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Catalyzing Conservation: An Analysis of Fish Stock Dynamics in a Marine Protected Area before and after Artificial Reef Deployment

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Abstract: The marine ecosystem's balance is crucial for sustaining biodiversity and supporting fisheries. Marine protected areas have been increasingly used to enhance marine habitats, yet their impact on fish populations remains a topic of debate. This study focuses on a marine protected area in Kitros, Pieria, in Greece, where an artificial reef was constructed, to understand its influence on coastal fish populations. The objectives were to investigate the changes in fish biomass and abundance, comparing the data from periods before and after the construction of an artificial reef. This research compares the data between 2007 and 2008 with the data between 2016 and 2017, collected with bottom trawl surveys strategically executed prior to and after the artificial reef's installation. Fish species captured were identified, with their lengths and masses measured. The findings indicate an increase in the biomass and abundance of certain fish species after artificial reef deployment, notably the commercially significant *Mullus barbatus* and *Pagellus erythrinus*. The artificial reef in Kitros, Pieria, with its surrounding marine protected area appears to have had a positive impact on the local fish populations over the years, suggesting that it can contribute to marine conservation and fishery enhancement. These results underscore the potential of artificial reefs as tools for marine ecosystem management, offering insights for policymakers and environmentalists into coastal resource management.

Keywords: fish population dynamics; coastal ecosystem management; marine biodiversity conservation; long-term environmental monitoring

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1. Introduction

The Kitros, Pierias marine protected area (MPA) in Greece, characterized by freshwater inputs from the Aliakmonas, Axios, and Loudias river deltas, undergoes significant seasonal environmental changes [1]. Factors, such as photoperiod and solar radiation, contribute to the creation of a thermocline in spring and summer. This period also sees an increased freshwater influx due to higher rainfall and ice melt from regional mountains, affecting water column stratification and river runoff in the area [2]. Moreover, the area is influenced by two primary water bodies: Black Sea Water (BSW) and Levantine Intermediate Waters (LIWs) [3,4]. A primary goal for establishing MPAs, such as the one in the Kitros, Pieria, region of the NW Aegean Sea, is to aggregate various fish species. This aggregation supports local fishing communities by increasing the catch per unit effort (CPUE) and enhancing access to marine resources [5]. Artificial reefs (ARs) provide a foundation for epifauna, utilizing organic waste discharged into the sea. They also protect marine life from trawling activities and support artisanal fisheries. Additionally, these reefs improve fish habitat, enhance coastal erosion protection, and offer marine research opportunities while serving as a haven for adult marine species [6]. Studies have demonstrated their effectiveness in increasing primary productivity and helping recreational fisheries [1,6]. When an AR is established, the area surrounding is declared as an MPA [2]. In 2014, an artificial reef was established in the Kitros, Pieria, area. A three-year monitoring program between 2015 and 2017, which employed bottom trawl methods, identified more than 70 fish species in the vicinity of the MPA surrounding the reef [1]. Prior to the reef's installation in 2007–2008 with no MPA present, a set of samplings was conducted through bottom trawl as part of an initial preliminary survey. The present study aims to compare the fish populations sampled before and after the MPA's creation. This comparison seeks to investigate any changes in the abundance and biomass of these populations over the years following the artificial reef's establishment.

2. Materials and Methods

2.1. Artificial Reef Construction

Constructing an AR under current Greek legislation involves a three-stage process. The initial stage entails identifying a potential area, conducting a preliminary field study, and determining the precise location for the artificial reef. Following these steps, requisite approvals are obtained from various authorities, including the Hydrographic Service, the Archaeological Service, and the State Land Service. Subsequently, the construction phase commences, typically spanning 2–3 years, including both the announcement and actual building phases. Post-construction, a scientific monitoring period of three years is mandated to evaluate the reef's impact on environmental enhancement, reduction in marine population mortality, and establishment of a protected area with specific regulations for fishing and other human activities. Within the marine protected area, key regulations included a complete prohibition on bottom trawling and seine fishing, the authorization of fishing nets with a minimum mesh size of 45 mm (stretched), and fish traps with a comparable mesh size, in addition to implementing a four-month annual ban on fish trap usage. Furthermore, minimum catch sizes were established for the most commercially valuable species caught within the MPA. A total ban on spearfishing was also imposed in the area. On average, the entire process, from planning to implementation, took approximately 10 years. This procedure was adhered to for the Kitros artificial reef. The preliminary study was conducted in 2007–2008, construction occurred in 2011–2013, and scientific monitoring was carried out in 2015–2017. The data presented in this work were derived from this entire process. Notably, all studies were conducted by the same entity using the exact same methodology, which was a rare opportunity that eventually led to the data processing and subsequent publication.

2.2. Sampling Site

The Thermaikos Gulf, located in the western part of the North Aegean Sea, experiences unique hydrological characteristics. This body of water is primarily influenced by the influx of freshwater from four main rivers: Axios, Aliakmonas, Loudias, and Gallikos. Among these, Axios and Aliakmonas stand out for their complex delta systems with multiple channels [7,8]. The Axios River has been pinpointed as a major contributor of pollution, funneling high levels of nutrients from its basin into the Thermaikos Gulf [9]. The gulf's water circulation is characterized by saltier water entering from the east and moving in a northwestern direction, while lighter river water flows southward along the western shore [10]. The Thermaikos Gulf is typically a mesotrophic zone, yet episodes of severe eutrophication have been recorded, especially during prolonged periods of southern winds [8]. Lastly, ref. [11] suggests a decline in the overall health of the ecosystem, evidenced by reduced fish populations and biomass, attributable to overfishing and various environmental stressors.

2.3. Seasonal Monitoring

Before the establishment of the AR, an ichthyological investigation was undertaken, encompassing four sampling events between 2007 and 2008. The preliminary sampling took place in May 2007, followed by subsequent ones in September 2007, April 2008, and June 2008. These samplings utilized a bottom trawl method within selected fishing routes in the

Thermaikos Gulf, off Kitros. The trawl employed was a modified bottom trawl featuring a small mesh opening (20 mm mesh size, stretched). The trawl's horizontal length was 20 m, and it was towed at a speed of 3 nautical miles per hour. Trawling operations were conducted using the same vessel during both sampling periods and at precisely identical locations. The trawling was strategically aligned to be perpendicular to pre-set transects and as parallel as feasible to the isobaths. Each sampling comprised three hauls, conducted at depths varying from approximately 27 to 36 m. Hauls were strategically positioned along the edges of the area that would become the artificial reef complex (Figure 1). This study aggregated the average abundance and biomass data from these three hauls into a single sampling value, hence presenting a consolidated figure for each species' abundance and biomass for each sampling date, despite the occurrence of three hauls per date.

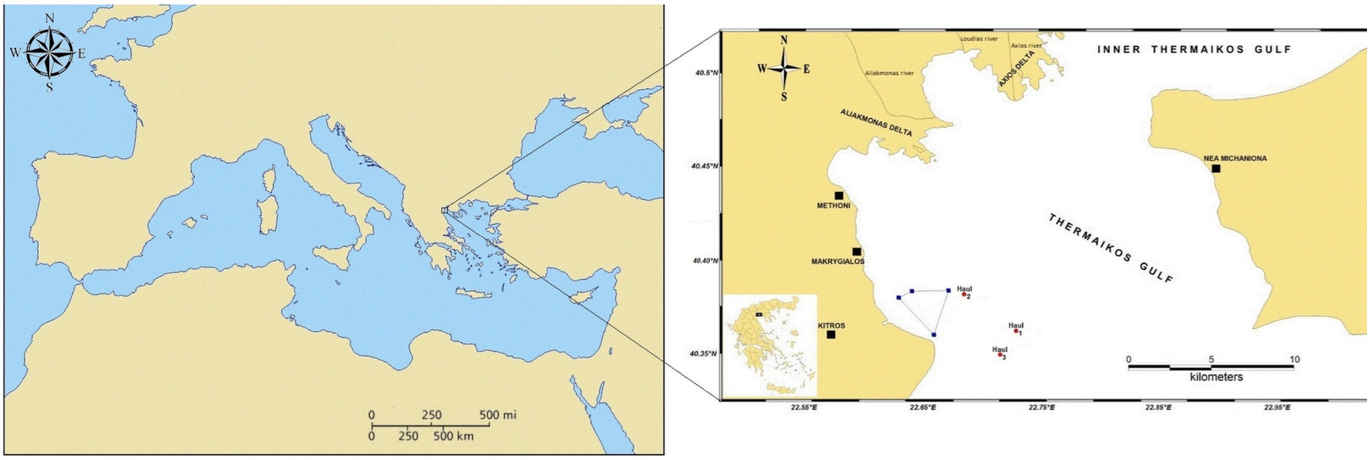

Figure 1. Haul sites (N = 3) for sampling with bottom trawl in the outer Thermaikos Gulf of the Aegean Sea offshore of the coastal zone of Kitros, in the Pieria region of Greece. Field sites were located on edge habitats of the marine area of a previously constructed artificial reef complex (polygon with blue edges) [1].

Following the construction of the artificial reef in 2014, a series of seasonal surveys were executed from June 2015 to September 2017. These surveys formed a part of the three-year monitoring initiative after the reef's establishment [1,2]. The sampling stations were the same in both surveys conducted in 2007–2008 and 2015–2017 (Figure 1).

2.4. Fish Abundance and Biomass Calculation

After each haul, the catch was identified to the species level [12,13]. Onboard, the length frequencies of each species and their abundance in terms of number and weight were recorded. The analyses utilized two primary measures: abundance and biomass. Abundance was expressed as the number of individuals per square kilometer (individuals/km^2) and biomass as kilograms per square kilometer (kg/km^2).

