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Artificial fish nurseries can restore certain nursery characteristics in marine urban habitats

Joubert Etienne [1, *], Gauff Robin P.M. [2], De Vogüé Benoist [1], Chavanon Fabienne [1], Ravel Christophe [1], Bouchoucha Marc [1]

[1] Ifremer, Lab Environm Ressources Provence Azur Corse, CS 20330, F-83507 La Seyne Sur Mer, France
[2] Chioggia Hydrobiological Station “Umberto D'Ancona”, Department of Biology, University of Padova, Chioggia, Italy

* Corresponding author : Etienne Joubert, email address : etiennejoubert29@gmail.com

Abstract :

Port areas are subjected to multiple anthropic pressures that directly impact residing marine communities and deprive them of most of their essential ecological functions. Several global projects aim to rehabilitate certain ecosystem functions in port areas, such as a fish nursery function, by installing artificial fish nurseries (AFN). In theory, AFNs increase fish biodiversity and juvenile fish abundance in port areas, but studies on this subject remain scarce. Thus, the present study aimed to examine whether the use of such AFNs could restore part of the nursery function of natural habitats by increasing fish and juvenile abundance, and by decreasing predation intensity compared to bare docks. Two years of monitoring on AFNs showed they hosted 2.1 times more fish than on control docks and up to 2.4 more fish juveniles. Fish community structures were influenced by both treatment (AFN and Control) and year of monitoring. In general, AFNs hosted a greater taxonomic diversity of fish than controls. The predation intensity around these structures was significantly lower in the AFNs than in controls. Part of the definition of a fish nursery was thus verified, indicating that AFNs might be an effective restoration tool. However, we also noted that total fish abundance and Young of the Year (YOY) abundance decreased in controls, possibly due to a concentration effect. Further detailed monitoring is necessary to distinguish between these effects.

Keywords : Ecological restoration, Rehabilitation, Fish, Nursery, Urbanization, Ocean sprawl, Predation

1. Introduction

The maritime coastline is a densely populated area. Indeed, 11 of the world’s 15 largest cities, half of the cities of more than 100 000 inhabitants, and 40% of the world’s population are located within 100km from the seashore (Barragán and de Andrés, 2015; Nazeer et al., 2020; Petrişor et al., 2020). This densification coupled with the intensification of international trade has led to a multiplication of infrastructures and the creation of large-scale port areas (Bugnot et al., 2021; Ducruet and Lee, 2006). This artificialization of the coastline (Fan et al., 2017; Ovejero Campos et al., 2022) in addition to other anthropogenic pressures (Ben Attia et al., 2021) has direct consequences that transform coastal marine habitat characteristics (Airoldi and Beck, 2007; Mooser et al., 2021; Poursanidis et al., 2018; Williams et al., 2022). The prevailing consensus suggests that artificialization is generally associated with a decrease in structural complexity (Bishop et al., 2022; Thrush et al., 2008). However, it is important to acknowledge that this may not always hold true, as it can depend on the specific material and configuration employed in an artificial habitat (Grasselli and Airoldi, 2021). It has been demonstrated that the reduction in complexity in marine environments, leads to a decline in the populations and survival rates of organisms (Brokovich et al., 2006; Fischer et al., 2007). This is linked with a reduction in ecological functions and services (Airoldi and Beck, 2007; Vozzo et al., 2021).

This reduction of complexity hampers one essential function of coastal habitats: their role as nurseries for juvenile fish (Courrat et al., 2009; Whitfield and Pattrick, 2015). To be considered a nursery, a juvenile fish habitat needs to meet four criteria: (i) it hosts high densities of juveniles, (ii) it provides local food for high juvenile fish growth, (iii) it decreases mortality due to predation, (iv) juveniles settling there actively participate in the renewal of adult populations (Beck et al., 2001). Fish species dependent on coastal nursery areas during their juvenile stage represent 66% of the total landing of the fishery industry and one third of the species surveyed by the ICES (Le Pape et al., 2020; Mora et al., 2008; Seitz et al., 2014). During the life cycle of nursery-dependent fishes, pelagic eggs and larval stages recruit as juveniles to shallow coastal and estuarine nurseries and then move on to adjacent deeper areas as adults (Beck et al., 2001). The survival of juvenile fish after benthic settlement in nurseries is mainly density dependent, and is affected by different biotic and abiotic factors such as food availability and predator abundance (Beck et al., 2001; Belharet et al., 2020; Cheminée et al., 2011; Ford et al., 2016; Ford and Swearer, 2013; Planes et al., 1998; Stewart and Jones, 2001). The surface area of nurseries is therefore essential for the maintenance of these populations (Le Pape and Bonhommeau, 2015). However, the loss of nursery habitats due to urbanization has led to the over-mortality of juveniles, allowing only very limited success for recruitment to adult populations (Bouchoucha et al., 2016; Cheminée et al., 2017; Harmelin-Vivien et al., 1995).

This impairs the renewal of adult nursery-dependent fish populations (Limiting Recruitment Hypothesis; Doherty, 1991).

Ecological rehabilitation operations have been considered to counteract the loss of ecosystem function due to urbanization. The principle of rehabilitation operations in port areas is broadly invariant and is based on eco-engineering (Airoldi et al., 2021; Dafforn et al., 2015; Strain et al., 2018). Flat, steep and smooth urban structures are considered inadequate for providing habitats for marine biodiversity, so artificial modules are added to them to increase their structural complexity (Bishop et al., 2022; Bradford et al., 2020). This approach is used to ensure marine benthic diversity (Bishop et al., 2022; Strain et al., 2020) as well as to restore the fish nursery function of urban habitats (Astruch et al., 2017; Bouchoucha et al., 2016; Lapinski et al., 2017; Patranella et al., 2017; Ushiama et al., 2019).

Previous studies have shown the ability of artificial fish nurseries (AFN) installed on port structures, docks or pontoons, to host important densities of juvenile fish (Bouchoucha et al., 2016; Mercader et al., 2017). However, studies focusing on multiple species and with robust designs remain rare (Firth et al., 2020). In particular, many studies focusing on juvenile fishes have been limited to measuring the abundance of individuals observed on AFNs (Astruch et al., 2017; Bouchoucha et al., 2016; Mercader et al., 2017; Patranella et al., 2017), neglecting to consider the crucial aspect of predation, which is one of the fundamental functions of fish nurseries (Beck et al., 2001).

The present study aimed to document the effect of AFNs installed on docks to increase their structural complexity. We tested the hypothesis of whether the addition of these AFNs increases the abundance and species diversity of fish and fish juveniles compared to bare docks, and whether they provide shelter from predation by reducing predation intensity. To do so, we monitored fish population, particularly juveniles, during a two-year campaign, on docks equipped with AFNs and on bare docks in a Mediterranean port. We also estimated pelagic predation intensity in the same areas. Our study is aimed at improving knowledge of the benefits of using AFNs for rehabilitating the nursery function in ports.

2. Material and Methods

2.1. Study site

The study was carried out on the docks of the industrial port of La Seyne-sur-Mer near Toulon (43.105960°N; 5.884599°E; Fig. 1). The Toulon Bay encompasses 9.8 km^2 of artificial habitats (military port, commercial port and 6 marinas), isolated from the open Mediterranean Sea by a 1.2 km long breakwater. The city’s industrial and military history make it one of the most polluted marine areas in Europe in terms of metallic trace elements (*e.g.* Cu, Pb, Hg) and persistent organic pollutants (PAH, PCB; Pougnet et al., 2014; Tessier et al., 2011; Wafo et al., 2016). Since 2019, several AFNs have been installed in certain ports of Toulon bay in the framework of an experimental assay to rehabilitate part of the fish nursery function lost in these areas (Bouchoucha et al., 2018a, 2018b, 2016; Gauff et al., 2023). Our monitoring focused on such structures, installed in June 2020 at La Seyne-sur-Mer. The docks studied were about 300 m long, up to 6 m deep, and designed to accommodate part of the French oceanographic fleet. Three 50 m² areas separated by at least 50 m (sites, Figure 1) were equipped with 2 x 5 m long strands covered with 30 cm long flexible polypropylene fiber rods. These AFNs are designed to mimic seagrass meadows (Figure 2). On each site, the sub-sets are arranged one under another at 50 cm intervals between 20 cm and 5.20 m depth (Figure 2 and 3). Fish diversity and abundance were assessed at least twice a month for a period of 24 months from June 2020 to May 2022. For each replicate site, fish abundance was recorded on an AFN as well as on a control area consisting of a 10 x 5 m (50 m²) vertical surface of bare dock. The distance between the AFN and the control was at least 20 m.

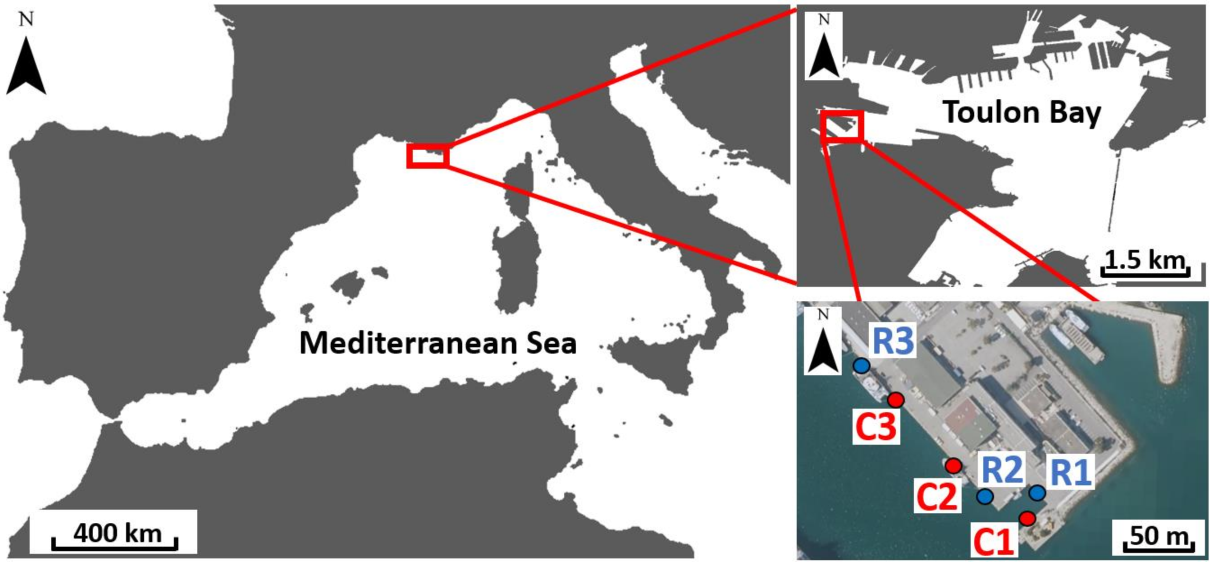


Figure 1: Map of the study site (La Seyne-sur-Mer, Toulon Bay, French Mediterranean). The position of the artificial fish nurseries studied (Blue; R) and control dock (Red; C) is indicated.

Figure 2: Picture of A.: Artificial fish nursery installed on the docks and B. control dock (photo credit, Ifremer O. Dugornay).

2.2. Fish abundance and diversity monitoring

Abundances for all fish species were estimated by underwater visual census using slow-swimming underwater transects (Cheminée et al., 2017; Harmelin-Vivien et al., 1995). Due to generally poor visibility conditions, the survey area was covered in three passes at three different depths (0 to 2 m, 2 to 4 m, 4 to 6 m), starting from the top of the AFN or dock. Each transect (replicate) corresponds to the sum of abundance of fish species observed during these three passes. The space between the AFN and the pier was also investigated. During the monitoring, all the individuals identified to the lowest possible taxonomic level (species) were counted and their sizes were estimated (total length, TL ± 5 mm) by the same diver. In order to distinguish between juvenile and adult individuals of each species, the Young of the Year (YOY) were identified *a posteriori* based on the size of the individuals compared to demographic data from Félix-Hackradt et al. (2013). In the absence of data on the YOY size of certain species, the size of the YOYs was considered to be 1/3 of the average observation size of adults, collected from FishBase (Froese and Pauly, 2022). The survey was carried out between 10:00 and 16:00 h, and poor visibility conditions were consistently avoided.

