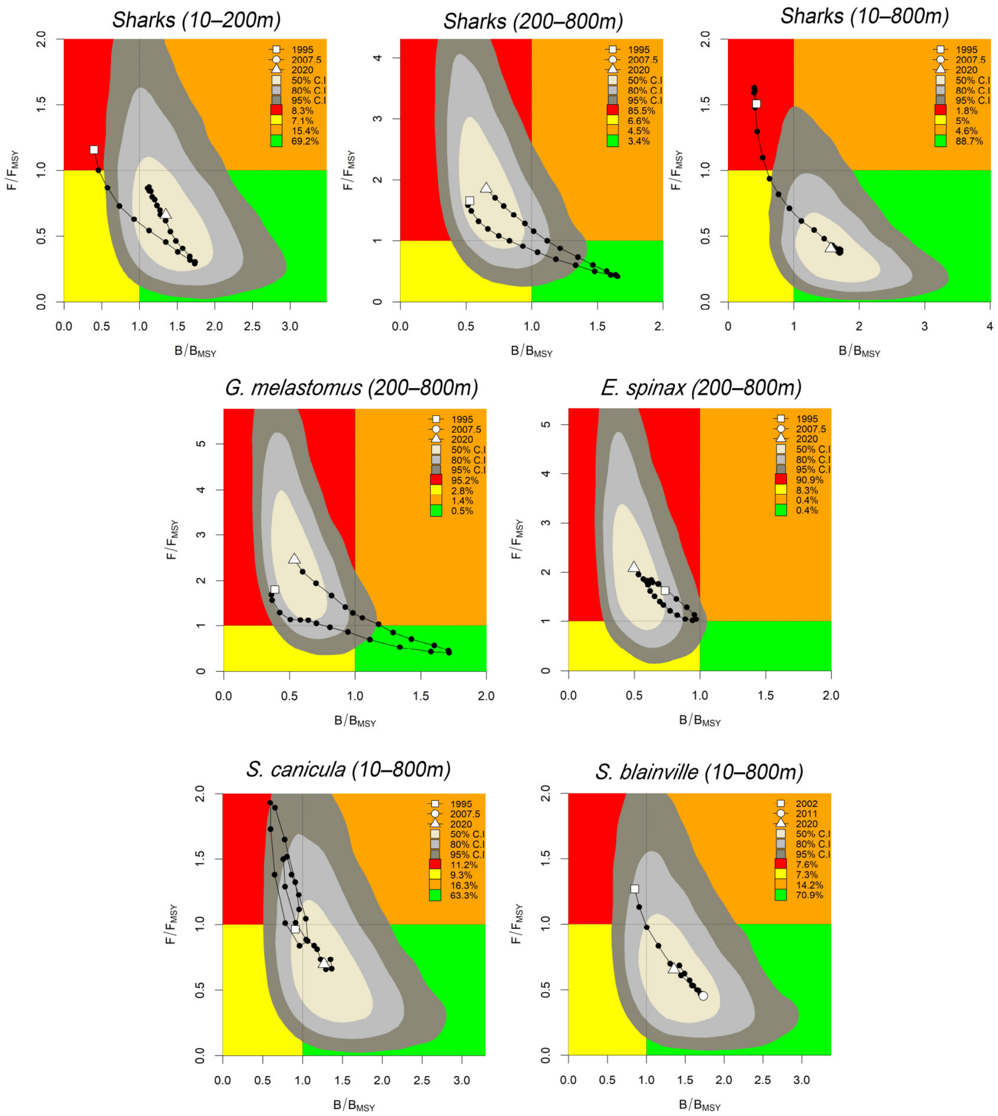

Figure 7. Dynamics of shark stocks in GSA 16 estimated by the AMSY model. F/F_{MSY} versus B/B_{MSY}. Quadrants are colour-coded: red: stocks that are both overfished (low relative biomass) and subject to overfishing (high exploitation rate) ($B \leq B_{MSY}$; $F \geq F_{MSY}$); orange: relative biomass is quite high but the exploitation rate is high ($B \geq B_{MSY}$; $F \geq F_{MSY}$); yellow: recovering stocks ($B \leq B_{MSY}$; $F \leq F_{MSY}$); green: stocks subject to a sustainable exploitation rate and with healthy stock biomass that can produce high yields close to MSY ($B \geq B_{MSY}$; $F \leq F_{MSY}$). Shaded areas indicate confidence intervals at 50% (light grey), 80% (grey) and 95% (dark grey) of reference points during the last year.