The trawl's scanning surface area was determined by calculating the door spread, using Carrothers' formula [14,15].

$$\text{area swept}(\text{km}^2) = (\text{door spread}, \text{km}) \times (\text{tow speed}, \frac{\text{km}}{\text{h}}) \times (\text{tow duration}, \text{h})$$

Fish density (individual/km^2) was then determined by calculating the area swept by the trawl net, estimating the density in that area and then extrapolating it to a larger area in km^2 [16] Similarly, the biomass was calculated by using weight data instead of individual number data [16,17].

$$\text{density}(\frac{\text{kg}}{\text{km}^2}) = \frac{\text{catch}(\text{kg})}{\text{area swept}(\text{km}^2)},$$

2.5. Data Analysis

Data analysis was performed using PRIMER v6. (PRIMER-E Ltd, Plymouth, UK) and Microsoft Excel 2019 for Windows (Microsoft Corporation, Redmond, WA, USA).

In this study, a similarity percentages (SIMPER) analysis was conducted to elucidate the specific contributions of various species to the observed dissimilarities between sampling events. This study concentrated on comparing the samples gathered before and after the artificial reef was constructed, using the Bray–Curtis dissimilarity index for the evaluation. Biomass values of species, were employed as average figures. For each species, one average value represented the 2007–2008 sampling period, and another average biomass value was used for the 2016–2017 period. Diversity indexes were determined across the sampling periods, before and after the establishment of the artificial reef. A non-metric multi-dimensional scaling (MDS) analysis of fish abundance data (individual/km^2), categorized by 8 sampling dates before 2007–2008 and after 2016–2017 regarding the artificial reef construction in Kitros, Pieria, was also performed.

3. Results

3.1. Species Presence, Abundance, and Biomass

3.1.1. Species Presence

In these series of samplings, 77 species were documented in total, belonging to 45 families. A total of 56 species of fish, 6 cephalopods, and 10 Malacostraca (Table 1) were identified, with the remaining 6 species belonging to Chondrichthyes class. A consistent presence of 24 species was seen across all 8 samplings (Tables 1 and 2). Those were *Arnoglossus laterna*, *Citharus linguatula*, *Sardina pilchardus*, *Engraulis encrasicolus*, *Merlangius merlangus*, *Trisopterus minutus*, *Gobius niger*, *Merluccius merluccius*, *Scorpaena notata*, *Scorpaena porcus*, *Serranus hepatus*, *Diplodus annularis*, *Spicara flexuosum*, *Trachurus mediterraneus*, *Chelidonichthys lucerna*, *Uranoscopus scaber*, *Loligo vulgaris*, *Eledone moschata*, *Octopus vulgaris*, *Medorippe lanata*, *Liocarcinus depurator*, *Squilla mantis*, *Torpedo marmorata*, and *Tetronarce nobiliana*.

Table 1. List of species present during the surveys before (2007–2008) and after (2016–2017) the creation of the artificial reef at field sites in the outer region of the Thermaikos Gulf in the Aegean Sea, offshore of the coastal zone of Kitros, in the Pieria region of Greece.

Class	Family	Species	May-07	Sep-07	Apr-08	Jun-08	Apr-16	Jun-16	Apr-17	May-17
Osteichthyes	Blenniidae	*Blennius ocellaris* (Linnaeus, 1758)	–	–	–	–	–	–	+	+
	Bothidae	*Arnoglossus laterna* (Walbaum 1792)	+	+	+	+	+	+	+	+
		Arnoglossus rueppelii (Cocco, 1844)	+	+	+	–	–	–	–	–
		Arnoglossus thori (Kyle, 1913)	–	–	+	–	–	–	–	–
	Callionymidae	*Callionymus risso* (Lesueur, 1814)	–	–	–	+	–	–	+	–
	Carangidae	*Caranx rhonchus* (Geoffroy Saint-Hilaire, 1817)	–	–	–	–	–	+	–	–
	Cepolidae	*Cepola macrophthalma* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Citharidae	*Citharus linguatula* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Alosidae	*Alosa fallax* (Lessepede, 1803)	+	–	–	+	–	+	–	+
	Clupeidae	*Sardina pilchardus* (Walbaum, 1792)	+	+	+	+	+	+	+	+
		Sardinella aurita (Valenciennes, 1847)	+	–	–	+	–	+	–	+
	Congridae	*Conger conger* (Linnaeus, 1758)	+	+	–	+	–	+	–	+
	Engraulidae	*Engraulis encrasicolus* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Gadidae	*Merlangius merlangus* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
		Micromesistious poutassou (Risso, 1827)	–	–	–	–	–	–	+	–
		Trisopterus minutus (Linnaeus, 1758)	+	+	+	+	+	+	+	+

Table 1. *Cont.*

Class	Family	Species	May-07	Sep-07	Apr-08	Jun-08	Apr-16	Jun-16	Apr-17	May-17
	Gobiidae	*Aphia minuta* (Risso, 1810)	+	–	–	–	–	–	–	–
		Gobius niger (Linnaeus, 1758)	+	+	+	+	+	+	+	+
		Lesueurigobius friesii (Malm, 1874)	+	+	+	+	–	–	–	–
		Lesueurigobius suerii (Risso, 1810)	+	+	+	–	–	–	–	–
	Labridae	*Symphodus tinca* (Linnaeus, 1758)	–	+	–	–	–	–	–	–
	Lophiidae	*Lophius budegasa* (Spinola, 1807)	+	+	+	+	+	–	+	+
	Merluciidae	*Merluccius merluccius* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Mullidae	*Mullus barbatus* (Linnaeus, 1758)	–	+	+	+	+	+	+	+
		Mullus surmuletus (Linnaeus, 1758)	–	+	–	–	–	–	–	–
	Pleuronectidae	*Platichthys flesus* (Linnaeus, 1758)	+	+	–	+	–	–	–	–
	Pomatomidae	*Pomatomus saltatrix* (Linnaeus, 1766)	–	–	–	–	+	+	+	+
	Scombridae	*Scomber japonicus* (Houttuyn, 1782)	–	–	+	+	–	–	–	+
		Scomber scombrus (Linnaeus, 1758)	–	+	–	+	+	–	+	–
	Scophthalmidae	*Scophtalmus rhompus* (Linnaeus, 1758)	–	–	–	–	+	+	+	+
	Scorpaenidae	*Scorpaena notata* (Rafinesque, 1810)	+	+	+	+	+	+	+	+
		Scorpaena porcus (Linnaeus, 1758)	+	+	+	+	+	+	+	+
		Scorpaena scrofa (Linnaeus, 1758)	–	–	–	–	–	–	–	–
	Serranidae	*Serranus cabrilla* (Linnaeus, 1758)	+	+	–	+	+	+	+	+
		Serranus hepatus (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Soleidae	*Pegusa lascaris* (Risso, 1810)	–	–	+	–	–	–	–	–
		Solea solea (Linnaeus, 1758)	+	+	–	+	+	+	+	+
	Sparidae	*Boops boops* (Linnaeus, 1758)	–	–	+	–	–	+	+	+
		Dentex gibbosus (Rafinesque, 1810)	–	–	–	–	–	+	–	–
		Diplodus annularis (Linnaeus, 1758)	+	+	+	+	+	+	+	+
		Diplodus vulgaris (Geoffroy Saint-Hilaire, 1817)	–	–	+	–	–	+	–	–
		Pagellus acarne (Risso, 1827)	+	+	–	–	–	+	+	–
		Pagellus bogaraveo (Brünnich, 1768)	+	+	–	–	–	+	+	+
		Pagellus erythrinus (Linnaeus, 1758)	+	–	+	+	+	+	+	+
		Sparus aurata (Linnaeus, 1758)	–	–	–	–	–	+	+	+
		Spicara flexuosum (Rafinesque, 1810)	+	+	+	+	+	+	+	+
		Spondyliosoma cantharus (Linnaeus, 1758)	–	–	+	–	–	–	–	–
	Sphyraenidae	*Sphyraena sphyraena* (Linnaeus, 1758)	–	–	–	–	–	+	–	–
	Trachinidae	*Trachinus draco* (Linnaeus, 1758)	+	–	–	–	–	–	–	+
		Trachurus mediterraneus (Steindachner, 1868)	+	+	+	+	+	+	+	+
		Trachurus trachurus (Linnaeus, 1758)	+	–	–	–	–	–	–	–
	Triglidae	*Lepidotrigla cavillone* (Lacépède, 1801)	–	+	+	–	–	–	+	+
		Chelidonichthys lastoviza (Bonnaterre, 1758)	+	+	+	+	+	+	+	+
	Uranoscopidae	*Uranoscopus scaber* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Zeidae	*Zeus faber* (Linnaeus, 1758)	+	–	–	–	–	+	+	+
Cephalopoda	Loliginidae	*Alloteuthis media* (Linnaeus, 1758)	+	+	+	–	–	+	+	+
		Loligo vulgaris (Lamarck, 1798)	+	+	+	+	+	+	+	+
	Octopodidae	*Eledone moschata* (Lamarck, 1798)	+	+	+	+	+	+	+	+
		Octopus vulgaris (Cuvier, 1797)	–	+	+	+	+	+	+	+
	Ommastrephidae	*Illex coindentii* (Vérany, 1837)	+	+	+	–	+	–	+	+
	Sepiidae	*Sepia officinalis* (Linnaeus, 1758)	+	+	+	+	–	+	+	+

Table 1. *Cont.*

Class	Family	Species	May-07	Sep-07	Apr-08	Jun-08	Apr-16	Jun-16	Apr-17	May-17
Malacostraca	Dorippidae	*Medorippe lanata* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Eriphiidae	*Eriphia verrucosa* (Forsskål, 1775)	+	−	+	−	+	−	+	+
	Goneplacidae	*Goneplax rhomboides* (Linnaeus, 1758)	+	+	+	+	+	−	+	+
	Munididae	*Munida rugosa* (Fabricius, 1775)	−	+	−	−	−	−	−	−
	Penaeidae	*Parapenaeus longirostris* (Lucas, 1846)	+	+	+	−	+	+	+	+
		Penaeus kerathurus (Forsskål, 1775)	−	+	+	−	+	+	+	+
		Penaeus aztecus (Ives, 1891)	−	−	−	−	+	+	+	+
	Portunidae	*Callinectes sapidus* (Rathbun, 1896)	−	−	−	−	−	+	−	−
		Liocarcinus depurator (Linnaeus, 1758)	+	+	+	+	+	+	+	+
	Squillidae	*Squilla mantis* (Linnaeus, 1758)	+	+	+	+	+	+	+	+
Chondrichthyes	Dasyatidae	*Dasyatis pastinaca* (Linnaeus, 1758)	−	−	−	−	−	−	+	−
	Myliobatidae	*Myliobatis aquila* (Linnaeus, 1758)	−	−	−	−	−	+	−	+
	Rajidae	*Raja brachyura* (Lafont, 1871)	−	−	−	+	−	−	−	−
		Raja montaqui (Fowler, 1910)	−	−	−	−	−	+	−	−
	Torpenididae	*Torpedo marmorata* (Risso, 1810)	+	+	+	+	+	+	+	+
		Tetronarce nobiliana (Bonaparte, 1835)	+	+	+	+	+	+	+	+

Table 2. List of species abundance /km^2 during the surveys before (2007–2008) and after (2016–2017) the creation of the artificial reef at field sites in the outer region of the Thermaikos Gulf in the Aegean Sea, offshore of the coastal zone of Kitros, in the Pieria region of Greece.