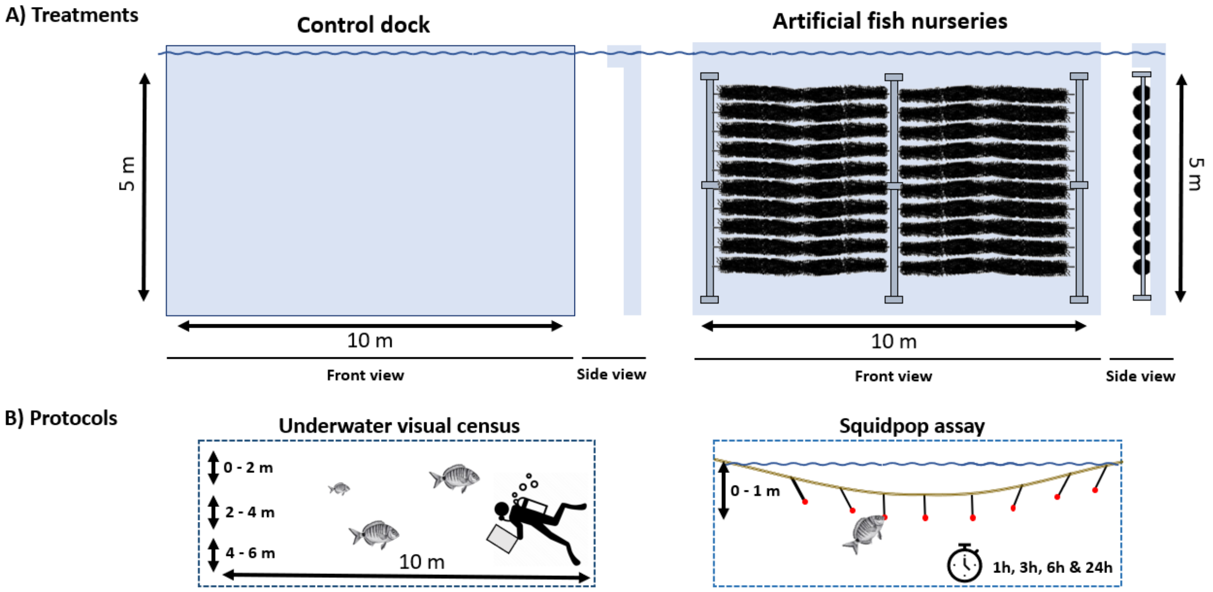


Figure 3: Illustration of the A) Treatments (Control & Artificial Fish Nurseries) and B) Protocols of experiments (Underwater visual census and Squidpop assay).

2.3. Identification of potential predators and predation intensity

To evaluate predation intensity among sites equipped with AFNs and control areas, a Squidpop feeding assay was used to directly measure predation intensity. The Squidpop assay was developed to measure fish predation intensity in different environments and consists of standardized squid baits attached to fiberglass stakes (Duffy et al., 2015). This assay has been used in various environments, including artificial habitats (Duffy et al., 2015; Gauff et al., 2022; Kough and Belak, 2022; Rodemann and Brandl, 2017). The choice of squid as bait is associated with its mechanical qualities (Gauff et al., 2022). Here, we used a modified version of the Squidpop protocol: for each of the three replication sites, 11 baits positioned 1 m apart were suspended on a rope between the surface and one meter deep for 24h, close to the AFN areas and at the control areas (Figure 3). This was repeated thrice (6th and 20th June, 7th July 2022), resulting in a total of 9 replicates for each treatment (AFN & Control). To provide higher resolution on bait consumption dynamics, the remaining baits were counted 1 h, 3 h, 6 h and 24 h after deployment, making it possible to carry out survival analysis (Gauff et al., 2022, 2018). The survival rate is considered to provide a *proxy* of predation intensity (Gauff et al., 2022).

2.4. Statistical analysis

All statistical analysis were performed using ‘R’ (version 4.2.2; R Core Team, 2022).

2.4.1. Fish abundance analysis

Mean density and associated standard error were expressed in individuals per 100 m^2. We tested the influence of the treatment (fixed, two levels: AFN and Control), the year of monitoring (fixed, two levels: Year 1 and Year 2), and their interaction on the observed density of fish and YOYs. Site (three levels: Site 1, Site 2, Site 3) was considered as a random factor. The density data did not follow a normal distribution. We thus fitted a generalized linear model following a negative binomial distribution (glmer.nb) from the 'lme4' R package (version 1.1-31; Bolker, 2022). The Goodness Of Fit (GOF) of the model was checked using the 'plotresid' function from the 'RVAideememoire' package (version 0.9-81-2; Hervé, 2022) which allowed us to graphically verify the model's residuals and then test dispersion using the 'dispersion_glmer' function from the 'blmeco' package (version 1.4; Korner-Nievergelt, 2019). When the interaction term was significant in the generalized model, we performed a post hoc comparison of density means using a 'Tukey contrast' multiple comparison test using the 'glht' function from the 'multcomp' package (version 1.4-20; Hothorn, 2022). During the multiple comparisons tests, the p-values were adjusted by the Benjamini and Hochberg (BH) correction (Benjamini and Hochberg, 1995).

2.4.2. Community analysis

The effect of treatment (fixed, two levels: AFN and Control), year of monitoring (fixed, two levels: Year 1 and Year 2) and their interaction on species richness was assessed with a generalized linear model with negative binomial distribution (Bolker, 2022). Subsequent analysis followed the workflow described for fish abundances (see §2.4.1.). Community structure analyses were conducted using Bray-Curtis dissimilarity matrices, obtained with the 'vegdist' function from the 'vegan' package (version 2.6-4; Oksanen, 2022). The specific communities during monitoring were visualized by plotting a Non-metric Multidimensional Scaling (NMDS) created using the 'metaMDS' function from the 'vegan' package (version 2.6-4; Oksanen, 2022). A PERMANOVA (10^4 permutations; Anderson, 2001) was performed to test the influence of the treatment, the year of monitoring, and their interaction on the observed community of all fish and YOYs. The permutation structure was nested within sites. Post hoc comparison was performed with a pairwise PERMANOVA (10^4 permutations) from the 'pairwiseAdonis' package (version 0.4; Martinez Arbizu, 2020). The p-values were adjusted by a Benjamini and Hochberg correction (Benjamini and Hochberg, 1995).

To assess whether certain species were representative of one treatment, we carried out a multipattern analysis (10^4 permutations) from the 'indicspecies' package (version 1.7.12; De Cáceres, 2022). The test was set up to perform comparisons within the two main factors (treatment and year) and their four interaction terms.

2.4.3. Predation intensity analysis

The Squidpop assays were analyzed *via* survival analysis (Pyke and Thompson, 1986) using the 'survival' package (version 3.4-0, Therneau, 2023). The time at which the absence of an individual bait was recorded was considered its survival time (Gauff et al., 2018). Kaplan-Meier curves of bait survival were computed for each treatment (George et al., 2014; Rich et al., 2010). Survival rates in different treatments were compared with a nested Cox model from the ‘NestedCohort’ package (version 1.1-3; A Katki, 2013) in order to test whether treatments differed in predation intensity (Pyke and Thompson, 1986; Rich et al., 2010). In this model individual baits were nested within site and date.

3. Results

During the first year, 52 surveys were carried out on AFNs and 51 on controls. Due to unexpected adverse environmental conditions (*e.g.,* occasional days with poor underwater visibility) or logistic constraints (*e.g.,* the presence of oceanographic vessels at dock, COVID lockdowns, etc.), the sampling effort was lower during the second year, with 29 censuses carried out on AFNs and 28 on controls. However, this did not prevent accurate investigation of AFNs, as all of the three sites were fully surveyed at least twice per month over the whole duration of the study.

3.1. Fish abundance monitoring

Over the surveyed time period a total of 3062 fish of 43 species were identified. The majority of the individuals (70%) were found in the AFNs, together with higher species richness (42 species on AFN compared to 29 on control; Table 1). Treatment significantly interacted with the Year of study for both models (GLMER.nb, z.value = -3.61, $p < 0.001$ and z.value = -2.73, $p = 0.006$; Tab. 2). During the first year of monitoring, fish density on AFNs (42.6 ± 4.4 ind.100 m^{-2}; all life stages combined) was significantly higher than on controls (28.2 ± 5.2 ind.100 m^{-2}; GLHT, z.value = -2.365, $p = 0.018$; Fig. 4, Tab. 2). This trend continued in the second year with a significantly higher fish density on AFNs (70.6 ± 8.4 ind.100 m^{-2}) than on control (17 ± 3 ind.100 m^{-2}; GLHT, z.value = -6.227, $p < 0.001$; Tab. 2). Concerning YOYs, 817 individuals were recorded, of which 72% were on AFNs. No significant difference in density was found for YOYs (GLHT, z.value = -1.811, $p = 0.098$) between AFNs (16 ± 2.8 ind.100 m^{-2}) and controls (9.3 ± 3 ind.100 m^{-2}) in the first year (Figure 3). However, in the second year higher densities were observed on AFNs (17.3 ± 5.8 ind.100 m^{-2}) compared to control (2.4 ± 1.2 ind.100 m^{-2}; GLHT, z.value = -4.515, $p < 0.001$; Tab. 2). A slight overall increase of fish densities but not YOY densities could be noted between the two years surveyed (main effect; GLMER.nb, z.value = 2.682, $p = 0.008$). Total fish densities on AFN increased between Year 1 and Year 2 (GLHT, z.value = 2.674, $p = 0.011$). On the contrary, total fish densities on controls decreased between Year 1 and Year 2. Concerning YOYs, their density on AFNs did not differ between the two years (GLHT, z.value = 0.22, $p = 0.82$; Tab. 2). This is not the case for control, where a significant decrease in the density of YOYs between Year 1 and Year 2 could be noted (GLHT, z.value = -3.39, p < 0.002; Fig. 4, Tab. 2).