The sensitivity analysis indicated that the model was quite robust for all considered sharks, except for *S. blainville*, for which only one configuration indicated an overfishing condition. The reliability of the model was corroborated by retrospective analysis, except for *S. canicula*, for which there was a slight shift in the model run with three years removed (Figure S1 and Table S2).

3.3. Trends in Fishing Efforts and Patterns

An analysis of the nominal fishing effort of trawlers showed a clear decreasing trend, which was stronger for large vessels (LOA > 24 m; Figure 8).

Figure 8. (**Left**): nominal fishing effort (kw*fishing days) of bottom trawlers registered in GSA 16 (DCF source) over the years; (**right**): landing trend expressed in tons over the years.

Along with a decrease in the nominal landing of GSA 16, a change in the fishing pattern of trawlers was evident. The trend in the indices of the fishing pattern clearly showed a progressive shift of targeted assemblages of trawlers operating in the GSA 16 from shallow to deep-water species (Figure 8).

4. Discussion

The present study represents the first attempt to assess the stock status of Elasmobranchii caught in the Strait of Sicily by using MEDITS survey data. In the investigated area, a progressively improving condition for shark and ray assemblages in both shelf and eurybathic zones was detected. Indeed, according to Demirel et al. [64], these assemblages, as well as the main species, were assessed as being in a healthy condition, except for *R. miraletus*, which was considered to be in a critical condition. As for those living on the slope, a horseshoe-shaped dynamic, characterized by a progressive decrease in relative harvesting pressure and increased relative biomass followed by increased fishing pressure and decreased biomass, was found. Supporting this, these assemblages and main species were found to have an overfished or critical status [64].

Based on the local ecological knowledge of fishers, Colloca et al. [66] reconstructed long-term population trends of Elasmobranchii populations in the Strait of Sicily. Comparing information on cartilaginous fish abundance from catch and by-catch between the 1940s and 2000s, about 95% of fishers reported a decline in commercially important species (e.g., *Mustelus* spp.) and indicated species that could have been depleted or locally extinct (e.g., *Squatina* spp., *Sphyrna lewini*, *M. asterias*, etc.). Although this study was based on a shorter, more recent time series (1995–2021), the outcomes indicate signs of stock rebuilding in the last decade, except for species living on the slope bottoms.

The complex dynamics of the Elasmobranchii living in the Strait of Sicily would seem to be related to changes in the fishing patterns of Italian trawlers operating in the GSA 16. In particular, the analysis of the catch composition indices clearly showed a progressive shift of bottom trawling targets from coastal to deep-water species in the last 15 years, although an overall decreasing trend of trawlers was recognized (Figure 8). This change in the fishing pattern was recently reported by GFCM [68] using AIS data, showing increased efforts by Italian trawlers in deep-water fishing grounds from 22,000 h in 2015 to 34,000 h in 2018. Furthermore, recently Tunisian trawlers targeting deep-water crustaceans started to exploit the slope fishing grounds of the GSA 16 [69].

Considering the above, the worsening state of Elasmobranchii living on the continental slope and the improved state of eurybathic and shelf species relate well to the available information on the dynamics of fishing efforts and the changes in fishing patterns of Sicilian trawling. Globally, a negative reaction of Elasmobranchii stocks to increased fishing efforts is well known in the literature [2,3,70,71]. In the Mediterranean, for example, Ordines et al. [72] reported that reduced bottom trawl fishing efforts off the Balearic Islands over the last few decades probably had a positive influence on the continental shelf Elasmobranchii populations. Ligas et al. [73], investigating time series of Elasmobranchii catch rates from trawl surveys and monitoring of landing off the Tuscany coast (Tyrrhenian Sea), reported a general decreasing trend in the catch rates of sharks and skates from the early 1960s to the mid-1990s, mainly influenced by increased fishing efforts.

The progressive reduction of fishing fleets by about 50% that occurred since the late 1990s seemed to affect the increasing trend of catch rates of *G. melastomus*, *S. canicula* and skates from 1991 to 2009 at Santo Stefano Port, which hosts the main trawler fleet of the area. Moreover, in the Aegean Sea, Tsikliras et al. [74], using an AMSY model, reported a situation of unsustainable harvesting for 6 out 10 assessed Elasmobranchii, with the worst situation for target species (*R. clavata* and *S. acanthias*) than by-catch species (*G. melastomus*, *Torpedo marmorata* and *S. blainville*). In the Strait of Sicily during the 1980s, Gristina et al. [75], using GRUND trawl survey data, reported negligible density of the Elasmobranchii population in areas with the greatest fishing effort and the absence of seven species of Elasmobranchii recorded in areas with medium and low fishing pressure. According to the literature (e.g., [72,76–79]), *S. canicula* and *G. melastomus*, due to their life traits, could maintain their populations despite the intense fishing efforts in some areas. However, *G. melastomus* populations in GSA 16 showed clear signs of a poor status, while *S. canicula* exhibited a fluctuating pattern of improving and worsening in the examined time series.