	30-May-07	10-Sep-07	14-Apr-08	13-Jun-08	7-Apr-16	8-Jun-16	7-Apr-17	8-May-17	7–8 Avg.	16–17 Avg.
Species	**Abundance N /km^2**									
Alloteuthis media	129	129	378	0	0	1	187	831	159	254
Alosa fallax	9	0	0	92	0	4	0	18	25	5
Aphia minuta	9	0	0	0	0	0	0	0	2.25	0
Arnoglossus laterna	4961	3061	3237	16,727	17	33	4073	6919	6996	2760
Arnoglossus rueppelii	92	37	28	0	0	0	0	0	39	0
Arnoglossus thori	0	0	83	0	0	0	0	0	20	0
Blennius ocellaris	0	0	0	0	0	0	10	27	0	9
Boops boops	0	0	28	0	0	2	137	82	7	55
Callinectes sapidus	0	0	0	0	0	3	0	0	0	0
Callionymus risso	0	0	0	166	0	0	20	0	41	4
Caranx rhonchus	0	0	0	0	0	2	0	0	0	0
Cepola macrophthalma	1014	1199	1309	2536	1	3	79	110	1514	48
Citharus linguatula	479	876	811	2729	179	30	520	1031	1223	440
Conger conger	9	18	0	18	0	16	0	9	11	6
Dasyatis pastinaca	0	0	0	0	0	0	10	0	0	2
Dentex gibbosus	0	0	0	0	0	17	0	0	0	4
Diplodus annularis	5754	2886	11,904	9461	137	245	5290	11,026	7501	4174
Diplodus vulgaris	0	0	111	0	0	40	0	0	27	9
Eledone moschata	18	55	9	28	2	14	39	9	27	16
Engraulis encrasicolus	15,095	2858	7958	3227	7	7	2287	10,826	7284	3281
Eriphia verrucosa	46	0	65	0	0	0	39	37	27	19
Peaneus aztecus	0	0	0	0	0	85	39	9	0	33
Gobius niger	1457	913	1724	3329	3	3	177	247	1855	107
Goneplax rhomboides	18	9	55	258	0	0	49	155	85	51
Illex coindetii	323	28	535	0	3	0	334	37	221	93
Lepidotrigla cavillone	0	74	65	0	0	0	29	64	34	23
Lesuerigobius friessi	3347	1909	1512	3071	0	0	0	0	2459	0
Lesuerigobius suerii	18	55	9	0	0	0	0	0	20	0
Liocarcinus depurator	2241	3310	950	16,302	52	3	88	456	5700	149
Loligo vulgaris	304	3882	120	46	1	20	59	18	1088	24
Lophius budegassa	18	9	37	46	3	0	29	9	27	10
Medorippe lanata	221	83	194	240	1	2	20	82	184	26
Merlangius merlangus	1466	913	369	461	13	1	10	110	802	33
Merluccius merluccius	1641	572	166	92	3	17	98	64	617	45
Micromesistius poutassou	0	0	0	0	0	0	10	0	0	2
Mullus barbatus	0	1014	775	101	60	1155	7979	1926	472	2780
Mullus surmuletus	0	369	0	0	0	0	0	0	92	0
Munida rugosa	0	46	0	0	0	0	0	0	11	0
Myliobatis aquila	0	0	0	0	0	72	0	9	0	20
Octopus vulgaris	0	37	9	28	16	18	10	9	18	13
Pagellus acarne	37	15,279	0	0	0	56	49	0	3829	26

Table 2. *Cont.*

	30-May-07	10-Sep-07	14-Apr-08	13-Jun-08	7-Apr-16	8-Jun-16	7-Apr-17	8-May-17	7–8 Avg.	16–17 Avg.
Species	**Abundance N /km²**									
Pagellus bogaraveo	65	645	0	0	0	41	49	420	177	127
Pagellus erythrinus	37	0	931	194	148	448	10,315	4865	290	3943
Paguridae	0	18	0	0	0	0	0	0	4.5	0
Parapenaeus longirostris	28	18	28	0	1	3	206	173	18	95
Penaeus kerathurus	0	55	18	0	12	24	79	55	18	42
Platichthys flesus	65	129	0	120	0	0	0	0	78	0
Pomatomus saltatrix	0	0	0	0	4	84	29	155	0	68
Raja brachyura	0	0	0	9	0	0	0	0	2.25	0
Raja montagui	0	0	0	0	0	15	0	0	0	3
Sardina pilchardus	221	8668	17,713	1632	1	3	39	4098	7058	1035
Sardinella aurita	9	0	0	314	0	1	0	18	80	4.9
Scomber japonicus	0	0	9	9	0	0	0	438	4.5	109
Scomber scombrus	0	249	0	9	0	0	49	0	64.5	12
Scophtalmus rhompus	0	0	0	0	7	8	10	18	0	10
Scorpaena notata	821	194	415	2305	100	124	2208	2008	933	1109
Scorpaena porcus	120	249	489	443	12	11	118	758	325	224
Scorpaena scrofa	0	0	0	0	0	0	0	0	0	0
Sepia elegans	0	0	0	0	0	0	0	0	0	0
Sepia officinalis	18	286	37	9	0	141	88	18	87	61
Serranus cabrilla	46	9	0	65	5	27	10	46	30	21
Serranus hepatus	4795	4583	12,734	25,210	22	20	2257	3459	11,830	1439
Solea lascaris	0	0	18	0	0	0	0	0	4.5	0
Solea solea	37	28	0	18	4	22	118	201	20	86
Sparus aurata	0	0	0	0	0	26	39	64	0	32
Sphyraena sphyraena	0	0	0	0	0	14	0	0	0	3
Spicara flexuosum	1365	2029	1780	2019	9	6	2346	5294	179	1913
Spondyliosoma cantharus	0	0	203	0	0	0	0	0	50	0
Squilla mantis	553	959	811	1180	13	41	648	429	875	282
Symphodus tinca	0	9	0	0	0	0	0	0	2	0
Torpedo marmorata	28	55	18	65	0	36	39	18	41	23
Tetronarce nobiliana	166	138	37	28	0	18	39	46	92	25
Trachinus draco	18	0	0	0	0	0	0	37	4	9
Trachurus mediterraneus	231	6298	65,413	10,973	124	211	4770	3186	20,728	2072
Trachurus trachurus	46	0	0	0	0	0	0	0	11	0
Chelidonichthys lucerna	46	562	55	46	70	249	1492	1059	177	717
Trisopterus minutus	2692	2010	7137	1272	7	4	0	46	3277	13
Uranoscopus scaber	46	28	46	37	10	128	98	155	39	97
Zeus faber	9	0	0	0	0	13	20	18	2	12

3.1.2. Species Abundance

Pagellus erythrinus (common pandora) experienced a notable increase from 290 to 3943 individuals/km^2 (Figure 2). *Mullus barbatus* (red mullet) saw its numbers rise from 472 to 2780 individuals/km^2 (Figure 3). *Scorpaena notata* (small red scorpionfish) also showed a positive trend with an increase from 933 to 1109 individuals/km^2. *Chelidonichthys lucerna* increased from 177 to 717 individuals/km^2. *Scomber japonicus* (Pacific mackerel) showed an increase from 4 to 109 individuals/km^2. *Uranoscopus scaber* (stargazer) saw an increase from 39 to 97 individuals/km^2. The abundance of *Solea vulgaris* (common sole) rose from 0 to 86 individuals/km^2. *Parapenaeus longirostris* (deepwater rose shrimp) showed an increase from 18 to 95 individuals/km^2.

Arnoglossus laterna (scaldfish) experienced a decrease from 6996 to 2760 individuals/km^2. *Engraulis encrasicolus* (European anchovy) saw a decline from 7284 to 3281 individuals/km^2. *Diplodus annularis* (annular seabream) decreased from 7501 to 4174 individuals/km^2. The group with reduced abundances post-artificial reef deployment included *Cepola macrophthalma* (red bandfish), which declined from 1514 individuals/km^2 to 0. *Lesuerigobius friessi* (yellow goby) declined from 2459 to no detectable individuals/km^2. *Gobius niger* (black goby) saw a reduction from 1855 individuals/km^2 to 107. *Trisopterus minutus* (poor cod) dropped from 3277 to 13 individuals/km^2. *Liocarcinus depurator* (harbor crab) decreased from 5700 to 149 individuals/km^2. *Sardina pilchardus* (European pilchard) declined from 7058 to 1035 individuals/km^2. *Serranus hepatus* (Brown comber) decreased from 11,830 to 1439 individuals/km^2. Lastly, *Trachurus mediterraneus* (Mediterranean horse mackerel) showed a significant reduction from 20,728 individuals/km^2 to 2072 individuals/km^2 following reef construction.