		Year.1		**Year.2**		
Family	**Species**	**AFN Tot. (YOY)**	**Control Tot. (YOY)**	**AFN Tot. (YOY)**	**Control Tot. (YOY)**	**Total (YOY)**
Atherinidae	*Atherina sp.*	73 (0)		33 (33)		**106 (33)**
Blenniidae	*Microlipophrys canevae*		3 (0)		22 (0)	**25** (0)
	Parablennius gattorugine		2 (0)			**2** (0)
	Parablennius sanguinolentus	1 (0)				**1** (0)
	Salaria pavo	1 (0)		1 (0)	1 (0)	**3** (0)
Carangidae	*Trachurus mediterraneus*	68 (68)	30 (30)			**98 (98)**
	Trachurus sp.		50 (50)			**50 (50)**
Gobiidae	*Aphia minuta*		94 (0)			**94** (0)
	Gobius cobitis		3 (0)	1 (0)	3 (0)	**7** (0)
	Gobius cruentatus	44 (1)	16 (0)	16 (0)	18 (0)	**94 (1)**
	Gobius geniporus	19 (2)	27 (2)	6 (0)	13 (0)	**65 (4)**
	Gobius niger	11 (4)	13 (0)	13 (1)	6 (1)	**43 (6)**
	Gobius paganellus		5 (0)	1 (0)	2 (0)	**8** (0)
	Gobius xanthocephalus	7 (0)	29 (0)	38 (8)	31 (0)	**105 (8)**
	Pomatoschistus quagga			1 (0)		**1** (0)
	Pseudaphya ferreri			2 (0)	10 (0)	**12** (0)
Labridae	*Labrus merula*	5 (1)		8 (1)		**13 (2)**
	Symphodus cinereus	48 (2)	39 (0)	24 (0)	9 (0)	**120 (2)**
	Symphodus mediterraneus	1 (0)		1 (0)		**2** (0)
	Symphodus melanocercus			1 (0)		**1** (0)
	Symphodus melops	2 (0)				**2** (0)
	Symphodus ocellatus	5 (0)		9 (1)	2 (0)	**16 (1)**
	Symphodus roissali	3 (0)	7 (0)	6 (2)		**16 (2)**
	Symphodus rostratus	6 (0)	1 (0)			**7** (0)
	Symphodus tinca	156 (16)	83 (23)	100 (2)	14 (0)	**353 (41)**
Moronidae	*Dicentrarchus labrax*	3 (0)		9 (3)		**12 (3)**
Mugilidae	*Mugil cephalus*			2 (0)		**2** (0)
	Mullus barbatus	13 (10)	1 (1)	2 (0)		**16 (11)**
	Mullus surmuletus	57 (28)	30 (29)	20 (11)	5 (3)	**112 (71)**
Scorpaenidae	*Scorpaena scrofa*	1 (0)				**1** (0)
	Scorpanena porcus	1 (0)				**1** (0)
Serranidae	*Serranus scriba*	2 (0)				**2** (0)
Sparidae	*Diplodus annularis*	79 (32)	18 (7)	106 (58)	6 (2)	**209 (99)**
	Diplodus puntazzo	22 (18)	4 (1)	7 (6)	2 (0)	**35 (25)**
	Diplodus sargus	215 (60)	61 (25)	349 (21)	9 (0)	**634 (106)**
	Diplodus vulgaris	101 (45)	63 (30)	86 (17)	35 (8)	**285 (100)**
	Pagellus sp.			4 (4)	8 (0)	**12 (4)**
	Sarpa salpa	125 (86)	84 (0)	149 (48)	11 (0)	**369 (134)**
	Sparus aurata	2 (0)		2 (0)		**4** (0)
	Spicara sp.	2 (2)			13 (13)	**15 (15)**
	Spondyliosoma cantharus	1 (1)				**1 (1)**
Tripterygiidae	*Tripterygion delaisi*	17 (0)	21 (0)	20 (0)	17 (0)	**75** (0)
	Tripterygion tripteronotum	15 (0)	11 (0)	6 (0)	1 (0)	**33** (0)
Total		**1106 (376)**	**695 (198)**	**1023 (216)**	**238 (27)**	**3062 (817)**
number of species (YOY)		**32 (16)**	**24 (10)**	**29 (15)**	**22 (5)**	**43 (23)**

Table 1: Assessment of fish abundance for the two years of monitoring of the artificial fish nurseries (AFN) and the control docks. Numbers expressed in total abundance with YOY (Young of The Year) in parenthesis. Note that absolute values of Year 1 and Year 2 are not comparable due to unequal sample sizes (52 and 29 respectively).

Test: GLMer (Number ~ Year*Treatment)		**Estimate**	**std.err**	**Z val**	**Pr(>|z|)**	
All stages						
	(Intercept)	3.043	0.116	26.13	< 0.001	***

	Year	0.521	0.194	2.682	0.007	**
	Treatment	-0.397	0.169	-2.353	0.018	*
	Year:Treatment	-1.027	0.284	-3.615	< 0.001	***
Random effect		Variance	std.dev			
	Site	< 0.001	< 0.001			
YOYs						
	(Intercept)	2.079	0.205	10.17	< 0.001	***
	Year	0.077	0.347	0.222	0.824	
	Treatment	-0.54	0.299	-1.811	0.070	
	Year:Treatment	-1.454	0.534	-2.723	0.006	**
Random effect		Variance	std.dev			
	Site	< 0.001	< 0.001			
Test: GLHT (Number~Year_Treatment)						
		Estimate	**std.err**	**Z val**	**Pr(>|z|)**	
All stages						
	Year1_Control – Year1 AFN	-0.398	0.168	-2.365	0.018	*
	Year2_Control – Year2 AFN	-1.423	0.229	-6.227	< 0.001	***
	Year2_AFN – Year1 AFN	0.519	0.194	2.674	0.011	*
	Year2_Control – Year1 Control	-0.506	0.207	-2.442	0.018	*
	Year2_AFN – Year1 Control	0.917	0.197	4.649	< 0.001	***
	Year2_Control – Year1 AFN	-0.904	0.204	-4.430	< 0.001	***
YOYs						
	Year1_Control – Year1 AFN	-0.542	0.299	-1.811	0.098	
	Year2_Control – Year2 AFN	-1.996	0.442	-4.515	< 0.001	
	Year2_AFN – Year1 AFN	0.077	0.347	0.222	0.824	
	Year2_Control – Year1 Control	-1.377	0.406	-3.390	0.001	***
	Year2_AFN – Year1 Control	0.619	0.355	1.744	0.098	
	Year2_Control – Year1 AFN	-1.919	0.399	-4.813	< 0.001	***
Test: GLHT (Number~Year)						
		Estimate	**std.err**	**Z val**	**Pr(>|z|)**	
All stages						
	Year1 – Year2	0.510	0.194	2.674	0.008	**
YOYs						
	Year1 – Year2	0.077	0.347	0.222	0.824	

Table 2: Results of the GLMer model and GLHT post-hoc evaluating the effect of treatment and year of survey on All fish and Young Of the Year abundances.

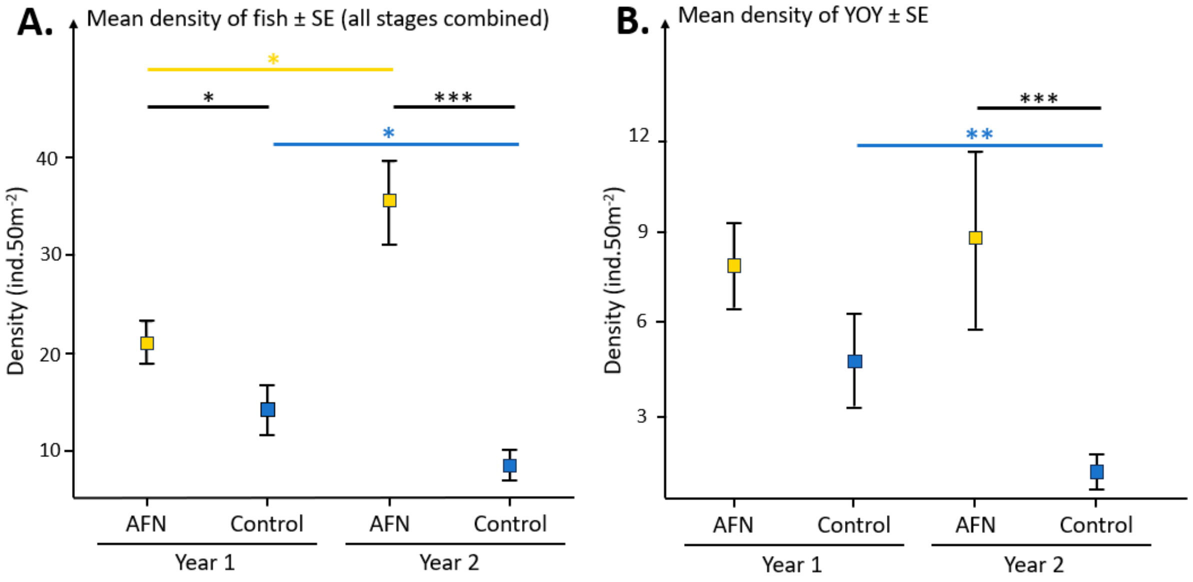


Figure 4: Mean A.: fish densities and B.: Young Of the Year (YOY) densities (± standard error) on artificial fish nurseries (AFN) and the control docks (Control) during the two years of monitoring. (p < 0.05, ** p < 0,01, *** p < 0.001).*

3.2. Community analysis

Treatment significantly influenced species richness with higher values on the AFN for all fish (13.6 ± 0.6 species.100 m^{-2} on AFN vs 8.2 ± 0.6 species on control; GLMER.nb, z.value = -4.622, $p < 0.001$, Tab. 3) and YOYs (4.6 ± 0.4 species.100 m^{-2} on AFN vs 2.0 ± 0.4 species on control; GLMER.nb, z.value = -4.159, $p < 0.001$, Tab. 3).

Test: GLMer (Species Richness ~ Year*Treatment)						
		Estimate	**std.err**	**Z val**	**Pr(>|z|)**	
All stages						
	(Intercept)	1.865	0.074	25.32	< 0.001	***
	Year	0.144	0.093	1.559	0.117	
	Treatment	-0.421	0.091	-4.622	< 0.001	***
	Year:Treatment	-0.265	0.154	-1.716	0.0861	
Random effect		Variance	std.dev			
	Site	0.006	0.081			
YOYs						
	(Intercept)	0.916	0.01	9.179	< 0.001	***
	Year	-0.243	0.183	-1.329	0.184	
	Treatment	-0.742	0.178	-4.159	< 0.001	***
	Year:Treatment	-0.582	0.377	-1.543	0.123	
Random effect		Variance	std.dev			
	Site	< 0.001	< 0.001			

Table 3: Results of the GLMer model testing for the effect of Year and treatment on species richness for all fish and Young Of the Year (YOY).

Treatment (AFN, Control) and year of monitoring (Year 1, Year 2) significantly influenced fish community structure for all stages (PERMANOVA, $R^2 = 0.104$, $p < 0.001$ and $R^2 = 0.026$, $p = 0.002$) and for YOYs (PERMANOVA, $R^2 = 0.028$, $p = 0.004$ and $R^2 = 0.038$, $p < 0.001$) (Fig. 5 and Tab. 4). The interaction between these two factors had a significant influence on community structure for all stages (PERMANOVA, $R^2 = 0.023$, $p < 0.001$, Tab. 4) but not for YOYs (PERMANOVA, $R^2 = 0.013$, $p = 0.22$). The pairwise PERMANOVA revealed that all possible interactions of treatment and year of monitoring were significantly different from each other (pairwise PERMANOVA; $R^2 > 0.03$, $p < 0.01$, Tab. 4) for all life stages.