It must be said that although the main driver of Elasmobranchii decline is overfishing, many other factors could negatively affect the dynamics of these species. For example, it was reported in the literature that climate change contributes to elevated extinction risk through habitat reduction and inshore distributional shifts [2,9,70,71]. In this sense, Follesa et al. [80], analysing MEDITS data from 2012 to 2015, found that areas under higher fishing pressure, such as the Adriatic Sea and the Spanish coast, show a low abundance of Elasmobranchii, but areas with higher fishing pressure, such as southwestern Sicily, show a high abundance, suggesting that other environmental drivers work together with fishing pressure to shape their distribution. Recently, Osgood et al. [81], at Cocos Island (Pacific Ocean), documented a decline in the abundance of some sharks and rays due to the effects of increased temperature. On the other hand, along the northern coast of Norway, Williams et al. [40] reported that the distribution and relative abundance did not appear to change significantly between 1992 and 2005, although average water temperatures rose during that period. However, it is expected that species with a K life history strategy, mostly those of larger size, will be more negatively affected by environmental change than smaller-sized species with the r life strategy [70].

In conclusion, although classical surplus production models are not able to account for changes in fishing patterns and fish stock productivity, they are considered robust tools to assess the dynamic response of fish populations to exploitation and eventually provide scientific advice on the state of the stocks [82]. The practice of keeping the assemblages (shelf, slope, and eurybathic) separate in fishery-independent catch rates allows us to limit the problem to the link with the change in fishing patterns when applying the surplus production model. However, the outcome of the present study shows that the estimate of the sum of K for single species exceeded that for aggregated species. This latter aspect seems to agree with results reported by Fogarty et al. [63], who assessed 12 demersal fish species in the Gulf of Maine at the single-species and aggregate levels by using surplus production models and reported that the maximum sustainable yield (MSY) and biomass at MSY (B_{MSY}) for the summed single-species production model exceeded the aggregate model by 28.0 and 27.5%, respectively. According to the authors, biological interactions such as predation and competition are potential reasons for differences between aggregate and summed results. On the other hand, it is reasonable to assume that Elasmobranchii assemblages living at different depths react to fishing efforts in an integrated way, considering the predation–competition dynamics. In addition, according to Bundi et al. [83], water temperature is the major environmental factor affecting system productivity when using the surplus production modelling approach to estimate the total aggregated catch and biomass of all major targeted bony fish species in 12 exploited Northern Hemisphere ecosystems.

5. Conclusions

In the present study, we estimated an improving exploitation status of the main single species (*R. clavata*, *S. blainville*, *S. canicula*) and assemblages of eurybathic and shelf Elasmobranchii living off the southern coast of Sicily by the surplus production model based on fishery-independent data. This pattern is in line with the reduced fishing effort that occurred in GSA 16 in the last 10 years due to the Common Fisheries Policy to make European fisheries more sustainable. Conversely, the shifting of the fishing pattern from shallow-water mixed fisheries to deep-water fisheries dedicated to high-priced crustaceans seems to be related to a worsening status of Elasmobranchii living on the slope of GSA 16. Considering the current change in the fishing pattern in the Strait of Sicily, attention should be paid to limiting the impact of deep-water red shrimp fisheries on sensitive species such as Elasmobranchii living on slope fishing grounds off the southern coast. Together with more effective control of fishing efforts, management measures aimed at increasing the selectivity of trawling gear, by either implementing an ad hoc modified sorting grid [62,84], raising the footrope [85], or cutting the rigging twine [39]; increasing the number of cartilaginous fish returned to the sea alive through education on proper handling [86–89], and protecting areas and periods where spawning and juveniles aggregate would contribute to improving the state of Elasmobranchii populations that suffer the impact of fisheries [90,91].

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/fishes7030136/s1, Table S1: Status of Elasmobranchii in the Mediterranean according to the classification of Dulvy et al. [17] and percentage of positive hauls of each species caught in each stratum (shelf, 10–200 m; slope, 200–800 m; overall, 10–800 m) during MEDITS survey in Strait of Sicily; Table S2: Outputs of the sensitivity analysis. *r*.est, estimated resilience; K.est, estimated carrying capacity; CI, 95% confidence interval; Figure S1: Retrospective analysis of investigated Elasmobranchii sampled during the MEDITS survey in GSA 16.

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Informed Consent Statement: Not applicable.

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