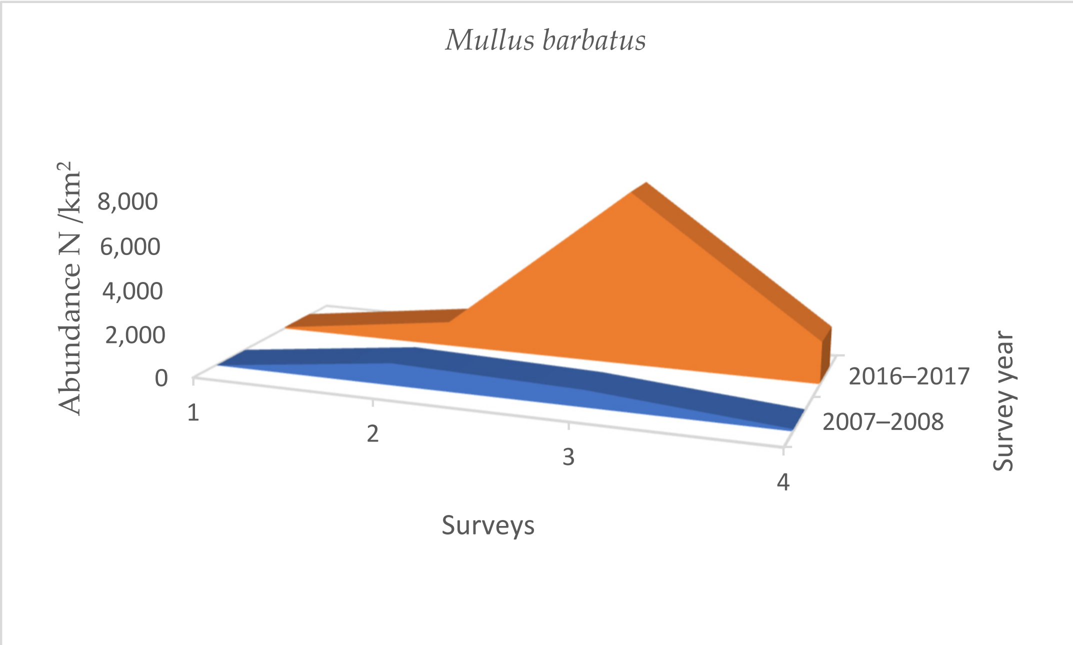

Figure 2. Abundance trends of *Mullus barbatus* across two distinct sampling intervals—using average values before (2007–2008) and after (2016–2017) the establishment of the artificial reef in Kitros, Pieria. On the horizontal axis, samplings 1–4 refer to the 4 seasonal surveys in 2007–2008 and 2016–2017.

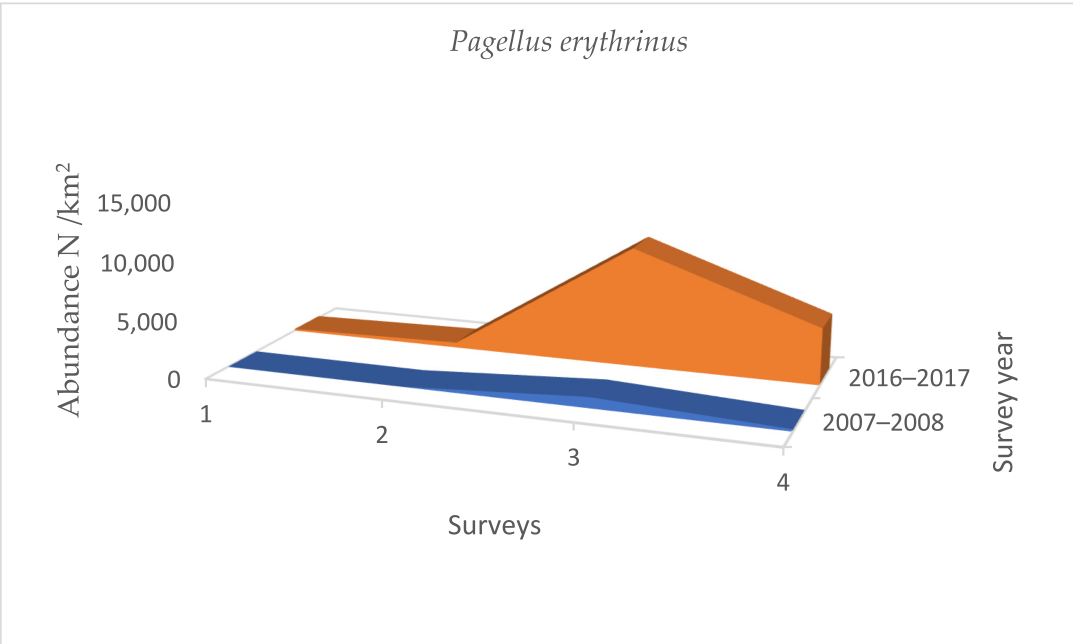

Figure 3. Abundance trends of *Pagellus erythrinus* across two distinct sampling intervals—using average values before (2007–2008) and after (2016–2017) the establishment of the artificial reef in Kitros, Pieria. On the horizontal axis, samplings 1–4 refer to the 4 seasonal surveys in 2007–2008 and 2016–2017.

3.1.3. Species Biomass

Species biomass changes before and after the establishment of the marine protected area are detailed in Table 3, highlighting three categories based on the nature of biomass change.

Table 3. List of species biomass (kg/km^2) during the surveys before (2007–2008) and after (2016–2017) the creation of the artificial reef at field sites in the outer region of the Thermaikos Gulf in the Aegean Sea offshore of the coastal zone of Kitros, in the Pieria region of Greece.

	Biomass kg/km^2									
Species	**30-May-07**	**10-Sep-07**	**14-Apr-08**	**13-Jun-08**	**7-Apr-16**	**8-Jun-16**	**7-Apr-17**	**8-May-17**	**08/09 Avg.**	**16/17 Avg.**
Alloteuthis media	0.4	0.2	0.8	0.0	17.8	209.2	1.2	6.8	0.4	58.8
Alosa fallax	0.7	0.0	0.0	3.9	0.0	47.5	0.0	2.0	1.2	12.4
Aphia minuta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Arnoglossus laterna	33.2	20.6	19.1	77.6	2226.2	4592.3	30.8	48.7	37.6	1724.5
Arnoglossus rueppelii	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Arnoglossus thori	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1	0.0
Blennius ocellaris	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.4	0.0	0.1
Boops boops	0.0	0.0	1.1	0.0	0.0	85.6	4.0	1.2	0.3	22.7
Callinectes sapidus	0.0	0.0	0.0	0.0	0.0	19.0	0.0	0.0	0.0	4.8
Callionymus risso	0.0	0.0	0.0	0.9	0.0	0.0	0.0	0.0	0.2	0.0
Caranx rhonchus	0.0	0.0	0.0	0.0	0.0	28.5	0.0	0.0	0.0	7.1
Cepola macrophthalma	23.3	22.4	21.6	39.1	53.4	152.1	0.8	1.1	26.6	0.0
Citharus linguatula	24.3	16.9	13.0	59.9	5164.8	1958.6	7.8	20.7	28.5	1788.0
Conger conger	5.0	6.6	0.0	11.1	0.0	28.5	0.0	11.0	5.7	9.9
Dasyatis pastinaca	0.0	0.0	0.0	0.0	0.0	0.0	14.7	0.0	0.0	3.7
Dentex gibbosus	0.0	0.0	0.0	0.0	0.0	142.6	0.0	0.0	0.0	35.7
Diplodus annularis	250.6	125.6	445.2	396.5	3624.3	7767.9	199.4	491.5	304.5	3020.8
Diplodus vulgaris	0.0	0.0	4.2	0.0	0.0	1188.5	0.0	0.0	1.1	297.1
Eledone moschata	7.6	33.6	2.6	12.9	8.9	38.0	18.1	2.2	14.2	16.8
Engraulis encrasicolus	132.5	17.1	64.4	17.1	1611.8	2453.0	13.6	48.9	57.7	1031.8
Eriphia verrucosa	0.2	0.0	0.8	0.0	106.9	19.0	0.1	0.1	0.3	31.5
Penaeus aztecus	0.0	0.0	0.0	0.0	8.9	209.2	2.5	0.2	0.0	55.2
Gobius niger	28.8	17.4	51.2	40.6	115.8	237.7	2.4	4.7	34.5	90.2
Goneplax rhomboides	0.1	0.1	0.3	2.2	53.4	0.0	0.1	0.6	0.7	13.5
Illex coindetii	28.2	1.7	14.4	0.0	35.6	0.0	5.6	2.5	11.1	10.9
Lepidotrigla cavillone	0.0	0.3	0.7	0.0	0.0	0.0	0.2	0.4	0.2	0.2
Lesuerigobius friessi	18.8	10.3	12.6	13.5	0.0	0.0	0.0	0.0	13.8	0.0
Lesuerigobius suerii	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Liocarcinus depurator	29.4	68.8	7.8	174.2	3606.4	247.2	0.3	4.9	70.0	964.7
Loligo vulgaris	5.1	82.8	6.9	2.6	44.5	599.0	5.4	0.1	24.3	162.3
Lophius budegassa	7.8	14.2	37.3	42.4	8.9	0.0	10.7	1.9	25.4	5.4
Medorippe lanata	5.0	1.8	2.7	3.8	142.5	66.6	0.1	0.8	3.3	52.5
Merlangius merlangus	76.5	72.8	29.8	14.6	133.6	19.0	2.3	0.7	48.4	38.9
Merluccius merluccius	112.1	23.7	22.5	8.9	124.7	351.8	30.3	14.0	41.8	130.2
Micromesistius poutassou	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.0	0.0	0.2
Mullus barbatus	0.0	20.0	18.0	1.7	1335.7	22219.8	247.3	89.8	9.9	5973.2
Mullus surmuletus	0.0	7.9	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.0
Munida iris	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Myliobatis aquila	0.0	0.0	0.0	0.0	0.0	76.1	0.0	11.0	0.0	21.8
Octopus vulgaris	0.0	27.0	14.0	35.5	17.8	28.5	10.8	5.7	19.1	15.7
Pagellus acarne	2.0	85.6	0.0	0.0	0.0	2158.3	0.4	0.0	21.9	539.7
Pagellus bogaraveo	2.8	10.7	0.0	0.0	0.0	4173.9	0.6	13.4	3.4	1047.0
Pagellus erythrinus	2.4	0.0	15.6	8.4	2920.8	5818.8	597.7	360.1	6.6	2424.4
Paguridae	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Parapenaeus longirostris	0.2	0.2	0.2	0.0	276.0	589.5	0.6	0.6	0.2	216.7
Penaeus kerathurus	0.0	0.8	0.2	0.0	320.6	1093.4	3.4	2.2	0.3	354.9
Platichthys flesus	31.4	27.0	0.0	39.2	0.0	0.0	0.0	0.0	24.4	0.0
Pomatomus saltatrix	0.0	0.0	0.0	0.0	44.5	1350.1	2.3	18.1	0.0	353.8
Raja brachyura	0.0	0.0	0.0	5.8	0.0	0.0	0.0	0.0	1.5	0.0
Raja montagui	0.0	0.0	0.0	0.0	0.0	19.0	0.0	0.0	0.0	4.8
Sardina pilchardus	3.7	74.0	283.3	18.4	62.3	209.2	0.2	48.7	94.8	80.1
Sardinella aurita	0.7	0.0	0.0	10.6	0.0	57.0	0.0	0.5	2.8	14.4
Scomber japonicus	0.0	0.0	0.6	0.3	0.0	0.0	0.0	20.1	0.2	5.0
Scomber scombrus	0.0	13.3	0.0	0.3	8.9	0.0	1.2	0.0	3.4	2.5
Scophtalmus rhompus	0.0	0.0	0.0	0.0	17.8	9.5	5.9	8.1	0.0	10.3
Scorpaena notata	34.0	8.1	11.7	99.7	1968.0	1968.1	124.4	103.1	38.4	1040.9
Scorpaena porcus	11.4	11.2	23.0	41.6	222.6	142.6	14.1	59.1	21.8	109.6
Scorpaena scrofa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sepia elegans	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sepia officinalis	2.2	10.3	6.0	0.9	0.0	1293.1	16.5	8.8	4.9	329.6
Serranus cabrilla	5.5	1.1	0.0	6.6	44.5	256.7	1.2	3.7	3.3	76.5
Serranus hepatus	64.5	62.9	153.8	331.5	1638.5	1350.1	31.5	50.9	153.2	767.8
Solea lascaris	0.0	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.5	0.0
Solea solea	3.9	2.6	0.0	1.7	0.0	0.0	0.0	0.0	2.0	0.0
Solea vulgaris	0.0	0.0	0.0	0.0	26.7	180.6	8.6	23.2	0.0	59.8
Sparus aurata	0.0	0.0	0.0	0.0	0.0	494.4	1.9	3.8	0.0	125.0