Test: PERMANOVA (Dist.matrix ~ Treatment * Year)								
		Df	**Sum of Sqs**	**R2**	**F**	**Pr(>F)**		
All stages								
	Treatment	1	4.747	0.105	18.75	0.001		***
	Year	1	1.196	0.027	4.723	0.001		***
	Treatment:Year	1	1.026	0.023	4.051	0.001		***
	Residual	152	38.48	0.847				
	Total	155	45.45	1.000				
YOYs								
	Treatment	1	0.711	0.028	2.924	0.004		**
	Year	1	0.954	0.038	3.923	0.002		**
	Treatment:Year	1	0.319	0.013	1.311	0.219		
	Residual	96	23.35	0.922				
	Total	99	25.34	1.000				
Post-Hoc test: Pairwise-PERMANOVA								
		Df	**Sum of Sqs**	**R^2**	**F-Model**	**Pr(>F)**	**p.adjust**	
All stages								
	Year1_Control – Year1 AFN	1	2.015	0.071	7.528	< 0.001	< 0.001	***

Year2_Control – Year2 AFN	1	3.758	0.239	16.62	< 0.001	< 0.001	***
Year2_AFN – Year1 AFN	1	1.382	0.072	6.239	< 0.001	< 0.001	***
Year2_Control – Year1 Control	1	0.839	0.039	2.910	0.007	0.007	**
Year2_AFN – Year1 Control	1	3.265	0.144	12.57	< 0.001	< 0.001	***
Year2_Control – Year1 AFN	1	3.166	0.143	12.83	< 0.001	< 0.001	***

Table 4: PERMANOVA and associated post-hoc Pairwise PERMANOVA outputs testing the fish community across each treatment and year

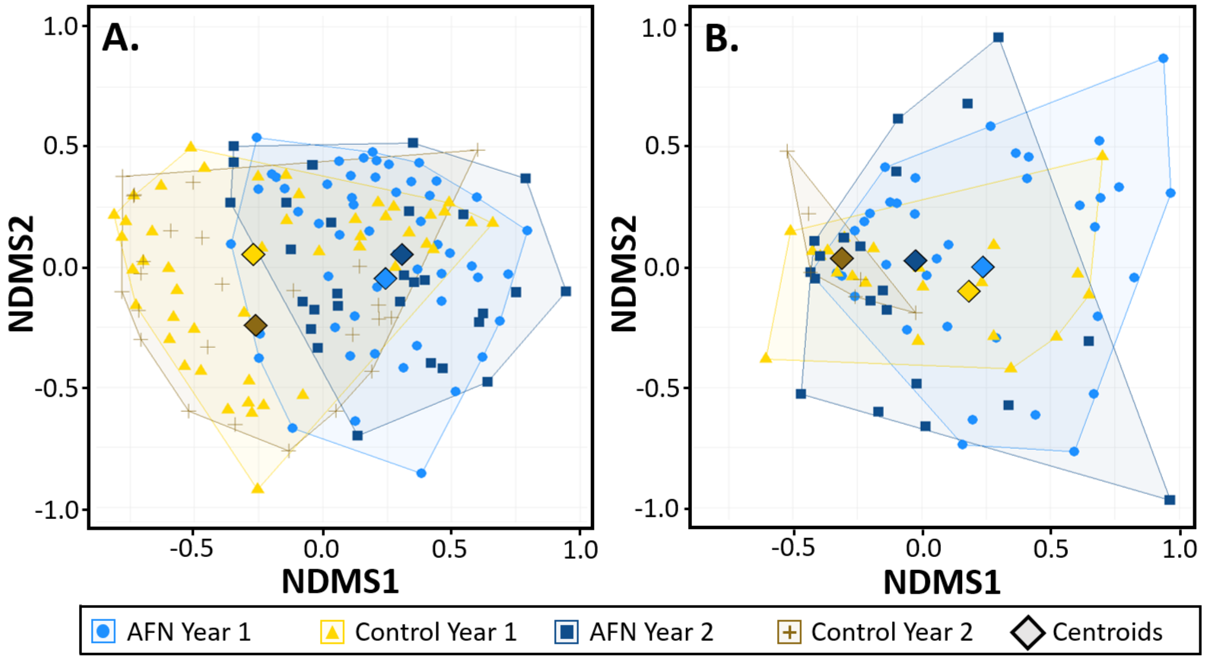
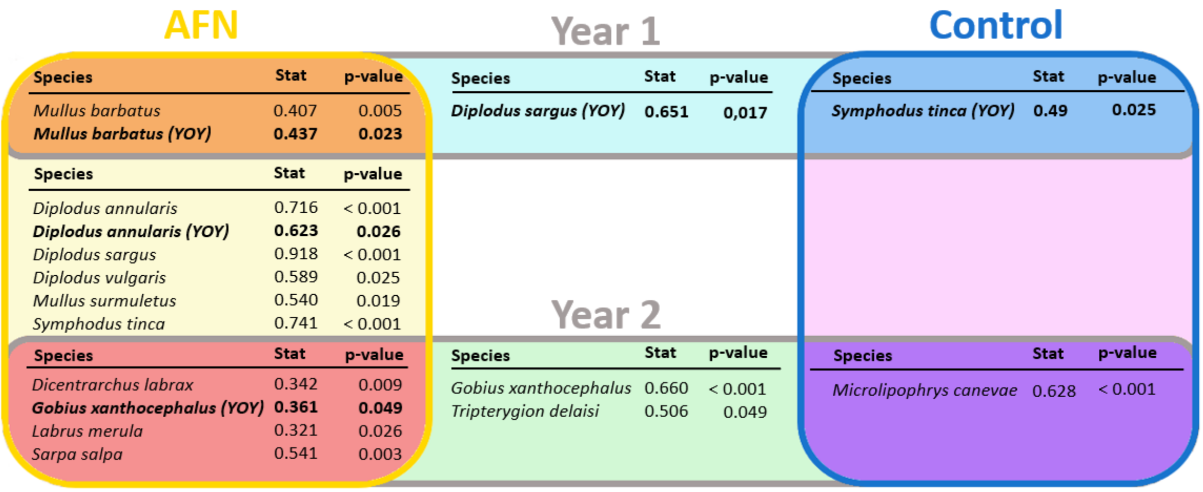


Figure 5: Non-metric Multidimensional Scaling (NMDS) of the fish community structure for each treatment and year for A) All stages and B) Young of the Year (YOY).

Indicator species analysis revealed 5 species to be associated with the AFN as well as YOYs of the species *Diplodus annularis* (Multipattern analysis, stat > 0.54, p < 0.026; Fig. 6). No species was identified as being associated with the control. YOYs of the species *Diplodus sargus* were associated with the first year of monitoring, and two species were associated with the second year of monitoring (Multipattern analysis, stat > 0.51, p < 0.049; Fig. 6). At least one species or YOY species was associated with each interaction term (Fig. 6).



Species	Stat	p-value
Mullus barbatus	0.407	0.005
***Mullus barbatus* (YOY)**	**0.437**	**0.023**

Species	Stat	p-value
***Diplodus sargus* (YOY)**	**0.651**	**0,017**

Species	Stat	p-value
***Symphodus tinca* (YOY)**	**0.49**	**0.025**

Species	Stat	p-value
Diplodus annularis	0.716	< 0.001
***Diplodus annularis* (YOY)**	**0.623**	**0.026**
Diplodus sargus	0.918	< 0.001
Diplodus vulgaris	0.589	0.025
Mullus surmuletus	0.540	0.019
Symphodus tinca	0.741	< 0.001

Species	Stat	p-value
Dicentrarchus labrax	0.342	0.009
***Gobius xanthocephalus* (YOY)**	**0.361**	**0.049**
Labrus merula	0.321	0.026
Sarpa salpa	0.541	0.003

Species	Stat	p-value
Gobius xanthocephalus	0.660	< 0.001
Tripterygion delaisi	0.506	0.049

Species	Stat	p-value
Microlipophrys canevae	0.628	< 0.001

Figure 6: Venn diagram of the indicator species (multipattern analysis) for each year and treatment. The association statistic (Stat) and p-value are given for each indicator species. YOYs are in brackets and in bold.

3.3. Estimation of the predation rate

Loss of squid baits to predators varied among treatments and predation intensity was significantly higher on controls compared to AFNs (Nested Cox, Hazard-ratio = 64.7%; Z = 4.1, p < 0.001; Figure 7). Nearly all the squidpops deployed on controls were consumed within 3 h, whereas almost 40% of them remained on the AFNs. By 6 h, however, most baits had been consumed in both treatments.

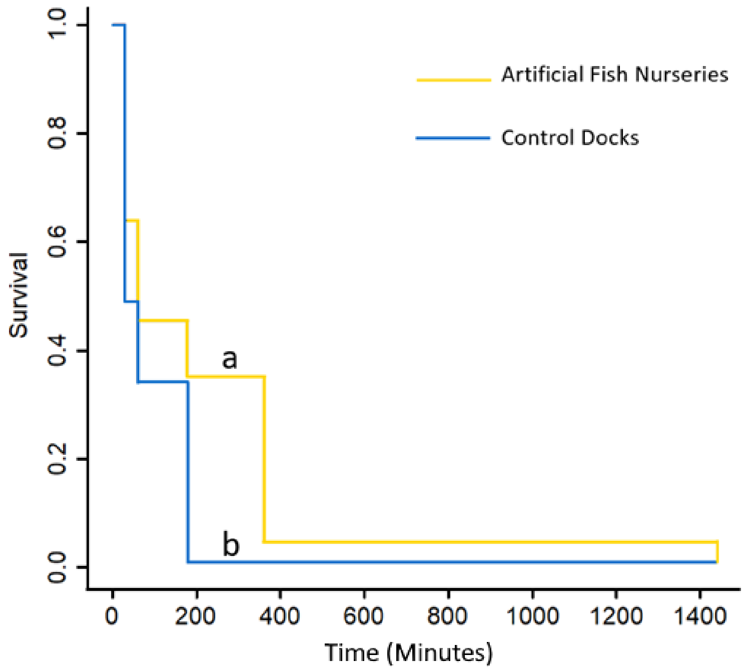


Figure 7: Kaplan-Meier survival curves of bait as proxy of predator activity. Lower-case letters indicate significant differences between sites (Nested Cox; Hazard-ratio = 64.7%, Z = 4.1, p < 0.001).

4. Discussion

Ecological restoration is aimed at assisting the recovery of a degraded or damaged ecosystem (Clewell and Aronson, 2013). Where degradation cannot be reversed, rehabilitation to the highest practicable ecological functionality and increasing similarity to the reference ecosystem are often favored (McDonald et al., 2016). Considering ports are irreversibly degraded coastal ecosystems, eco-engineering approaches like artificial habitat units may help to improve the ecological performance and can be part of ecological rehabilitation projects (Komyakova et al., 2019). Various solutions have been proposed all around the world to improve their ecological status by attempting to increase benthic biodiversity (Bishop et al., 2022; Firth et al., 2014; Strain et al., 2020; Vozzo et al., 2021) and rehabilitate their fish nursery function (Astruch et al., 2017; Bouchoucha et al., 2016; Mercader et al., 2017; Patranella et al., 2017; Strain et al., 2018). However, up to now these potential solutions have remained at a very experimental scale and research on their success remains scarce or is often driven by economic and/or regulatory factors (Firth et al., 2020). Here, we aimed to improve knowledge of the potential benefits of Artificial Fish Nurseries (AFN) on fish abundance in marine urban habitats, by monitoring AFNs installed in a large port in the northwestern Mediterranean Sea for two years. While our study still lacks in terms of optimal experimental design, duration or scale it may still contribute to better understand the function such AFNs may provide. In accordance with our initial hypotheses, AFNs had higher densities of fish over the whole study duration. However, densities of Young of the Year (YOYs) were higher on the AFN only during the second study year compared to bare docks. AFN hosted a greater diversity of fish overall. Community structure varied over treatments and years. Predation intensity was lower on AFNs.

The carried-out monitoring showed that fish densities were more than two times higher on AFNs than on bare docks for all life stages combined as well as for YOYs. This higher density was significant for both study years for all life stages and for YOYs in the second year of the study. It should be noted that this difference between the two treatments is significant whereas fish abundance and biodiversity may be underestimated on AFNs. The AFNs were colonized by benthic fouling communities, which may increasingly hinder a reliable count of local fish populations, which was not the case on control. However, great care was taken to avoid this bias and other ecological processes may also explain these observations. Therefore, it seems that the addition of structural complexity by the AFNs led to an increase in fish density. This is consistent with previous results obtained with other types of AFNs, which have already demonstrated their ability to increase fish abundance and to partly participate in the rehabilitation of the nursery function in ports (Bouchoucha et al., 2016; Mercader et al., 2017; Patranella et al., 2017). A study carried out in the same region showed a two-fold increase of YOYs on AFNs compared to areas without AFNs (Bouchoucha et al., 2016). This order of magnitude is strikingly similar to those observed in our study. This may indicate that AFNs might be an effective tool for increasing fish and YOY abundances in marine urban habitats, potentially by rehabilitating part of the nursery function lost during urbanization.