Table 3. *Cont.*

Species	Biomass kg/km²									
	30-May-07	10-Sep-07	14-Apr-08	13-Jun-08	7-Apr-16	8-Jun-16	7-Apr-17	8-May-17	08/09 Avg.	16/17 Avg.
Sphyraena sphyraena	0.0	0.0	0.0	0.0	0.0	133.1	0.0	0.0	0.0	33.3
Spicara flexuosum	45.9	63.2	62.9	30.9	249.3	161.6	70.9	170.3	50.7	163.0
Spondyliosoma cantharus	0.0	0.0	4.9	0.0	0.0	0.0	0.0	0.0	1.2	0.0
Squilla mantis	15.0	17.6	17.2	11.9	623.3	1435.7	15.1	11.0	15.4	521.3
Symphodus tinca	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Torpedo marmorata	1.5	17.6	1.5	4.6	17.8	76.1	5.2	16.6	6.3	28.9
Tetronarce nobiliana	7.8	6.6	1.7	0.8	8.9	28.5	1.4	2.1	4.2	10.2
Trachinus draco	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.3	0.1
Trachurus mediterraneus	8.5	141.7	942.2	222.8	2769.4	3879.2	287.6	180.6	328.8	1779.2
Trachurus trachurus	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0
Chelidonichthys lucerna	16.4	47.2	14.6	12.6	926.1	2272.4	151.0	138.7	22.7	872.1
Trisopterus minutus	107.0	70.1	259.9	35.5	89.0	47.5	0.0	0.7	118.1	34.3
Uranoscopus scaber	9.1	2.1	11.2	6.8	35.6	599.0	16.2	39.8	7.3	172.7
Zeus faber	6.6	0.0	0.0	0.0	0.0	85.6	10.4	12.8	1.7	27.2

The most notable increase was seen in *Mullus barbatus*, with the biomass rising from 9.9 kg/km^2 to 5973.2 kg/km^2. *Pagellus erythrinus* also saw a significant increase from 6.6 kg/km^2 to 2424.4 kg/km^2. Likewise, *Arnoglossus laterna* went up from 37.6 kg/km^2 to 1724.5 kg/km^2, and *Citharus linguatula* from 28.5 kg/km^2 to 1788.0 kg/km^2. The biomass values of *Diplodus annularis* and *Diplodus vulgaris* significantly increased from 304.5 kg/km^2 to 3020.8 kg/km^2 and from 1.1 kg/km^2 to 297.1 kg/km^2, respectively. Other species, like *Liocarcinus depurator*, *Scorpaena notata*, and *Serranus hepatus*, showed notable increases, indicating enhanced habitat and resource availability within the marine protected area. *Penaeus kerathurus* also saw an increase from 0.3 kg/km^2 to 354.9 kg/km^2.

Several species experienced declines post-establishment. *Cepola macrophthalma* dropped from 26.6 kg/km^2 to 0 kg/km^2. Significant decreases were also seen in *Lesuerigobius friessi* from 13.8 kg/km^2 to 0 kg/km^2; *Platichthys flesus* from 24.4 kg/km^2 to 0 kg/km^2; *Aphia minuta* from 0 kg/km^2 to 0 kg/km^2; *Arnoglossus rueppelii* from 0.1 kg/km^2 to 0 kg/km^2; and *Arnoglossus thori* from 0.1 kg/km^2 to 0 kg/km^2. Other species with notable decreases included *Callionymus risso*, *Lesuerigobius suerii*, *Mullus surmuletus*, *Munida iris*, *Raja brachyura*, *Pegusa lascaris*, *Solea solea*, *Spondyliosoma cantharus*, *Symphodus tinca*, and *Trachurus trachurus*.

In contrast, species like *Trachinus draco* and *Blennius ocellaris* showed minor biomass fluctuations. *Trachinus draco* slightly increased from 0.3 kg/km^2 to 0.1 kg/km^2, while *Blennius ocellaris* appeared post-reef construction with a biomass of 0.1 kg/km^2. Other species with minor changes included *Micromesistius poutassou*, increasing from 0 kg/km^2 to 0.2 kg/km^2; *Dasyatis pastinaca* from 0 kg/km^2 to 3.7 kg/km^2; and *Raja montagui* from 0 kg/km^2 to 4.8 kg/km^2. Additional species showing minor increases post-reef construction included *Callinectes sapidus*, *Caranx rhonchus*, *Scomber japonicus*, and *Scophtalmus rhompus*.

3.2. Statistical Analysis

3.2.1. SIMPER Analysis

The results demonstrate significant changes in the biomass of certain species after the establishment of the artificial reef. Notably, *Mullus barbatus* and *Pagellus erythrinus*, two prominent commercial species in the region, showed an increase in biomass. The average biomass of *Mullus barbatus* escalates from 1.77 to 8.79 kg/km^2, and *Pagellus erythrinus* from 1.6 to 7.02 kg/km^2, as indicated in Table 4. These species were the main contributors to the dissimilarities observed between the sampling periods. This can be further proven by comparing specific sampling months. The *Mullus barbatus* biomass obtained in June 2016 is 22,219.8 kg/km^2, showing 1335.7 kg/km^2 and 1.66 kg/km^2 for June and April 2008, respectively. (Table 3). Similarly, the *Pagellus erythrinus* biomass values were 2920.8 kg/km^2 and 5818.8 kg/km^2 in April and June 2016, respectively, showing 15.58 and 8.39 in April and June of 2008.

Table 4. Similarity percentage analysis (SIMPER) using average biomass values for species caught in 2007–2008 and 2016–2017.

	Group 2007–2008	**Group 2016–2017**			
Species	**Av. Biomass**	**Av. Biomass**	**Av. Diss**	**Contrib%**	**Cum.%**
Mullus barbatus	1.77	8.79	2.25	5.02	5.02
Pagellus erythrinus	1.6	7.02	1.74	3.87	8.9
Penaeus kerathurus	0.25	4.34	1.39	3.11	12
Pomatomus saltatrix	0	4.34	1.39	3.1	15.11
Pagellus bogaraveo	1.35	5.69	1.39	3.1	18.21
Citharus linguatula	2.31	6.5	1.35	3	21.21
Arnoglossus laterna	2.48	6.44	1.27	2.84	26.95
Sparus aurata	0	3.34	1.07	2.39	29.34
Chelidonichthys lucerna	2.18	5.43	1.04	2.33	31.67
Diplodus annularis	4.18	7.41	1.04	2.32	33.98
Parapenaeus longirostris	0.63	3.84	1.03	2.29	36.28
Scorpaena notata	2.49	5.68	1.03	2.28	38.56
Diplodus vulgaris	1.01	4.15	1.01	2.25	40.81
Engraulis encrasicolus	2.76	5.67	0.94	2.08	42.89
Squilla mantis	1.98	4.78	0.9	2	44.89
Solea vulgaris	0	2.78	0.89	1.99	46.88
Sepia officinalis	1.48	4.26	0.89	1.99	48.87
Penaeus aztecus	0	2.73	0.88	1.95	50.82
Liocarcinus depurator	2.89	5.57	0.86	1.92	54.66
Pagellus acarne	2.16	4.82	0.85	1.9	56.56
Dentex gibbosus	0	2.44	0.78	1.75	58.31
Sphyraena sphyraena	0	2.4	0.77	1.72	60.03
Cepola macrophthalma	2.27	0	0.73	1.63	61.65
Trachurus mediterraneus	4.26	6.49	0.72	1.6	63.25
Platichthys flesus	2.22	0	0.71	1.59	64.84
Myliobatis aquila	0	2.16	0.69	1.55	66.39
Alloteuthis media	0.77	2.77	0.64	1.43	67.82
Uranoscopus scaber	1.64	3.62	0.64	1.42	69.23
Lesuerigobius friessi	1.93	0	0.62	1.38	70.61
Scophtalmus rhompus	0	1.79	0.58	1.28	71.9
Serranus hepatus	3.52	5.26	0.56	1.25	73.15
Eriphia verrucosa	0.71	2.37	0.53	1.18	74.33
Caranx rhonchus	0	1.63	0.52	1.17	75.5
Serranus cabrilla	1.35	2.96	0.52	1.15	76.65
Callinectes sapidus	0	1.48	0.47	1.06	77.71
Raja montagui	0	1.48	0.47	1.06	78.76
Boops boops	0.73	2.18	0.47	1.04	79.81
Dasyatis pastinaca	0	1.38	0.44	0.99	80.8
Loligo vulgaris	2.22	3.57	0.43	0.96	81.76
Medorippe lanata	1.35	2.69	0.43	0.96	82.72
Solea solea	1.19	0	0.38	0.85	83.58
Mullus surmuletus	1.19	0	0.38	0.85	84.43
Zeus faber	1.14	2.28	0.37	0.82	85.25
Raja brachyura	1.1	0	0.35	0.79	86.03
Scorpaena porcus	2.16	3.24	0.35	0.77	86.8
Spondyliosoma cantharus	1.05	0	0.34	0.75	87.56
Goneplax rhomboides	0.9	1.92	0.33	0.73	88.28
Spicara flexuosum	2.67	3.57	0.29	0.65	88.93
Trisopterus minutus	3.3	2.42	0.28	0.63	89.56
Pegusa lascaris	0.85	0	0.27	0.61	90.17

Other significant contributors to this dissimilarity included *Pomatomus saltatrix*, which appeared only in the latter group, and *Pagellus bogaraveo* and *Citharus linguatula*, which exhibited an increase in biomass. A noteworthy point is the increased biomass values for species like *Arnoglossus laterna*, *Sparus aurata*, *Chelidonichthys lucerna*, and *Diplodus annularis*. It is also important to mention that, out of the 52 species in Table 4 contributing to the dissimilarity between the periods, only 8 species showed a decrease in biomass or a complete absence in the post-reef creation period. The completely absent species were *Cepola macrophthalma*, *Platichthys flesus*, *Leuerigobius friessi*, *Solea solea*, *Mullus surmuletus*, and *Pegusa lascaris*. *Trisopterus minutus* displayed a slight decline, from 3.3 kg/km^2 in the initial period to 2.42 kg/km^2 in the latter.

3.2.2. Diversity Indexes

In the assessment of the Kitros MPA's impact on local fish biodiversity, the investigation included an analysis of species richness, abundance, and diversity indices before and after the reef's establishment (Table 5), with a consideration for seasonal variation influences. The pre-construction phase, spanning from May 2007 to June 2008, revealed an average species richness of 46.5 and an average total abundance of 210.5 individuals per square kilometer. Diversity indices averaged as follows: Shannon's Diversity Index (H′ log_e) at 3.6595, Simpson's Diversity Index (1-Lambda) at 0.9755, Brillouin's Index at 3.345, and Fisher's Alpha at 18.5475, indicating a stable biodiversity level with an even species distribution.

Table 5. Diversity indexes are shown for each sampling period. S shows number of species present, N shows similarity percentage analysis (SIMPER) using average biomass values for species caught in 2007–2008 and 2016–2017.

Sample	S	N	d	J′	Brillouin	Fisher	H′ (Loge)	1-Lambda′
30 May 2007	48	195	8.917	0.9633	3.363	20.37	3.729	0.9777
10 September 2007	49	224	8.872	0.9675	3.429	19.37	3.765	0.9786
14 April 2008	46	216	8.372	0.9537	3.327	17.9	3.652	0.9737
13 June 2008	43	207	7.879	0.9551	3.261	16.52	3.592	0.9728
7 April 2016	33	63	7.714	0.9769	2.809	27.8	3.416	0.98
8 June 2016	52	115	10.75	0.9773	3.303	36.57	3.861	0.9855
7 April 2017	50	188	9.354	0.9623	3.384	22.24	3.765	0.9783
8 May 2017	52	211	9.528	0.9615	3.384	22.04	3.799	0.9789

In contrast, the post-construction phase, from April 2016 to May 2017, exhibited a slight increase in average species richness to 48.25, with a marked decrease in the average total abundance to 119.25 individuals per square kilometer. Despite the reduced abundance, diversity indices improved, with an average Shannon's Index of 3.70825 and Simpson's Index of 0.980675, alongside a Brillouin's Index of 3.195 and Fisher's Alpha of 27.155, suggesting enhanced and more stable biodiversity outcomes post-reef construction.

The analysis acknowledges the role of seasonal variations, which are evident in the fluctuations observed in species richness and total abundance across the sampling periods. Such variations underline the dynamic nature of marine ecosystems and the adaptability of fish communities to environmental changes. The consistent improvement in diversity indices post-construction underscores the MPA's beneficial impact on local biodiversity, beyond mere seasonal effects.

In summary, the post-reef construction period demonstrated an overall increase in species richness and a fluctuating, but generally higher, level of diversity indices, suggesting that the artificial reef may have had a beneficial impact on local fish biodiversity.

3.2.3. Non-Metric Multi-Dimensional Scaling

The multi-dimensional scaling (MDS) analysis, focusing on fish sampling data before and after the artificial reef construction in Kitros, Pieria, reveals distinct groupings based on the sampling dates (Figure 4). This analysis utilized Kruskal's stress formula 1 with a minimum stress threshold of 0.1. The results are reported in both three-dimensional (3D) and two-dimensional (2D) configurations, each achieving a stress value of 0, indicating a representation of the dataset in the reduced-dimensional space. In the 3D configuration, sampling dates from May 2007 to June 2008, corresponding to the period before the reef construction, are primarily negative along the first axis. This contrasts with the post-reef construction dates from April 2016 to May 2017, which exhibit positive values along the same axis. The 2D configuration also shows a clear separation; the pre-reef samples are clustered on the negative side of axis 1, while the post-reef samples predominantly lie on the positive side. The percentages accompanying each sample in both configurations indicate the contribution of each sampling date to the overall stress, with the pre-reef dates contributing more significantly in the 2D configuration. This distinct separation in the 2D configuration highlights a significant shift in the fish community composition associated with the artificial reef's establishment. The April 2016 and June 2016 samples, for instance, demonstrate a notable shift toward the positive end of axis 1. The 3D configuration provides a more detailed spatial representation, showing a similar pattern of separation but with additional complexity due to the third dimension. These MDS results, particularly the low stress values and clear delineation between the pre- and post-reef periods, strongly suggest that the construction of the artificial reef has a measurable impact on the structure of the fish community in the area. The separation patterns observed in the MDS analysis offer a clear visualization of the ecological shifts attributable to the artificial reef's installation.

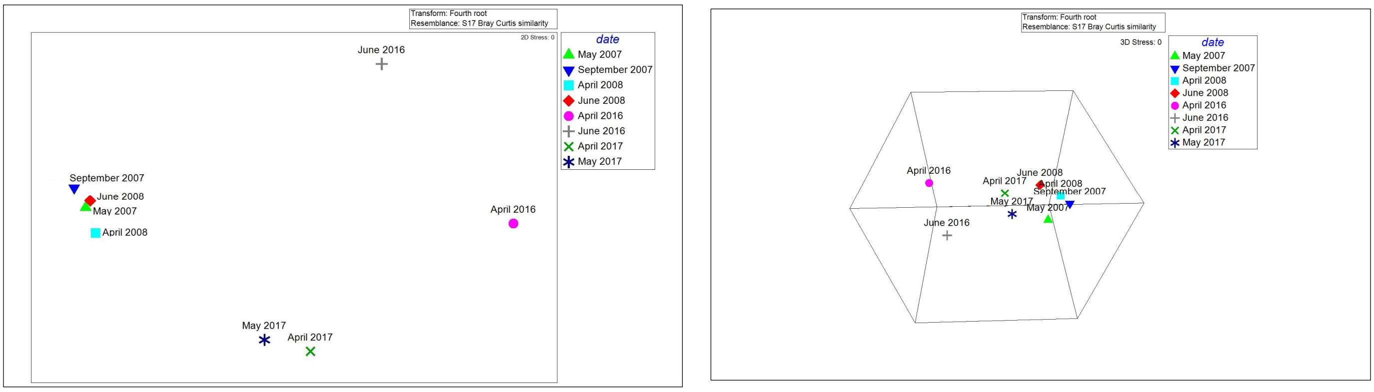

Figure 4. Non-metric multi-dimensional scaling (MDS) analysis of fish abundance data (individual/km^2), categorized by 8 sampling dates before (2007–2008) and after (2016–2017) the artificial reef construction in Kitros, Pieria. The analysis is visualized in both three-dimensional (3D) and two-dimensional (2D) configurations. The 3D graph illustrates the spatial distribution of sampling dates in a three-axis system, while the 2D graph provides a simplified view with a clear separation along the first axis. Negative values along axis 1 in both configurations are associated with pre-reef construction dates, whereas positive values are linked with post-reef construction dates. These spatial patterns demonstrate a shift in the fish community composition corresponding to the periods before and after the artificial reef's establishment.