Here, the overall densities of YOY abundances slightly decreased between Year 1 and Year 2 due to a significant decrease in YOY abundance on control. Inter-annual variability in fish settlement and juvenile assemblages has already been shown in natural areas (Anderson, 1988; Beraud et al., 2018; Félix-Hackradt et al., 2013; Hogan et al., 2012) as well as in port areas (Bouchoucha et al., 2016). The variation of propagule production is generally the determining process for these differences (Di Franco et al., 2012; Faillettaz et al., 2020; Planes et al., 1998) and is highly dependent on the physico-chemical characteristics of the local water column (O’Connor et al., 2007; Ottmann et al., 2018; Tanner et al., 2017). They can also be explained by the match/mismatch hypothesis (Cushing, 1990), where a time lag between the larval phase of the fish and the presence of their planktonic food may be a cause of increased mortality (Di Franco et al., 2015; Hidalgo et al., 2009). This discrepancy between the control group, which experienced a significant decrease in YOY abundance between both years, and the AFN treatment, where YOY abundance remained constant, cannot be fully explained by interannual variation alone. The observation might be attributed to stochasticity, as even in natural habitats, the abundance of juveniles within nurseries does not consistently remain constant. In fact, previous studies have documented interannual variability in the distribution of post-larvae within nursery sites, both on a large and small scale (Victor, 1986). More troubling, however is the possibility that AFNs could act as concentrators for YOYs and do not effectively increase the population (Bohnsack and Sutherland, 1985; Grossman et al., 1997). While our experimental design does not allow to precisely show it, a concentrator effect for YOY would imply that those that would have been present on the control docks have settled preferentially on the AFNs, gradually increasing in these areas while decreasing in others, with potentially no net benefit in terms of population size. This could potentially be what can be observed when considering all fish sizes, as their abundance significantly increased on the AFNs, while it decreased on controls between the two years of monitoring. This reflection on fish attraction versus fish production of AFNs is a recurrent question when trying to assess the efficiency of AFNs (Bouchoucha et al., 2016; Mercader et al., 2017) and more generally that of artificial reefs (Cresson et al., 2019; Grossman et al., 1997; Pickering and Whitmarsh, 1997). It is obviously impossible to draw definitive conclusions from these observations alone and it is important to note that attraction versus fish production characteristics of artificial fish habitats are not mutually exclusive (Pickering and Whitmarsh, 1997; Roa-Ureta et al., 2019; Smith et al., 2015). Future studies should focus their designs on this question as it seems crucial for the overall fish population benefits of these eco-engineering strategies.

The structure of the communities and the species observed on the AFN were similar to the observations made in other port areas (Clynick, 2006; Mercader et al., 2017). However, surveys carried out in natural areas close to Toulon Bay, such as the Iles des Embiez and Cap Sicié (Couvray, 2020) and in the Port Cros National Park (Astruch et al., 2018; Francour, 1997) show greater taxonomic diversity and pelagic fish (excluding *Blenniidae*, *Gobiidae* and *Tripterygiidae*) compared to our study (> 47 species as opposed to 28). The addition of AFNs on port structures seems to increase species richness by adding complexity to the environment (Santos and Monteiro, 1997) and seems to have a fish community more similar to those observed in natural environments (Paxton et al., 2020). We indeed noted a higher fish diversity on AFNs than on control docks, however we did not monitor natural environments, which does not allow making a direct comparison in terms of community structure. Nonetheless, community structure was significantly different between AFNs and control docks and between the two years of monitoring for all fish and for YOYs. This result is also expressed in the changes observed in indicator species associated with the two main effects (Treatment, Year). This observation may be the result of the substrate differences between the two treatments. The substrate is an element likely to influence the structure of the communities at a site. In the natural environment, different fish and YOY communities can be observed depending on the nature of the bottom (Cheminée et al., 2021; Di Lorenzo et al., 2016; Luckhurst and Luckhurst, 1978). This observation has also been made for different artificial substrates (Cheminée et al., 2021; Mercader et al., 2017). Particularly noteworthy here: juveniles of the species *Diplodus annularis* were found as an indicator species for the AFN substrate compared to the control substrate. The greater presence of this species on AFNs than on docks in port areas has already been noted in previous studies (Bouchoucha et al., 2016; Mercader et al., 2017), which implies that for this species in particular the AFN seem to be a suitable habitat. We also observed significant changes in community structure between Year 1 and 2 for all stages and YOYs. The interannual difference between communities can be explained by the variability of abiotic factors, which are known to strongly influence the establishment of fish communities (Ajemian et al., 2015). The fact that the densities of YOYs did not differ between the two treatments during Year 1 and became significantly different during Year 2 may be indicative of a maturation of the AFNs in their function as fish nurseries (Becker et al., 2018; Charbonnel et al., 2002; Cresson et al., 2019). The residence time of AFNs in the environment allows fish communities to develop, leading to a temporal increase in the specific diversity of such structures (Cresson et al., 2019). It is still too early to conclude on this observation, but further monitoring would allow verifying this result.

The Squidpop assay showed less predation on the AFNs than on bare docks with a 64.7% risk decrease on AFNs, and this despite higher abundance and diversity of potential prey items (juveniles). The imitation of seagrass beds by the AFNs provides hiding places used by fleeing prey (Thiriet et al., 2022), allowing for greater survival success. Habitat complexity has been demonstrated to diminish the impact of predation on prey fish on numerous occasions (Almany, 2004; Heck Jr. and Orth, 2006; Jones et al., 2021). However, as our squid baits were unable to actively flee, the higher survival observed here may indicate that predators might avoid AFNs due to lower predation success. Predators that have lower foraging success in complex habitats (Gotceitas and Colgan, 1989; Warfe and Barmuta, 2004) might avoid such areas in order to optimise foraging (Eklöv and Diehl, 1994; Sims et al., 2008). This might indicate that the increase of 3D complexity through AFNs reduces predation intensity and might thus increase juvenile fish survival. Unfortunately, here the predators causing the attacks on squid baits could not be precisely identified. However, past studies indicate that *Sparidae* might be the most prolific predators in marine urban habitats (Gauff et al., 2022; Oricchio et al., 2016; Rodemann and Brandl, 2017). This may mean that one of the essential functions of a nursery (Beck et al., 2001) was potentially partially rehabilitated in our study. However, one should note that the habitat features that optimize the probability of survival of fish juveniles depend on the species considered (Mercader et al., 2019). Moreover, over time AFNs are colonized by different benthic species (Gauff et al., 2023). It is possible that the presence of these organisms provides an abundant food source for generalist predatory fish, which could result in a decrease in the predation rate on AFNs. The presence of this fauna on the AFNs can be beneficial as it is a source of food for potential predators as well as juvenile fish (Saulnier et al., 2020; Tableau et al., 2019). However, this colonization can also be associated with negative side effects like providing refuges for introduced species (Gauff et al., 2023).

Our study demonstrated the potential benefits of installing AFNs in view to rehabilitating the fish nursery function in port areas. We have shown that AFN structures host a higher abundance of fish, including YOYs, than bare docks, with increased fish biodiversity and lower predation intensity. Although we are unable here to precisely identify the processes responsible for these observations, AFNs seem to partly fulfil the definition of a nursery by sheltering a greater abundance of juvenile fish and protecting them against predation (Beck et al., 2001; Dahlgren et al., 2006). Although our results concern only a specific port area and one type of AFNs and, unfortunately, lack the initial state before the rehabilitation action, they agree with an increasing number of studies showing similar results (Astruch et al., 2017; Bouchoucha et al., 2016; Lapinski et al., 2017; Mercader et al., 2017; Patranella et al., 2017). However, although this approach appears promising, there are still many uncertainties regarding the functionality and efficiency of such structures and further studies should be carried out. The hypothesis of the complete rehabilitation of the nursery function in port areas by AFNs can only be confirmed once the effective connectivity between juvenile fish present on AFNs and adult populations has been demonstrated and quantified. Furthermore, it remains essential that the potential benefits of ecological rehabilitation methods are weighed against the potential problems they might cause (Firth et al., 2020; Gauff et al., 2023; Schaefer et al., 2023), as they may also provide ecological disservices such as being a refuge for non-indigenous species (Gauff et al., 2023). In addition, the ropes making up the AFNs in this study are composed of polypropylene. Plastic pollution presents a global environmental challenge (Li et al., 2021; Moore, 2008; Welden, 2020). As nations worldwide strive to minimize plastic waste in marine environment (Horejs, 2020; Jia et al., 2019), it can be contradictory to advocate for the use of plastic structures in habitat restoration initiatives. These materials are generally used for their very high mechanical resistance but in the marine systems, they have the potential to fragment into smaller plastic particles known as microplastics and nanoplastics (Andrady and Zhu, 2021; Sipe et al., 2022) causing both impacts on marine organisms and human health issues (Cho et al., 2019; Rezania et al., 2018). Additionally, they can release plasticizers (such as di-(2-ethyl hexyl) phthalate) into the surrounding environment (Gunaalan et al., 2020). These impacts alone should be sufficient evidence to abandon their use in restoration programs. Moreover, plastic structures are also typically at risk of invasion by non-native species for several reasons, including open niche opportunities. Rather than enhancing habitat quality for native species, plastic habitat structures can favor colonization and establishment of non-native species (Glasby et al., 2007; Pinochet et al., 2020). It is therefore important to ensure that the benefits of AFN are not outweighed by greater negative effects. Whatever the case, public policies should include the management and protection of natural fish nurseries before considering ecological engineering as a solution.

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Author contributions

Etienne Joubert: Methodology, Formal analysis, Investigation, Writing – Original Draft, Visualization; **Robin P.M. Gauff:** Conceptualization, Methodology, Investigation, Formal analysis, Resources, Writing – Review & Editing; **Benoist de Vogüé, Christophe Ravel, and Fabienne Chavanon:** Investigation; **Marc Bouchoucha:** Conceptualization, Methodology, Investigation, Writing – Review & Editing, Project administration, Funding acquisition;

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

A Katki, H., 2013. NestedCohort.

Airoldi, L., Beck, M., 2007. Loss, Status and Trends for Coastal Marine Habitats of Europe. An Annual Review 45, 345–405. https://doi.org/10.1201/9781420050943.ch7

Airoldi, L., Beck, M., Firth, L., Bugnot, A.B., Steinberg, P., Dafforn, K., 2021. Emerging solutions to return nature to the urban ocean. Annual review of marine science 13, 445–477. https://doi.org/10.1146/annurev-marine-032020-020015.

Ajemian, M.J., Wetz, J.J., Shipley-Lozano, B., Shively, J.D., Stunz, G.W., 2015. An Analysis of Artificial Reef Fish Community Structure along the Northwestern Gulf of Mexico Shelf: Potential Impacts of “Rigs-to-Reefs” Programs. PLOS ONE 10, e0126354. https://doi.org/10.1371/journal.pone.0126354

Almany, G.R., 2004. Does increased habitat complexity reduce predation and competition in coral reef fish assemblages? Oikos 106, 275–284. https://doi.org/10.1111/j.0030-1299.2004.13193.x

Anderson, J.T., 1988. A Review of Size Dependant Survival During Pre-recruit Stages of Fishes in Relation to Recruitment. J. Northw. Atl. Fish. Sci. 8, 55–66. https://doi.org/10.2960/J.v8.a6

Anderson, M.J., 2001. A new method for non-parametric multivariate analysis of variance. Austral Ecology 26, 32–46. https://doi.org/10.1111/j.1442-9993.2001.01070.x

Andrady, A., Zhu, L., 2021. Microplastics as Pollutants in the Marine Environment, in: Häder, D.-P., Helbling, E.W., Villafañe, V.E. (Eds.), Anthropogenic Pollution of Aquatic Ecosystems. Springer International Publishing, Cham, pp. 373–399. https://doi.org/10.1007/978-3-030-75602-4_17

Astruch, P., Boudouresque, C.-F., Rouanet, É., Le Direach, L., Bonhomme, P., Bonhomme, D., Goujard, A., Ruitton, S., Harmelin, J.-G., 2018. A quantitative and functional assessment of fish assemblages of the Port-Cros Archipelago (Port-Cros National Park, north-western Mediterranean Sea). Scientific Reports of the Port-Cros National Park 32, 17–82.