4. Discussion

Several species made their first appearance in the area post-AR construction, highlighting the transformative impact of the reef on the local marine ecosystem. The presence *of Blennius ocellaris* post-reef construction was particularly noteworthy, as this species was not previously recorded in the area. This emergence suggests the reef's potential for creating suitable habitats or conditions favorable for species not formerly prevalent. Similarly, *Trachinus draco* and *Lepidotrigla cavillone* appeared only after the reef was established and the MPA was declared, indicating possible shifts in habitat preferences or expansions in habitat ranges facilitated by the artificial reef structures. The presence of *Micromesistius poutassou*, *Dasyatis pastinaca*, and *Raja montagui* further exemplifies the MPA's influence on a wider range of species, possibly due to changes in the benthic environment or enhanced food availability.

In the years following the artificial reef's development, a significant increase in biomass was observed in several marine species. Among the top performers, *Mullus barbatus* experienced a remarkable rise, leading the list of species benefiting from the reef. *Pagellus erythrinus* also showed a notable enhancement in its biomass, following closely behind. Interestingly, species like *Penaeus kerathurus* and *Pomatomus saltatrix*, which were either few or not present in the previous data, emerged with substantial biomass values, indicating the reef's role in supporting new marine life. *Pagellus bogaraveo*, *Citharus linguatula*, and *Arnoglossus laterna* also demonstrated considerable increases, reflecting the positive ecological impact of the reef. *Sparus aurata*, a species previously absent, made its debut in the ecosystem, further underscoring the diversity fostered by the artificial reef. *Chelidonichthys lucerna* and *Diplodus annularis* both showed significant improvements, thus highlighting the protected area's role in enhancing marine biodiversity and biomass.

As described before, the strong increase in the biomass of *Mullus barbatus* and *Pagellus erythrinus* from 2007–2008 to 2016–2017 deserves a special mention, due to the importance of these species as commercial catch (Figures 2 and 3, respectively). The populations of these species may also have flourished due to the fishing restrictions imposed for bottom trawlers within the marine protected area of Kitros, Pieria, after the artificial reef's development. Therefore, setting the probable beneficial effect of the artificial reef aside, population mortality may have been reduced due to trawling restrictions that came with the declaration of the reef's marine protected area. Coastal fisheries with gillnets and trammel nets, however, continued throughout the years, despite the ban on trawling.

Both *Mullus barbatus* and *Pagellus erythrinus* prefer softer substrates and gravelly sea bottoms [18,19], like the ones that formed around the area of the artificial reef [1,2]. As the substrate within the marine protected area transitioned from muddy to a gravel-dominated environment, these species notably thrived. However, the shift proved less advantageous for species such as *Gobius niger* and *Leuserigobius friesii*, which did not benefit as much from the new gravelly substrate.

By definition, pelagic fish live in the pelagic domain, that is, they move freely in the water column where they spend most of their time. The presence of small pelagic fish in this study, such as *Trachurus mediterraneus*, *Sardina pilchardus*, and *Engraulis encrasicolus*, can be characterized as random. These species live across the water column and their presence in the bottom trawl samples may be considered as random [20].

Several studies have researched artificial reefs for aspects like abundance, biomass, and species diversity [21,22]. However, using a species composition index is more advisable to prevent skewed interpretations of effectiveness [23]. The evaluation of the ARs' impact on restoration, using genuinely comparable and appropriate reference sites, is scarce. The majority of AR deployments suffer from a lack of comprehensive ecological data, posing challenges for thorough ecosystem assessments [24]. The results of this study portray differences in the abundance and biomass in local fish populations before and after the creation of the artificial reef in 2014.

Restoring marine ecosystems, including the use of active interventions, is considered beneficial for promoting natural species recruitment and survival, reinstating ecosystem structure and function, and enhancing the abiotic processes that influence community dynamics. This is particularly vital in the context of the extensive degradation of reef ecosystems due to climate change [25]. Employing innovative artificial reef strategies in coastal and offshore regions can be used for facilitating habitat restoration. However, this requires a well-structured, pragmatic, and scalable approach that identifies the strengths and weaknesses of these methods. It is important to conduct thorough assessments of local regeneration requirements and constraints to ensure effective restoration efforts [23].

However, it is worth mentioning that the Intermediate Disturbance Hypothesis (IDH) posits an optimal level of disturbance within ecosystems that can maximize biodiversity, supporting a diverse array of species by preventing dominance by any single species. This principle, when applied to marine protected areas (MPAs), suggests that not all disturbances are detrimental; moderate disturbances, whether natural or controlled human activities, can in fact enhance biodiversity within MPAs. Such disturbances can maintain a balance between early successional and more competitive species, thereby promoting a rich diversity of marine life. This perspective advocates for a management strategy for MPAs that not only aims to minimize human impacts, but also recognizes the potential ecological benefits of maintaining intermediate levels of disturbance to foster biodiversity and ecological health [26].

In the Pieria region, alongside the artificial-reef-designated marine protected area (MPA) near Kitros, a similar initiative was launched near Litochoro in 2017, located 36 km to the south of Kitros, resulting in another MPA. The development of networks of MPAs, as opposed to isolated entities, represents a modern conservation strategy. Such networks enhance marine biodiversity benefits by facilitating species movement across protected zones and promoting genetic diversity. Transitioning from solitary MPAs to comprehensive MPA networks necessitates an expansion of governance models, incorporating both top-down strategies to manage human and ecological connections across the MPA spectrum. This approach must strike a balance between enabling local participation within each MPA and addressing broader challenges to fulfill overarching conservation goals, integrating top-down governance mechanisms. Addressing this balance is critical yet often overlooked in MPA discourse [27]. When the possibility of a network of MPAs is discussed, it is perhaps worthy to mention that a study assessed the vulnerability of Mediterranean marine protected areas (MPAs) to the invasion of Lessepsian fish species under current and future climate scenarios. It was found that MPAs, especially in the Levantine Sea, are at a high risk of invasion by these species, with projections indicating an increase in suitable habitats for these invasive fish by 2050. This poses a challenge for conservation efforts in the region [28]. This however may not be the case in the region of Pieria as the heavy freshwater inflow from nearby rivers may act preventively against many Lessepsian fish species. As seen in Table 1, no Lessepsian migrant species were caught in the area of Kitros. The only migrant species caught was the northern brown shrimp (*Penaeus aztecus*) that originates from the east coast of the US and Mexico. As this species is the only migrant species observed in the entire region of Pieria, it is widely speculated that its existence is due to an accidental release from a failed aquaculture attempt.

Constructing artificial reefs is costly and logistically difficult [29]. Hence, an evaluation of the scientific basis for reef construction and deployment is critical. In the past, a philosophical assumption was stated underlying the construction of artificial reefs, indicating that regional fish production is limited by a paucity of hard bottom habitats [30,31]. However, this assumption may have been supported by short-term descriptive studies of individual reefs [30].

If habitat is limiting, new reefs can potentially increase fish production through an increase in the foraging habitats of adult, juvenile, or newly recruited fishes, an increase in the nesting habitats of adult fishes, and an increase in the number of resting habitats from predators. As a result, stock sizes of economically important species increase, and commercial fishers can benefit. And, since all artificial reefs are colonized by fishes, increasing habitats can mean that local increases in fish abundance and biomass are produced [32]. Hence, an evaluation of the scientific basis for reef construction and deployment is critical.

The continued monitoring of both natural and artificial reefs would provide estimates of the population size on individual reefs and the total regional population size. The relative importance of habitat and recruitment could be further tested by increasing the number of artificial reefs within an area and measuring the relationships formed. Any positive relationship would indicate some value in constructing artificial reefs.

There is a lack of knowledge in several important scientific domains. Scientific studies have to focus on ecosystem variability, on the scales to be considered, and the appropriate experimental designs to reveal representative results. Ultimately, the success of a MPA or an AR will reflect the quality of the prior planning and ongoing management [33].

The differences in marine biodiversity and biomass before and after the AR implementation highlight the importance of adopting a holistic management approach. Such approaches are crucial for addressing anthropogenic pressures and ensuring the resilience of marine ecosystems. The case of Cocos Island, as part of the Eastern Pacific Marine Corridor, exemplifies how national-scale efforts can create biological corridors, enhancing the connectivity between MPAs and contributing to the conservation of globally significant marine biodiversity [34,35].

It is, however, worth mentioning that the effectiveness of marine protected areas (MPAs) in meeting their conservation objectives has sometimes been met with skepticism, as some MPAs have not achieved their intended outcomes, despite various promising signs. This discrepancy has prompted several researchers to critically examine MPAs' capacity to prevent biodiversity loss [36–38].

5. Conclusions

In conclusion, the research conducted on the impact of the artificial reef of Kitros and its surrounding marine protected area has yielded significant results. The study's primary objective, assessing the changes in species biomass and diversity post-AR development, was effectively met. The key findings reveal a notable increase in both the biomass and diversity of certain marine species, for example, the highly commercial *Mullus barbatus* and *Pagellus erythrinus*, indicating that artificial reefs can positively influence marine habitats. However, the research also highlighted a major gap in understanding the long-term ecological impacts of artificial reefs and their surrounding MPAs. While benefits were observed, the study suggests that continuous monitoring is essential to fully comprehend the effects over extended periods. This is particularly relevant for assessing the sustainability of such interventions and their alignment with broader conservation goals. Based on these results, future studies should focus on longitudinal assessments of ARs, examining their ecological impact over decades rather than just years. This would provide more comprehensive insights into their roles in marine ecosystem restoration and conservation, helping to inform more effective environmental management strategies. Additionally, expanding the research to include a wider range of ecological parameters can further help us understand the multifaceted impacts of artificial reefs.

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References

1. Kallianiotis, A.A.; Batjakas, I.E. Temporal and Environmental Dynamics of Fish Stocks in the Marine Protected Area of the Artificial Reef of Kitros, Pieria (Northern Greece, Mediterranean Sea). *J. Mar. Sci. Eng.* **2023**, *11*, 1773. [CrossRef]
2. Kallianiotis, A.A.; Kamidis, N.; Tselepides, A.; Batjakas, I.E. Spatiotemporal and Environmental Dynamics of Abundances and Diversity of Larval Fish in Artificial Reef Edge Habitats of Kitros, Pieria (Northern Aegean Sea, Eastern Mediterranean). *J. Mar. Sci. Eng.* **2023**, *11*, 40. [CrossRef]
3. Zervakis, V.; Georgopoulos, D.; Karageorgis, A.P.; Theocharis, A. On the response of the Aegean Sea to climatic variability: A review. *Int. J. Climatol.* **2004**, *24*, 1845–1858. [CrossRef]

4. Karageorgis, A.P.; Nikolaidis, N.P.; Karamanos, H.; Skoulikidis, N. Water and sediment quality assessment of the Axios River and its coastal environment. *Cont. Shelf Res.* **2003**, *23*, 1929–1944. [CrossRef]
5. Ramos, J.; Santos, M.; Whitmarsh, D.; Monteiro, C. Patterns of use in an artificial reef system: A case study in Portugal. *Bull. Mar. Sci.* **2006**, *78*, 203–211.
6. Relini, G. The Loano Artificial Reef. In *Artificial Reefs in European Seas*; Jensen, A.C., Collins, K.J., Lockwood, A.P.M., Eds.; Springer: Berlin/Heidelberg, Germany, 2000. [CrossRef]
7. Krestenitis, Y.; Androulidakis, Y.; Makris, C.; Kombiadou, K.; Baltikas, V.; Diamanti, P. Evolution of Storm Surge Extreme Events in Greek Seas under Climate Change Scenario. In Proceedings of the 11th Symposium of Oceanography and Fisheries, Mytilene, Greece, 13–17 May 2015; pp. 849–852.
8. Androulidakis, Y.; Kolovoyiannis, V.; Makris, C.; Krestenitis, Y.; Baltikas, V.; Stefanidou, N.; Chatziantoniou, A.; Topouzelis, K.; Moustaka-Gouni, M. Effects of ocean circulation on the eutrophication of a Mediterranean gulf with river inlets: The Northern Thermaikos. *Gulf Cont. Shelf Res.* **2021**, *221*, 104416. [CrossRef]
9. Skoulikidis, N.; Gritzalis, K.; Kouvarda, D.; Buffagni, A. The Development of An Ecological Quality Assessment and Classification System for Greek Running Waters Based on Benthic Macroinvertebrates. *Hydrobiologia* **2004**, *516*, 149–160. [CrossRef]
10. Poulos, S.E.; Chronis, G.T.; Collins, M.B.; Lykousis, V. Thermaikos Gulf coastal system, NW Aegean Sea: An overview of water/sediment fluxes in relation to air–land–ocean interactions and human activities. *J. Mar. Syst.* **2000**, *25*, 47–76. [CrossRef]
11. Dimarchopoulou, D.; Makino, M.; Prayoga, M.R.; Zeller, D.; Vianna, G.; Humphries, A.T. Responses in fisheries catch data to a warming ocean along a latitudinal gradient in the western Pacific Ocean. *Environ. Biol. Fishes* **2022**, *105*, 1347–1362. [CrossRef]
12. Miller, P.J.; Loates, M.J. *Collins Field Guide to the Sea Fishes of the Mediterranean and Adriatic*; HarperCollins Publishers: New York, NY, USA, 1986; ISBN 0002192551.
13. Food and Agriculture Organization of the United Nations. The Mediterranean and Black Sea Fish Identification Guide. In *FAO Species Identification Guide for Fishery Purposes*; FAO: Rome, Italy, 2018; ISBN 9251306078.
14. Carrothers, P.J.G. Estimation of trawl door spread from wing spread. *J. Northwest Atl. Fish. Sci.* **1980**, *1*, 81–90. [CrossRef]
15. Cadrin, S.X.; DeCelles, G.R.; Reid, D. Informing fishery assessment and management with field observations of selectivity and efficiency. *Fish. Res.* **2016**, *184*, 9–17. [CrossRef]
16. Gunderson, D.R. *Surveys of Fisheries Resources*; Wiley: Hoboken, NJ, USA, 1993.
17. Schreck, C.B.; Moyle, P.B. (Eds.) *Methods for Fish Biology*; American Fisheries Society: Baltimore, MD, USA, 1990; ISBN 0913235581.
18. Relini, G.; Bertrand, J.; Zamboni, A. Mullus barbatus. In *FAO AdriaMed—Species Fact Sheets*; FAO: Rome, Italy, 1999; Available online: https://www.faoadriamed.org/html/Species/MullusBarbatus.html (accessed on 15 September 2022).
19. Vasilopoulou, V.; Tserpes, G.; Maravelias, C.D. Intra- and interspecific variability among congeneric *Pagellus* otoliths. In *Scientific Reports*; Nature Publishing Group: London, UK, 2020; Volume 10, Available online: https://www.nature.com/articles/s41598-020-63561-9 (accessed on 10 September 2022).
20. Fréon, P.; Cury, P.; Shannon, L.; Roy, C. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: A review. *Bull. Mar. Sci.* **2005**, *76*, 385–462.
21. Paxton, A.B.; Shertzer, K.W.; Bacheler, N.M.; Kellison, G.T.; Riley, K.L.; Taylor, J.C. Meta-Analysis Reveals Artificial Reefs Can Be Effective Tools for Fish Community Enhancement but Are Not One-Size-Fits-All. *Front. Mar. Sci.* **2020**, *7*, 282. [CrossRef]
22. Hunter, W.R.; Sayer, M.D.J. The comparative effects of habitat complexity on faunal assemblages of northern temperate artificial and natural reefs. *ICES J. Mar. Sci.* **2009**, *66*, 691–698. [CrossRef]
23. Bracho-Villavicencio, C.; Matthews-Cascon, H.; Rossi, S. Artificial Reefs around the World: A Review of the State of the Art and a Meta-Analysis of Its Effectiveness for the Restoration of Marine Ecosystems. *Environments* **2023**, *10*, 121. [CrossRef]
24. Roa-Ureta, R.H.; Santos, M.N.; Leitão, F. Modelling long-term fisheries data to resolve the attraction versus production dilemma of artificial reefs. *Ecol. Model.* **2019**, *407*, 108727. [CrossRef]
25. Gann, G.D.; McDonald, T.; Walder, B.; Aronson, J.; Nelson, C.R.; Jonson, J.; Hallett, J.G.; Eisenberg, C.; Guariguata, M.R.; Liu, J.; et al. International principles and standards for the practice of ecological restoration. Second edition. *Restor. Ecol.* **2019**, *27*, S1–S46. [CrossRef]
26. Connell, J.H. Diversity in Tropical Rain Forests and Coral Reefs. *Science* **1978**, *199*, 1302–1310. [CrossRef] [PubMed]
27. Solandt, J.-L.; Jones, P.; Duval-Diop, D.; Kleiven, A.R.; Frangoudes, K. Governance Challenges in Scaling Up from Individual MPAs to MPA Networks. *Aquat. Conserv. Mar. Freshw. Ecosyst.* **2014**, *24*, S2.
28. D'Amen, M.; Azzurro, E. Lessepsian Fish Invasion in Mediterranean Marine Protected Areas: A Risk Assessment Under Climate Change Scenarios. *ICES J. Mar. Sci.* **2020**, *77*, 388–397. [CrossRef]
29. Seaman, W.; Sprague, L.M. Artificial habitats for marine and freshwater fisheries. *Rev. Fish Biol. Fish.* **2004**, *3*, 80–81.
30. Bohnsack, J. Are High Densities of Fishes at Artificial Reefs the Result of Habitat Limitation or Behavioral Preference? *Bull. Mar. Sci.* **1989**, *44*, 631–645.
31. Polovina, J.J. Fisheries applications and biological impacts of artificial habitats. In *Artificial Habitats for Marine and Freshwater Fisheries*; Academic Press: New York, NY, USA, 1991; p. 153176.
32. Grossman, G.; Jones, G.; Seaman, W. Do Artificial Reefs Increase Regional Fish Production? A Review of Existing Data. *Fisheries* **1997**, *22*, 17–23. [CrossRef]
33. Baine, M. Artificial reefs: A review of their design, application, management and performance. *Ocean Coast. Manag.* **2001**, *44*, 241–259. [CrossRef]

34. Maestro, M.; Pérez-Cayeiro, M.L.; Chica-Ruiz, J.A.; Reyes, H. Marine protected areas in the 21st century: Current situation and trends. *Ocean. Coast. Manag.* **2019**, *171*, 28–36. [CrossRef]
35. Cortés, J. Marine protected areas importance and effectiveness: Insights from the Eastern Pacific Marine Corridor and Cocos Island MPA. *Mar. Biol.* **2016**, *163*, 1–12.
36. Jameson, S.C.; Tupper, M.H.; Ridley, J.M. The three screen doors: Can marine "protected" areas be effective? *Mar. Pollut. Bull.* **2002**, *44*, 1177–1183. [CrossRef]
37. Mora, C.; Andrefouet, S.; Costello, M.J.; Kranenburg, C.; Rollo, A.; Veron, J.; Gaston, K.J.; Myers, R.A. Coral reefs and the global network of Marine Protected Areas. *Science* **2006**, *312*, 1750–1751. [CrossRef]
38. Charles, A.; Wilson, L. Human dimensions of Marine Protected Areas. *ICES J. Mar. Sci.* **2009**, *66*, 6–15. [CrossRef]