Astruch, P., Lucken, A., Rouanet, E., Goujard, A., Montagne, G., 2017. Evaluation de l'efficacité des nurseries artificielles ReFISH immergées dans le port de Bormes-les-Mimosas. Contrat SUEZ Consulting– GIS Posidonie, GIS Posidonie publ., Marseille : 73 p.

Barragán, J.M., de Andrés, M., 2015. Analysis and trends of the world's coastal cities and agglomerations. Ocean & Coastal Management 114, 11–20. https://doi.org/10.1016/j.ocecoaman.2015.06.004

Beck, M.W., Heck, K.L., Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Halpern, B., Hays, C.G., Hoshino, K., Minello, T.J., Orth, R.J., Sheridan, P.F., Weinstein, M.P., 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: A better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. BioScience 51, 633–641. https://doi.org/10.1641/0006-3568(2001)051[0633:TICAMO]2.0.CO;2

Becker, A., Taylor, M.D., Folpp, H., Lowry, M.B., 2018. Managing the development of artificial reef systems: The need for quantitative goals. Fish and Fisheries 19, 740–752. https://doi.org/10.1111/faf.12288

Belharet, M., Franco, A.D., Calò, A., Mari, L., Claudet, J., Casagrandi, R., Gatto, M., Lloret, J., Sève, C., Guidetti, P., Melià, P., 2020. Extending full protection inside existing marine protected areas, or reducing fishing effort outside, can reconcile conservation and fisheries goals. Journal of Applied Ecology 57, 1948–1957. https://doi.org/10.1111/1365-2664.13688

Ben Attia, O., Fersi, F., Rejab, H., 2021. The Environment and Sustainable Development in Front of the Artificialisation of the Coastlines: Coasts of Tunisia, Morocco and Algeria, in: Abu-hashim, M., Khebour Allouche, F., Negm, A. (Eds.), Agro-Environmental Sustainability in MENA Regions, Springer Water. Springer International Publishing, Cham, pp. 209–229. https://doi.org/10.1007/978-3-030-78574-1_9

Benjamini, Y., Hochberg, Y., 1995. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. Journal of the Royal Statistical Society: Series B (Methodological) 57, 289–300. https://doi.org/10.1111/j.2517-6161.1995.tb02031.x

Beraud, C., van der Molen, J., Armstrong, M., Hunter, E., Fonseca, L., Hyder, K., 2018. The influence of oceanographic conditions and larval behaviour on settlement success—the European sea bass Dicentrarchus labrax (L.). ICES Journal of Marine Science 75, 455–470. https://doi.org/10.1093/icesjms/fsx195

Bishop, M.J., Vozzo, M.L., Mayer-Pinto, M., Dafforn, K.A., 2022. Complexity–biodiversity relationships on marine urban structures: reintroducing habitat heterogeneity through eco-engineering. Philosophical Transactions of the Royal Society B: Biological Sciences 377, 20210393. https://doi.org/10.1098/rstb.2021.0393

Bohnsack, J.A., Sutherland, D.L., 1985. Artificial Reef Research: A Review with Recommendations for Future Priorities. Bulletin of Marine Science 37, 11–39.

Bolker, B., 2022. lme4.

Bouchoucha, M., Brach-Papa, C., Gonzalez, J.-L., Lenfant, P., Darnaude, A.M., 2018a. Growth, condition and metal concentration in juveniles of two Diplodus species in ports. Marine Pollution Bulletin 126, 31–42. https://doi.org/10.1016/j.marpolbul.2017.10.086

Bouchoucha, M., Darnaude, A.M., Gudefin, A., Neveu, R., Verdoit-Jarraya, M., Boissery, P., Lenfant, P., 2016. Potential use of marinas as nursery grounds by rocky fishes: insights from four Diplodus species in the Mediterranean. Marine Ecology Progress Series 547, 193–209. https://doi.org/10.3354/meps11641

Bouchoucha, M., Pécheyran, C., Gonzalez, J.L., Lenfant, P., Darnaude, A.M., 2018b. Otolith fingerprints as natural tags to identify juvenile fish life in ports. Estuarine, Coastal and Shelf Science 212, 210–218. https://doi.org/10.1016/j.ecss.2018.07.008

Bradford, T.E., Astudillo, J.C., Lau, E.T.C., Perkins, M.J., Lo, C.C., Li, T.C.H., Lam, C.S., Ng, T.P.T., Strain, E.M.A., Steinberg, P.D., Leung, K.M.Y., 2020. Provision of refugia and seeding with native bivalves can enhance biodiversity on vertical seawalls. Marine Pollution Bulletin 160, 111578. https://doi.org/10.1016/j.marpolbul.2020.111578

Brokovich, E., Baranes, A., Goren, M., 2006. Habitat structure determines coral reef fish assemblages at the northern tip of the Red Sea. Ecological Indicators 6, 494–507. https://doi.org/10.1016/j.ecolind.2005.07.002

Bugnot, A.B., Mayer-Pinto, M., Airoldi, L., Heery, E.C., Johnston, E.L., Critchley, L.P., Strain, E.M.A., Morris, R.L., Loke, L.H.L., Bishop, M.J., Sheehan, E.V., Coleman, R.A., Dafforn, K.A., 2021. Current and projected global extent of marine built structures. Nature Sustainability 4, 33–41. https://doi.org/10.1038/s41893-020-00595-1

Charbonnel, E., Serre, C., Ruitton, S., Harmelin, J.-G., Jensen, A., 2002. Effects of increased habitat complexity on fish assemblages associated with large artificial reef units (French Mediterranean coast). ICES Journal of Marine Science 59, S208–S213. https://doi.org/10.1006/jmsc.2002.1263

Cheminée, A., Francour, P., Harmelin-Vivien, M., 2011. Assessment of Diplodus spp. (Sparidae) nursery grounds along the rocky shore of Marseilles (France, NW Mediterranean). Scientia Marina 75, 181–188. https://doi.org/10.3989/scimar.2011.75n1181

Cheminée, A., Le Direach, L., Rouanet, E., Astruch, P., Goujard, A., Blanfuné, A., Bonhomme, D., Chassaing, L., Jouvenel, J.-Y., Ruitton, S., Thibaut, T., Harmelin-Vivien, M., 2021. All shallow coastal habitats matter as nurseries for Mediterranean juvenile fish. Sci Rep 11, 14631. https://doi.org/10.1038/s41598-021-93557-2.

Cheminée, A., Rider, M., Lenfant, P., Zawadzki, A., Mercière, A., Crec'hriou, R., Mercader, M., Saragoni, G., Neveu, R., Ternon, Q., Pastor, J., 2017. Shallow rocky nursery habitat for fish: Spatial variability of juvenile fishes among this poorly protected essential habitat. Marine Pollution Bulletin 119, 245–254. https://doi.org/10.1016/j.marpolbul.2017.03.051

Cho, Y., Shim, W.J., Jang, M., Han, G.M., Hong, S.H., 2019. Abundance and characteristics of microplastics in market bivalves from South Korea. Environmental Pollution 245, 1107–1116. https://doi.org/10.1016/j.envpol.2018.11.091

Clewell, A., Aronson, J., 2013. The SER primer and climate change. Ecological Management & Restoration 14, 182–186. https://doi.org/10.1111/emr.12062

Clynick, B., 2006. Assemblages of fish associated with coastal marinas in north-western Italy. J. Mar. Biol. Ass. U.K 86, 847–852. https://doi.org/10.1017/S0025315406013786

Courrat, A., Lobry, J., Nicolas, D., Laffargue, P., Amara, R., Lepage, M., Girardin, M., Le Pape, O., 2009. Anthropogenic disturbance on nursery function of estuarine areas for marine species. Estuarine, Coastal and Shelf Science 81, 179–190. https://doi.org/10.1016/j.ecss.2008.10.017

Couvray, S., 2020. Six years of monitoring of fish assemblages in shallow bottoms around the Embiez islands and cap Sicié (French Mediterranean sea). Life and environment 70, 83–87.

Cresson, P., Le Direach, L., Rouanet, E., Goberville, E., Astruch, P., Ourgaud, M., Harmelin-Vivien, M., 2019. Functional traits unravel temporal changes in fish biomass production on artificial reefs. Marine Environmental Research 145, 137–146. https://doi.org/10.1016/j.marenvres.2019.02.018

Cushing, D.H., 1990. Plankton Production and Year-class Strength in Fish Populations: an Update of the Match/Mismatch Hypothesis, in: Blaxter, J.H.S., Southward, A.J. (Eds.), Advances in Marine Biology. Academic Press, pp. 249–293. https://doi.org/10.1016/S0065-2881(08)60202-3

Dafforn, K.A., Glasby, T.M., Airoldi, L., Rivero, N.K., Mayer-Pinto, M., Johnston, E.L., 2015. Marine urbanization: an ecological framework for designing multifunctional artificial structures. Frontiers in Ecology and the Environment 13, 82–90. https://doi.org/10.1890/140050

Dahlgren, C.P., Kellison, G.T., Adams, A.J., Gillanders, B.M., Kendall, M.S., Layman, C.A., Ley, J.A., Nagelkerken, I., Serafy, J.E., 2006. Marine nurseries and effective juvenile habitats: concepts and applications. Marine Ecology Progress Series 312, 291–295.

De Cáceres, M., 2022. indicspecies.

Di Franco, A., Coppini, G., Pujolar, J.M., Leo, G.A.D., Gatto, M., Lyubartsev, V., Melià, P., Zane, L., Guidetti, P., 2012. Assessing Dispersal Patterns of Fish Propagules from an Effective Mediterranean Marine Protected Area. PLOS ONE 7, e52108. https://doi.org/10.1371/journal.pone.0052108

Di Franco, A., Gianni, F., Guidetti, P., 2015. Mismatch in early life traits between settlers and recruits in a Mediterranean fish: Clue of the relevance of the settlement tail? Acta Ichthyol. Piscat. 45. https://doi.org/10.3750/AIP2015.45.2.05

Di Lorenzo, M., Fernandez, T.V., Badalamenti, F., Guidetti, P., Starr, R.M., Giacalone, V.M., Di Franco, A., D'Anna, G., 2016. Diel activity and variability in habitat use of white sea bream in a temperate marine protected area. Marine Environmental Research 116, 1–9. https://doi.org/10.1016/j.marenvres.2016.02.007

Doherty, P.J., 1991. Spatial and temporal patterns in recruitment. The ecology of fishes on coral reefs 509, 261–293. https://doi.org/10.1016/B978-0-08-092551-6.50015-5

Ducruet, C., Lee, S.-W., 2006. Frontline soldiers of globalisation: Port–city evolution and regional competition. GeoJournal 67, 107–122. https://doi.org/10.1007/s10708-006-9037-9

Duffy, J.E., Ziegler, S.L., Campbell, J.E., Bippus, P.M., Lefcheck, J.S., 2015. Squidpops: A Simple Tool to Crowdsource a Global Map of Marine Predation Intensity. PLOS ONE 10, e0142994. https://doi.org/10.1371/journal.pone.0142994

Eklöv, P., Diehl, S., 1994. Piscivore efficiency and refuging prey: the importance of predator search mode. Oecologia 98, 344–353. https://doi.org/10.1007/BF00324223

Faillettaz, R., Voué, R., Crec'hriou, R., Garsi, L.H., Lecaillon, G., Agostini, S., Lenfant, P., Irisson, J.O., 2020. Spatio-temporal patterns of larval fish settlement in the northwestern Mediterranean Sea. Marine Ecology Progress Series 650, 153–173. https://doi.org/10.3354/meps13191

Fan, X., Dai, X., Yang, G., Jia, Z., Liu, L., Sun, N., 2017. Detecting artificialization process and corresponding state changes of estuarine ecosystems based on naturalness assessment. Ocean & Coastal Management 146, 178–186. https://doi.org/10.1016/j.ocecoaman.2017.07.007

Félix-Hackradt, F.C., Hackradt, C.W., Treviño-Otón, J., Pérez-Ruzafa, A., García-Charton, J.A., 2013. Temporal patterns of settlement, recruitment and post-settlement losses in a rocky reef fish assemblage in the South-Western Mediterranean Sea. Mar Biol 160, 2337–2352. https://doi.org/10.1007/s00227-013-2228-2

Firth, L.B., Airoldi, L., Bulleri, F., Challinor, S., Chee, S.-Y., Evans, A.J., Hanley, M.E., Knights, A.M., O'Shaughnessy, K., Thompson, R.C., Hawkins, S.J., 2020. Greening of grey infrastructure should not be used as a Trojan horse to facilitate coastal development. Journal of Applied Ecology 57, 1762–1768. https://doi.org/10.1111/1365-2664.13683

Firth, L.B., Schofield, M., White, F.J., Skov, M.W., Hawkins, S.J., 2014. Biodiversity in intertidal rock pools: informing engineering criteria for artificial habitat enhancement in the built environment. Mar Environ Res 102, 122–130. https://doi.org/10.1016/j.marenvres.2014.03.016

Fischer, P., Weber, A., Heine, G., Weber, H., 2007. Habitat structure and fish: assessing the role of habitat complexity for fish using a small, semiportable, 3-D underwater observatory. Limnology and Oceanography: Methods 5, 250–262. https://doi.org/10.4319/lom.2007.5.250

Ford, J.R., Shima, J.S., Swearer, S.E., 2016. Interactive effects of shelter and conspecific density shape mortality, growth, and condition in juvenile reef fish. Ecology 97, 1373–1380. https://doi.org/10.1002/ecy.1436

Ford, J.R., Swearer, S.E., 2013. Two's company, three's a crowd: food and shelter limitation outweigh the benefits of group living in a shoaling fish. Ecology 94, 1069–1077. https://doi.org/10.1890/12-1891.1

Francour, P., 1997. Fish Assemblages of Posidonia oceanica Beds at Port-Cros (France, NW Mediterranean): Assessment of Composition and Long-Term Fluctuations by Visual Census. Marine Ecology 18, 157–173. https://doi.org/10.1111/j.1439-0485.1997.tb00434.x

Froese, R., Pauly, D., 2022. FishBase [WWW Document]. World Wide Web electronic publication. URL www.fishbase.org (accessed 2.6.23).

Gauff, R.P.M., Bejarano, S., Madduppa, H.H., Subhan, B., Dugény, E.M.A., Perdana, Y.A., Ferse, S.C.A., 2018. Influence of predation risk on the sheltering behaviour of the coral-dwelling damselfish, Pomacentrus moluccensis. Environ Biol Fish 101, 639–651. https://doi.org/10.1007/s10641-018-0725-3

Gauff, R.P.M., Joubert, E., Curd, A., Carlier, A., Chavanon, F., Ravel, C., Bouchoucha, M., 2023. The elephant in the room: Introduced species also profit from refuge creation by artificial fish habitats. Marine Environmental Research 185, 105859. https://doi.org/10.1016/j.marenvres.2022.105859

Gauff, R.P.M., Lejeusne, C., Arsenieff, L., Bohner, O., Coudret, J., Desbordes, F., Jandard, A., Loisel, S., Schires, G., Wafo, E., Davoult, D., 2022. Alien vs. predator: influence of environmental variability and predation on the survival of ascidian recruits of a native and alien species. Biol Invasions 24, 1327–1344. https://doi.org/10.1007/s10530-021-02720-3

George, B., Seals, S., Aban, I., 2014. Survival analysis and regression models. J Nucl Cardiol 21, 686–694. https://doi.org/10.1007/s12350-014-9908-2

Glasby, T.M., Connell, S.D., Holloway, M.G., Hewitt, C.L., 2007. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar Biol 151, 887–895. https://doi.org/10.1007/s00227-006-0552-5

Gotceitas, V., Colgan, P., 1989. Predator foraging success and habitat complexity: quantitative test of the threshold hypothesis. Oecologia 80, 158–166. https://doi.org/10.1007/BF00380145

Grasselli, F., Airoldi, L., 2021. How and to What Degree Does Physical Structure Differ Between Natural and Artificial Habitats? A Multi-Scale Assessment in Marine Intertidal Systems. Frontiers in Marine Science 8.

Grossman, G.D., Jones, G.P., Seaman, W.J., 1997. Do Artificial Reefs Increase Regional Fish Production? A Review of Existing Data. Fisheries 22, 17–23. https://doi.org/10.1577/1548-8446(1997)022<0017:DARIRF>2.0.CO;2

Gunaalan, K., Fabbri, E., Capolupo, M., 2020. The hidden threat of plastic leachates: A critical review on their impacts on aquatic organisms. Water Res 184, 116170. https://doi.org/10.1016/j.watres.2020.116170

Harmelin-Vivien, M.L., Harmelin, J.G., Leboulleux, V., 1995. Microhabitat requirements for settlement of juvenile sparid fishes on Mediterranean rocky shores. Hydrobiologia 300, 309–320. https://doi.org/10.1007/BF00024471

Heck Jr., K.L., Orth, R.J., 2006. Predation in Seagrass Beds, in: LARKUM, A.W.D., ORTH, R.J., DUARTE, C.M. (Eds.), SEAGRASSES: BIOLOGY, ECOLOGYAND CONSERVATION. Springer Netherlands, Dordrecht, pp. 537–550. https://doi.org/10.1007/978-1-4020-2983-7_22

Hervé, M., 2022. RVAidememoire.

Hidalgo, M., Tomás, J., Moranta, J., Morales-Nin, B., 2009. Intra-annual recruitment events of a shelf species around an island system in the NW Mediterranean. Estuarine, Coastal and Shelf Science 83, 227–238. https://doi.org/10.1016/j.ecss.2009.03.037

Hogan, J.D., Thiessen, R.J., Sale, P.F., Heath, D.D., 2012. Local retention, dispersal and fluctuating connectivity among populations of a coral reef fish. Oecologia 168, 61–71. https://doi.org/10.1007/s00442-011-2058-1

Horejs, C., 2020. Solutions to plastic pollution. Nat Rev Mater 5, 641–641. https://doi.org/10.1038/s41578-020-00237-0

Hothorn, T., 2022. multcomp.

Jia, L., Evans, S., Linden, S. van der, 2019. Motivating actions to mitigate plastic pollution. Nat Commun 10, 4582. https://doi.org/10.1038/s41467-019-12666-9

Jones, T.R., Henderson, C.J., Olds, A.D., Connolly, R.M., Schlacher, T.A., Hourigan, B.J., Goodridge Gaines, L.A., Gilby, B.L., 2021. The Mouths of Estuaries Are Key Transition Zones that Concentrate the Ecological Effects of Predators. Estuaries and Coasts 44, 1557–1567. https://doi.org/10.1007/s12237-020-00862-6

Komyakova, V., Chamberlain, D., Jones, G.P., Swearer, S.E., 2019. Assessing the performance of artificial reefs as substitute habitat for temperate reef fishes: Implications for reef design and placement. Science of The Total Environment 668, 139–152. https://doi.org/10.1016/j.scitotenv.2019.02.357

Korner-Nievergelt, F., 2019. blmeco.

Kough, A.S., Belak, C.A., 2022. Piscine predation rates vary relative to habitat, but not protected status, in an island chain with an established marine reserve. Frontiers in Marine Science 9:921463. https://doi.org/10.3389/fmars.2022.921463

Lapinski, M., Boissery, P., GRANDRIVE, R., Blouet, S., Foulquie, M., Chéré, E., Perrot, M., 2017. Innovative solutions for the enhancement of biodiversity on coastal infrastructures : case studies of artificial port nurseries and modular mooring reefs 222. https://doi.org/10.5150/cmcm.2017.040

Le Pape, O., Bonhommeau, S., 2015. The food limitation hypothesis for juvenile marine fish. Fish and Fisheries 16, 373–398. https://doi.org/10.1111/faf.12063

Le Pape, O., Vermard, Y., Guitton, J., Brown, E.J., van de Wolfshaar, K.E., Lipcius, R.N., Støttrup, J.G., Rose, K.A., 2020. The use and performance of survey-based pre-recruit abundance indices for possible inclusion in stock assessments of coastal-dependent species. ICES Journal of Marine Science 77, 1953–1965. https://doi.org/10.1093/icesjms/fsaa051

Li, P., Wang, X., Su, M., Zou, X., Duan, L., Zhang, H., 2021. Characteristics of Plastic Pollution in the Environment: A Review. Bull Environ Contam Toxicol 107, 577–584. https://doi.org/10.1007/s00128-020-02820-1

Luckhurst, B.E., Luckhurst, K., 1978. Analysis of the influence of substrate variables on coral reef fish communities. Mar. Biol. 49, 317–323. https://doi.org/10.1007/BF00455026

Martinez Arbizu, P., 2020. pairwiseAdonis.

McDonald, T., Jonson, J., Dixon, K.W., 2016. National standards for the practice of ecological restoration in Australia. Restoration Ecology 24, S4–S32. https://doi.org/10.1111/rec.12359

Mercader, M., Blazy, C., Di Pane, J., Devissi, C., Mercière, A., Cheminée, A., Thiriet, P., Pastor, J., Crec'hriou, R., Verdoit-Jarraya, M., Lenfant, P., 2019. Is artificial habitat diversity a key to restoring nurseries for juvenile coastal fish? Ex situ experiments on habitat selection and survival of juvenile seabreams. Restoration Ecology 27, 1155–1165. https://doi.org/10.1111/rec.12948

Mercader, M., Mercière, A., Saragoni, G., Cheminée, A., Crec'hriou, R., Pastor, J., Rider, M., Dubas, R., Lecaillon, G., Boissery, P., Lenfant, P., 2017. Small artificial habitats to enhance the nursery function for juvenile fish in a large commercial port of the Mediterranean. Ecological Engineering 105, 78–86. https://doi.org/10.1016/j.ecoleng.2017.03.022

Moore, C.J., 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. Environ Res 108, 131–139. https://doi.org/10.1016/j.envres.2008.07.025

Mooser, A., Anfuso, G., Williams, A.T., Molina, R., Aucelli, P.P.C., 2021. An Innovative Approach to Determine Coastal Scenic Beauty and Sensitivity in a Scenario of Increasing Human Pressure and Natural Impacts due to Climate Change. Water 13, 49. https://doi.org/10.3390/w13010049

Mora, C., Tittensor, D.P., Myers, R.A., 2008. The completeness of taxonomic inventories for describing the global diversity and distribution of marine fishes. Proceedings: Biological Sciences 275, 149–155. https://doi.org/10.1098/rspb.2007.1315

Nazeer, M., Waqas, M., Shahzad, M.I., Zia, I., Wu, W., 2020. Coastline Vulnerability Assessment through Landsat and Cubesats in a Coastal Mega City. Remote Sensing 12, 749. https://doi.org/10.3390/rs12050749

O'Connor, M.I., Bruno, J.F., Gaines, S.D., Halpern, B.S., Lester, S.E., Kinlan, B.P., Weiss, J.M., 2007. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. Proceedings of the National Academy of Sciences 104, 1266–1271. https://doi.org/10.1073/pnas.0603422104

Oksanen, J., 2022. vegan.

Oricchio, F.T., Pastro, G., Vieira, E.A., Flores, A.A.V., Gibran, F.Z., Dias, G.M., 2016. Distinct community dynamics at two artificial habitats in a recreational marina. Marine Environmental Research 122, 85–92. https://doi.org/10.1016/j.marenvres.2016.09.010

Ottmann, D., Grorud-Colvert, K., Huntington, B., Sponaugle, S., 2018. Interannual and regional variability in settlement of groundfishes to protected and fished nearshore waters of Oregon, USA. Marine Ecology Progress Series 598, 131–145. https://doi.org/10.3354/meps12616

Ovejero Campos, A., Fernández, E., Eiroa, B.S., Urbieta, P., Martínez, G.M., 2022. A composite indicator to assess artificialization at the land-sea interface: A case study in NW Spain. Regional Studies in Marine Science 54, 102468. https://doi.org/10.1016/j.rsma.2022.102468

Patranella, A., Kilfoyle, K., Pioch, S., Spieler, R.E., 2017. Artificial Reefs as Juvenile Fish Habitat in a Marina. Journal of Coastal Research 33, 1341–1351. https://doi.org/10.2112/JCOASTRES-D-16-00145.1

Paxton, A.B., Shertzer, K.W., Bacheler, N.M., Kellison, G.T., Riley, K.L., Taylor, J.C., 2020. Meta-Analysis Reveals Artificial Reefs Can Be Effective Tools for Fish Community Enhancement but Are Not One-Size-Fits-All. Frontiers in Marine Science 7:282. https://doi.org/10.3389/fmars.2020.00282

Petrişor, A.-I., Hamma, W., Nguyen, H.D., Randazzo, G., Muzirafuti, A., Stan, M.-I., Tran, V.T., Aştefănoaiei, R., Bui, Q.-T., Vintilă, D.-F., Truong, Q.H., Lixăndroiu, C., Ţenea, D.-D., Sîrodoev, I., Ianoş, I., 2020. Degradation of Coastlines under the Pressure of Urbanization and Tourism: Evidence on the Change of Land Systems from Europe, Asia and Africa. Land 9, 275. https://doi.org/10.3390/land9080275

Pickering, H., Whitmarsh, D., 1997. Artificial reefs and fisheries exploitation: a review of the 'attraction versus production' debate, the influence of design and its significance for policy. Fisheries Research 31, 39–59. https://doi.org/10.1016/S0165-7836(97)00019-2

Pinochet, J., Urbina, M.A., Lagos, M.E., 2020. Marine invertebrate larvae love plastics: Habitat selection and settlement on artificial substrates. Environmental Pollution 257, 113571. https://doi.org/10.1016/j.envpol.2019.113571

Planes, S., Jouvenel, J.-Y., Lenfant, P., 1998. Density dependence in post-recruitment processes of juvenile sparids in the littoral of the Mediterranean sea. Oikos 83, 293–300. https://doi.org/10.2307/3546840

Pougnet, F., Schäfer, J., Dutruch, L., Garnier, C., Tessier, E., Dang, D.H., Lanceleur, L., Mullot, J.-U., Lenoble, V., Blanc, G., 2014. Sources and historical record of tin and butyl-tin species in a Mediterranean bay (Toulon Bay, France). Environ Sci Pollut Res Int 21, 6640–6651. https://doi.org/10.1007/s11356-014-2576-6

Poursanidis, D., Topouzelis, K., Chrysoulakis, N., 2018. Mapping coastal marine habitats and delineating the deep limits of the Neptune's seagrass meadows using very high resolution Earth observation data. International Journal of Remote Sensing 39, 8670–8687. https://doi.org/10.1080/01431161.2018.1490974

Pyke, D.A., Thompson, J.N., 1986. Statistical Analysis of Survival and Removal Rate Experiments. Ecology 67, 240–245. https://doi.org/10.2307/1938523

R Core Team, 2022. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Rezania, S., Park, J., Md Din, M.F., Mat Taib, S., Talaiekhozani, A., Kumar Yadav, K., Kamyab, H., 2018. Microplastics pollution in different aquatic environments and biota: A review of recent studies. Marine Pollution Bulletin 133, 191–208. https://doi.org/10.1016/j.marpolbul.2018.05.022

Rich, J.T., Neely, J.G., Paniello, R.C., Voelker, C.C.J., Nussenbaum, B., Wang, E.W., 2010. A practical guide to understanding Kaplan-Meier curves. Otolaryngol Head Neck Surg 143, 331–336. https://doi.org/10.1016/j.otohns.2010.05.007

Roa-Ureta, R.H., Santos, M.N., Leitão, F., 2019. Modelling long-term fisheries data to resolve the attraction versus production dilemma of artificial reefs. Ecological Modelling 407, 108727. https://doi.org/10.1016/j.ecolmodel.2019.108727

Rodemann, J.R., Brandl, S.J., 2017. Consumption pressure in coastal marine environments decreases with latitude and in artificial vs. natural habitats. Marine Ecology Progress Series 574, 167–179. https://doi.org/10.3354/meps12170

Santos, M.N., Monteiro, C.C., 1997. The Olhão artificial reef system (south Portugal): Fish assemblages and fishing yield. Fisheries Research 30, 33–41. https://doi.org/10.1016/S0165-7836(96)00567-X

Saulnier, E., Le Bris, H., Tableau, A., Dauvin, J.C., Brind’Amour, A., 2020. Food limitation of juvenile marine fish in a coastal and estuarine nursery. Estuarine, Coastal and Shelf Science 241, 106670. https://doi.org/10.1016/j.ecss.2020.106670

Schaefer, N., Sedano, F., Bishop, M.J., Dunn, K., Haeusler, M.H., Yu, K.D., Zavoleas, Y., Dafforn, K.A., 2023. Facilitation of non-indigenous ascidian by marine eco-engineering interventions at an urban site. Biofouling 1–14. https://doi.org/10.1080/08927014.2023.2186785

Seitz, R.D., Wennhage, H., Bergstrom, U., Lipcius, R.M., Ysebaert, T., 2014. Ecological value of coastal habitats for commercially and ecologically important species. ICES Journal of Marine Science 71, 648–665. https://doi.org/10.1093/icesjms/fst152

Sims, D.W., Southall, E.J., Humphries, N.E., Hays, G.C., Bradshaw, C.J.A., Pitchford, J.W., James, A., Ahmed, M.Z., Brierley, A.S., Hindell, M.A., Morritt, D., Musyl, M.K., Righton, D., Shepard, E.L.C., Wearmouth, V.J., Wilson, R.P., Witt, M.J., Metcalfe, J.D., 2008. Scaling laws of marine predator search behaviour. Nature 451, 1098–1102. https://doi.org/10.1038/nature06518

Sipe, J.M., Bossa, N., Berger, W., von Windheim, N., Gall, K., Wiesner, M.R., 2022. From bottle to microplastics: Can we estimate how our plastic products are breaking down? Sci Total Environ 814, 152460. https://doi.org/10.1016/j.scitotenv.2021.152460

Smith, J.A., Lowry, M.B., Suthers, I.M., 2015. Fish attraction to artificial reefs not always harmful: a simulation study. Ecol Evol 5, 4590–4602. https://doi.org/10.1002/ece3.1730

Stewart, B.D., Jones, G.P., 2001. Associations between the abundance of piscivorous fishes and their prey on coral reefs: implications for prey-fish mortality. Marine Biology 138, 383–397. https://doi.org/10.1007/s002270000468

Strain, E.M.A., Cumbo, V.R., Morris, R.L., Steinberg, P.D., Bishop, M.J., 2020. Interacting effects of habitat structure and seeding with oysters on the intertidal biodiversity of seawalls. PLOS ONE 15, e0230807. https://doi.org/10.1371/journal.pone.0230807

Strain, E.M.A., Olabarria, C., Mayer-Pinto, M., Cumbo, V., Morris, R.L., Bugnot, A.B., Dafforn, K.A., Heery, E., Firth, L.B., Brooks, P.R., Bishop, M.J., 2018. Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? Journal of Applied Ecology 55, 426–441. https://doi.org/10.1111/1365-2664.12961

Tableau, A., Bris, H.L., Saulnier, E., Pape, O.L., Brind’ Amour, A., 2019. Novel approach for testing the food limitation hypothesis in estuarine and coastal fish nurseries. Marine Ecology Progress Series 629, 117–131. https://doi.org/10.3354/meps13090

Tanner, S.E., Teles-Machado, A., Martinho, F., Peliz, Á., Cabral, H.N., 2017. Modelling larval dispersal dynamics of common sole (Solea solea) along the western Iberian coast. Progress in Oceanography 156, 78–90. https://doi.org/10.1016/j.pocean.2017.06.005

Tessier, E., Garnier, C., Mullot, J.-U., Lenoble, V., Arnaud, M., Raynaud, M., Mounier, S., 2011. Study of the spatial and historical distribution of sediment inorganic contamination in the Toulon bay (France). Marine Pollution Bulletin 62, 2075–2086. https://doi.org/10.1016/j.marpolbul.2011.07.022

Therneau, T., 2023. survival.

Thiriet, P.D., Di Franco, A., Cheminée, A., Mangialajo, L., Guidetti, P., Branthomme, S., Francour, P., 2022. Adaptive Vertical Positioning as Anti-Predator Behavior: The Case of a Prey Fish Cohabiting with Multiple Predatory Fish within Temperate Marine Algal Forests. Animals 12, 826. https://doi.org/10.3390/ani12070826

Thrush, S.F., Halliday, J., Hewitt, J.E., Lohrer, A.M., 2008. The Effects of Habitat Loss, Fragmentation, and Community Homogenization on Resilience in Estuaries. Ecological Applications 18, 12–21. https://doi.org/10.1890/07-0436.1

Ushiama, S., Mayer-Pinto, M., Bugnot, A.B., Johnston, E.L., Dafforn, K.A., 2019. Eco-engineering increases habitat availability and utilisation of seawalls by fish. Ecological Engineering 138, 403–411. https://doi.org/10.1016/j.ecoleng.2019.07.022

Victor, B.C., 1986. Larval Settlement and Juvenile Mortality in a Recruitment-Limited Coral Reef Fish Population. Ecological Monographs 56, 145–160. https://doi.org/10.2307/1942506

Vozzo, M.L., Mayer-Pinto, M., Bishop, M.J., Cumbo, V.R., Bugnot, A.B., Dafforn, K.A., Johnston, E.L., Steinberg, P.D., Strain, E.M.A., 2021. Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates. Marine Environmental Research 165, 105243. https://doi.org/10.1016/j.marenvres.2020.105243

Wafo, E., Abou, L., Nicolay, A., Boissery, P., Perez, T., Ngono Abondo, R., Garnier, C., Chacha, M., Portugal, H., 2016. A chronicle of the changes undergone by a maritime territory, the Bay of Toulon (Var Coast, France), and their consequences on PCB contamination. SpringerPlus 5, 1230. https://doi.org/10.1186/s40064-016-2715-2

Warfe, D.M., Barmuta, L.A., 2004. Habitat structural complexity mediates the foraging success of multiple predator species. Oecologia 141, 171–178. https://doi.org/10.1007/s00442-004-1644-x

Welden, N.A., 2020. Chapter 8 - The environmental impacts of plastic pollution, in: Letcher, T.M. (Ed.), Plastic Waste and Recycling. Academic Press, pp. 195–222. https://doi.org/10.1016/B978-0-12-817880-5.00008-6

Whitfield, A.K., Pattrick, P., 2015. Habitat type and nursery function for coastal marine fish species, with emphasis on the Eastern Cape region, South Africa. Estuarine, Coastal and Shelf Science 160, 49–59. https://doi.org/10.1016/j.ecss.2015.04.002

Williams, B.A., Watson, J.E.M., Beyer, H.L., Klein, C.J., Montgomery, J., Runting, R.K., Roberson, L.A., Halpern, B.S., Grantham, H.S., Kuempel, C.D., Frazier, M., Venter, O., Wenger, A., 2022. Global rarity of intact coastal regions. Conserv Biol 36, e13874. https://doi.org/10.1111/cobi.13874